

Ball lightning development:

"in increments of 10^{-3} sec the researchers record the plasma ball's growth. Salts in the water give it a greenish glow." The final picture shows a peculiar optical appearance of the boundary of the fireball, which is likely to be associated with the measured much lower temperature of the outer boundary of the fireball. After Bührke (2008). Image provided as a courtesy of the Max-Planck-Institut für Plasmaphysik.

This issue : Fig . 10 in The physics of electrical discharges – I. Small-scale phenomena

**Special Issue on
Air-Earth Currents**



Earth & Space

NCGT International Conference

September 21-24, 2026

Parma (Italy)



– *An international journal for New Concepts in Global Tectonics* –

NCGT  **JOURNAL**

Volume 14, Number 2, February 2026. ISSN 2202-0039.

EDITORIAL BOARD

Editor-in-Chief: Bruce LEYBOURNE, USA (leybourneb@iascc.org)
Co-Editor-in-Chief: Valentino STRASER, Italy (valentino.straser@gmail.com)
Masahiro SHIBA, Japan (shiba@dino.or.jp)
Giovanni P. GREGORI, Italy (giovannipgregori38@gmail.com)
Louis HISSINK, Australia (louis.hissink@outlook.com)
Per MICHAELSEN, Mongolia (perm@must.edu.mn)
Biju LONGHINOS, India (biju.longhinos@gmail.com)
Vladimir ANOKHIN, Russia (vladanokhin@yandex.ru)

CONTENTS

EDITOR'S CORNER - Comments by Editor in Chief - Bruce Leybourne.....	115
Announcements on Upcoming Conferences - " CALL FOR PAPERS "	115
Letters to the Editor.....	117
Online Book.....	118
Company Profiles.....	119
Article: Measuring the electric field at ground: Giovanni Pietro Gregori, Bruce Allen Leybourne.....	120
 The physics of electrical discharges – I. Small-scale phenomena: Giovanni Pietro Gregori, Bruce Allen Leybourne.....	129
 The physics of electrical discharges – II. RB & TGFs Runaway breakdown –terrestrial gammaflashes – GK effect: Giovanni Pietro Gregori, Bruce Allen Leybourne.....	153
 The physics of electrical discharges – III. Large-scale phenomena Sparks and lightning - Electrostatics of the ionosphere – TLEs Plasma jets collimation – Birkeland currents and sea-urchin spikes - Solar γ-rays - Stellar and galactic alignments: Giovanni Pietro Gregori, Bruce Allen Leybourne.....	171
 The Fukushima theorem: Giovanni Pietro Gregori, Bruce Allen Leybourne.....	208
 Space weather related to potentially destructive seismic activity: Valentino Straser , Gabriele Cataldi, Daniele Cataldi.....	220
 About the NCGT Journal	224

For donations, please feel free to contact the Research Director of the Geoplasma Research Institute, Mr. Bruce Leybourne, at leybourneb@iascc.org. For contact, correspondence, or inclusion of material in the NCGT Journal please use the following methods: *NEW CONCEPTS IN GLOBAL TECTONICS*. 1. E-mail: leybourneb@iascc.org (files in MS Word or ODT format, and figures in gif, bmp or tif format) as separate files; 3. Telephone, +61 402 509 420. **DISCLAIMER**: The opinions, observations and ideas published in this journal are the responsibility of the contributors and do not necessarily reflect those of the Editor and the Editorial Board. *NCGT Journal* is a refereed quarterly international online journal and appears in March, June, September and December. *ISSN number*; ISSN 2202-0039.

EDITOR'S CORNER: - Comments by Editor in Chief - Bruce Leybourne

Announcements on Upcoming Conferences - "CALL FOR PAPERS"

21-24 September 2026 – NCGT in Italy

Organized by Valentino Straser (valentino.straser@gmail.com)

Timetable for participating in the conference:

Open abstract March 1, 2026

Abstract acceptance May 31

Payment due by June 15, 2026 (To organizing committee)

Publication of conference and abstract book September 1, 2026

September 21-24, 2026, International NCGT Conference - Parma, Italy



Regarding information for authors:

Abstract: 150 words (maximum)

Short CV: 300 words (maximum) and a photo.

For formatting and fonts, use NCGT Journal.

Abstract submission opens March 15, 2026

Conclusion: May 31, 2026

Confirmation of abstract acceptance: June 15, 2026

Information website about the city of Parma and its province:

[homepage - Informazioni turistiche su Parma e provincia](#)

Attempting for hotel with a meeting room in the center of Parma less than 500 meters from the train station.

"Earthquake Forecasting with Space Weather between Heaven and Earth" summarizes the contents of the NCGT 2026 Conference scheduled in Parma from September 21 to 24, 2026. The NCGT team returns after fifteen years, to discuss Earth model innovations and scenarios for understanding geophysical processes and space weather effects. And, more traditionally, new models of Global Tectonics.

Understanding the Earth today means looking beyond the traditional boundaries of geology and geophysics, combining expertise ranging from electromagnetism to atmospheric physics to space weather. The "Earth & Space" conference was born with this objective: to propose an integrated interpretation of geophysical phenomena, exploring the role of electromagnetic signals as potential precursor indicators of seismic events and analyzing the contribution of new technologies for data observation and interpretation.

In recent decades, studies inspired by the global electric circuit model, a concept developed from the insights of scientists in recent decades, have highlighted how the Earth's atmosphere, ionosphere, and planetary surface constitute an electrically connected system. From this perspective, processes occurring in the lithosphere, including those preceding an earthquake, could produce measurable variations in electromagnetic fields and ionospheric properties.

The conference aims to further analyze the so-called "candidate seismic precursors" of electromagnetic nature, evaluating their potential and limitations considering the latest scientific evidence. The integration of highly sensitive ground-based sensors, satellite networks, and ionospheric monitoring systems opens new perspectives in multi-parametric data collection and modeling of phenomena.

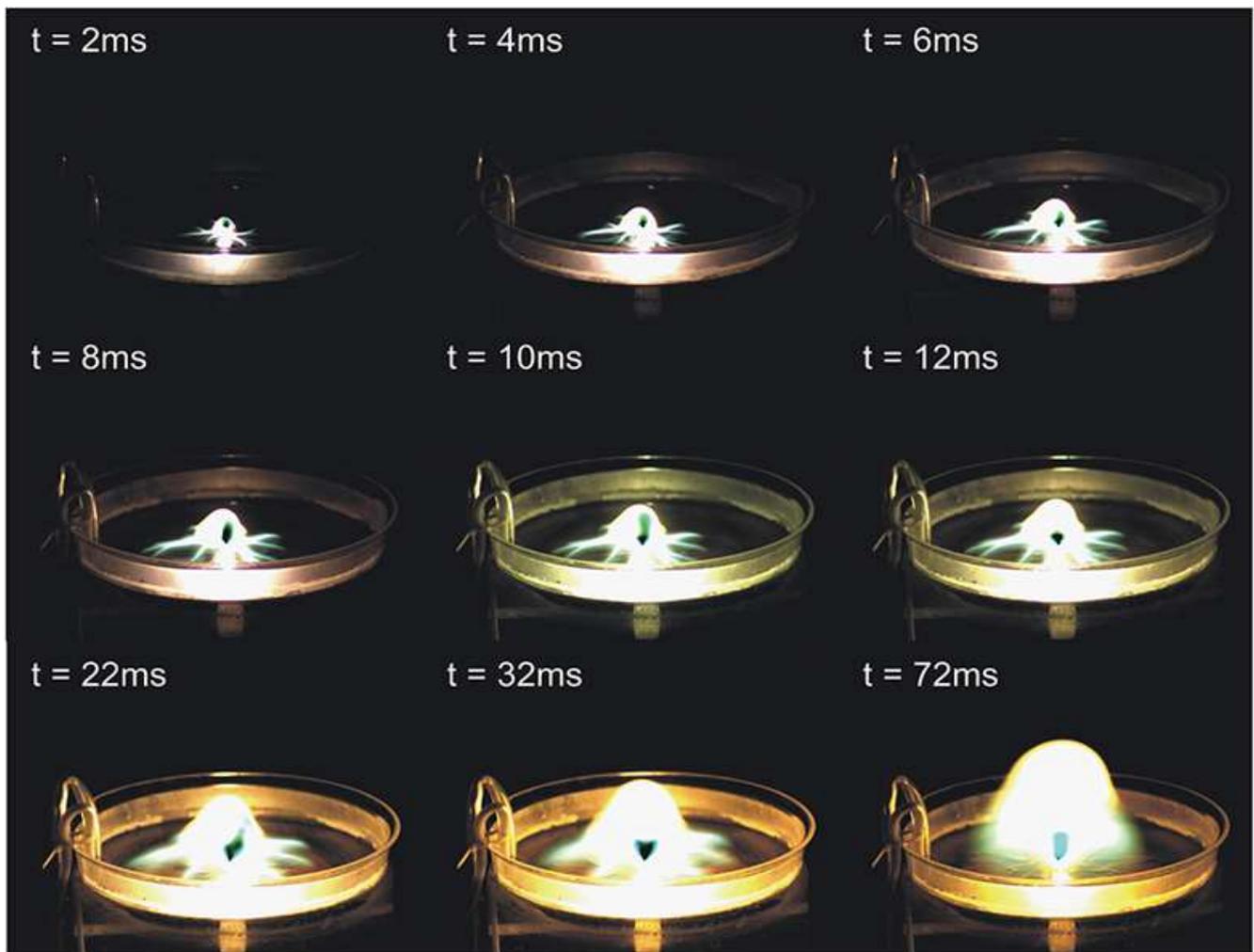
Special focus will be on the role of the Sun. Solar activity monitoring from NASA missions and international space weather programs, indicate influences in the ionosphere and Earth's magnetic field, have potential implications for climate and geodynamic systems. Understanding the interactions between the solar wind, the magnetosphere, and Earth's internal processes represents a crucial frontier for interpreting complex geophysical events from a systemic perspective.

"Earth & Space" therefore proposes new interpretative concepts, encouraging us to move beyond compartmentalized visions to embrace a dynamic and interconnected model of the planet. Earth's evolution is not merely the result of endogenous forces but can be interpreted as the product of a continuous dialogue between space and the surface, between solar energy and deep-seated processes.

The conference is aimed at researchers, professionals, administrators, and citizens interested in understanding how new technologies and interdisciplinary models can contribute to a more advanced understanding of natural phenomena. It will provide an opportunity for scientific and cultural exchange to explore the future challenges of prevention, sustainability, and risk management on an increasingly complex planet.



- 1.) Straser - EQ forecasting (Abstracts requested)
- 2.) Leybourne - Stellar Transformer - Global Space Weather interactions (6 Abstracts in Editor's Corner within New Concepts in Global Tectonics Journal - Volume 12, Number 4, December 2024)
- 3.) Anokhin - Lake Ladoga - Siberia (2 Abstracts in Editor's Corner within New Concepts in Global Tectonics Journal - Volume 13, Number 1, March 2025 pp. 5-8, more abstracts requested)
- 4.) Longhinos - Indian Tectonics (Abstracts requested)



Cover Image : “Ball lightning development: in increments of 10^{-3} sec the researchers record the plasma ball’s growth . Salts in the water give it a greenish glow.” The final picture shows a peculiar optical appearance of the boundary of the fireball, which is likely to be associated with the measured much lower temperature of the outer boundary of the fireball. See text. Figure and captions after Bührke (2008). Image provided as a courtesy of the Max-Planck -Institut für Plasmaphysik. See this issue: **Fig. 10 in The physics of electrical discharges – I. Small-scale phenomena**

Letters to the Editor: Giovanni Gregori discusses research papers

The present issue contains the following six papers:

~Gregori, G.P., and B.A. Leybourne, 2025d. Measuring the electric field at ground.

~Gregori, G.P., and B.A. Leybourne, 2025e. The physics of electrical discharges – I. Small-scale phenomena - Fog - atmospheric precipitation – *BLs*.

~Gregori, G.P., and B.A. Leybourne, 2025f. The physics of electrical discharges – II. *RB & TGFs* - Runaway breakdown – terrestrial gamma flashes – *GK* effect.

~Gregori, G.P., and B.A. Leybourne, 2025g. The physics of electrical discharges – III. Sparks and lightning - electrostatics of the ionosphere – *TLEs* - plasma jets collimation – Birkeland currents & sea-urchin spikes - stellar and galactic alignments.

~Gregori, G.P., and B.A. Leybourne, 2025h. The Fukushima theorem.

~Straser, V., G. Cataldi, and D. Cataldi. Space weather related to potentially destructive seismic activity.

The measurements of the electric field E at ground have always been biased by some severe physical misconception. Owing to this reason they were finally abandoned, even though, historically, they had been started at the same time of the early measurements of the geomagnetic field.

The former fabulous records by Friedrich Heinrich Alexander Freiherr von Humboldt (1769-1859) later evolved into the present planetary network of geomagnetic permanent observatories. Much different was the fate of E records - even though another drawback that prevented to associate a clear significance of E records was probably related to the larger point-to-point variability. By the way, this is related to the heart of the delicate physics associated to atmospheric precipitation phenomena.

The first paper deals with a correct physical assessment of this basic historical gap in E records for Earth monitoring. The next three papers address the physics of an “electrical discharge”. Note that even one moving electron alone must be considered as an electrical discharge. Phenomena of electrical discharge are extremely varied. In addition, as often stressed in the literature, the concern has been generally devoted to the way to prevent the damages caused by an electrical discharge (such as a lightning), rather than focusing on the basic physical processes that are involved. The set of three papers is therefore an attempt to put an order into this difficult, – and sometime debated – multi-faceted difficult topic.

The fifth paper focuses on a classical topic, which is now basically only of historical interest. It deals with the long-lasting and vivid debate about the dichotomy between the so-called Chapman-Vestine currents and the Birkeland-Alfvén currents. The Chapman-Vestine currents rely on the rationale formerly envisaged in a famous article for the *Encyclopædia Britannica* by Balfour Stewart (1828-1887), who in 1882 argued that electric currents flow in the layers of the tenuous upper atmosphere that is now called ionosphere. The concept was later shared in the famous classical book by Sydney Chapman and Julius Bartels of 1940, which remained for several decades the basic reference for the formation of all geophysicists. The concept was later supported by the American scientist Ernest Harry Vestine (1906-1968).

An alternative viewpoint was formerly proposed in 1901 by the Norwegian scientist Kristian Olaf Bernhard Birkeland (1867-1917), while dealing with polar auroræ that he explained by means of electric currents precipitating over the polar caps along B field lines. These are now called Birkeland currents, or also field-aligned currents (FACs), and the concept was later shared and revived by the Swedish scientist Hannes Olof Gosta Alfvén (1908-1995), Noble Laureate for his contributions to the study of plasmas.

The dichotomy between the two-current systems persisted until 1967, when a large meeting was held at Sandefjord, in the Oslo fjord. A hard, though always polite, debate was held. It appeared clear that the progressively available records confirm that both processes occur. In fact, tidal motions in the atmosphere are associated with the co-called Sq and L geomagnetic variations, which are associated to Chapman-Vestine currents. However, a permanent and time-varying bunch of FACs always occurs over both polar caps.

During his flight back home to Tokyo after the meeting, Naoshi Fukushima (1925-2003) - a very kind and nice person and friend who for several years served as General Secretary of IAGA - found the argument that was later called “Fukushima theorem”. He showed that it is conceptually impossible, by ground-based records alone, to distinguish between Chapman-Vestine currents and Birkeland-Alfvén currents. I believe that Professor Naoshi Fukushima was one of the most astute minds of the 20th century. The fifth paper in this special issue is a review of this general item, which is now of mainly historical interest.

By the way, to my knowledge Professor Naoshi Fukushima has been the only scientist who recently emphasized the need to reconsider the former working hypothesis by Gauss, who assumed that, as a planetary mean, one can neglect the role of air-earth currents. This is the leading anthem of the several papers that we devoted to the discussion of air-earth currents.

The last paper investigates the potential coupling between (i) solar ion flux in the solar wind and (ii) over 1,300 earthquakes of magnitude 6 or greater, occurred on a global scale. The study highlights the non-randomness of seismic events compared to increases of the proton density. The result has statistical value, because a convincing and rigorously proven scientific theory has not yet been fully formulated. The present large set of papers devoted to the air-earth currents can certainly provide several issues suited for a better understanding of the interaction between electrical circuits in the Sun-Earth relations and crustal stress, which eventually leads to the occurrence of a strong earthquake.

New Book

G. P. Gregori (born 1938), Degree in Physics (1961, Univ. of Milan),

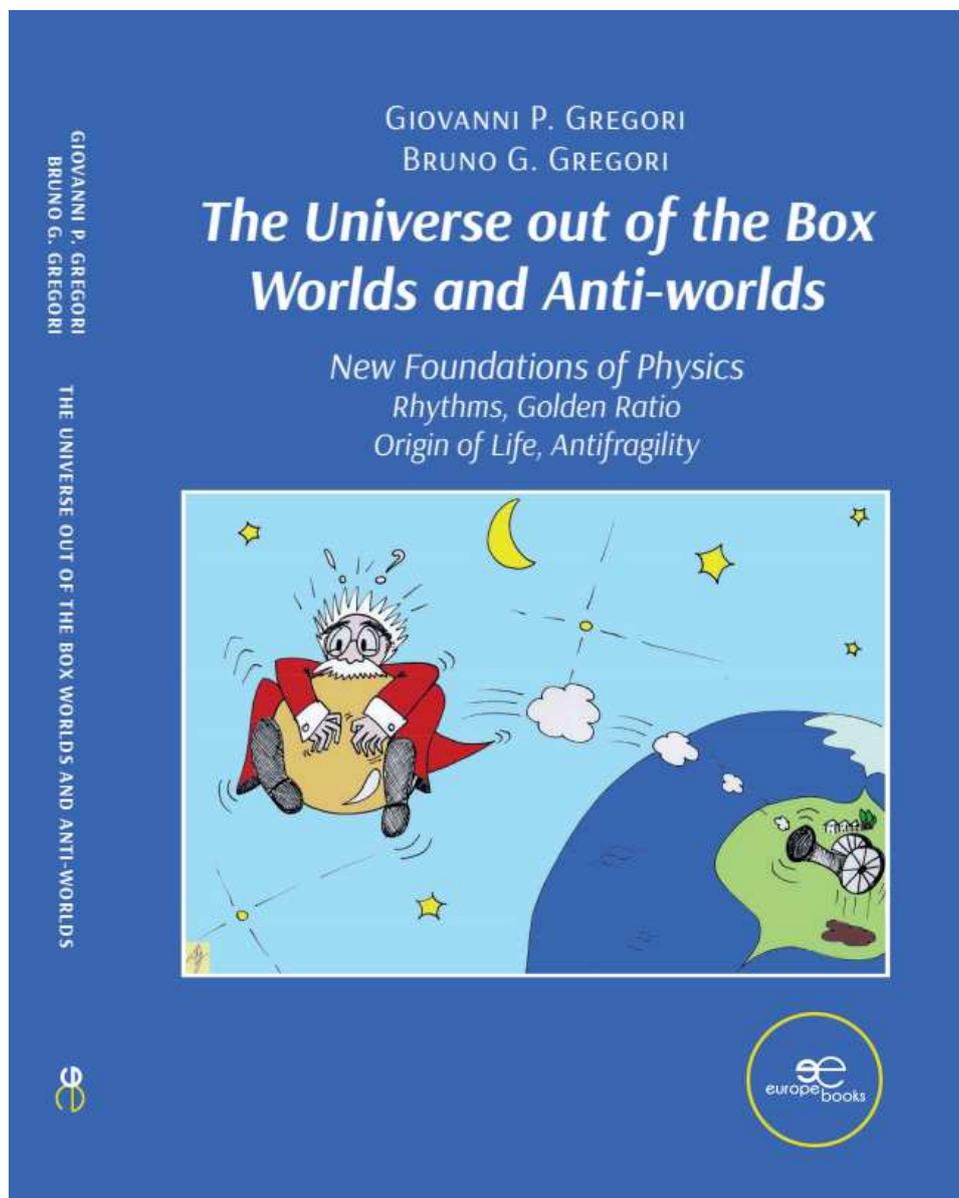
B. G. Gregori (born 1967), Degree in Medicine and Surgery (1992) and Specialization in Neurology (1999)

Science is suffering an identity crisis. Our “widespread scientific knowledge” is “static”.

Our mind dislikes uncertainty. Not relying on the mainstream is uncomfortable, but we gain better awareness of the world and of ourselves. This book is challenging. It stimulates the reader also on a psychological level, and tries to explain concepts that to most people consider abstruse. It is a journey where mind can dance between quantum physics, cosmology, theology, Greek philosophy and the mystery of life and death. Science is logic, and a scientist can never give up. Many present unsolved paradoxes can find a solution.

At present, we are biased by: 3 “original sins” in Newton’s principles, by an Einstein’s mistake, and by a misconception of “absolute” time and of the perception of time passing. A new formulation is presented, which is a substantial advancement compared to Galileo, Newton, Maxwell and Einstein.

<https://www.europebookstore.com/products/the-universe-out-of-the-box-worlds-and-anti-worlds-g-p-gregori-and-b-g-gregori/>



Company Profiles:

Tesla 3D, Inc. is an independent research and development company with a strong applied science foundation, enabling rapid and practical innovation in the energy and exploration sectors. While not a large enterprise, Tesla 3D, Inc. stays well informed about breakthroughs in electrical generation, storage, and mining technologies. When called upon, the company can comprehend complex challenges and develop strategic, real-world plans that effectively navigate regulations, funding mechanisms, and policies. Tesla 3D, Inc. actively contributes to national and industry advancement through volunteer leadership, including participation in the Homeland Security Taskforce focused on energy resilience and EMP (electromagnetic pulse) threats. The company also set a precedent by independently qualifying for federal Innovation (R&D) Tax Credits; demonstrating that small, agile innovators can leverage these incentives to streamline regulatory solutions and tackle critical infrastructure challenges. This involvement underscores Tesla 3D, Inc.'s commitment to advancing energy security and shaping the transformative role of technology in resource development. Founded: 2011 Colorado by R. Miller.

Geo-Transect LLP (www.tgeo.co.in) Geo-Transect LLP is a knowledge-driven geoscience consultancy, specializing in subsurface exploration and environmental intelligence across India. With core expertise in subsurface mapping, groundwater zonation, aquifer recharge quantification, coastal and shoreline analysis, landscape and topological planning, and island conservation, the firm delivers data-driven insights that empower sustainable planning and development. Representing the forefront of India's earth-science services sector, Geo-Transect blends scientific precision with advanced technologies to support governmental, industrial, and research-based initiatives across southern India and beyond. Integrating indigenous knowledge with global best practices, the firm is committed to environmental stewardship and responsible resource management. Guided by the ethos "With Wisdom in Nature," Geo-Transect envisions a future where scientific understanding harmonizes development with the natural world.

Stellar Transformer Technologies (<https://stellartransformertechnologies.com/>) is a private geophysical modeling company specializing in modeling the dynamic electro-magnetic Stellar Transformer interactions between Earth-Sun and planets within our solar system. Original research started in 1995 by the current owner and founder during investigations of the seafloor as a geophysicist with the Naval Oceanographic Office at Stennis Space Center. Leading to an understanding and application of new tectonic theories. Later research confirmed dynamic links to space weather affecting a myriad of environmental factors: such as everyday weather; hurricanes; tornadoes; sever weather outbreaks; earthquakes; global climate-change; and certain types of wildfire outbreaks from passing coronal mass ejections induced by internal core generated Electro-Magnetic Pulses (EMP). Current and planned services include mapping of Stellar Transformer circuits; innovative modeling of deep earth magnetics, forecasting Earth's natural hazards listed above; database development and more. Combining big data and AI to find inter-relationships. Developing algorithm inputs for forecasting, data visualization and simulations. All leading to new forecasting technologies. We are actively assisting the EMP Task Force power grid protection efforts with direct input and evaluation of EMP threats. Our company comprehends the complex challenges of geophysical modeling and development of real-world forecasting applications. Electro-magnetic or magnetic induction is the production of an electromotive force, or voltage, across an electrical conductor in a changing magnetic field. The Stellar Transformer Concept contends that simple step-down energy induction occurs between Sun and Earth, much like the transformer process that steps down your household energy from higher voltage transmission lines sourced from the power company. The Sun represents a large coil from the power company, while the Earth represents the smaller coil to your home. The larger coil element generally excites current into the smaller coil element by induction of "step down energy", although lesser feedback mechanisms occur due to the action/reaction principles. Layers within the Earth hold and release charge acting as condensers, or capacitance layers. Thus, the Earth operates somewhat like a battery where energy is either stored or released through time-change of state-of-matter. We combine new Geophysical Intelligence with AI for a winning combination of innovations that will bring new mitigation strategies for space weather to the forefront. Bringing a paradigm shift to the business community for global environmental forecasting based on solar and planetary effects. This will save lives and mitigate property damage using new science and innovative technologies. Many of these ideas were first presented at EU2015 - Electric Universe (<https://www.youtube.com/watch?v=IoggZhbxxhU>). Followed up at EU2016 with discussions on geometrical modeling applications, adhering to golden ratio principles (<https://www.youtube.com/watch?v=Q355Haapq-0>). Founded: 2023 in Colorado by Bruce Leybourne – Owner/Operator.

Measuring the electric field at ground

Giovanni Pietro Gregori¹, Bruce Allen Leybourne²

¹Former Senior Researcher at IDASC-Institute of Acoustics and Sensors O. M. Corbino (CNR), Rome, now merged into IMM Istituto per la Microelettronica e Microsistemi (CNR) Italy; and ISSO-International Seismic Safety Organization, Italy

²GeoPlasma Research Institute-(GeoPlasmaResearchInstitute.org), Aurora, CO 80014, USA

Corresponding Author:

Giovanni Pietro Gregori
IDASC-Istituto di Acustica e
Sensoristica O. M. Corbino
(CNR), Roma, now merged
into IMM-Istituto per la
Microelettronica e
Microsistemi (CNR) Italy

e-mail:

giovannipgregori38@gmail.com;

leybourneb@iascc.org

Abstract: The measurement of the electric field E at ground, i.e., the so-called “potential-gradient”, is generally carried out by measuring the voltage difference between two points, one in air, the other in ground. The “contact” between either point or the probe is, however, biased by disturbances that largely overwhelm the effect to be measured. This most serious drawback caused severe controversies. Past records are basically useless. Measurements are rather to be carried out by means of induction in a rotating electrostatic device (*r.e.d.*). The perturbations are also discussed of conducting objects in air.

Keywords: atmospheric potential gradient – grounding – contact probe/air - rotating electrostatic device

Introduction

“Obviousness”, “well-known facts”, “college physics”, “general agreement” sometimes are a bias, mainly when dealing with comparatively “elementary” items. It thus happened, in the past and even at present, that several misconceptions still bias the measurement of the electric field E at ground, i.e., the so-called “potential gradient”. The records are useless. The whole item must be physically and critically reconsidered. Reliable records are essential for the understanding of the atmospheric electric circuit, and for the exploitation of the electrostatic energy of the atmosphere.

Scale-size of the electromagnetic field

The scale-size is very often misunderstood of electromagnetic (e.m.) phenomena in the natural environment. A researcher is acquainted with laboratory experiments, and the focus is therefore on the continuity approximation. This is a mathematical concept. The explanation of instrumental-scale measurements is interpreted in terms of laws that apply to the infinitesimal scale-size. Owing to the continuity approximation, the ultimate role is thus neglected both of the molecular and atomic structure of phenomena, and of the relevant role played by the great mobility of electrons. Even a very tiny presence of free electrons can dramatically change the occurrence of local phenomena. The associated physical and chemical processes are very likely to be fundamental for several often-unexplained observations, either in the environment or even in biology.

As far as the environment is concerned, two leading items are here to be recalled.

The “Cowling dynamo” process (Gregori et al., 2024d) is a ubiquitous process that occurs on every scale-size - and derives from the generalized Cowling theorem. This property seems to be “universal”, almost as general as the Pythagoras theorem. It transforms every motion of charged

particles (hence every thermal convection etc.) into an e.m. field with toroidal magnetic field B . Consider that, since every natural system is contained inside a space domain of finite volume, every motion is always associated to a closed trajectory, such as a convective cell but also every other loop.

On the several centimeters scale-size, this is the explanation for the mysterious ball-lights (BLs). On the same scale-size, it justifies several previously unexplained features of a spark or of a lightning discharge. The measured speed of a lightning is much lower than the speed of light. In addition, the linear pattern of a discharge is explained, in contrast with any possible very large volumetric scale of a discharge – i.e., a lightning ought to look like a diffuse glow, rather like a zig-zag line. See Gregori and Leybourne (2024e).

On the scale-size of the cloud convection cells, the Cowling dynamo provides an excellent explanation (Gregori and Leybourne, 2024f, 2024g), of the lightning discharges, which are observed mainly intra-cloud (IC) than as cloud-ground (CG) discharges. In addition, the Cowling dynamo explains the mysterious transient luminous emissions ($TLEs$) of the middle atmosphere (above clouds), and mostly the electrostatic charge of the ionosphere. Moreover, the phenomenon is certainly extended through the magnetosphere, thus determining a projection of E field from the lower atmosphere into the magnetosphere and solar wind, just like a thermally supplied e.m. generator with effects projected into the solar wind (Gregori and Leybourne, 2021). But, also phenomena enter into play that are of a smaller scale-size, as mentioned below.

On the larger scale-size, the Cowling dynamo justifies the unexplained self-collimation of the solar wind, that has important consequences on the impact of the electrostatic charge of the expanding solar corona, hence of the solar wind and on its impact on the Earth (Gregori et al., 2024a and 2024b).

Other related, and often unexplained phenomena – even though they are often tentatively explained by some *ad hoc*

speculated mechanism – are concerned, e.g., with the filamentary patterns observed in solar and stellar phenomena, and also in the observed alignment of stars inside galaxies and their jets (e.g., Fukui et al., 2006; Taylor and Jagannathan, 2016), and also of galaxies inside supergalactic clusters (Tully et al., 2014). See also Gregori et al. (2024w) for extensive discussion.

As far as the present discussion is concerned, the focus is rather on the smallest scale-sizes.

On the sub-millimeter scale-size, micro-convection cells, owing to air ionization, imply two important, and presently otherwise unexplained, phenomena.

One process originates the deadly "terrestrial gamma flashes" (*TGFs*), i.e., violent bursts of intense γ -rays, that are generated inside clouds, being Bremsstrahlung radiation released by abruptly accelerated electrons. The acceleration occurs through the so-called "runaway breakdown" (*RB*) process that derives from the fact that the cross-section of the interaction of electrons with air molecules dramatically decreases when the E field gets above a threshold. Refer, e.g., to Gurevich and Zybin (2005) and references therein. The concern is therefore about the "seed" E -field that accelerates electrons above some minimum threshold in order to trigger the *RB* process. The seed E field is provided by the Cowling dynamo process, as a comparatively more intense small convection cell is sufficient to generate the needed E .

TGFs are believed to be responsible for several unexplained plane crashes. A *TGF* produces neutrons that instantaneously damages all electronic circuits (Tavani et al., 2013a). Every manmade device is instantaneously affected. Abruptly all electronics stop working, including, e.g., every device on an airplane and all portable satellite-connected phones. An aircraft instantaneously and totally disappears from flight-control monitors, and no recovery can anymore occur of any electronic device. Even the aircraft black-box contains no information, as at the same time instant the black-box abruptly stops to record any malfunctioning.

Another fundamental process of micro-Cowling-dynamos is the unexplained coalescence of water vapor on condensation nuclei. In fact, at present, it is well-known that no explanation is available for atmospheric precipitations. Whenever a droplet is formed, its accretion is controlled by thermodynamic processes (i.e., balance between evaporation and surface tension of the droplet). However, the previous formation of a small droplet is unexplained. In fact, an ion is a potential condensation nucleus, but the time needed for the formation of a droplet is unrealistically long.

A micro-convection cell transforms a tiny thermal energy into a tenuous E field, which is active only on charged ions through the electrically neutral water molecules. A water molecule is an electric dipole and coalesces on the outer surface either of an ion or of an extremely tiny droplet (Fig. 1). That is, either the ion or a tiny droplet, owing to the E field of the micro-Cowling-dynamos, moves through the neutral water molecules and

operates like a broom that collects water. Hence, the E field is crucial for the formation of droplets that later either remain suspended in air (fog), or precipitate by gravity. The Cowling dynamo is the crucial mechanics.¹

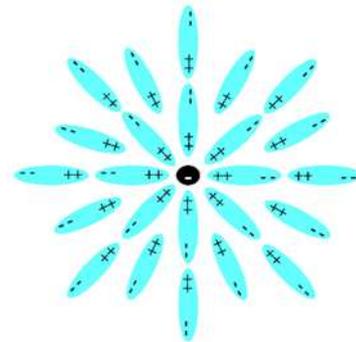


Fig. 1 – A cartoon showing the agglomeration of water molecules like electric dipoles around a condensation nucleus with negative electric charge. A symmetric case history occurs for a positively charged ion or particle. Unpublished figure.

In addition, also on the atomic or molecular scale-size the e.m. field plays a fundamental and extremely important role. In fact, it must be considered that the presence of even a very small number of excess free electrons can determine a dramatic change of processes. The effect is probably very important in the largely unexplored realm of molecular biology. As far as environmental processes are concerned, the electrical conductivity of air is a fundamental controller of the role played by the E field in the planetary electrical circuit. These extremely tiny effects cannot be neglected as they are likely to be often the leading drivers (see, e.g., the extensive discussion in Gregori et al., 2024w).

The E field is one facet of the e.m. field. In addition, probably, as far as the micro-scale-size is concerned, the E field is (maybe) more critical than the B field. Owing to this reason, historically, monitoring of B field records had a better luck than concerning the E field (see below).

In any case, the extremely delicate and crucial role has always been underestimated, due to a "general agreement", of the space-gradient of the e.m. field in environmental phenomena.

A matter of grounding – Spontaneous potentials

An unfortunate, generally agreed and conventional, assumption deals with the speculated electric potential of planet Earth, by which the Earth is likened to a huge approximately perfect equipotential conductor. That is, the grounding of every instrument is assumed to be the same all over the globe.

This fundamental misconception, which still survives in the scientific community, has a root in the hectic time of the early decades of 1800, when Earth sciences enjoyed a strong impulse following the marvelous "dream" of the Enlightenment. Among several best-

precipitations cannot be effective, as the phenomenon is mostly electrostatic.

¹ Note that the often-reported attempts of chemicals injected in the atmosphere aimed to trigger

known scientists, Humboldt² and Gauss³ were, maybe, the most outstanding leaders.

In 1798, Humboldt had started his expedition to Southern and Central America (during 1799-1804). He started several measurements of the magnetic field at different sites, also investigating time-variation, etc. Between April and November 1829, he made a journey in Central Asia and Siberia - with talks given at the *St. Petersburg Academy of Sciences* before and after the journey, recommending to install geomagnetic observatories. By the middle of 1830, 11 observatories were in operation (Rykatchew, 1900) from Arkhangel'sk to Beijing, from St Petersburg to Sitka (Alaska was part of Russia, as the U.S. purchased Alaska in 1867). This Humboldt's initiative represented an impulse to several other geomagnetic observatories and represented the start of the present international network. Several observatories were installed for Earth sciences based on the existing network of astronomical observatories. In 1839, Macedonio Melloni (1798-1854) was appointed Director of the *Osservatorio Meteorologico Vesuviano* - that was formerly established in 1841 (at that time geomagnetism and volcanology were considered part of meteorology). This has been the very first historical volcanological observatory. The *First International Polar Years (IPY)* was held in 1882-1883.

Also "telluric currents" - i.e., records that at present are generally called "spontaneous potentials" - were recorded by putting two electrodes in ground connected by a cable in order to measure the potential difference between the electrodes. Several groups carried out measurements, with orthogonal lines of length ranging from a few hundred kilometers through a few hundred meters. When Gish (1936a, 1936b) authoritatively attempted to make an exhaustive review of the available records, he just missed the correct phase of the planetary currents by $\sim 90^\circ$ (see details in Lanzerotti and Gregori, 1986).

During the 1870s, a particularly harsh controversy afflicted the scientific community on these items. The young generation of scientists later abandoned this discipline, while the geomagnetic records experienced an impressive flourishing. The reason of such a scientific debacle of "telluric currents" is clearly - though unconsciously - explained by Airy (1868), who used two orthogonal lines in London, each one a few kilometers long. His wires were grounded to the water pipes of the London aqueduct. That is, he recorded, not the telluric currents in ground, rather the potential induced into the pipes of the aqueduct that operated like a receiving antenna. In general, other experimenters did not explain diligently the way they grounded their electrodes. Therefore, no agreement could be found between different records, as every record had a different bias. A harsh debate followed and could not be settled.

Moreover, another drawback became progressively evident. It was concerned with electrode polarization

caused by Galvanic effects, by which the grounding efficiency was progressively deteriorated. This drawback represented therefore a most serious bias for long-lasting monitoring.

The best known present surviving technique is the so-called magnetotelluric (*MT*) technique that combines two orthogonal records of spontaneous potential - called *E*-field records, collected by cables at least a few ten meter long - with simultaneous records at the same location of two horizontal components of the geomagnetic field *B*. Usually, a campaign is carried out, which lasts, say, typically a couple of weeks. Electrode polarization is bypassed by putting in ground some semi-permeable buckets (e.g., in ceramic) filled with a slightly acidic water solution. The semipermeable material ensures a flow with the ground. Every electrode is immersed in the water bucket. The Galvanic effects associated with the polarization of the electrode are avoided, as the electrode is promptly polarized when it is put in contact with the acidic solution.

On the other hand, this technique introduces a potential between electrode a ground that changes vs. time depending on the varying acid concentration in the bucket (see Fig. 2d). That is, only the timescale is changed of the drift of the electrode performance. This device is therefore suited for campaigns of limited duration - in fact *MT* is used for prospecting purpose - while it is unsuited for long-lasting *E* monitoring.

In addition, the most serious basic physical bias for these measurements is derived by planetary-scale telluric currents that are channeled through the most conductive layers close to Earth's surface. The electrical conductivity of sea water is $\sim 40,000$ times greater than dry rocks'. See Lanzerotti and Gregori (1986) and references therein. One should consider that the instant telluric currents that flow underneath a given observatory can be originated even at an antipodal location, as the whole Earth responds like a unique conductor embedded in the e.m. signal originated by the solar wind. In the case of *MT* prospecting, a particularly perturbed period of records is just rebutted and the measurement repeated.

In the late 1960s, or early 1970s, *IAGA* asked a group of scientists, chaired by Professor Juan G. Roederer, to review and check the possible use of available historical dataset of "telluric current" records. The leading idea was that much like it occurs for geomagnetic observatories, the *E* records ought to be worthy of international coordination. After careful analysis, the available past records resulted incomparable with one another, having evidently some serious instrumental bias. Data were therefore rebutted.

Grounding and potential gradient - "Field mill"

At present, the instrument grounding is still used,

² Friedrich Wilhelm Heinrich Alexander von Humboldt (1769-1859).

³ Johann Carl Friedrich Gauss (1777-1855).

particularly to record the E -field at ground – i.e., of the so-called “atmospheric potential gradient”. Maybe, the best-known instrument is the so-called “field-mill”. A “mill” is a miniaturized replica (on the $\sim 1m$ scale-size or even smaller) of the several meters instrument of the former potential-gradient test-plate apparatus used by the famous Charles Thomson Rees Wilson (1869-1959) (see Torreson, 1939).

The operative principle is shown in Fig. 2a. A vertical rod A with a ball B (sometimes a spike) on top of it, is grounded. Another rod C is rotated in such a way that a plate D is alternatively located either on top of the rod A, or not - being thus a periodical Faraday screen against electrostatic induction. The electric potential is measured between ground and point B – upon supposing that point B is at the same potential of surrounding air (see below). Upon suitable calibration, the environmental electric field- E can be monitored vs. time.

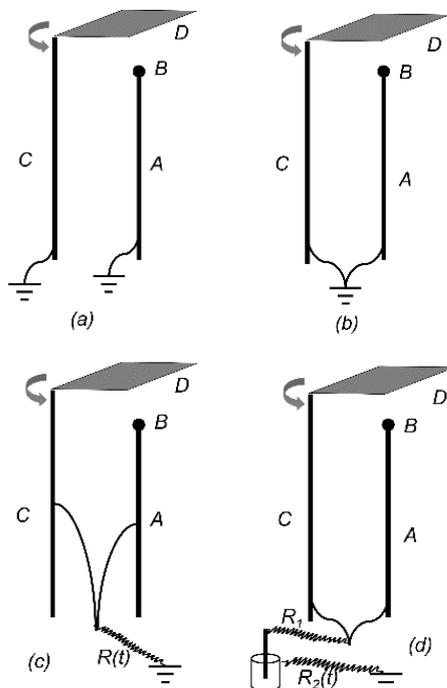


Fig. 2 - Working principle of a "mill" detector for measuring the atmospheric potential gradient. See text. Unpublished figure.

The choice of a ball or a spike located at point B implies a different impact caused by the self-charging (hence self-screening) of the instrument. That is, using a ball instead of a spike is a way of getting rid of the nuisance represented by point-discharge (“corona”) phenomena. As a practical way of operation, one unique grounding can be used, such as in Fig. 2b. In the original large-scale device operated by C.T.R. Wilson this grounding was simply made by means of a buried large metal plate.

The device of Fig. 2b ought rather to be considered according to Fig. 2c. The so-called grounding point results

connected to soil through a resistance $R(t)$, which is not constant in time. Galvanic effects enter into play. The water content of soil - in addition to its chemistry and temperature, and to vegetation - plays a crucial role. In fact, vegetation is critical due to corona effect, particularly, e.g., on the points of grass leaves. Hence, the amount of this unwanted perturbation also depends on the vegetative stage of the biosphere, such as the height of grass leaves, etc. In addition, the metal, which is in contact with ground, suffers from oxidation, i.e., the electrode is subjected to progressive polarization vs. time (Galvanic effect).

If one applies the aforementioned MT technique by means of a bucket with tenuous acidic solution (see Fig. 2d), the device - rather than solving the problem - shifts the experimental setting from of Fig. 2c into the experimental setting of Fig. 2d. That is, in this way the former resistance $R(t)$ was split into the sum of a resistance R_1 (which is constant in time because the electrode is polarized at the very beginning of the experiment) plus a resistance $R_2(t)$, which accounts for the Galvanic effects associated with the contact between the acidic solution and ground. This $R_2(t)$ depends on the chemistry of soil, also including the water content and temperature, the vegetative stage of the biosphere, soil porosity and soil exhalation, hydrology (underground water circulation, depending on rain and springs, geothermal effects), etc.

Air-electrode contact

Another - even more serious - concern deals with the electrical contact between the spike or ball at point B in Fig. 2 and surrounding air. Two devices are used.

One technique is to put - at the spike or ball B - a tiny amount of a weak radioactive source. The purpose is to increase the local air conductivity. This is, however, as discussed above, a dramatic perturbation of the natural electrical conductivity of air, which is crucial to control the local E -field. That is, such a device is definitely unacceptable.⁴

Another technique is to leave a water droplet to fall from a metal spike connected to the small conductor B. Electrostatic charges concentrate on sharp points. Hence, when a water droplet falls from the metal point, it takes off electric charges from the small B conductor.

The drawback is that, when a droplet is detached, the electric state is changed of the small B conductor. How can water be refilled to the small ball B? That is, every long-lasting record is likely to be biased.

Therefore, long-lasting monitoring must rely on some alternative and reliable techniques that avoid relying on the contact either with ground or with air.

The rotating electrostatic device (r.e.d.)

A device must be used that relies on a principle already applied aloft by airborne and rocket born campaign. This device is here called “rotating electrostatic device” or *r.e.d.*

⁴ Also a simpler device is sometimes used with a simple voltmeter operated between point B and ground.

(Fig. 3). The operative principle is the same as the low-mass balloon-borne E -field meter (EFM) (see Marshall et al., 1995b or MacGorman and Rust, 1998), which was envisaged for balloon operation. The same principle was also used for satellites and/or space probes, although by a much different implementation.

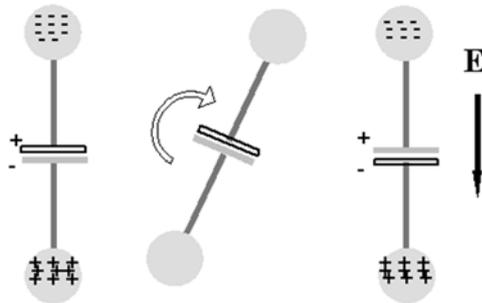


Fig. 3 - A conductor, with a condenser at its middle, (*ball recorder*) rotates inside an environmental E . The voltage difference between the plates of the condenser monitors E . Reproduced with kind permission of *Acoustics* ("Open Access"). After Gregori (2020).

Two different implementations were implemented by the students of the late Professor Arnaldo D'Amico.⁵ One experiment relied on a rotating boom. In the other, the boom was substituted by a simple CD disk, with its cover divided into 4 sectors, that alternated electrically conducting and non-conducting sectors. Both devices were successfully tested and gave comparable results.

The use of a bar with two balls, however, avoids the drawback of corona discharge from sharp surfaces. This warning is well-known and applied in every instrument used for airborne or satellite records, etc. In contrast, this bias is relevant in the case of the CD rims. The amount of this unwanted effect can be quantitatively evaluated by a simultaneous operation of the two devices within dry weather environment (the dry weather is recommended in order to avoid the disturbance by humidity or by atmospheric precipitation).

On the other hand, a serious operational difficulty deals with measurements carried out during perturbed atmospheric conditions, due either (i) to the electrostatic charging of the components of the monitoring device caused either by wind or by atmospheric precipitation, or (ii) by the leakage discharge through the humid or dirty surface of the booms or of the CD.

No screening cover of the instrument can be used. In fact, if the cover is made of a conductor, the cover is a Faraday cage and the measured E is unreliable. If the cover is made of insulator, it accumulates electrostatic charge due to friction with winds and/or precipitation. The effect also depends on pollution. Therefore, every *r.e.d.* instrument must be operated with great care in open air.

The two implementations (with balls or with a CD) have a substantially different aerodynamic impact with their environment (wind and/or precipitation) - and a different

surface exposure to humidity and dirtiness. In this respect, the CD implementation is, perhaps, better suited than the two-ball implementation. On the other hand, the two-ball version is substantially less biased by corona discharge.

A concrete operative suggestion is to calibrate in the laboratory the performance of a *r.e.d.* instrument by operating it into a wind tunnel, with a given humidity, with or without simulation of rain of a given intensity, with air either polluted or not, etc. In principle, it is thus possible to construct nomograms aimed to evaluate the correction to be applied to the records depending on the atmospheric environment. In this way, one can quantitatively estimate the competitive performance of either one aforementioned *r.e.d.* instrument.

The effect must be taken into account originated by friction electricity on non-conducting surfaces with different wind speed and direction (relative to the *r.e.d.*), by comparing *r.e.d.* devices with different radii of each ball, etc.

In addition, every measurement carried out by an array of *r.e.d.* instruments in the field should be simultaneously operated with standard meteorological monitoring, in order to measure the relevant environmental parameters needed for carrying out a significant correction of the records for any unwanted effect.

Summarizing, in the case of dry weather, the disturbance originated by the sharp rims of the CD can be quantitatively estimated by direct calibration. But the same target can be achieved also by laboratory calibration in a non-ideal environment, with adverse meteorological conditions, etc.

To our understanding, at present, no better device than the *r.e.d.* can be envisaged for measuring the atmospheric potential gradient at ground. In principle, every aforementioned warning applies also to aloft measurements. But in these other applications, new concerns are raised depending on the carrier and/or platform that is used, on the speed and trajectory of the platform, on environment, etc. Every case history requires both a suitable discussion of lesser, although always fundamental and critical, details - and a corresponding careful calibration and discussion of the significance of the records.

A specific strategy has, therefore, to be exploited in order to implement a *r.e.d.* array that can be operated permanently. These details are not here pertinent. There is need for a TV record of cloud cover, a meteorological station aimed to provide the state of air (temperature, humidity, rain, wind, hail, pollution, etc.). Trained operators ought to select reliable data from records that are to be rejected due to unrecoverable perturbation. That is, the operation of the *r.e.d.* array - located on a test area of at least a few kilometers linear size - is to be managed with particular great care. All these items cannot here be discussed, as they require devoted discussion and planning, specific for every application.

⁵ Emeritus Professor at the Second University of Rome "Tor Vergata" until passing away on November 12th, 2020.

Sensor-generated perturbations

Quite a few essential - and generally unnoticed - arguments from college electrostatics are strictly needed in order to evaluate the physical significance of several aforementioned measurements.

I - Let's start by considering E measurements carried out by a radioactive source probe. Consider Fig. 4a. The case history is first envisaged of a perfectly flat, uniform - and electrically highly conducting - Earth's surface, such as, e.g., the sea water' surface. Atmospheric conductivity is essentially neglected, at least as a first order approximation.

A uniform vertical E component, E_z , which is supposed to be positive, i.e., downward oriented, is represented by perfectly horizontal equipotential surfaces. The E field-lines end at Earth's surface, which is supposed perfectly conducting. The Gauss theorem, applied to a small volume cutting across Earth's surface, owing to electrostatic induction by E , implies the existence of electron density at Earth's surface.

Suppose to include an object, e.g., a spherical ball, which is supposed to be perfectly conducting, as in Fig. 4b. Electrostatic induction causes separation of electric

charges. The outer surface of the object must be equipotential, with the electric potential of the surface denoted by A. The surrounding equipotential surfaces and E field-lines are therefore perturbed, and modified as it is qualitatively shown in Fig. 4b. The positive/negative charge density locally found at the surface of the object is physically related - through the Gauss' theorem - to the local E , or to the local number of E field-lines ending at the object's surface.

If one measures the potential difference between the object and Earth's surface, the measurement is reliable as far as the object is sufficiently far away from Earth's surface. In the opposite case, the perturbation on the equipotential surfaces around the object must penetrate inside the Earth's body, thus significantly changing the Earth's potential.

That is, the measurement is reliable only if the object is small compared to its distance from Earth's surface.

In the case of rain - hence of varying electrical conductivity σ depending, e.g., on whether it is acid rain or not, etc., or on breeze or wind, on air pollution, etc. - the assumption is no more suitable of a negligible σ of air. Therefore, measurements can be severely biased.

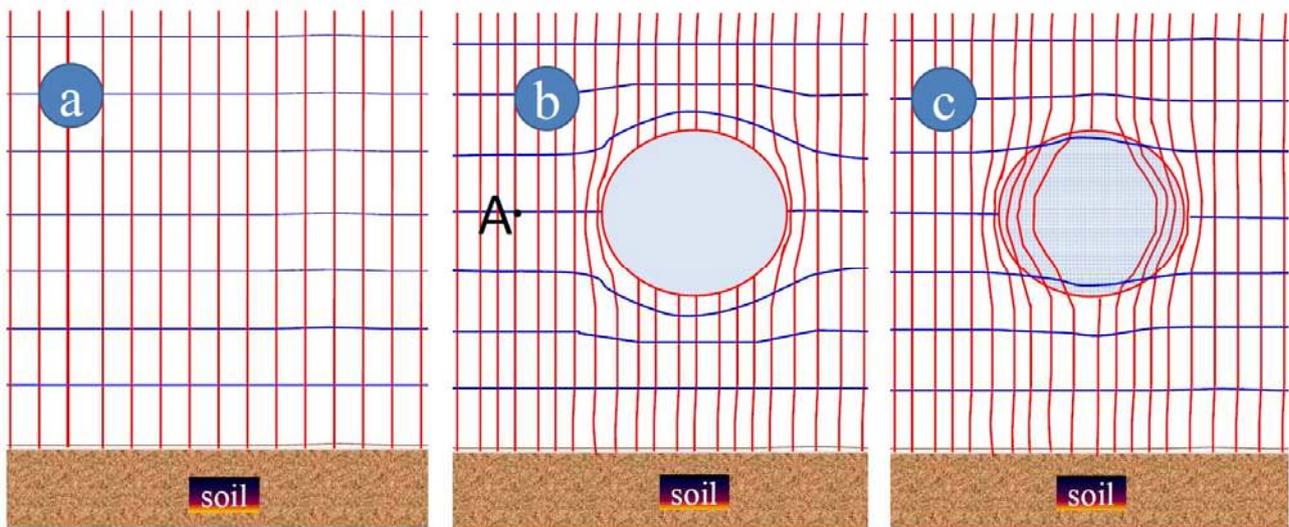


Fig. 4. The perturbation caused by a radioactive source. (a) A flat and electrically conducting Earth's surface is overlain by flat and regular electric equipotential surfaces (in blue), while E is uniform, positive, i.e., pointing downward (E field-lines in red). (b) Insert a perfectly conducting object, such as, e.g., a spherical ball. Equipotential surfaces are perturbed and deformed. The electric potential of the object is identical to the equipotential surface denoted by A. The object should be located at a sufficient height above Earth's surface in order to avoid that its perturbation penetrates underneath Earth's surface. (c) The perfectly conducting object of case (b) is substituted by an object with no clearly defined boundaries, such as, e.g., a "cloud" of air that is ionized by a gentle radioactive source. The effect is the same as in case (b). However, some equipotential surfaces can penetrate inside the "cloud". The electric potential of the support of the radioactive source can be likened to the potential of the surface denoted by A. But micrometeorological conditions can alter the insulation of the "cloud" relative to Earth's surface. It is therefore possible that the "cloud" temporarily can become an upward extension of Earth's surface. Thus, in these conditions, the measured potential of the support of the radioactive source cannot be representative of the atmospheric potential-gradient. See text. Unpublished figure.

Consider now the case of Fig. 4c, where the object - or spherical ball - has been substituted by another object, which has no sharp boundary. Rather, it has an outer layer which is not "perfectly" conducting. This is the typical case history of a small "cloud" of air, which is ionized by a feeble radioactive source.

The same argument of Fig. 4b applies, except that some equipotential surface penetrates inside the "object" - which is now a small ionized "cloud".

The measured potential difference - between the support of the radioactive source and Earth's surface - makes sense, but only as far as (i) the size of the "cloud" is small compared to its distance from Earth's surface, (ii) we are not concerned with scale sizes smaller than the typical size of the measuring apparatus, and (iii) breeze, wind, water precipitation, etc. do not change the size of the "cloud". In fact, a short-circuiting between "cloud" and Earth's surface makes the cloud to be an upward protuberance of Earth's surface. That is, rain or any other conducting medium acts like a shunt between "cloud" and soil. This is the next kind of perturbation, discussed below, which is here briefly called "St. Elmo perturbation".

That is, the measurement can be seriously biased in the case of rain or of any other atmospheric precipitation, or also of an unknown varying air pollution.

Owing to these reasons, all measurements carried out by means of a radioactive source are to be considered with great care, as they can be strongly biased by local time-varying micrometeorological conditions, which are normally not monitored at the recording site with the required and lesser spacetime details.

II - Consider now the perturbation introduced by a spike, or by a sharp blade, etc. It is associated with a corona effect, being responsible for St. Elmo fires, etc. It typically represents a serious concern for E measurements, because either a tree - which grows taller with age, hence it causes a time varying perturbation - or a chimney, or a bell tower, or a tall building of any kind, are a well-known crucial bias for measurements of atmospheric potential-gradient.

Fig. 5a shows the case of an unperturbed situation, identical to the case of Fig. 4a. Consider the perturbation caused by a sharp object elevated from the Earth's surface, which is considered to be as conductive as the Earth's body, such as in Fig. 5b. The equipotential surfaces are violently perturbed, hence also E .

The measured quantity is the electric current that outflows from the top point of the sharp object. Owing to this specific feature, we can briefly call "St. Elmo perturbation" this kind of bias. This is the kind of

measurements that are carried out by point-discharge sensors.

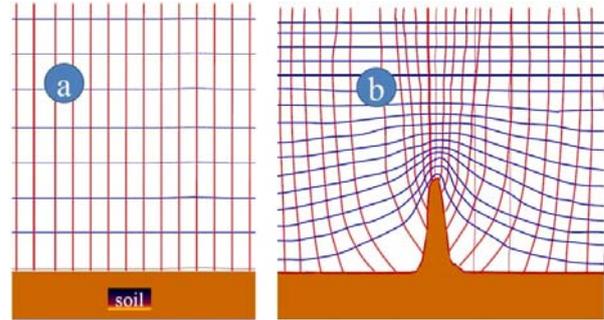


Fig. 5. The perturbation caused by corona discharge. (a) A flat and electrically conducting Earth's surface is overlain by at and regular electric equipotential surfaces, while E is slightly more intense close to Earth's surface. (b) A spike feature, such as a pole, a tree, a chimney, a tall building, etc., which are likened to an upward extension of soil, introduces a relevant disturbance. The corona discharge, or St. Elmo fire, can be measured and, through suitable calibration, can be considered a measurement of E . The result is biased by the varying electrical conductivity of air. See text. Unpublished figure.

The calibration of the measuring device is essential - as the phenomenon depends on the geometry and relative size of the different components of the entire physical system. The instrument in the laboratory is therefore put inside a known E , and its output measured. If no calibration is feasible, it is awkward, if at all possible, to evaluate a model of the perturbation caused by a point-like probe into an E environment that must be monitored.

The measurement is biased by rain or by any change of the air σ , hence by atmospheric pollution. In principle, this error can, however, be partly corrected by means of a careful calibration, by varying the amount of precipitation, or by reproducing different kinds of pollution of the environment, etc. Then, the wind speed must be taken into account, in order to evaluate the amount of the perturbation that impinges on the instrument, etc. Thus, some nomograms can be constructed, and a correction approximately evaluated.

The twofold role must be pointed out of this perturbation. It can be used as a sensor for measuring E . Otherwise, it is a serious drawback, and all sharp surfaces must be avoided as much as possible in order to minimize this possible bias (see the discussion above).

III - Suppose now that, either we can easily put a spike like in Fig. 5b, or we can equally easily take it off. And suppose that we can repeat this double operation put-and-take-off several times in a given time lag (a minute or so). This is the case history of an electric field mill.

Summarizing, every measurement of E is potentially affected by some severe bias, unless one considers the perturbations that can be much different at different locations, and also at different times at one and the same location.

Conclusion

The study of the electrostatic phenomena in the atmosphere - aimed to monitor air-earth currents and to exploit the electrostatic energy of the atmosphere - cannot rely on the present generally applied techniques for recording the atmospheric potential gradient.

Every technique must be avoided that relies on the contact between electrode and ground or air. Electrostatic induction devices are rather required.

There is need to rely on the unprecedented *r.e.d.* device that must be operated in selected *r.e.d.* arrays, located in a few suitable test areas, requesting a particular great care by expertized operators, in order to monitor the space- and time-gradient of the natural E -field.

The information is needed to design an effective energy-exploitation technique, upon correctly taking into account cost/benefit.

Latitudinal variations are also to be expected, in addition to an obvious relevant dependence on meteorological conditions (see Gregori and Leybourne, 2024l).

Acknowledgement

G.P. Gregori wrote the basic draft, and B.A. Leybourne contributed with substantial discussion. We thank all colleagues and friends, who during several decades contributed with their discussion.

In particular, we are grateful to the late Professor Arnaldo D'Amico - a gentleman and dear friend - for implementing the preliminary experiments of *r.e.d.* instruments.

Funding Information

G.P. Gregori retired since 2005. B.A. Leybourne is a semi-retired self-funded independent researcher.

Author's Contributions

This study is a lesser detail of a long-lasting cooperation by both authors and resulted from the emergence of suitable discussions.

Ethics

This article is original and contains unpublished material. Authors declare that there are not ethical issues and no conflict of interest that may arise after the publication of this manuscript.

References

- Airy, Sir G.B., 1868. Comparison of magnetic disturbances recorder by self-registering magnetometers at the Royal Observatory, Greenwich, with magnetic disturbances described by the corresponding terrestrial galvanic currents recorded by self-registering galvanometers at the Royal Observatory, Philosophical Transactions of the Royal Society, 158A: 465-472
- Fukui, Y., H. Yamamoto, M. Fujishita, N. Kudo, K. Torii, S. Nozawa, K. Takahashi, R. Matsumoto, M. Machida, A. Kawamura, Y. Yonekura, N. Mizuno, T. Onishi, and A. Mizuno, 2006. Molecular loops in the galactic center: evidence for magnetic flotation, Science, 314 (5796): 106-109; DOI:10.1126/science.1130425
- Gish, O.H., 1936a. Electrical messages from the Earth, their reception and interpretation. Journal of the Washington Academy of Sciences, 26: 267-289.
- Gish, O.H., 1936b. The natural electric currents in the earth. The Scientific Monthly, 43 (1): 47-57
- Gregori, G.P., 2020. Climate change, security, sensors. Acoustics, 2: 474-504; DOI:10.3390/acoustics2030026, [<https://www.mdpi.com/2624-599X/2/3/26/html>]
- Gregori, G.P., and B.A. Leybourne, 2021. An unprecedented challenge for humankind survival. Energy exploitation from the atmospheric electrical circuit, American Journal of Engineering and Applied Science, 14 (2): 258-291. DOI:10.3844/ajeassp.2021.258.291
- Gregori, G.P., and B.A. Leybourne, 2024b. The electrostatic Sun, present issue
- Gregori, G.P., and B.A. Leybourne, 2024e. The physics of electrical discharges – 1. Small-scale phenomena - Fog - atmospheric precipitation – BLs, present issue
- Gregori, G.P., and B.A. Leybourne, 2024f. The physics of electrical discharges – 2. RB & TGFs - Runaway breakdown – terrestrial gamma flashes – GK effect, present issue
- Gregori, G.P., and B.A. Leybourne, 2024g. The physics of electrical discharges – 3. Sparks and lightning - electrostatics of the ionosphere – TLEs - plasma jets collimation – Birkeland currents & sea-urchin spikes - stellar and galactic alignments, present issue

- Gregori, G.P., and B.A. Leybourne, 2024l. Conclusion – Exploitation of the electrostatic energy of the atmosphere, present issue
- Gregori, G.P., B.A. Leybourne, and J.R. Wright, 2024d. Generalized Cowling theorem and the Cowling dynamo, present issue
- Gregori, G.P., B.A. Leybourne, G. Paparo†, and M. Poscolieri, 2024a. The global Sun-Earth circuit, (including a Supplement) present issue
- Gregori, G.P., M.T. Hovland, B.A. Leybourne, S. Pellis, V. Straser, and B.G. Gregori, G.M. Gregori, and A.R. Simonelli, 2024w. Air-earth currents and a universal “law”: filamentary and spiral structures - Repetitiveness, fractality, golden ratio, fine-structure constant, antifragility and “statistics”- The origin of life, present issue
- Gurevich, A.V., and K.P. Zybin, 2005. Runaway breakdown and the mysteries of lightning, *Physics Today*, 58 (5): 37-43
- Lanzerotti, L.J., and G.P. Gregori, 1986. Telluric currents: the natural environment and interactions with man-made systems. In *The Earth's Electrical Environment*, Krider, E. P., and R.G. Roble, (eds), National Academy Press, Washington, D. C.; DOI:10.17226/898, pp: 232-257
- MacGorman, D.R., and W.D. Rust, 1998. *The electrical Nature of storms*, Oxford Univ. Press, Oxford and New York, pp: 1-422
- Marshall, T.C., W. Rison, W. D. Rust, M. Stolzenburg, J.L. Willett, and W.P. Winn, 1995b. Rocket and balloon observations of electric field in two thunderstorms- *Journal of Geophysical Research*, 100: 20,815-20,828
- Rykatchew, M., 1900. *Histoire de l'Observatoire Physique Centrale pour les Premières 50 années de son Son Existence, 1849-1899*, Imprimerie de l'Académie impériale des Sciences. St-Petersbourg, pp: 1-392
- Tavani, M., A. Argan, A. Paccagnella, A. Pesoli, F. Palma, S. Gerardin, M. Bagatin, A. Trois, P. Picozza, P. Benvenuti, E. Flamini, Martino Marisaldi, C. Pittori, and P. Giommi, 2013a. Possible effects on avionics induced by terrestrial gamma-ray flashes, *Natural Hazards and Earth System Sciences*, 13: 1127–1133; DOI:10.5194/nhess-13-1127-2013.
- Taylor, A.R., and P. Jagannathan, 2016. Alignments of radio galaxies in deep radio imaging of ELAIS N1, *Monthly Notices of the Royal Astronomical Society*, 459 (1): L36-L40
- Torreson, G.W., 1939. Instruments used in observations of atmospheric electricity. In *Terrestrial Magnetism and Electricity*, J.A. Fleming, J.A. (ed.), McGraw-Hill Book Co., New York and London, pp: 231-269
- Tully, R.B., H. Courtois, Y. Hoffman, and D. Pomarède, 2014. The Laniakea supercluster of galaxies, *Nature*, 513: 71–73; DOI:10.1038/nature13674

Acronyms

- BL - ball-light
CG - cloud-ground (discharge)
e.m. - electromagnetic
EFM -electric field meter
IAGA –International Association of Geomagnetism and Aeronomy
IC - intra-cloud (discharge)
MT - magnetotelluric
r.e.d. - rotating electrostatic device
RB - runaway breakdown (process)
TGF - terrestrial gamma flashes
TLE - transient light emission

The physics of electrical discharges – I. Small-scale phenomena

Giovanni Pietro Gregori¹, Bruce Allen Leybourne²

¹Former Senior Researcher at IDASC-Institute of Acoustics and Sensors O. M. Corbino (CNR), Rome, now merged into IMM Istituto per la Microelettronica e Microsistemi (CNR) Italy; and ISSO-International Seismic Safety Organization, Italy

²GeoPlasma Research Institute-(GeoPlasmaResearchInstitute.org), Aurora, CO 80014, USA

Corresponding Author:
Giovanni Pietro Gregori
IDASC-Istituto di Acustica e
Sensoristica O. M. Corbino
(CNR), Roma, now merged
into IMM-Istituto per la
Microelettronica e
Microsistemi (CNR) Italy
e-mail:
giovannipgregori38@gmail.com;
leybourneb@iascc.org

Abstract: The innovations implied by the Cowling dynamo process are discussed concerning some microphysical effects in the Earth's atmosphere. Some general preliminary morphological features of an electrical discharge are considered. Then, two presently poorly understood - or non-understood - phenomena are discussed, i.e., (i) water condensation and precipitation in the atmosphere, and (ii) ball lightning (*BL*) formation and evolution. As far as water condensation and precipitation are concerned, the effect deals with the presently non-understood process of water agglomeration around a condensation nucleus. The result of the Cowling dynamo process is the formation of the earliest tiny water droplets or icelets that subsequently evolve and determine fog phenomena and/or atmospheric precipitation. Hail phenomena are the subsequent extreme event. The installment of a lightning rod in a field ought to reduce, in principle, the occurrence of hail precipitation inside some large area. This effect, however, must be assessed. This experiment could be a way to check and “calibrate” in quantitative terms the entire effect. A better assessment of these details can be relevant also for the investigation of the possibility to exploit the enormous amount of free and clean electrostatic energy of the atmosphere. Concerning *BLs*, the scale size ranges from, say, ~ 10 cm upward. In addition, speculation about a peculiar quantum configuration envisages the nature of *BL* as an e.m. knot, named “skyrmion”. The physics of this presently debated and apparently mysterious phenomenon is fundamental for the explanation of the physics of sparks and lightning, which is discussed in the next papers.

Keywords: Cowling dynamo – microphysics of the atmosphere - water agglomeration around a condensation nucleus - water condensation and precipitation – fog - hail & lightning rods - exploitation of the electrostatic energy of the atmosphere - ball lightning (*BL*) - skyrmion

Introduction

The common meaning of the term “discharge” is related to the frightening observation of lightning and to old fashioned classical experiments in vacuum tubes, which are the forefathers of plasma physics. According to Waymouth (2001) and as stressed by Miller (2007), our present understanding has several gaps, when dealing with phenomena that occur inside a plasma discharge. Voluminous treatises are available on these topics, but no full account can be given here - although, at present, several past arguments have some historical interest.

One must consider the medium where the discharge occurs. Inside solid matter, electrons move from the orbitals of one atom or molecule to the next. The moving electrons can affect – or not – the crystalline bonds, hence the temperature of the medium. Eventually, melt occurs. This is the Ohm's law. In contrast, inside fluids, advection of ionized matter occurs. In either case, the magnetic field \mathbf{B} plays a crucial role, although the earlier theoretical formulations dealt with \mathbf{B} like an accessorial

feature (concerning the discharge in gases see, e.g., Raizer, 1991). Only in 1950, Alfvén proposed systematic reference to Magneto-Hydro Dynamics (*MHD*). With this concept, he filled a gap of almost three centuries in physics, after Newton, which had biased science in favor of gravitation. In several respects, this bias still affects present science (see Gregori et al., 2025a).

The Cowling dynamo brings a new perspective. It shows that a toroidal \mathbf{B} self-confines and collimates every flow of charged matter (see Gregori et al., 2026d). As far as the magpol state is concerned (see details in Gregori et al., 2025a and 2025w) – which is a state of matter composed of nuclei that are “naked”, i.e., totally ionized with no electrons in their respective orbitals – all nuclei interact through magnetic nuclear moments, and no free electron is available. Hence, no electric current is possible, i.e., the electrical conductivity σ of magpol state is null.

The present discussion addresses the direct implications of the Cowling dynamo. As far as the previous models and explanations are concerned - which

are reported in the literature – only a few related items are mentioned for completeness.

In general, “electrical discharge” is usually called a visible event - but even one electron alone in motion is an electrical discharge. When we deal with lightning, the focus is on a specific phenomenon, which is eventually manifested like an extreme event, in terms of photon emission etc. However, the “discharge” of the atmospheric condenser is not restricted to lightning alone. In fact, the leading part of the phenomenon is undetectable by conventional tools. This is the implicit, and ever challenging, bias due to the empirical constraint - i.e., we can observe only a very limited amount of phenomena. However, our interpretation cannot rely only on what we can observe. Conversely, we must appeal to imagination and speculation, and check with observations.

The largest fraction of electrical discharges in our environment cannot be detected, although their effects are essential for several phenomena. The focus of the present discussion deals with discharges that are responsible of detectable phenomenon, such as, e.g., the formation of a droplet of fog or of atmospheric precipitation (rain, snow, hail) - and only a mention is given, mainly in the accompanying papers, about several other facts through much larger scale-sizes, up to the alignments of galaxies inside galactic superclusters.

These are intricate topics, and - for purposes of discussion on air-earth currents – a distinction ought to be made between the following items that are concisely discussed in the following three papers:

- first present paper (small-scale phenomena)
 - micro Cowling dynamos (fog and atmospheric precipitation)
 - ball lightning (*BLs*)
- second paper
 - runaway-breakdown (*RB*) process, *GK* effect,
 - terrestrial gamma flashes (*TGFs*), which are also called gamma ray flashes (*GRFs*) or terrestrial gamma bursts (*TGBs*)
- third paper (large-scale phenomena)
 - sparks and lightning
 - cloud phenomena, charging of the ionosphere, transient luminous events
 - transient luminous phenomena (*TLEs*)
 - plasma jets collimation, and sea-urchin spikes
 - stellar and galactic alignments.

A general perspective

The electric discharge of a condenser - such as the atmospheric condenser between subsoil and ionosphere/outer space – must be conceived as a smooth charge transport, either by electrons or by ionized particles. A lightning - or any other “instant” and very intense phenomenon - is only an extreme occurrence, even though the microphysics of a lightning is basically

unexplained.¹ The physics, of both smooth and extreme events, can be understood by some detailed modeling aimed to achieve a reliable explanation of the morphology of several observations. In any case, a lightning can occur inside air and solid media. See, e.g., Denault et al. (2013) and references therein.

The starting process is a corona or point-discharge. High-time-resolution monitoring of the very early stage of a discharge was carried out by Wagenaars et al. (2007) (see also Miller, 2007) based on the Stark effect for measuring *E* inside *Xe*. But the same principle can be applied to other gases. Fig. 1 shows their results. They used two parabolic electrodes so that the discharge always occurs approximately at the same location. They carried out observations at a point, located half-a-millimeter above the cathode.

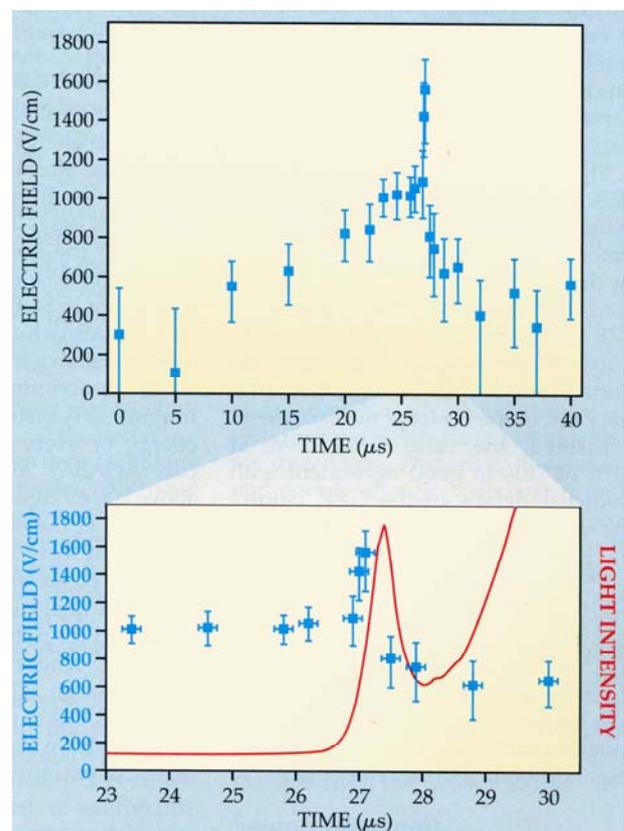


Fig. 1. “Electric-field measurements (blue) and visible light emitted (red) from a measurement volume 0.5 mm above the cathode. During the period 0 – 25 μsec , the voltage between the electrodes is increased without inducing plasma breakdown. The sharp peak and subsequent drop in *E* around 27 μsec are due to a front of positively charged *Xe* ions crossing the measurement volume. Adapted from Wagenaars et al. (2007).” Figure and captions after Miller (2007). Reproduced with kind permission of *Physical Review Letters*.

The field *E* increases during 25 μsec , although no significant ionization occurs of *Xe* atoms. A uniform drop in potential occurs in space from anode to cathode.

¹ Some large amount of literature can be found, also including some “exotic” theories. For instance, refer to

Mesenyashin (1999) and to the accompanying editorial comment.

Close to $27 \mu\text{sec}$ a sharp maximum of E occurs followed by an abrupt drop down to values lower than the previous $25 \mu\text{sec}$. This peculiar behavior can be explained upon considering the particular geometry of the apparatus and of the consequent motion of positive ions inside the spark volume. In fact, an “ionization front” of positive Xe ions crosses through the measurement volume.

In fact, before such an occurrence, the positive Xe ions are close to the positively charged anode and contribute to enhance the observed E . In contrast, when the positive Xe ions move on the opposite side of the measurement volume, the E of the ions is opposite to the applied E . Simultaneously, Xe atoms, which had been excited by scattering with electrons, relax back to the ground state and release photons.

That is, light emission - whenever phenomena are sufficient to trigger luminescence - is a paramount tool for diagnosing electric discharges. The peak of the visible light was observed *a few hundred nsec* after the E peak. The time delay is the result of the time interval implied by the excitation of Xe ions by electron scattering, and by the decay of excited Xe ions. The light peak is broader than the E peak.

This laboratory experiment mimics - in some idealized way - the physically much more complicated case history of a natural lightning - including the combined, although much different, roles of “*e*-discharge” and “*ion* discharge” in a volcanic plume (see Gregori et al., 2025t). The trigger is always a sufficiently intense E . The very early beginning of the lightning occurs at one given and well defined point. In addition, the next step has to be justified in some way - i.e., the evolution of the discharge towards a linear and approximately segmented linear flash, the so-called “*channel*” (see Gregori and Leybourne, 2026f, 2026g).

This experiment shows that a “discharge” through an ionized gas implies the motion of both electrons and various kinds of ions. Their interaction with electrodes - whether a metal object or a cloud or ground - implies a feedback reaction from the electrode that changes the constituents of the system in terms of electrons and ion density and composition. A change of morphology occurs *vs.* time, as the physical system changes. E.g., one can eventually observe formation of soot. That is, the so-called transient phenomena always play a crucial role.

When the entire discharge involves extreme conditions - and compared to human standards it has a “very short” time duration - it is named spark, with or without a light flash. When the phenomenon is steady during some longer time, the system eventually “resonates”, as it occurs inside every circuit. Charged particles in an ionized gas are part of an electrical circuit, which is characterized by a typical resonance frequency, etc. Every discharge, of every kind, should be interpreted inside this whole rationale. Lightning displays patterns that remind one about a damped oscillation (see Gregori and Leybourne, 2026g).

Fig. 2 shows an electric discharge triggered in the laboratory, when a couple of laser beams produces the ionization between the two electrodes. A laser beam is

concerned with a very narrow volume in space. *A priori* one can speculate that the trigger causes a 3D ionization, by which the discharge ought to involve a diffuse 3D light emission, almost like in a huge gas lamp. In contrast, the discharge displays a linear - continuous though brief - roughly segmented structure. That is, the discharge involves a much-limited subset of the volume between the two electrodes. This linear structure is usually called the “*channel*”. In this experiment, the upper electrode is the point of a rod, and the lower electrode, at ground, is an array of horizontal cables.

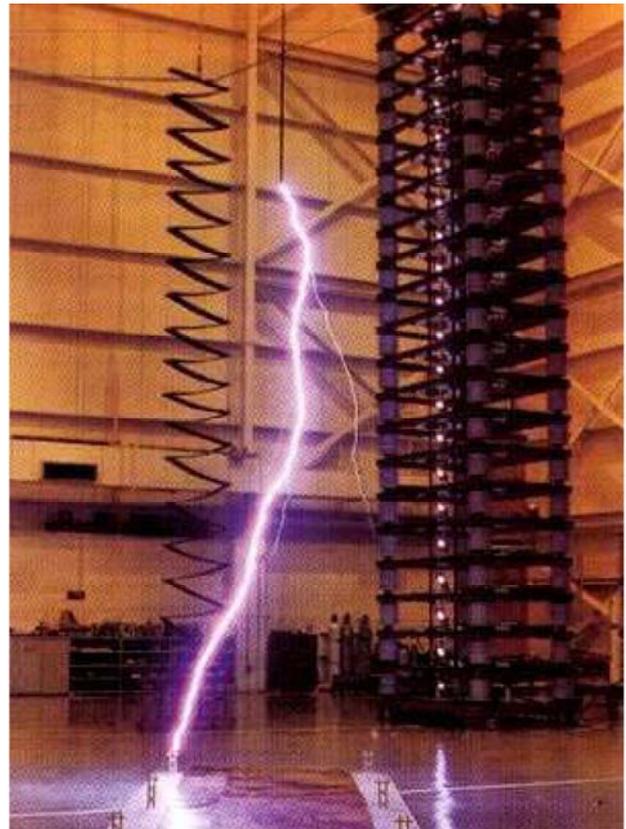


Fig. 2. A luminous discharge triggered in the laboratory between two electrodes, by ionizing the medium by a couple of laser beams. After Diels et al. (1997) who acknowledge a courtesy by Stan Grzybowski of the *Mississippi State University High Voltage Laboratory*. Reproduced with kind permission from JeanClaude Diels.

The visible luminous discharge is the region where the largest concentration of conduction charges occurs - i.e., mainly electrons - that heat or excite air molecules to release photons. However, all discharges in 3D space, either visible or not, must converge on the point-like upper electrode. Hence, it is reasonable to expect that every lesser and “thinner” luminous discharge, which is sometimes visible, ought to appear to detach from the main discharge, and to converge on the upper point-like electrode. The general pattern will appear like a set of thin luminous filaments that ought to branch always from the point-like upper electrode. The lower electrode is widespread over the floor of the laboratory. All these features are observed in Fig. 2.

Also lightning in the atmosphere, which is shown in every photo, always branch top-to-bottom (except a few case histories, see Gregori and Leybourne, 2026g). This fact denotes that the upper electrode of the atmospheric condenser has a spatial extension that is spatially narrower, and less widespread, than the ground electrode. Consider, however, that the lower electrode has often to be associated with some sea urchin spike(s) (Gregori, 2002, Gregori and Leybourne, 2021). That is, the cross-section of the upper electrode is eventually smaller than the cross-section of the region that contains several sea-urchin spikes underground. That is, lightning strike preferential sites at ground, a fact that was well known throughout antiquity. This warning applies also to a volcanic plume, which is a projection above Earth's surface of an approximately point-like feature above a sea-urchin spike, although volcanic plumes of different extension should be taken into account. In addition, several volcanoes are not related to sea-urchin spikes, although they are always a site of very intense soil exhalation of hot fluids, i.e., of intense electric currents.

For complete discussion the “lightning-branching criterion” was originally used - although sometimes with controversial arguments - in order to determine “the polarity of the two ends of a lightning-discharge” (Schonland, 1939, p. 666). That is, the branching direction, which is here interpreted as evidence of the different relative extension of the two electrodes of the discharge, was tentatively associated with the polarity of each electrode. However, this approach implied some controversy (see below).

In any case, as a basic matter of fact, the reason must be explained by which the discharge in Fig. 2 - and in every lightning - is compact around a “thin” linear trend. Differently stated, the charge occurs along a “channel”, rather than spreading out in 3D space to give a volumetric light emission. A lightning looks composed of different linear luminous segments, rather than like light emission inside a gas tube. When a lightning strikes ground, it hits almost a point-like area, rather than a more extended surface. All these features must be explained. Indeed, this is the self-confinement effect that is typical of the Cowling dynamo on every scale size, including even much larger scale-size, through the solar wind, up to the alignments of galaxies inside galactic superclusters.

Only a historical curiosity is the comment by Schonland (1939, p. 676). “The current-density in the lightning-channel and the diameter of the conductive portion of the channel are very uncertain qualities (Schonland, 1937). Toepler (1926) gives an upper limit of 20 cm to the diameter but points out that much smaller values are suggested by the holes sometimes made by the stroke in solid bodies ...”

Few (1986, p. 50-51) comments as follows the tortuosity of the channel. “With respect to the effects of lightning-channel tortuosity on the thunder signal, there

is almost unanimous agreement among researchers. Lightning channels are undeniably tortuous and are tortuous apparently on all scales (Few et al., 1970). For convenience in discussing channel tortuosity Few (1969) employed the terms microtortuosity, mesotortuosity, and macrotortuosity relative to the relaxation radius of the lightning shock wave.

For a lightning channel having an internal energy of 10^5 J m^{-1} ..., $R = 0.5 \text{ m}$. The microtortuous features smaller than R - although optically resolvable - are probably not important to the shock wave as measured at a distance, because the high-speed internal waves ($3 \times 10^3 \text{ m sec}^{-1}$) are capable of rearranging the distribution of internal energy along the channel while the shock remains in the strong-shock regime. [This is not consistent with the argument that is here proposed. In fact, the self-confinement is an implication of the Cowling dynamo, and its effects are generated at a speed comparable to the speed of light, unlike the high-speed internal waves that are much slower.] At the mesotortuous scale ($\sim R$) the outward propagating shock wave decouples from the irregular line source because the acoustic waves from the extended line source can no longer catch up with the shock wave. [The physics of thunder is presently claimed to be poorly understood, and shock waves are likely to play a crucial role. See Gregori et al. (2026d).] Somewhere in this mesotortuous range the divergence of the shock waves makes the transition from cylindrical to spherical ...”

In any case, Krider (1986) warns that “the peak power and total energy of lightning are very large. Thus far, it has not been possible to simulate in the laboratory either the geometrical development of a lightning channel or the full extent of lightning damage.”

For the sake of completeness, concerning the most extreme manmade phenomenon, maybe, the most intense spark - except nuclear explosions - can be generated by means of a pulsed MHD generator. Limited information² is here reported, borrowed after Martellucci and Gregori (1989) and Gregori and Martellucci (1992). Russian scientists developed this technology, also for studying the deep electrical structure of the Earth (e.g., Velikhov, 1989). The leading idea relies on two electromagnets, each one identified with the space comprised between a couple of iron disks with a diameter of, say, $\sim 2 \text{ m}$. Three parallel disks confine two spaces between them, each one being one electromagnet.

Begin and switch-on a standard energy source, serving as a trigger to activate the two electromagnets. Then, simultaneously shoot, into both electromagnets, the exhaust of two solid-fuel boosters that are strongly anchored to soil. The plasma of the exhaust is split by the \mathbf{B} that is generated by the standard energy source. Positive and negative particles are collected on conducting plates at the boundary of the “plasma channel”. In this way, the system is a powerful current generator.

2 We are indebted to Professor Vladimir Zeigarnik for relevant discussions and information on these items.

Raizer (1991) is an authoritative treatise that does not mention such an item.

One of the two electromagnets supplies the energy that is required to sustain the current for both electromagnets during the entire time-lag of the experiment. The other electromagnet provides the useful energy output. The guiding idea of principle is that the kinetic energy of the directional plasma of the exhaust of one rocket is transformed into an electric current. Note that the crucial difference between a directional plasma and a nondirectional heat source.

A shot from a pulsed *MHD* generator is called “hot” when it is carried out according to the aforementioned procedure, while it is said “cold” when the boosters are not fired and the shot is simply supplied by a standard energy source, i.e., a battery bank.

As far as a continuous – rather than a short-pulse - process is concerned, remind about *MHD* generators that are well-known to engineers, operated by means of a steady plasma, rather than by a rocket exhaust. These devices improve the performance of carbon power plants. The opposite process is the transformation of an electric current into the motion of a conducting fluid.

Table I. Indicative orders of magnitude performance of pulsed *MHD* generators

useful output	1.0 – 1.5 kV $n \times 10 - n \times 100 MW$ for ~ 10 sec pulse duration (but it is possible to store the output and to release it in ~ 1 sec with a power 10 times larger)
conversion rate for high enthalpy solid fuels (per unit volume of the plasma channel)	500 – 600 MW m
energy yield	~8%
“hot” shot (one shot feasible per day)	~ 2.7 kA for ~ 10 sec
“cold” shot (one shot feasible per hour depending on the availability of standard energy source)	~ 5 kA for ~ 0.5 sec

Only “pulsed” *MHD* generators are here considered. Their performance is synthesized in Table 1, which is based on material used for Gregori and Martellucci (1992). For comparison purpose, recall that, as mentioned above, “the peak optical power emitted from a lightning flash is ~ $10^9 W$ ” (Finke and Hauf, 2002), and “the peak electric power that is dissipated by a return stroke is of the order of ~ $10^8 W$ meter of channel⁻¹” (Krider and Roble, 1986a). Therefore, this kind of *MHD* pulsed generators can attain a power comparable to a lightning flash.

Fog and atmospheric precipitation

The motion of a single charged particle is a “discharge”. The concern is about assessing the

threshold of transported electric charge to get a detectable effect.

Begin and refer to phenomena in the subatomic domain, where Feynman graphs and quantum electrodynamics apply. Maxwell’s equations apply as soon as some large ensembles of particles are involved. At this stage, a phenomenon can be described, based on rigorous implications of Maxwell’s laws, and the description is correct if Maxwell’s laws can be applied.

Therefore, in the atomic or subatomic domain, the same argument cannot hold, as Feynman’s graphs apply. In contrast, the rigorous argument applies to every larger spacetime domain - even on the scale sizes of astrophysics, such as stars, galaxies, black holes, galactic superclusters, etc.

The rigorous application of Maxwell equations relies on two theorems: the virial theorem applied to plasmas, and the generalized Cowling theorem (see Gregori et al., 2026d). The virial theorem applied to plasmas (Chandrasekhar and Fermi, 1953, or Rossi and Olbert, 1970) states that an ionized fluid – with no internal source - cannot be self-contained. Every ionized fluid must therefore expand in space as much as possible. In contrast, if some internal source affects the dynamics of the system, a dynamo is active, and the magnetic field **B** can confine the fluid. The generalized Cowling theorem applies. That is, an endogenous energy source is strictly necessary to trigger and supply the dynamo mechanism, which generates a **B** and is eventually capable to activate a self-containment. This is a rigorous theorem that applies everywhere through the universe, on every scale-size in space and time, above the subatomic scale.

The phenomenon exists and is relevant. The concern is about assessing under what circumstances it originates observable effects. Differently stated, there is need to assess what observational features are to be expected.

Consider a fluid and let some internal heat source to generate some thermal heterogeneity. It is usually stated that thermal “diffusion” is in progress. This occurs, in general, by implying some vorticity or micro-vorticity. Express such a concept by stating that the system displays some kind of “granular” structure, where every “granule” is identified with some micro-convective cell. Every “granule” is the location of a Cowling “micro-dynamo”.

Every “micro-dynamo” is active with the size of a “granule”. For the time being, there is no need to speculate about the size of such a “granule”, as the same argument applies to all scale-sizes larger than the one-atom or one molecule scale. This is an electrodynamic phenomenon that - in the case of an ionized medium - must always occur, associated to every thermodynamic convection.

The argument leads to the physics of fog, of precipitation phenomena, and of clouds, i.e., of the interaction between electromagnetic (e.m.) radiation and water contained in the atmosphere. At present, these phenomena are claimed to be poorly understood. They are the weakest points – as it is complained by the best-known numerical modelers of climate - although these

phenomena are responsible for a relevant greenhouse effect - while it is generally agreed that water in the atmosphere is certainly one of the leading causes for the greenhouse effect.

The interpretation, which is here proposed, deals with microphysical details. The official “best known” literature relies on a generally assumed standard simplification based on the “principle of sufficient reason”. However, the great amount of knowledge that became available during Space Age provides a much more profound cognitive scheme, altogether with an unprecedented logical frame.

The “principle of sufficient reason” is a classic concept in philosophy. It states that, whenever there is no reason by which we can envisage anything more complicated than some simple hypothesis, we can infer that such a hypothesis is likely to be correct. Note the difference with the Ockham’s razor that states that, whenever we have to choose either one of different seemingly possible tentative explanations, the simplest argument should be preferred. That is, the Ockham’s razor emphasizes the need for respecting the primary role of observations, while the principle of sufficient reason is just an assumption suited to support a mere *ad hoc* “simple” speculation lacking any alternative explanation.

The innovative model that is here proposed begins and considers that a water molecule is an electric dipole. A condensation nucleus, i.e., either an ion or a tiny aerosol or a cosmic particle, is either positively or negatively charged. Water molecules orient themselves according to the ambient E , as it is indicatively sketched in the cartoon shown in Fig. 3. In principle, several layers of electric dipoles - i.e., of water molecules - are thus formed. This is the process called “ion-induced nucleation” shown e.g. in Fig. 4.

However, this growth process is excessively slow. On the other hand, it is largely amplified when the charged condensation nucleus moves through air due to the ambient E that is generated by the Cowling dynamo of a “granule”. In fact, the condensation nucleus moves through - and scatters with and captures - other water molecules, which are electrically neutral and are unaffected by E . That is, the charged condensation nucleus operates like a broom that collects ambient water molecules that are neutral. The result leads to the formation of a water agglomerate, by means of a process that, e.g., reminds about the formation of clathrates, etc. The ubiquitous Cowling micro-dynamo is the crucial process.

A contrasting effect mostly deals with temperature, which determines the kinetic energy of the scattering of every water agglomerate with the surrounding molecules or with other water agglomerates. The chemistry of the atmosphere affects this process - as it implies some changes of the energy levels of the electron clouds that are associated to the bonds between different molecules and the central agglomerating nucleus.

In addition, suitable consideration must be given for the presence of an externally applied E , either if it is

directly generated *in situ* by some larger-size Cowling dynamo (such as a cloud, see Gregori and Leybourne, 2026f, 2026g), or if it derives from the inhomogeneity of the electric charge distribution in the ionosphere. Every applied external E accelerates the agglomeration speed, as tested in the laboratory. In every case, the process relies on formal application of the Schrödinger’s equation.

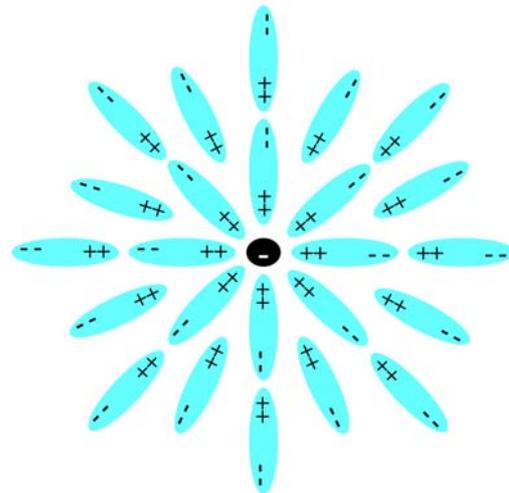


Fig. 3. The cartoon shows the agglomeration of water molecules like electric dipoles around a condensation nucleus with negative electric charge. A symmetric case history occurs for a positively charged nucleus. Unpublished figure.

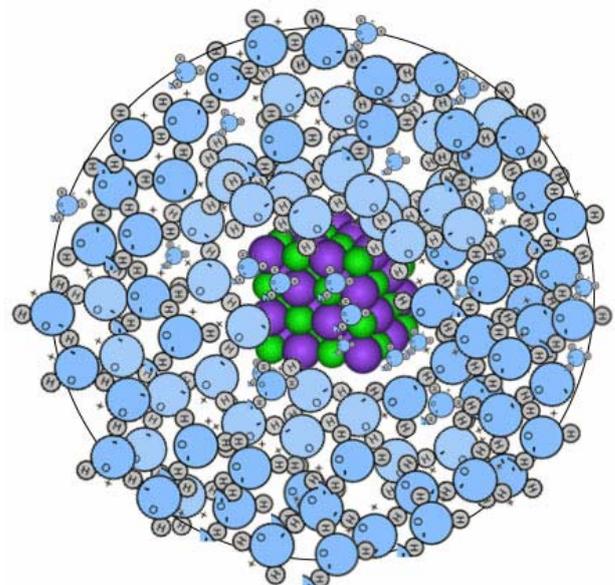


Fig. 4. Cartoon showing the concept of “ion-induced nucleation”. After Ouzounov et al. (2014). With kind EGU permission (CC BY 4.0 license).

Some experiments deal with the role of electrostatic forces in water condensation. For instance, Dayan and Gallily (1975) focus on charge-induced multipole interaction. They measured “the size increase of a charged droplet falling through a cloud of neutral, almost uniform small particles ..., and an average

collection efficiency ... The experimental results indicated efficiencies of one to two orders of magnitude greater than the values for neutral droplets under otherwise similar conditions. Likewise, the efficiencies were found to increase with the ratio of collected to collecting droplet sizes, and were insensitive to variations of the electric charge of the particles.” That is, the phenomenon looks more sensible to geometrical factors (the radii of droplets) than to the intensity of the electrostatic force. Hence, the role of surface tension of the colliding droplets is more important than electrostatic forces. In addition, this result holds for droplets that already attained a “macroscopic” size, while - on the much smaller spatial scale - some substantially different inference is to be considered.

This branch of investigation is known to be very difficult - as the energy, which is involved in interatomic interactions, is extremely faint and quantum effects typically enter into play. A great amount of investigation is likely to be required, and it is expected to give relevant information on precipitation mechanisms of water in the atmosphere. See also Cohen and Gallily (1977) and Gallily (1984).

Maybe, the most developed branch of these investigations deals with the study of snowflakes (see below), with ice formation and structure, with related abrupt changes, evolution, etc. This whole discipline is still concerned with several unexplained facets, even though it plays a relevant role in atmospheric phenomena. Water (haze, fog, clouds, rain and snow, hail, greenhouse effect, radiation balance, etc.) has a strong control on the interaction of a photon with the atmosphere.

The general rationale, which is here proposed, requires that water condensation and/or precipitation in the atmosphere occurs only if three ingredients are available:

- ✓ a sufficient amount of water content in air;
- ✓ a sufficient concentration of condensation nuclei;
- ✓ a sufficient amount of atmospheric dynamics capable to trigger a relevant effect by the Cowling microdynamo.

Condensation nuclei originate by either one of four sources, which can also be simultaneously operative:

- ✓ meteoroids (“Bowen hypothesis”);
- ✓ cosmic rays (“Svensmark hypothesis”);
- ✓ ions produced by friction electricity at the contact between blowing air and Earth’s surface (either ocean surface, or land surface with all possible cover);
- ✓ ions injected into the atmosphere either sporadically by explosive volcanism, or more or less regularly by anthropic actions (pollution, smog, rockets, bombs, etc.).

Concerning the Bowen hypothesis, a short synthesis is given, e.g., by McNaughton (1980). Concerning the Svensmark hypothesis, the latest revival is in terms of

“cosmic influences on the atmosphere” (Arnold and Neubert, 2002) or “cosmoclimatology” (Svensmark, 2007). In some respect, some skepticism is concerned with the amount of every given effect. This drawback is shared by both Bowen and Svensmark hypotheses. The Svensmark hypothesis is presently very fashionable - and its origin dates back much earlier than Svensmark. In fact, it has a clear and substantial observational support. However, it cannot explain the whole observed effects, as one must, rather, take into account also condensation nuclei originated by the additional aforementioned sources.

Note that, contrary to the present generally reported interpretation - which addresses two small droplets or icelets that were already formed - even one-ion alone can be a condensation nucleus. There is only need for a sufficiently intense Cowling micro-dynamo that originates a sufficiently strong E . The initial micro-agglomerate of water molecules around an ion (or any other tiny, charged corpuscle) grows up as long as the condensation nucleus moves through air - and as long as the temperature and the amount of water concentration are such that the scatter with other water molecules permits to collect additional molecules.

The process continues up to some threshold. If accretion stops when the droplet is still comparably tiny, the droplet cannot precipitate. It stays suspended in air, almost like floating inside it. If the size of the droplet is such as to determine atmospheric opacity, we claim that we observe a cloud, or fog, or mist.

The term “cloud” applies only for phenomena that occur at some comparative high atmospheric layer. The distinction between fog and mist depends on visibility (“fog” applies³ with visibility at 1 km).

If a gentle breeze moves the suspended water droplets or icelets between contiguous areas, the phenomenon is named “advection fog”. In contrast, with calm conditions and clear sky, it often happens that the thermal interaction with land or sea of the calm atmosphere causes a local cooling of air. Thus, owing to the reduced thermal motion of air-molecules and ions, the reduced temperature permits ions to easily aggregate into water molecules. In this case, “radiation fog” is the conventional name.

If the droplet or icelet eventually affords to become sufficiently heavy, it precipitates like rain or snow crystal. When some cycle occurs of melting and refreezing, the snowflake eventually evolves into “granular snow”, or even into a “snowpack”, etc. In every case, convection and micro-convection inside small or large clouds is fundamental, because it is essential in order to supply the Cowling dynamo mechanism, which generates the E that moves ions in air through the neutral water molecules.

When the phenomenon gets more intense, a compact ice specimen can be formed: this is the case-history of hail. Hail precipitation is well-known to occur along

3 “Federal Meteorological Handbook Number 1: Chapter 8 - Present Weather”. Office of the Federal Coordinator

for Meteorology. 1 September 2005. pp. 8-1, 8-2. Retrieved 14 December 2013.

stripes of a linear size a few hundred meters across. That is, the hail-cloud moves parallel to Earth's surface, and it is characterized by an intense anomalous internal convection. This physical model has several astute implications.

Rain and/or fog droplets ought to be electrically charged. Atmospheric precipitation is a diffuse electrical discharge. Fog can be dissipated by a gentle thermal anomaly that triggers some lesser convection - and the water droplets of fog are thus compelled to coalesce, and to precipitate. Ignaccolo and De Michele (2011) show a figure, which is an example of the time evolution of rain precipitation. They comment "*weather reports and many scientific models treat rainfall as a continuous process, but to truly understand rain and its effects, one must consider its fundamentally discrete nature.*"

The great observed variety of phenomena shows that no "simple" rule can explain the transition from "fog" to "rain" (or "snow"). In contrast, a large number of drivers controls phenomena, and we miss several details. A full observation and understanding is still beyond our reach.

For instance, while driving along a highway immersed in a thick fog, when you cross over the bridge on a river, the fog abruptly disappears: the thermal contrast with the water of the river determines some convection, which is sufficient to make fog-droplets to coalesce and precipitate. Similarly, the heat island of a town - or also of a small hill - is often sufficient to break through the thick fog that occurs through a flat surrounding country, etc. A lesser breeze is sufficient to affect the delicate equilibrium of fog droplets.

An old-fashioned and harshly debated concern deals with active prevention against hail hazard. Somebody fired small rockets inside clouds, to release condensation nuclei. The rationale was that, by increasing the space density of condensation nuclei, water had to precipitate into a larger number either of droplets or of smaller hail grains. The potential hail damage is thus reduced. On the other hand, in principle, the greater availability of condensation nuclei can generate a greater number of hail grains, and the damage is increased, etc. Several decades ago experiments of this kind were carried out. To our knowledge, they were later abandoned as the results looked inconclusive.

An analogous phenomenon is concerned with the well-known fog dissipation that often occurs after sunrise (see Fig. 5). The atmospheric warming due to sunrays makes the fog to fade off. The mechanism is twofold. Either (i) micro-convection triggers the Cowling dynamo process, which causes the increase of water droplet size, until they fall on ground: in this case, ground is wet. (ii) Otherwise, the increase of air temperature is the opposite mechanism, by which water droplets evaporate and water concentration increases in air, with no precipitation: soil is not wet. In general, both mechanisms can be operative, depending on site and on time. That is, a simple diffuse heat source can get rid of the old-concern about fog dissipation. The concern is, in fact, about the spatial extension and intensity of the needed heat source. Farmers worry about hail - as in a few ten minutes they lose a year-round crop. However, the introduction of the (unprecedented) new concept - i.e.,

the Cowling microdynamo - opens a new perspective. In fact, paradoxically a lightning-rod installed in the field of a farmer can result, perhaps, much effective. The argument is as follows.

Consider Fig. 6a. The thunderstorm cloud has a negative charge at the bottom - due to the positive charge of the ionosphere (see Gregori and Leybourne, 2026g). The origin is the Cowling dynamo inside the cloud (this is a macro-scale phenomenon as shown below). Some "large" conductor, insulated with respect to ground, stands up above ground. The E determines electrostatic induction inside the "large" conductor. The final energy balance is that E spent a small amount of energy to cause the electrostatic polarization of the "large" conductor. When the polarization is complete, no additional energy is required. Hence, the overall energy balance of the Cowling dynamo is almost unaffected by this comparatively lesser energy loss for electrical polarization.



Fig. 5. This phenomenon is a typical occurrence in several valleys. This example refers to the western Po Valley, in southern Piedmont. The village is Altavilla Monferrato in the Province of Alessandria, on the first hills on the sides of the flat plain of the Po Valley. The Alps are in the background. During night and early morning, with calm weather a radiation fog covers the lower part of the valley, like a blanket. This phenomenon is often extended and it involves a large area, e.g., the entire Po Valley. However, after the early hours of the day the fog eventually - although not always - fades off. See text. Figure borrowed after a local tourist advertisement.

In the case of Fig. 6b the "large" conductor is grounded, and the Earth is supposed to have a very large electrical conductivity $\sigma \rightarrow \infty$. In this case, the "large" conductor includes the whole Earth's body. However, as far as $\sigma \rightarrow \infty$, the same argument applies as in the case of Fig. 6a. That is, the time variation of the total energy balance of the Cowling dynamo is affected only by some negligible amount.

In the case of Fig. 6c the experimental setting is similar to Fig. 6b. However, the Earth has a finite σ . This is the real case-history of a lightning rod. The work spent to cause the electrostatic polarization of the "large" conductor (or of the lightning-rod, which is the same) is entirely spent like Joule heat into ground. The phenomenon is steady, and the Cowling dynamo inside clouds is the primary energy supply. In principle, the efficiency of the Cowling dynamo

is steadily reduced vs. time, and less hail ought thus to be formed. Therefore, the power of the Cowling dynamo - in terms of hail production capability - weakens inside the cloud. In principle, this phenomenon occurs independent of whether a lightning discharge strikes the lightning-rod or not, as the phenomenon can occur through simple corona discharge from the lightning-rod, with no real visible manifestation. The effectiveness of this effect depends,

rather, on the cross section of the wire of the lightning-rod, on the quality of the grounding of the rod, and/or on the number of lightning rods located in the area. The target is to cause a large dissipation of electrostatic energy. On the other hand - in principle - such a dissipated energy ought to be exploited, and this seems, maybe, possible (Gregori, 2020, and Gregori and Leybourne, 2025l).

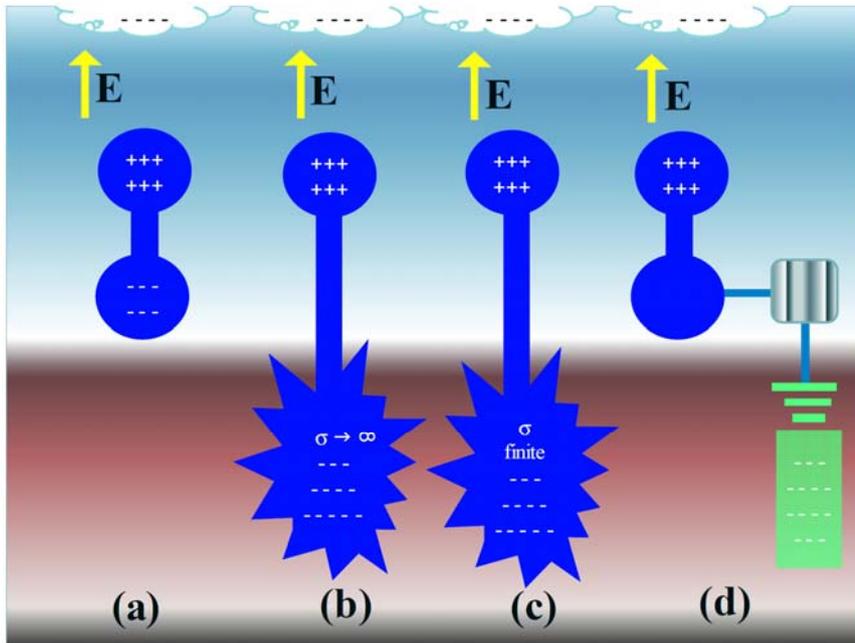


Fig. 6. The bottom of clouds has negative charge. (a) A “large” conductor, unconnected with ground, is suspended above ground surface. The E of the cloud causes electrostatic polarization by induction. (b) The same as in figure (a), but the “large” conductor is grounded to soil. Ground, and the whole Earth, is supposed to have electrical conductivity $\sigma \rightarrow \infty$. (c) The same as in figure (b), but ground and Earth have finite σ . (d) The same as figure (c), but the grounding occurs through a “device” that transforms into some useful energy source the energy that is captured through the “large” conductor. See text. Unpublished figure.

The concern is therefore about the intensity of the total final effect on the availability of primary energy for the Cowling dynamo. Differently stated, suppose that this experimental setting is effective - and that it lowers by a significant amount the energy available for the local Cowling dynamo process. Note that we cannot know *a priori* how far this assumption is reasonable or just nonsensical. If it holds, the concern is about the radius - around the vertical direction above the lightning rod - of the cloud volume where the effect of the lightning-rod on hail production, can be effective.

In general - while dealing either with clouds, or with water condensation and precipitation, or with fog formation, or with atmospheric transparency, or with atmospheric electricity, etc. - a conspicuous amount of speculation biases the present knowledge. There is need for finalized and quantitative measurements. These disciplines are very difficult. Even carrying out any significant measurement often looks like an almost desperate job. One should feel free to consider even some seemingly “exotic” possibility, which is to be suitably tested and eventually rebutted, although only after a suitable physical discussion.

Consider Fig. 6d. It is similar to Fig. 6c. The difference is that the “large” object (i.e., some kind of lightning-rod) is not directly connected to ground. Rather, grounding occurs via some “device” that transforms into some useful output the energy that is “captured” by the lightning-rod. The result is the same as when the energy is spent like Joule

heat in the ground (as in Fig. 6c). In fact, the concern is about whether, in the case of a lightning, this “device” is going to be fully disrupted by the huge amount of electric current that crosses through it. The focus is just on the aforementioned exploitation of the electrostatic energy of the atmosphere (Gregori, 2020 and Gregori and Leybourne, 2025l).

In any case, the central and crucial role of the Cowling dynamo must be stressed for all phenomena that occur inside a cloud, either for water condensation and precipitation, or for hail formation, or for fog, or for the e.m. coupling either with soil and also (see Gregori and Leybourne, 2026g) with ionosphere and space, even with violent phenomena, such as the *TGFs* (see Gregori and Leybourne, 2026f) etc.

Just as a curiosity, several decades ago a popular custom of small farmer in the Po Valley was concerned with the hazard of night-frosts during springtime, when the vines already put the gems. A gem is particularly helpless against frost. One frost night can destroy a significant large percent of the future harvest of the whole season. The custom was that - during particularly cold nights - the farmers lighted bonfires in the vineyards. Consider that the economy was poor, with very limited cash availability, and they were certainly reluctant to bear unnecessary costs. However, it is likely that they made a comparison between the harvest of nearby vineyards, whether bonfires had been switched on, or not. They believed that bonfires were effective. Popular

wisdom should never be underestimated, as it relies on a long lasting and unbiased observational database.

This custom can be explained, and a rationale is envisaged. In the case of frost, a plant finds advantage from an insulating screen made of a very thin layer of ice: this is the well-known frost observed on all vegetation. Every plant needs water in order for this screen. However, the endogenous water availability of a plant is limited. In addition, very cold nights are normally dry, with no breeze, with a cloudless sky. A bonfire triggers some local feeble convection that favors some tiny water condensation into invisible droplets that fall on vegetation.

The standard present way to conceive water condensation and precipitation phenomena is the object of a conspicuous literature. Several features are said to be unexplained. Owing to brevity purpose, no detailed quotation is given. Refer, e.g., to the brief and authoritative short report by Furukawa and Wetzlaufer (2007). In addition, from a “poetic” viewpoint in realm of these disciplines, the geometry of snowflakes has been in the past - and it is at present - one of the most fascinating performances of nature (see Nakaya, 1954, and Gregori et al., 2025w).

Ball lightning (BLs) and plasmoids

Refer to the *several 10 cm* (or larger) scale-size. A presently seldom reported optical phenomenon is called “ball lightning” (BL), also called more seldom “globular lightning”. Alternative names are in French “boules de feu”, or “éclair en boule”, or “foudre sphérique”, in German “Kugelblitz”, in Italian “fulmini globulari”, in Japanese “hitodama”, in Norwegian “kulelyn”, in Portuguese “relampagos globulares”, or “bola de fogo”, or “raios-bola”, in Russian “zharovaya molneya”, in Spanish “rayo globular”, or “descarga esferica”, or “bola de fuego”, in Swedish “klotblixten”, in Ukrainian “kylova bluskavka”, etc. In general, they claim that the phenomenon is unexplained. “At least 2000 research articles have been published on BL since 1970 (see e.g. Journal of Meteorology, 28, 2003) and over 100 hypotheses for its nature and behavior have been put forward ...” (Durand and Wilson, 2006). No review can be here given.

A BL looks like a glowing fireball, roughly spherical. In general, its size ranges from a tennis ball to a basketball. Case histories with several meters diameter were sometimes reported (e.g., Muir, 2001, 2006). Haines (2010) quotes sizes between $< 1\text{ cm} - 1\text{ m}$, although he mentions “one reliable sighting 100 m diameter.” He refers to Abrahamson et al. (2002), and specifies that this “very large self-luminous phenomenon was not a ball seen in the air but at ground level with an estimated width of $> 100\text{ m}$ and height of $\sim 200\text{ m}$ in a ‘fan shape’. It lasted only about $\sim 7\text{ min}$ and changed from a deep red to orange-yellow to white with a red halo”.

A standard lightning flash lasts only a small fraction of a second. A BL lasts many seconds or minutes, in general typically $\sim 2 - 8\text{ sec}$ (e.g., Muir, 2001, 2006). Haines (2010) mentions that “one source cited a BL in

Japan that allegedly remained for $\sim 2\text{ hours}$ and was $\sim 6\text{ m}$ in diameter. Of course, whether it really was BL or not was never verified.” According to the explanation here given, this was a true anomalous large BL.

The typical BL intensity is comparable to a standard lamp of $\sim 100\text{ W}$ (Abrahamson and Dinniss, 2000).

“Some 85% of the observers agree that the size and brightness of the ball remains roughly constant throughout the period of observation and that no changes occur even immediately prior to its disappearance” (Altschuler, 1999). A multiple BL is a seldom occurrence. When BLs appear in series they are named “bead lightning” (see Fig. 1 in Gregori and Leybourne, 2026g). A BL typically moves at a speed $\sim 4 \pm 1\text{ m sec}^{-1}$ (Davis, 2003). “One in six observers report speeds in excess of 25 m sec^{-1} . Several reports do indicate some guidance from telephone or power lines and by grounded objects” (Altschuler, 1999).

According to Haines (2010), a BL “can pass through glass, attracted to electrical conductor(s), independent of wind or air turbulence, pass through narrow cracks and reform on other side in original shape, burn holes through brick walls, does not discharge on touching a conductor to ground ... As Singer (1971) has documented, ...BLs ... have appeared near airplanes in flight and some have entered the interior, often by passing directly through the cockpit windshield! Modern airplane windshields are made of multiple bonded panes of thick plano-glass with extremely strong frames. They may be over-coated with certain deposited filters to reduce solar radiation transmission.”

The holes in a window show no mechanical stress on the glass, recalling rather an effect similar to the effect of a laser beam (Smirnov, 1993), although a BL eventually burns a hole through a brick wall.

Grigor’ev et al. (1992) report 43 detailed eyewitness accounts, dealing with BL penetration into closed rooms through window glass (very often leaving no holes) or entering houses through radio and electric sockets. On some occasions perfectly circular holes were left into the glass of windows. Grigor’ev et al. (1992) also show two photos.

Scientific data, which refer to the natural (non-laboratory) phenomenon, are scarce. The phenomenon is very rare and unpredictable, although several photographs exist. Observations and reports generally rely on non-professional people. Hence, these reports often include also somewhat inconsistent data, and it is difficult, if even possible, to check the reliability of the information. Therefore, they have often been considered only a matter of fantasy (e.g., Muir, 2001, 2006).

According to Smirnov (1989, 1993) (also Carbognani, 1999) the mean internal energy of a BL is $\sim 160\text{ kJ}$ that, if the average radius is $\sim 23\text{ cm}$, corresponds to a mean energy density of $\sim 25\text{ J cm}^{-3}$. The state-of-the-art is briefly summarized as follows by Altschuler (1999).

“... Not long ago, considerable scientific discussion ensued on the question of whether BL is a real phenomenon. Scientists believed that BL could be

- ✓ a retinal afterimage of a lightning flash,
- ✓ an intense coronal point discharge near a lightning target below a thundercloud,
- ✓ some burning or incandescent material thrown from the impact point of a lightning bolt.

Today most researchers believe that Kugelblitz is a genuine electrical effect. A recent survey indicates that BL may be extremely commonplace, but that the observer must be relatively close to the ball to be able to see it. Kugelblitz is probably invisible or indistinguishable in daylight at distances greater than ~ 40 m, which would explain why it is incorrectly believed to be a rare phenomenon.

The median distance between an observer outdoors and BL is ~ 30 m. Sometimes BL floats through buildings. The median distance between indoor observers and BL is only 3 m. The reported distance of the observer seems to be closely correlated with the reported size of the ball. A more distant observer is less likely to notice luminous balls of small diameter, and more likely to misjudge the diameter.”

Different kinds of laboratory experiments were attempted for simulating a BL. All experiments produce effects that look morphologically similar to observations. In general, however, since no final and fully agreed physical explanation is available for a real BL, every experiment might only be apparent, and unrelated to true natural occurrence.

As far as the present illustration is concerned, the discussion is limited only to the possible e.m. aspects of BL. No exhaustive review is here given - either of the (anecdotic) observations, or of the tentative and largely speculative proposed explanations. Rather, an interpretation is here proposed. It is a “simple” application of different primary physical principles that are here applied to the Earth. From such a viewpoint, a BL can thus be most simply likened to a very small scale-size model of phenomena – the Cowling dynamos - that are ubiquitous in the natural environment, although on much different spacetime scales. The final assessment of the correctness of this suggestion can be attained only by carrying out suitable laboratory experiments.

An internal energy source supplies a convection cell, and the Cowling dynamo determines a self-confinement of the plasma by means of toroidal \mathbf{B} . The electrodynamic process *per se* implies almost no motion of molecules, rather only of electrons. Hence, the mere electrodynamic phenomenon can freely propagate through every suitable dielectric (e.g., “solid” objects, such a wood, glass, or metal), by implying almost no motion of molecules, etc. This also explains why BLs seem to be attracted to electrical conductors, where a greater amount is available of free electrons. Atoms, molecules, the crystalline structure - or more generally the “solid” structure of the object - can result to be finally more or less seriously affected, depending on the severity of the perturbation that is applied to electrons that are responsible for crystalline bonds. Also, case histories with no real damage can be eventually observed.

As a premise to this entire discussion, let us stress the kind of environment inside which a BL is generally reported. Sometimes a BL was observed during thunderstorms, sometimes issuing from a lightning flash. Sometimes it was associated with an earthquake (similarly to earthquake lights), or with a volcanic eruption, or with a tornado. Altschuler (1999) gives a list of different witnesses of luminous phenomena reported in coincidence of tornados. The morphology mostly deals with luminous clouds, and sometimes with smell. In every case both features are very likely associated to an electric discharge.

In addition, sometimes a BL appears during calm weather, with no storms in the vicinity. BLs are often reported also in closed environments. In any case, some perturbation very seemingly always occurs before the observation of a BL. For instance, the trigger perturbation can be much varied (a lightning, or the flame in a fireplace, or the switching on or off of a powerful e.m. device, or a rapid melting of a sample that generates a plasmoid, ...). That is, a sudden injection of energy occurs into a suitable small “micro-system”, where a (more or less ionized) plasma is abruptly generated. After the injection of energy, the system enters a temporarily self-sustaining state, almost like a self-sustaining dynamo that confines electromagnetically the system.

Self-sustaining systems - in terms of a self-confinement of e.m. phenomena on the photon scale - recently entered into the domain of nanotechnologies. “Plasmons” is the name coined in 2000 by the Caltech group of Professor Atwater for the generation of the propagation of self-sustaining waves at the interface between a metal and a dielectric. That is, under suitable circumstances, it is possible to achieve a resonant interaction between an impinging wave and the free electrons of a conductor. The result is the generation of surface “plasmons”, i.e., waves of density of electrons that propagate along the surface much like pressure waves on the water surface of a pond stricken by a falling stone (Atwater, 2007). By the way, such a kind of pressure waves can be speculated to be related to the presently not fully understood phenomenon of thunder. See Gregori et al. (2026d).

Differently stated, the physical system of a BL is composed of a limited amount of plasma, which reminds about the state-of-matter during the very early stage of implosion of matter inside a galaxy, or during the formation of a star, etc. In fact, the leading anthem of the present discussion is the general behavior of a cloud of ionized matter.

Smirnov (1990) is an extensive and systematic statistical study on the properties of all reported observations of BLs. These very detailed items are not of direct concern for the present discussion. Just point out that - as it will be here stressed in the following - the physical process responsible for BL seems likely to be a very frequent and ubiquitous occurrence, although occurring on much different spacetime scale-sizes. The capability to detect the effects is limited by the empirical constraint, i.e., by the sensors that are available to the humans.

Straser (2016) contains a list of several *BL*s observations associated with oil fields and soil exhalation in their respective areas. This list derived from a careful compilation of information reported during over one century in central Italy (in the Regione Emilia-Romagna). He shows that this phenomenon can occur everywhere, i.e., either depending on some “micro”-soil-exhalation, or in a fireplace hearth, etc. It is ubiquitous, although its detectability ought to require a specific devoted concern - as these transient and rapid phenomena are otherwise normally unnoticed. Soil exhalation occurs in areas with oil underground, and exhalation depends on the amount of soil stress that determines crustal fracturing.

Singer (1971) criticizes several classes of theory, because in general they match only some *BL* properties, though not all of them. Singer (1977) is an authoritative author, who includes a detailed table comparing different hypotheses. In the ultimate analysis, it appears that no theory seems convincing to him.

A few laboratory experiments that are likely to generate *BL*s like plasmoids

Only a few main laboratory experiments are here recalled, which are pertinent for the present discussion. In general, the candidate theories can be distinguished depending on whether they are energetically self-sufficient, or they need for energy being continuously supplied by an external source. In any case, some energy input is needed, at least as a trigger to start the process. Hence, either the entire required energy is supplied by the starting trigger, or some kind of steady energy supply is required during the entire *BL* lifetime.

Take for granted that a *BL* is an electrodynamic system. It must remain self-confined for a while. Four key items are to be decided: (i) the constituents of the system, (ii) the more or less stable mechanism for self-confinement, (iii) the trigger responsible for the start of the process, and (iv) the energy source, which can be entirely operative at the very beginning of the process, or it can elapse and distribute its supply during the entire observation of the *BL*.

The model that is here proposed relies on the requirement that a *BL* is a Cowling dynamo, powered by an internal source, and this dynamo can generate a toroidal **B** (and not a poloidal **B**). The toroidal **B** is not an actual knotted **B** field. However, the toroidal feature displays field-lines that close on themselves within a much-limited spatial range, reminding in some way about a structure that, intuitively, can be approximately likened to a knotted field. That is, in some respect, a model proposed by Rañada et al. (1998; see below) can be considered a precursor of the more exhaustive argument and proof of the Cowling dynamo (see Gregori et al., 2026d).

Heating is the primary energy supply for a *BL*. In general, it is Joule heat that can be attained in the laboratory

either by a high voltage discharge or by an e.m. resonance to microwaves, i.e., much like it occurs inside a common microwave oven.

If *BL* are plasmoids - and if the gas is highly ionized - it is reasonable to guess that the gas is near thermodynamic equilibrium. It must be very hot: hence, plasmoids should float much rapidly inside surrounding air. This does not occur. One explanation can be that the **B** are intense, keeping the constituents of the plasmoid compressed in such a way that its density is as heavy as needed to avoid floating. In fact, floatation is sometimes reported, but sometimes clearly denied by observations (see below).

Another possibility is that the plasma is composed of heavy ions, both positive and negative, such as it occurs in the case of molten silica (see below). In contrast, in the natural environment, this hypothesis should have, as a byproduct, some implication: (i) for the seeds for water condensation and precipitation, (ii) for the observed color of *BL*, and (iii) for the sometimes-reported smell of a *BL* when it fades off (see below). Or one can also speculate about a combined action by all these aforementioned mechanisms.

A seemingly very clear reply to every concern derives from the following experiment. Gerd Fußmann carried out an intriguing experiment that overcomes several previous difficulties (Bürke, 2008, and Versteegh et al., 2008). Fußmann (Bührke, 2008) had previously seen a few photos - although no measurement - of fireballs generated in an experiment carried out at the *Institute for Nuclear Physics* in St. Petersburg, with the purpose of disinfecting water by a high voltage discharge. Fußmann tried to repeat the experiment to investigate and to measure *BL*s. Fußmann and colleagues produced a cloud of ionized water by means of a huge electric current crossing a vessel of water (Fig. 7). They achieved ball diameters of $\sim 10 - 20$ cm with lifetimes of ~ 0.3 sec. That is, their *BL*s lasted as long as the electric current could supply Joule heat.

A powerful capacitor-bank is used.⁴ A glass beaker, ~ 22 cm in diameter, is filled with regular tap water, either adding or not some salt of some kind (different salts can be used). It contains two electrodes. One electrode has the shape of a circular plate and is at the bottom. The second electrode is a copper wire insulated from the surrounding water by a clay tube (~ 1 cm in diameter). The space between tube and wire is almost completely filled with an insulator. Only the end of the central copper electrode is uncovered. The wire and the ceramic tube stick only slightly out of the water, just to have a water droplet laying around the uncovered piece of copper wire.

When the high voltage (5000 V) is abruptly switched on, the water droplet vaporizes and a luminous plasmoid (20 cm in diameter) appears, composed of ionized water molecules (Figs 8 and 9). The plasmoid raises about half a meter above water level. The color depends on the salt solution in the water. A current of up to ~ 60 A flows through the water during ~ 0.15 sec.

⁴ Fig. 7 indicates a capacity of 2.48 mF. Another figure, not here shown, indicates 0.5 mF.

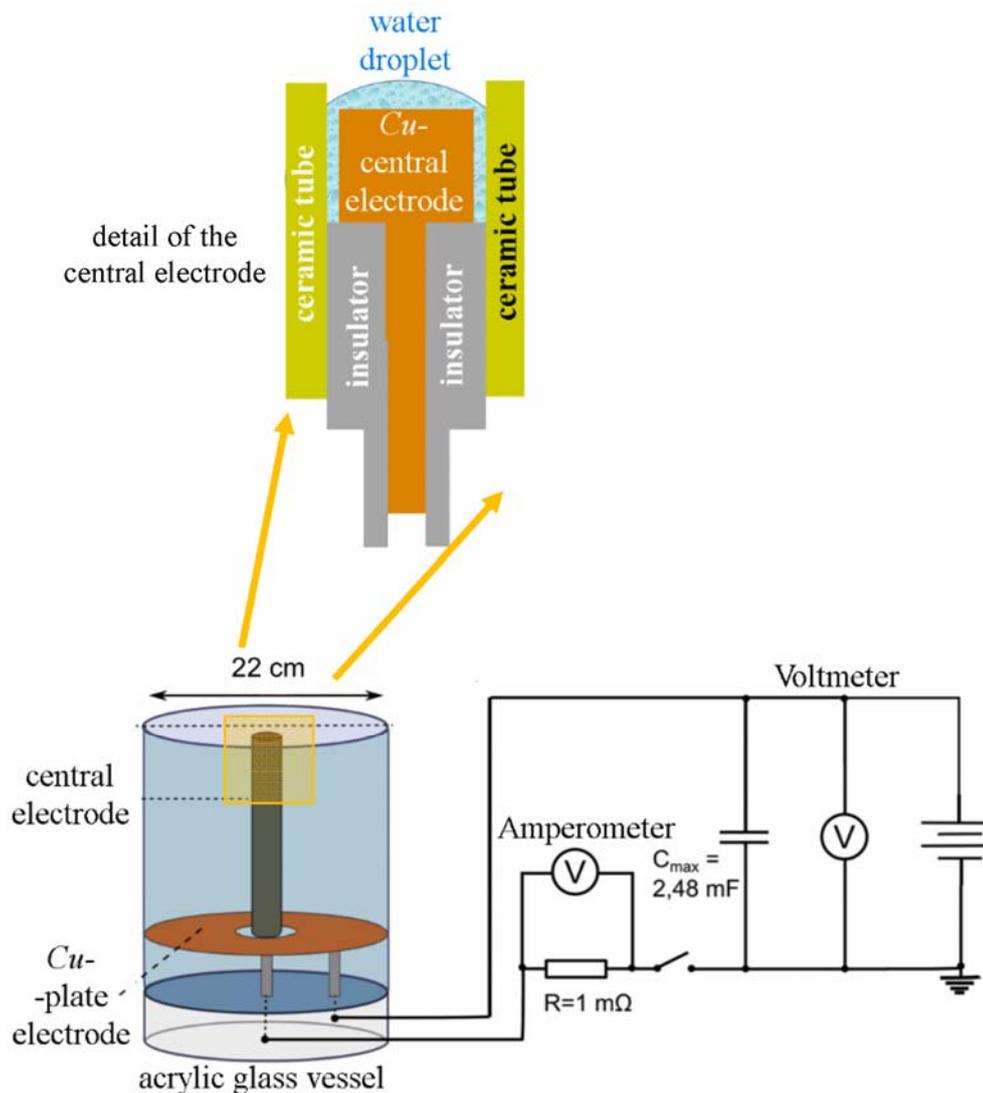


Fig. 7. Principle of the experimental device for generating a ball of plasma from a high-voltage discharge between two electrodes. The lower electrode is a circular copper plate. The central electrode is surrounded by an insulator and a ceramic tube. It protrudes a few millimeters out of the water, carrying a droplet of water. See text. See Bührke (2008). Unpublished figure based on a figure kindly provided as a courtesy of the Max-Planck-Institut für Plasmaphysik.

“High-speed cameras show a spidery, glowing net spreading over the surface of the water around the uppermost electrode shortly after the voltage discharge – within a few 10^{-3} sec ... [see Fig. 10]. The diameter of the ball of light rising at ~ 1 m sec^{-1} grows from ~ 8 to ~ 20 cm. Then the ball morphs into a tire-shaped form and disappears. The plasma bubble contains just $\sim 1 - 3$ g of gas.

Experiments with thermoelements yielded the first temperature findings. The thermoelements in this case are two extremely thin wires made of different metals, welded together at both ends ... In these experiments, the physicists held the thermoelement in the ball of plasma. They recorded temperature of around ~ 1300 °C - and then the wire melted” (Bührke, 2008).

Hence, they shifted to the use of spectroscopic techniques, and “deduced that the initial temperature in the

balls was on the order to ~ 5000 °C, and that it fell about half within the first ~ 0.1 sec ... “

By means of this facility they afforded to generate an impressive “BL”, about every 5 min, in every possible manifestation and color. Luminous phenomena continued to be visible ~ 0.3 sec after the current had decayed and the energy input cut off. This was, however, a real surprise for the experimenters, as the phenomenon really had to be quenched after at most a few milliseconds. That is, the plasma confinement was found to be very effective and persistent in time.

Furthermore, the plasma appeared very brightly, although the plasmoids looked rather cold. “During the first few experiments, Fußmann and his colleagues placed pieces of paper in the path of the rising balls. As the paper did not burn on contact, the scientists suspected that the

balls of light were relatively cool. This turned out to be wrong” (Bührke, 2008).



Fig. 8. A ball-lightning-like plasma cloud generated by an underwater discharge. (Photo: D. Lange, IPP). After Bührke (2008). Image reproduced by courtesy of the MaxPlanck-Institut für Plasmaphysik.



Fig. 9. A blazing ball of plasma generated by an electric discharge from a droplet of water. See text. Image provided as a courtesy of the Max-Planck-Institut für Plasmaphysik. The ball of plasma sometimes displays a regular mushroom, or jellyfish, shape, as shown in the insert, which is an unpublished hand-made sketch based on a photograph shown by Bührke (2008) and of unknown copyright-holder.

According to Versteegh et al. (2008), the plasmoids are formed by a true plasma inside a cold envelope. During the initial formation phase, Stark-broadening showed a decreasing electron densities in the order of $10^{20} - 10^{22} \text{ m}^{-3}$, while during most of the plasmoid’s lifetime the electron temperature was found to be $2000 - 5000 \text{ K}$, and the temperature of the neutral particles sometimes exceeded 1300 K . “Calcium hydroxide molecular band emission is the major source of visible radiation in the autonomous phase. Chemiluminescence reactions between dissociation products of water and dissolved calcium are proposed as a source for this emission. The plasmoid’s colder boundary layer consists of electric double layers that may be attributed to the characteristic shape of the balls” (Versteegh et al., 2008). [In fact, a layer of firmly trapped electrons on toroidal \mathbf{B} field-lines has a much lower temperature, due to the strong trapping.]

“... The scientists’ latest discoveries show that it is these that are responsible for most of the glow. At these high temperatures, the water gives rise to hydroxide radicals,

which in turn react with calcium to form calcium hydroxide. This reaction also occurs in flames and causes a light emission known as chemoluminescence. Although Gerd Fußmann and his team have largely solved the riddle of the glowing plasma, one big issue remains unresolved: the sodium and calcium atoms also emit light in characteristic colors: sodium glows yellow; calcium, reddish-orange. But they can do this only when continuously bombarded by hot and fast electrons. By rights, the electrons should quickly cool down in a plasma, and thus the light from the plasma ball should quickly extinguish, too. More quickly than the Berlin scientists have been seeing, at any rate. That means that the electrons must continue being heated for as long as the ball is aglow. The researchers suspect that the energy needed to do this is stored in the molecules and released to the electrons in an as yet unknown manner - a baffling procedure, and one that the scientists are still looking into” (Bührke, 2008).

This means that the fireball has a long-lasting energy source, originated in its interior, which keeps it hot and fairly well confined. Its outer boundaries are much colder. An upwelling convective plume lifts up on top of it, holding, e.g., a paper sheet. On the other hand, this plume is essentially much colder than the ball interior. These are key observational features that we must explain when implementing a theoretical model. All these statements fit very well with the expectation of the Cowling dynamo mechanism, with no need to appeal to any additional energy stored in the molecules.

As far as the energy balance is concerned, “a total of some $\sim 8 \text{ kJ}$ of energy flow from the high voltage into the discharge, with about $\sim 3 \text{ kJ}$ going directly into the water droplet. The vaporization of the liquid and the heating of the water vapor consume around half of this. Approximately $\sim 30\%$ of the remaining $\sim 50\%$ goes into dissociating the molecules and ionizing the atoms, and about $\sim 20\%$ goes into the light emission.

So ... only a few percent of the total electric energy is converted into light. [That is, only a minor fraction of the original convection energy is manifested like photon emission, while the largest part is spent for other purposes, such as, in the case of cloud-size convection cells, to supply electrostatic charge to the ionosphere; see Gregori and Leybourne, 2026g] The percentage can be increased by using a material with low electrical resistance as a conductor, which would therefore consume less energy. Completely different dielectric materials also have this effect, in addition to a higher salt content in the water ... In the meantime, the researchers have discovered why they were convinced right from the start that the balls were relatively cool: they discovered that they have a thin, relatively cool outer layer. This was indicated in the photos from the high-speed camera. [See Fig. 10.] However, it can be seen more clearly with laser beams. One of the students arranged 20 laser pointers so that their light illuminated the rising bubbles in intervals of 0.05 sec and then hit a wall 5 m away on the other side.

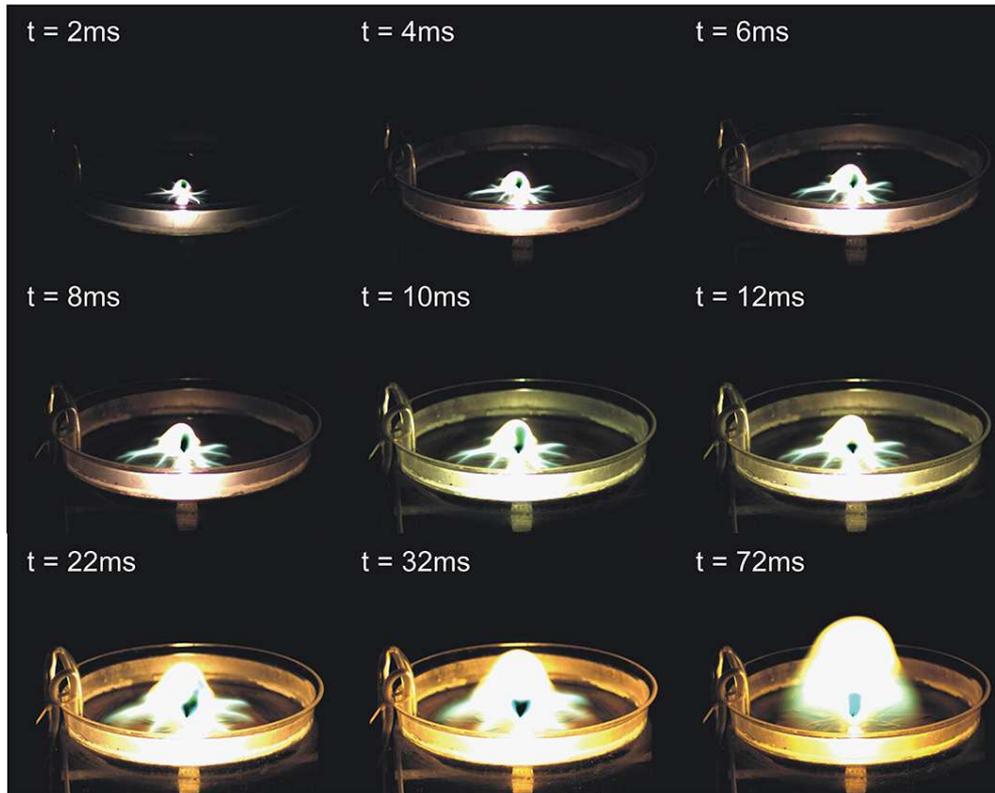


Fig. 10. “Ball lightning development: in increments of a few 10^{-3} sec the researchers record the plasma ball’s growth. Salts in the water give it a greenish glow.” The final picture shows a peculiar optical appearance of the boundary of the fireball, which is likely to be associated with the measured much lower temperature of the outer boundary of the fireball. See text. Figure and captions after Bührke (2008). Image provided as a courtesy of the Max-Planck-Institut für Plasmaphysik.

When these laser lights cross through the outer layers and turbulent interiors, they are strongly deflected as a result of the changing refraction index. This makes the points of light dance several centimeters back and forth on the rear wall ... The preliminary, still fairly rough, finding is that the outer, relatively cool, shell is only $\sim 40\%$ as dense as air. A second, much thinner shell with a temperature, of $\sim 2,000$ °C or more, attaches to it on the inside. So the external shell envelops the hot plasma in the interior and gives the ball of gas its stability... “(Bührke, 2008). [The external shell is thin due to the strong trapping of electrons on the toroidal \mathbf{B} field-lines.]

Bührke (2008) concludes that “when lightning strikes a pond, e.g., no balls of plasma will be formed, as the energy dissipates in the vast quantity of water. It would have to be a small vessel, like a glass of water or a small puddle that the lightning struck. However, the occurrence of such conditions is rather improbable ...”

In this respect, Gregori and Leybourne (2026g) is devoted – among other items - to explain a spark as a chain of BLs. For instance, Figs 4 and 5 of Gregori and Leybourne (2026g) show two case histories of an intense lightning flash striking on the surface of a lake. If the lightning discharge is a moving BL, maybe, it damps off when it strikes the water. However, according to the

aforementioned Gerd Fußmann’s experiment, under peculiar circumstances the BL might, perhaps, behave even almost like in the case that it is “reflected” by the water surface. The occurrence of such an eventual curious behavior can be understood upon considering the model here proposed for the interpretation of these phenomena, although the amount of energy ought to be taken into account that is stored inside a BL. In fact, the specific parameters of a BL determine, perhaps, whether the BL is just absorbed by water, or it is eventually reflected like by a mirror, thus “jumping” on the water surface. To our understanding, *a priori* both possibilities seem possible (see Gregori and Leybourne, 2026g).

Other experiments, similar to the Fußmann’s experiment, were carried out, e.g., by Egorov and Stepanov (2002, 2008) and by Egorov et al. (2004). They showed that their fireball contains stable clusters composed of two hydrated ions of opposite sign, $H_3 O^+$ and OH^- , and water molecules. Water molecules prevent the hydrate ions to recombine. Thus, compared to the usual electron-ion recombination time, the lifetime of ions is much longer.

Sakawa et al. (2006) investigated the timing of these phenomena. They generated a fireball in a water discharge and studied the time evolution of visible spectra. “Clear ball-shaped fireballs appeared when $NaHCO_3$ was added to pure water. The emission of ionic lines of Ca and atomic

lines of Na, K, Li, and Ca appeared early in time, followed by unidentified molecular-like spectra, and the emission of NaI resonance lines remained at the final stage of the fireball.” For details of the experimental setting, refer to the original paper.

Egorov and Stepanov (2008) claim having thus generated “thousands of floating glowing plasmoids ~ 20 cm in diameter ... It is found that short-lived BLs live for ~ 1 sec and carry an electric charge. The lightning are shown to have a complex structure: a central kernel containing a rich variety of hydrated ions and aerosol of decay products is surrounded by a thin negatively charged shell.”

Other authors developed theories or experiments based on a production of a metallic vapor, instead of water vapor, e.g., a vapor of silicon. Abrahamson and Dinniss (2000) (also Hubler, 2000) speculated that the nanoparticle cloud is generated by oxidation when a normal lightning strikes on soil. “When normal lightning strikes soil, chemical energy is stored in nanoparticles of Si, SiO or SiC, which are ejected into the air as a filamentary network. As the particles are slowly oxidized in air, the stored energy is released as heat and light. [They] investigated this basic process by exposing soil samples to a lightning-like discharge, which produced chain aggregates of nanoparticles: these particles oxidize at a rate appropriate for explaining the lifetime of BL.”

That is, a BL is just the result of burning vaporized Si. When a standard lightning strikes the silica-rich soil, the Si ought to be instantly vaporized. The vapor then condenses and slowly burns by combining with the oxygen in the surrounding air. This is the mechanism that originates a “fulgurite” (sometimes also called “petrified lightning”), which is the name given to the mineral formed when a lightning hits soil. According to Schonland (1939) their typical diameter is ~ 5 cm.

Also, other kind of more “exotic” models have been sometimes proposed for BLs. Black holes, anti-matter, nuclear phenomena, and neutrinos have sometimes been speculated to be the primary responsible agent.

Neutrinos and heavy neutrinos were appealed to for explaining extreme ball lightning (EBL) of a highly energetic violent kind (Abrahamson and Dinniss, 2000; also Hubler, 2000). The source of the following information is Thornhill (2006), who reports about the Plenary Talk by J. Pace VanDevender, given at the *IEEE International Conference on Plasma Science (ICOPS 2006)*, held in Michigan in June 2006, titled “Ball lightning: new physics, new energy source, or just entertainment”. Thornhill (2006) distinguished between ordinary lightning and EBL.

An ordinary BL lasts < 10 sec, it is benign, and it spontaneously appears in the open-air, in closed rooms, inside aircraft at altitude (Uman, 1968), in submarines, etc. Instead, an EBL has the following characteristics (quoting Thornhill, 2006):

- “it glows in air;

- it originates from nothing visible;
- it lasts between 10 – 1200 sec;
- it floats at about ~ 1 m sec⁻¹;
- it is lethal or potentially lethal;
- it causes significant damage;
- it contains energy estimated at 10⁵ – 10⁹ J, far in excess of the energy density attributable to chemicals or electrostatics;
- it penetrates walls, glass and metal, generally without leaving a hole;
- it induces large currents but is in radial force equilibrium;
- it leaves black streaks on corpses without the spasm of electrocution;
- it can excavate tons of earth.”

Just point out that an EBL can penetrate - without leaving a hole - walls, glass and metal, although it can excavate tons of matter. That is - in general - a very rapid transit of the discharge through matter leaves unchanged the crystalline structure of solid materials. However, when the discharge is absorbed and damps off inside matter, it releases a destroying power.

According to the interpretation here proposed, there is no gap between a very feeble and a very intense phenomenon. Hence, there is no need to introduce any distinction between different observed patterns. In fact, it is perhaps even impossible to define a threshold suited to distinguish separate classes of phenomena.

In any case, according to Muir (2006) and Thornhill (2006), J. Pace VanDevender was impressed by a report on an EBL, occurred in County Donegal, Ireland, on August 6, 1868. It moved for ~ 1.6 km while excavating, in ~ 1200 sec, ~ 200 m of water saturated peat. It left a ~ 6 m² hole, a ~ 90 m long trench, a second trench ~ 25 m long, and a small cave in the peat bog.

Other analogous small-scale phenomena are sometimes observed.

In order to detect the phenomenon while it is in progress, the size and intensity of the event must be above our observational sensitivity. The dynamo must be intense in order to accelerate electrons up to an energy sufficient to trigger photon release from ions, atoms and molecules of the ionized fluid. The space size must be sufficiently large, and the observer should be reasonably close to it. The time duration must be sufficiently long. In addition, the luminous contrast during observations must be sufficient, i.e., we must carry out observations in sufficient darkness, with a reasonable total thickness of the emitting source (e.g., consider TLEs, the “Andes lights” or “hot weather flashes”; see Gregori and Leybourne, 2026g) etc. These very peculiar conditions can occur on some special circumstances, thus displaying phenomena that should look much like BLs.

Even the “orb” phenomenon – if it exists - could perhaps be a similar, although less spectacular, occurrence. In fact, sometimes photographic pictures show a typically circular artifact called orb, and sometimes it looks in motion, leaving a trail. The most obvious explanation is in

terms of backscatter from a dust particle etc., or by a near-camera reflection. This can occur particularly in modern ultra-compact cameras, which have an optical system of reduced size. On the other hand, it might be excessively unscientific to explain every evidence by an understating assumption.

No scientific documentation seems to exist, rather only some pictures and reports by non-professional people. Unless all of them are false and *ad hoc*, sometimes the images look curious. In the case that the phenomenon is real, one possible and reasonable guess is that orb is a small, faint, temporary *BL*, which is excessively feeble and thus undetected by human eye.

Other possibilities, however, can be considered even dealing with some much smaller spacetime scales. The detection is low when the scale size is very small. However, an eventually integrated effect of several “almost simultaneous” and very “small” similar occurrences can sometimes result sufficient for enabling detection and observation, such as, e.g., dealing with atmospheric fog or precipitations. This is essentially the explanation of the *GK effect* (see Gregori and Leybourne, 2026f). Also unexplained phenomena, however, exist, such as, e.g., the Hessdalen lights (see Gregori and Leybourne, 2026g).

This argument is consistent, e.g., with Tarr (2006), who distinguishes between *BLs* that are phenomena of conspicuous energy and can result harmful, and *LBs* (light balls) that involve only a limited amount of energy and are harmless. They are observed inside buildings, where they receive no energy input from the exterior. In contrast, *BLs* can receive energy, e.g., from a usual lightning etc. Tarr (2006) stresses that “*Stepanov provided good statistics on high damage until 10 MJ, attributed to BL all of which happened mainly outside of buildings, where DC electrostatic fields could act (Stepanov et al., 1997, 1997a).*” The most intense *BL* was seemingly reported by Stenhoff (1999, pp. 167, 212, 233). However, in contrast with other theories that hypothesize a preliminary generation of a vortex ring of plasma, which is triggered by some external cause, Stenhoff (1999) only envisages a simpler hydrodynamical vortex ring.

For the sake of completeness, a curious theoretical hypothesis deserves a mention. An earlier paper (Rañada and Trueba, 1996) speculated about a peculiar quantum configuration and envisaged the possible nature of *BL* as an e.m. knot, named “*skyrmion*”. On the other hand, nobody ever afforded to make it experimentally. In some way, the Gerd Fußmann experiment (and analogous experiments) is a way to generate an e.m. knot through the role of the Cowling dynamo.

Lee et al. (2018), which is also illustrated by Letzter (2018i), claim that they “*experimentally realize a simulation in which a charged quantum particle interacts with the knotted e.m. fields peculiar to a topological model of BL. These phenomena are induced by precise spatiotemporal control of the spin field of an atomic Bose-Einstein condensate, simultaneously creating a Shankar*

skyrmion - a topological excitation that was theoretically predicted four decades ago but never before observed experimentally ... “

Letzter (2018i) comments that “*scientists bound the B of a supercooled quantum object into a complex knot ... That bizarre knot was a quantum object called a ‘Shankar skyrmion’ that was first theorized in 1977, but that no one had ever managed to generate in a lab. A skyrmion is a tightly clustered group of circular B, with each circle crossing each other circle exactly once ... The researchers built the skyrmion out of a cloud of atoms supercooled into a dense blob called a ‘Bose-Einstein condensate’ - a state of matter that emerges just at the edge of absolute zero, where the borders between atoms blend together, and quantum effects start to take place at a scale humans can more easily detect and observe.*

Using techniques developed to build an exotic class of quantum magnet, the researchers nudged the spins, or magnetic orientations, of the atoms in the condensate until the interlocking rings of the skyrmion emerged ... “

That is, this is a peculiar environmental configuration, implying a Bose-Einstein condensate - unlike the ubiquitous role played by the Cowling dynamo that implies no kind of “exotic” and/or specific requirement. In any case, the principle is the same to explain a *BL* either by a Cowling dynamo or by a “*skyrmion*”. The key pattern is a **B** knot. The innovation here proposed relies on the key role of the ubiquitous Cowling dynamo.

Flames in micro-gravity environment

A definitely impressive similarity with Figs 8, 9 and 10 is displayed by a *NASA* movie (Phillips, 2014j) that shows “*jellyfish flames*” on the *ISS (International Space Station)*. Owing to the impossibility to show here several details, the following detailed description is here reported that is given by Phillips (2014j).

According to the Cowling dynamo mechanism, this jellyfish-flame phenomenon can be explained by stating that micro-gravity permits an easier and more stable formation of a large *BL*. It appears that usual gravity environment favors the development of well-formed convective cells that permit no formation of a *BL* pattern. Therefore, in a standard gravity environment, a flame is the simple result of thermal excitation of atoms and molecules that decay and release photons of some given energy.

Conversely, in a micro-gravity environment, lesser micro-turbulence originates some smaller *BLs* inside every main *BL*. These smaller *BLs* appear like light spots, and move through the main *BL* interior, until they eventually cross its outer boundary, and fade off outside it, as soon as their internal thermal energy has exhausted. Moreover, eventually one of these lesser *BLs* can be tracked and it appears like a slowly moving twisted beam.

Some excerpts of the description given by Phillips (2014j) are as follows.

“... Unlike flames on Earth, which have a tear-drop shape caused by buoyant air rising in a gravitational field, flames in space curl themselves into tiny balls. Untethered by gravity, they flit around ...”

“... flameballs” were observed by astronauts. The movie was made on August 21st, 2014 by the astronaut Reid Wiseman (“it was a jellyfish of fire”) while “running an experiment called FLEX-2, short for Flame Extinguishment Experiment 2.”

“ ‘Combustion in microgravity is both strange and wonderful’, says Forman Williams, the principal investigator of FLEX-2 from UC San Diego. ‘The ‘jellyfish’ phenomenon Wiseman witnessed is a great example.’ He points out some of the key elements of the video.

‘Near the beginning we see two needles dispensing a droplet mixture of heptane and iso-octane between two igniters. The fuel is ignited ... then the lights go out so we can see what happens next.’

‘The flame forms a blue spherical shell 15 – 20 mm in diameter around the fuel. Inside that spherical flame we see some bright yellow hotspots. Those are made of soot.’ Heptane produces a lot of soot as it burns, he explains. Consisting mainly of carbon with a sprinkling of hydrogen, soot burns hot, around 2000 K, and glows brightly as a result.

‘Several globules of burning soot can be seen inside the sphere’, he continues. ‘At one point, a blob of soot punctures the flame-sphere and exits. The soot that exits fades away as it burns out.’

There is also an S-shaped object inside the sphere. ‘That is another soot structure’, he says. The ‘jellyfish phase’ is closely linked to the production of soot. Combustion products from the spherical flame drift back down onto the fuel droplet. Because sooty material deposited on the droplet is not perfectly homogeneous, ‘we can get a disruptive burning event’, says Forman. In other words, soot on the surface of the fuel droplet catches fire, resulting in a lopsided explosion.”

Forman also specifies that “we first saw these disruptive burning events in labs and microgravity drop towers more than 40 years ago. The space station is great because the orbiting lab allows us to study them in great detail. Tom Avedisian at Cornell is leading this particular study. We’re learning about droplet burning rates, the soot production process, and how soot agglomerates inside the flame.”

Phillips (2014j) concludes and states that “at the end of Wiseman’s video, the soot ignites in a final explosion ...”

A NASA didactic video (Tasoff, 2018a) shows and stresses the role of gravity for the generation of standard convection cells that play a crucial role in flame formation. In contrast, it shows images of flames in a gravity-free environment with patterns that clearly show toroidal structures with orthogonal jets etc. It also announces a set of six major studies called the *Advanced Combustion via*

Microgravity Experiments (ACME), which began in November 2017 to be carried out on board ISS.

The interaction of BLs with matter

Summarizing, the physical details can be very complicated of a discharge through the atmospheric condenser. Several related aspects are discussed in Gregori and Leybourne, (2026f, 2026g). Some details, however, are often concerned with the temporary state of the dielectric inside the condenser.

In contrast, the present discussion is focused on the physics of drivers that trigger a “discharge” in the widest sense. Understanding all details is likely to require much hard thinking. The availability of additional observational parameters will certainly help to achieve a better assessment. For instance, some unprecedented evidence is related to the specific e.m. emission associated to different kinds of lightning (Hare et al., 2019). In any case, the hypothesis looks realistic (see Gregori and Leybourne, 2026g) of a domino effect of BL Cowling micro-dynamos, which is certainly in agreement with observations and with several features that are unexplained by previous interpretations.

A particular and different class of electric discharges deals with all different TLEs (see Gregori and Leybourne, 2026g). They are faint emissions, hence of difficult detection. The detection, however, depends on source height that sometimes has a wide spatial range, by which optical contrast is eventually low. On the other hand, the involved total energy can eventually be remarkable. Much fainter electric discharges include the St. Elmo fire, the “Andes lights” or “hot weather flashes”, and the Caronia phenomenon (see Gregori and Leybourne, 2026g; Gregori et al., 2025b).

The faintest discharges include BL - and, maybe, also the orb phenomenon. In any case, owing to sound physical reasons, the micro-dynamo phenomenon must exist, independent of BL, or of the orb, or others. Therefore, the concern is only about the way a micro-dynamo can be detected, or about the peculiar circumstances needed to detect it.

Differently stated, the concern is not about proving - or disproving - that the aforementioned model for different observed phenomena is the correct support to prove BLs. The physical model is certainly correct, and a phenomenon of this kind must occur in any case. The morphology of a BL seems to be the same as expected by the model. Hence, it is reasonable to associate the model to BLs. In the opposite case, one should eventually prove that some mechanism other than the micro-dynamo process can justify with comparable detail a BL and all related morphological features.

In the final analysis, one can achieve an ultimate confirmation of the model - which is here proposed - by reproducing in the laboratory some conditions comparable to what occurs in the environment. A corona effect, or a spark triggered through a gas, is a confirmation. Analogous

experiments can be assembled for reproducing other “exotic” luminous phenomena. For instance, refer to all aforementioned Gerd Fußmann’s experiment aimed to reproduce in the laboratory some plasmoids that reminds about a *BL*.

The *BL*, or every other optical phenomenon, will be observed if the conditions are satisfied in order to supply micro-convection. With no internal energy supply, the Chandrasekhar and Fermi theorem applies, and plasma is rapidly dispersed through space - thus, the micro-dynamo no more confines plasma, while ionized atoms eventually become neutral atoms. In this case one eventually feels an unusual smell. This explains all typical morphological features of the observed fading off of a *BL*.

It is interesting to consider the damage of a lightning that strikes on the green of a golf course. The lightning produces cracks in solid ground due to thermal dilatation (Fig. 11). The reason is that, when a discharge (i.e., a domino “chain” of micro-dynamos; see Gregori and Leybourne, 2026g) strikes on a slab of finite thickness, it eventually crosses through it. In addition, if its intensity is sufficiently strong, it can produce a hole that appears to be burned through the thickness of the slab. In contrast, if the target is not a slab, rather a plane that defines a half-volume, the spark enters into all electrical circuits that it generates - and that are circuits that flow through the whole medium in the half volume. The medium is thus strongly warmed, as the micro-dynamo process spends the whole lifespan and energy inside the medium - unlike when it crosses a finite thickness slab. The consequent thermal expansion causes fractures that, in a homogeneous medium, are radially symmetric around the striking point. In this respect, also remind about the aforementioned *EBLs* that can excavate tons of ground while they move.



Fig. 11. “Lightning damage caused by a direct strike to a golf course green (photo courtesy of Weatherwise).” Art work, ink and pencil sketch based on an image, and captions, after Uman (1986a), also in Salanave (1980, p. 121).

A discharge that crosses through a medium burns it locally, but in general no fracture is triggered. For instance, see in Fig. 12, which shows the hole burned in an aircraft by a lightning (not by a *BL*), and envisages that a lightning discharge causes the same damage as a *BL* of sufficient intensity. Differently stated, the effect looks similar to, and comparable with, the effect of an intense laser beam.

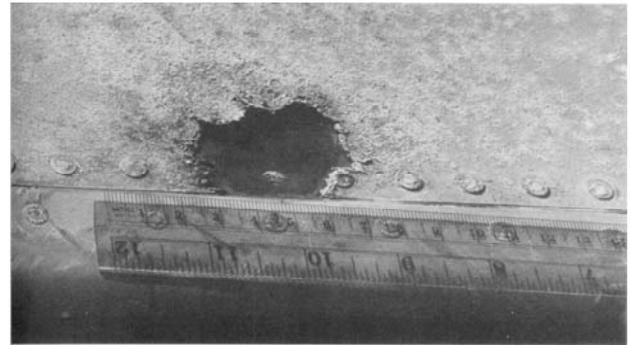


Fig. 12. “A lightning hole burned in the wing tip of a Boeing 707.” Figure after Uman (1971) and captions after Uman (1986a). Reproduced with kind permission from the *National Academy of Sciences*. Courtesy of the *National Academies Press*, Washington, D.C.

If the discharge propagates through a thick medium, it causes a thermal effect. Therefore, fracturing derives from the equation-of-state of the medium that expands due to its increased local temperature. An analogous effect occurs when a lightning strikes a tree. The shock on the tree is not lethal - unlike it occurs in an animal, as the electric shock eventually stops heartbeats, and it can interfere with the nervous system. A tree is physiologically less critical, although heat vaporizes the internal moisture of the wood, which will break by hot vapor due to internal pressure (Uman, 1986a).

Uman (1986a) specifies that “*the heating of many objects and the explosion of insulators is, to a first approximation, due to the value of the action integral. In the case of wires, the action integral represents the heat that is generated by the resistive impedance of the wire.*” The action integral is defined by $I^2 dt$. Uman (1986a) also reports some nomograms by Fisher and Plumer (1977) that show the temperature increase of wires of various materials and different cross-section, for typical lightning action integrals. “*About 1% of negative strokes to ground have action integrals exceeding 10^6 . About 5% of positive strokes is thought to exceed 10^7 .*”

Experiments were carried out in order to inspect the dependence of the amount of damage in different materials (Fig. 13).

Uman (1986a) states that “*the heating or burn through metal sheets - such as airplane wings or metal roofs - is, to a first approximation, proportional to the lightning charge transferred (average current, times time). Generally, large charge transfer are due to long-duration (tenths of second to seconds) lightning currents in the 100 – 1000 A range, rather than to peak currents that have a relatively short duration ... [that is, a short-duration peak current causes less thermal deformation and melt than a weaker, although prolonged, discharge. Intuitively, the process reminds about some kind of “elastic” feedback. A similar behavior refers to the aforementioned *EBLs*.] A typical lightning transfers $\sim 20 - 30 C$ and extreme lightning hundreds of Coulombs but, fortunately, the lightning does not often stay attached to one place on an aircraft in flight for the duration of the transfer.*”

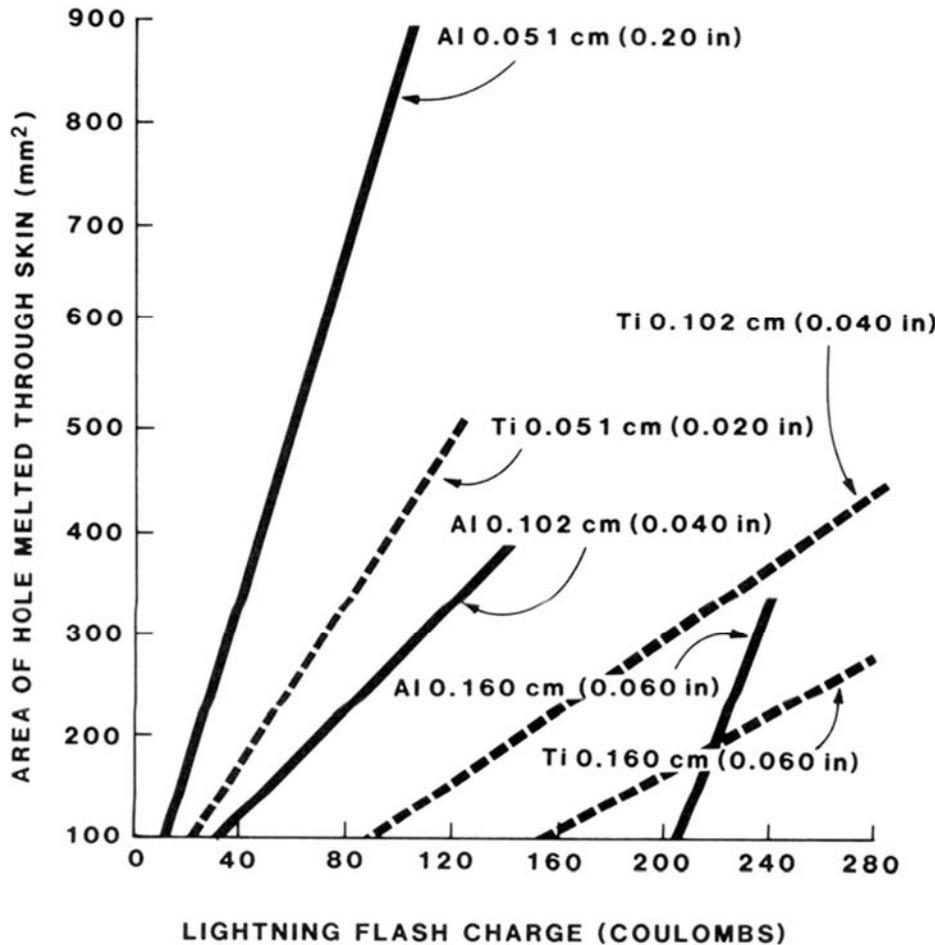


Fig. 13. "Areas of holes melted through Al and Ti of various thicknesses by lightning discharge (Fisher and Plumer, 1977)." Figure and captions after Uman (1986a). Reproduced with kind permission of the National Academy of Sciences. Courtesy of the National Academies Press, Washington, D.C.

This comparatively "slow" speed of evolution of the discharge is consistent with the model here envisaged (see Gregori and Leybourne, 2026g), because every micro-dynamo spends some time before causing - by thermodynamics - the ejection of thermal energy that triggers a new micro-dynamo close to it, thus giving rise to the domino- "chain" of microdynamos. Differently stated, a very rapid discharge triggers the motion of electrons, although *per se* it does not seriously affect the crystalline bonds of the solid structure. However, a sufficiently long impulse affords to generate a sufficient amount of ions that finally contribute and support micro-convection.

Conclusion

The physics of electrical discharges is more intricate than formerly envisaged according to the previous standard formulation of physics. The Cowling dynamo plays a key role, as it explains (i) the mysterious water condensation around condensation nuclei, and fog, rain, snow, hail, and (ii) ball lightning (BLs), which are the micro-ingredients for the explanation of sparks, lightning, and other large-scale phenomena. In addition, the Cowling dynamo gets rid of the perplexities involved with the old-fashioned, and still used, Wilson's hypothesis concerning the mechanism that

generates the electrostatic charges of the ionosphere (see Gregori and Leybourne, 2026g).

The present first paper also shows how the BL phenomenon can be reproduced in the laboratory, and how several features can be experimentally checked, dealing with the role of toroidal B for the confinement of plasma inside a limited and closed volume.

The implication dealing with other important effects are discussed in the subsequent papers of the present series (Gregori and Leybourne, 2026f, 2026g). The Cowling dynamo is the crucial key that can justify several phenomena that were previously considered mysterious and possibly unrelated one another.

In particular, a new perspective is suggestive of the possibility to exploit the free and ubiquitous enormous source of clean energy - i.e., the electrostatic energy of the ionosphere - that will exist as long as the Sun will be shining (see Gregori and B.A. Leybourne, 2025l).

Acknowledgements

We want to acknowledge all co-workers that, in different ways and at different times, contributed to the exploitation of the analyses mentioned in the present study. We like also to thank for the warm encouragement we had from several outstanding scientists.

Funding Information

G. P. Gregori is retired since 2005. B. A. Leybourne is a semi-retired self-funded independent researcher.

Author's Contributions

This study derived from a long-lasting cooperation by both authors. The backbone draft was prepared by the first author, although a large number of ideas resulted from the emergence of long-lasting discussions.

Ethics

This article is original and contains unpublished material. Authors declare that there are not ethical issues and no conflict of interest that may arise after the publication of this manuscript.

References

- Abrahamson, J., A.V. Bychov, and V.L. Bychkov, 2002. Recently reported sightings of ball lightning: observations collected by correspondence and Russian and Ukrainian sightings. *Philosophical Transactions of the Royal Society of London*, 360 (1790): 11-35
- Abrahamson, J., and J. Dinniss, 2000. Ball lightning caused by oxidation of nanoparticle networks from normal lightning strikes on soil. *Nature*, 403 (6769): 519-521; DOI:10.1038/35000525
- Altschuler, M.D., 1999. Atmospheric Electricity and Plasma Interpretations of UFOs. In *Scientific Study of Unidentified Flying Objects*, E.U. Condon, (ed.), The Regents of The University of Colorado Ch. 7, pp: 1156-1204
- Arnold, N., and T. Neubert, 2002. Cosmic influences on the atmosphere, *Astronomy & Geophysics*, 43 (6): 6.9-6.12
- Atwater, H.A., 2007. The promise of plasmonics, *Scientific American*, 296, (April). Italian translation, *Le promesse della plasmonica. Le Scienze*, (467): 96103
- Bührke, T., 2008. Ball lightning from a water beaker, IPP, Max-Planck-Institut für Plasmaphysik news, (2): 3438
- Carbognani, A., 1999. Ball lightning bibliography, 8 pp., www.fis.unipr.it/~albino/documenti/Bibliografia_BL.html
- Chandrasekhar, S., and E. Fermi, 1953. Problems of gravitational stability in the presence of a magnetic field. *Astrophysical Journal*, 118: 116-141
- Cohen, A.-H., and I. Gallily, 1977. On the collision efficiency and the coalescence of water droplets under the influence of electric forces. II. Calculations, small Reynolds numbers, *Journal of Atmospheric Sciences*, 34: 827-842
- Davis, E.W., 2003. Ball lightning study, AFRLPR-ED-TR-2002-0039; pp:1-56
- Dayan, N., and I. Gallily, 1975. On the collection efficiency of water droplets under the influence of electric forces. I: Experimental, charge-multipole effects, *Journal of Atmospheric Sciences*, 32: 1419-1429
- Denault, K.A., M. Cantore, S. Nakamura, S.P. DenBaars, and R. Seshadri, 2013. Efficient and stable laserdriven white lighting, *AIP Advances*, 3: 072107; DOI:10.1063/1.4813837
- Diels, J.-C., R. Bernstein, K.E. Stahlkopf, and Xin Miao Zhao, 1997. Lightning control with lasers, *Scientific American*, 277, August 6 pp., Italian translation Il controllo dei fulmini con il laser, *Le Scienze*, 59 (350): 46-51
DOI:10.1134/S1063784208060029]
- Durand, M., and J.G. Wilson, 2006. Ball lightning and fireballs during volcanic air pollution, *Weather*, 61 (2): 40-43
- Egorov, A.I., and S.I. Stepanov, 2002. Long-lived plasmoids produced in humid air as analogues of ball lightning, *Zhurnal tekhniceskoj fiziki*, 72: 102- [Journal of technical physics, 47: 1584-1586.]
- Egorov, A.I., and S.I. Stepanov, 2008. Properties of short-living ball lightning produced in the laboratory, *Zhurnal tekhniceskoj fiziki*, 78 (6): 15-19 [Journal of technical physics, 53 (6): 688-692;
- Egorov, A.I., S.I. Stepanov, and G.D. Shabonov, 2004. Laboratory demonstration of ball lightning, *Uspekhi Fizicheskikh Nauk*, 174: 107-. [Physics-Uspekhi, 47 (1): 99-.]
DOI:10.1070/PU2004v047n01ABEH001691
- Few, A.A., 1969. Power spectrum of thunder, *Journal of Geophysical Research*, 74: 6926-6934
- Few, A.A., H.B. Garrett, M.A. Uman, and L.E. Salanave, 1970. Comments on letter by W. W. Troutman, Numerical calculation of the pressure pulse from a lightning stroke, *Journal of Geophysical Research*, 75: 4192-4195
- Few, A.A., Jr, 1986. Acoustic Radiations from Thunderstorms. In E.P. Krider, and R.G. Roble, (eds), National Academy Press, Washington, D. C.; DOI:10.17226/898, pp: 46-60
- Finke, U., and O. Kreyer, 2002. Detect and locate lightning events from geostationary satellite observations. Report, Part I - Review of existing lightning location systems, EUM/CO/02/1016/SAT, Institut für Meteorologie und Klimatologie, Leibniz Universität Hannover; pp: 1-43
- Finke, U., and T. Hauf, 2002. Detect and locate lightning events from geostationary satellite observations Report Part II. Feasibility of lightning location from a geostationary orbit, Report EUM/CO/02/1016/SAT, Institut für Meteorologie und Klimatologie, Leibniz Universität Hannover; pp:1-17
- Fisher, F.A., and J.A. Plumer, 1977. Lightning protection of aircraft, NASA Reference Publ. 1008
- Furukawa, Y., and J.S. Wettlaufer, 2007. Snow and ice crystals, *Physics Today*, 60, (12): 70-71
- Gallily, I., 1984. Transport and Mechanics of Nonspherical Aerosols Particles, Elsevier, Amsterdam
- Gregori, G. P., and B. A. Leybourne, 2025. Conclusion – Exploitation of the electrostatic energy of the

- atmosphere, *New Concepts in Global Tectonics, Journal*, 13, (2): 336-343
- Gregori, G. P., B. A. Leybourne, and G. Paparo†, 2025b. Introduction – Anomalous lesser air-earth phenomena. In press in *New Concepts in Global Tectonics, Journal*
- Gregori, G. P., B. A. Leybourne, and J. R. Wright, 2026d. Generalized Cowling theorem and the Cowling dynamo. In press in *New Concepts in Global Tectonics, Journal*
- Gregori, G. P., B. A. Leybourne, G. Paparo†, and M. Poscolieri, 2025a. The global Sun-Earth circuit. In press in *New Concepts in Global Tectonics, Journal*
- Gregori, G. P., B. A. Leybourne, U. Coppa, and G. Luongo, 2025t. Lightning and volcanic plumes. *New Concept of Global Tectonics*, 13, (6): 920-967
- Gregori, G. P., M. T. Hovland, B. A. Leybourne, S. Pellis, V. Straser, B. G. Gregori, G. M. Gregori, and A. R. Simonelli, 2025w. Air-earth currents and a universal “law”: filamentary and spiral structures - Repetitiveness, fractality, golden ratio, fine-structure constant, antifragility and “statistics” - The origin of life, *New Concepts in Global Tectonics, Journal*, 3, (1): 106-225
- Gregori, G.P., 2002. Galaxy – Sun – Earth relations. The origin of the magnetic field and of the endogenous energy of the Earth, with implications for volcanism, geodynamics and climate control, and related items of concern for stars, planets, satellites, and other planetary objects. A discussion in a prologue and two parts. *Beiträge zur Geschichte der Geophysik und Kosmischen Physik*, 3 (3): 1-471 [Available at <http://ncgtjournal.com/additional-resources.html>].
- Gregori, G.P., 2020. Climate change, security, sensors. *Acoustics*, 2: 474-504; DOI:10.3390/acoustics2030026.[<https://www.mdpi.com/2624-599X/2/3/26/htm>]
- Gregori, G.P., and B.A. Leybourne, 2021. An unprecedented challenge for humankind survival. Energy exploitation from the atmospheric electrical circuit, *American Journal of Engineering and Applied Science*, 14 (2): 258-291; DOI:10.3844/ajeassp.2021.258.291
- Gregori, G.P., and B.A. Leybourne, 2026f. The physics of electrical discharges – 2. RB & TGFs - Runaway breakdown – terrestrial gamma flashes – GK effect, present issue
- Gregori, G.P., and B.A. Leybourne, 2026g. The physics of electrical discharges – 3. Sparks and lightning - electrostatics of the ionosphere – TLEs - plasma jets collimation – Birkeland currents & sea-urchin spikes - stellar and galactic alignments, present issue
- Gregori, G.P., and S. Martellucci, 1992. *MHD* pulsed generators in Antarctica: man-made production of magnetospheric substorms, and underground surveying-proposals and perspectives. In M.. Colacino, G., Giovannelli, and L. Stefanutti, (eds), 4th Workshop-Italian Research on Antarctic Atmosphere. *Conference Proceedings*, 35, Società Italiana di Fisica, Bologna, pp: 351-359
- Grigor’ev, A.I., I.D. Grigor’eva, and S.O. Shiryayeva, 1992. Ball lightning penetration into closed rooms: 43 eyewitness accounts, *Journal of Scientific Exploration*, 6 (3): 261-279.
- Haines, R.F., 2010. Ball lightning and earthlights, *NARCAP Project Sphere*, Sect. 4.3, pp: 1-14
- Hare, B.M., O. Scholten, J. Dwyer, T.N.G. Trinh, S. Buitink, S. ter Veen, A. Bonardi, A. Corstanje, H. Falcke, J.R. Hörandel, T. Huege, P. Mitra, K. Mulrey, A. Nelles, J. P. Rachen, L. Rossetto, P. Schellart, T. Winchen, J. Anderson, I. M. Avruch, M. J. Bentum, R. Blaauw, J.W. Broderick, W.N. Brouw, M. Brügger, H.R. Butcher, B. Ciardi, R.A. Fallows, E. de Geus, S. Duscha, J. Eislöffel, M.A. Garrett, J.M. Grießmeier, A.W. Gunst, M.P. van Haarlem, J.W.T. Hessels, M. Hoefl, A.J. van der Horst, M. Iacobelli, L.V.E. Koopmans, A. Krankowski, P. Maat, M.J. Norden, H. Paas, M. Pandey-Pommier, V.N. Pandey, R. Pekal, R. Pizzo, W. Reich, H. Rothkaehl, H.J.A. Röttgering, A. Rowlinson, D.J. Schwarz, A. Shulevski, J. Sluman, O. Smirnov, M. Soida, M. Tagger, M.C. Toribio, A. van Ardenne, R.A.M.J. Wijers, R. J. van Weeren, O. Wucknitz, P. Zarka, and P. Zucca, 2019. Needlelike structures discovered on positively charged lightning branches, *Nature*, 568 (7752): 360–363; DOI:10.1038/s41586-019-1086-6
- Hubler, G.K., 2000. Lightning: fluff balls of fire, *Nature*, 403 (6769): 487-488; DOI:10.1038/35000674.
- Ignaccolo, M., and C. De Michele, 2011. The discrete charm of rain, *Physics Today*, 64 (1): 68-69; DOI:2076/10.1063/1.3541954
- Krider, E. Philip, and R.G. Roble, 1986a. Overview and recommendations. In E.P. Krider, and R.G. Roble, (eds), National Academy Press, Washington, D. C.; DOI:10.17226/898, pp: 1-20
- Krider, E.P., 1986. Physics of lightning. In E.P. Krider, and R.G. Roble, (eds), National Academy Press, Washington, D.C.; DOI:10.17226/898, pp: 30-40
- Lee, Wonjae, A.H. Gheorghe, K. Tiurev, T. Ollikainen, M. Möttönen, and D.S. Hall1, 2018. Synthetic electromagnetic knot in a three-dimensional skyrmion, *Science Advances*, 4 (3): eaao3820; DOI:10.1126/sciadv.aao3820
- Letzter, R., 2018i. The 'skyrmion' may have solved the mystery of ball lightning, *Live Science*, issued MarCH 6, 2018
- Martellucci, S., and G.P. Gregori, 1989. World Laboratory: Progetto HEFEST-Applicazioni dei generatori MHD impulsati. In G.C. Righini (ed.), 5° Convegno Nazionale di Elettronica Quantistica e Plasmi, Firenze, 16-19 Novembre 1988, *Conference Proceedings*, 21, Società Italiana di Fisica, Bologna, pp: 561-566
- McNaughton, D. L., 1980. Meteor streams and rainfall calendaricities, *British Yearbook of Astronomy*, pp: 144-154

- Miller, J., 2007. Time-resolved electric-field measurements probe plasma breakdown, *Physics Today*, 60 (5): 19-22
- Muir, H., 2001. Ball lightning scientists remain in the dark, *New Scientist*, (20 December)
- Muir, H., 2006. Blackholes in your backyard, *New Scientist*, 192 (2583/2584): 48-51; DOI:10.1016/S0262-4079(06)61459-0
- Nakaya, U., 1954. *Snow Crystals: Natural and Artificial*, Harvard University Press, Cambridge, pp.:1-510
- Ouzounov, D., S. Pulinets; M. Hernandez-Pajares, K. Hattori, and A. Garcia-Rigo, 2014. Geo-Space observation of atmospheric environmental effects associated with 2011 Fukushima nuclear accident, (poster), EGU General Assembly
- Phillips, T., 2014j. Jellyfish flames on the ISS, *Science@NASA*, issued September 10, 2014
- Raizer, Y.P., 1991. *Gas Discharge Physics* [Translated from the Russian original published by Nauka, Moscow, in 1987], Springer, Berlin; ISBN 3-54019462-2; pp.: 1-449
- Rañada, A., M. Soler, and J.L. Trueba, 1998. A model of ball lightning as a magnetic knot with linked streamers, *Journal of Geophysical Research*, 103 (D18): 23,309-23,313
- Rañada, A.F., and J.L. Trueba, 1996. Ball lightning an electromagnetic knot? *Nature*, 383: 32; DOI:10.1038/383032a0
- Rossi, B., and S. Olbert, 1970. *Introduction to the Physics of Space*. McGraw-Hill Book Co., New York, etc.; pp.: 1-454
- Sakawa, Y., K. Sugiyama, T. Tanabe, and R. More, 2006. Fireball generation in a water discharge, *Plasma and Fusion Research, Rapid Communications*, 1 (039), pp.: 1-2; DOI:10.1585/pfr.1.039
- Salanave, L.E., 1980. *Lightning and its Spectrum. An Atlas of Photographs*. The University of Arizona Press, Tucson, Arizona, pp.: 1-136
- Schonland, B.F.J., 1937. The diameter of the lightning channel, *Philosophical Magazine*, 23: 503-508
- Schonland, B.F.J., 1939. Thunder-clouds, Showerclouds, and their Electrical Effects. In *Terrestrial Magnetism and Electricity*, J.A. Fleming, (ed.), McGraw-Hill Book Co., New York and London, pp.: 657-678
- Singer, S., 1971. *The Nature of Ball Lightning*. Plenum Press, New York. Also MIR Publishers, Moscow (1973)
- Singer, S., 1977. Ball Lightning. In R.H. Golde, (ed.), *Lightning I: Physics of Lightning*, Academic Press, London, pp.: 409-436
- Smirnov, B.M., 1989. Electrical and radiative processes in ball lightning, *Il Nuovo Cimento*, 12c (5): 575-595
- Smirnov, B.M., 1990. Physics of ball lightning, *Soviet Physics Uspekhi*, 33 (4): 261-288; DOI:10.1070/PU1990v033n04ABEH002573 [Uspekhi Fizicheskikh Nauk, 160: 1-]
- Smirnov, B.M., 1993. Physics of Ball Lightning, *Physics Reports*, 224: 150-236
- Stenhoff, M., 1999. *Ball Lightning, an Unsolved Problem in Atmospheric Physics*. Kluwer Academic/Plenum Publishers., New York, etc.; pp.: 1-349
- Stepanov, S. et al., 1997a. Electric Machine in Ball Lightning. In Y.H. Ohtsuki, (ed.), *Proceedings of the 5th International Symposium on Ball Lightning*, Tsugawa, Japan, pp.: 183-187
- Stepanov, S., et al., 1997. On the Energy of Ball Lightning. In Y.H. Ohtsuki, (ed.), *Proceedings of the 5th International Symposium on Ball Lightning*, Tsugawa, Japan, pp.: 61-62
- Straser, V., 2016. Ball lightning, oilfields and earthquakes, *New Concepts in Global Tectonics, Journal*, 4 (3): 432-444
- Svensmark, H., 2007. Cosmoclimatology: a new theory emerges, *Astronomy & Geophysics*, 48 (1): 1.18- 1.24
- Tarr, D., 2006. Observation of lightning ball (ball lightning): a new phenomenological description of the phenomenon. In G.C. Dijkhuis, D.K. Callebaut and M.Lu, (eds), *Proceedings of the 9th International Symposium on Ball Lightning (ISBL-06)*, 16-19 August 2006, Eindhoven, The Netherlands, pp.: 222232
- Tasoff, H., 2018a. 'Flames in space' might help clean Earth's air (Video), *Space.com*, issued April 19, 2018
- Thornhill, W., 2006. The IEEE, plasma cosmology and extreme ball lightning, *Thunderbolt.info*, 30 June
- Toepler, M., 1926. *Gewitter, Blitze und Wanderwellen auf Leitungsnetzen, Mitteilungen des HermsdorfSchomburg-Isolatoren GmbH*, (25): 743-786
- Uman, M.A., 1968. Some comments on ball lightning, *Journal of Atmospheric and Terrestrial Physics*, 30 (6): 1245-1246
- Uman, M.A., 1971. *Understanding Lightning*, Bek Technical Publications Incorporated, Carnegie, PA; pp.: 1-166
- Uman, M.A., 1986a. Applications of advances in lightning research to lightning protection. In E.P. Krider, and R.G. Roble, (eds), *National Academy Press*, Washington, D.C.; DOI:10.17226/898, pp.: 61-69
- Velikhov, E.,P. (ed.), 1989. *Geoelectricheskie Issledovania s Motsnim Ostotchnikom toka na Baltiskom tsite* (in Russian), Nauka, Moscow; pp.: 1-272
- Versteegh, A., K. Behringer, U. Fantz, G. Fußmann, B. Jüttner, and S. Noack, 2008. Long-living plasmoids from an atmospheric water discharge, *Plasma Sources Science and Technology*, 17 (2): 1-8; DOI:10.1088/0963-0252/17/2/024014
- Wagenaars, E., M.D. Bowden, and G.M.W. Kroesen, 2007. Measurements of electric-field strengths in ionization fronts during breakdown, *Physical Review Letters*, 98: 075002 [4 pp.]; DOI:10.1103/PhysRevLett.98.075002
- Waymouth, J.F., 2001. Physics for profit and fun, *Physics Today*, 54 (2): 38-42

Acronyms

ACME - Advanced Combustion via

Microgravity Experiments

BL - ball lightning

EBL - extreme ball lightning

FLEX-2 - Flame Extinguishment Experiment 2

GK - Gurevich and Karashtin (effect)

GRF - gamma ray flashes, synonymous of TGB, or

TGF *ISS - International Space Station*

LB – light balls

MHD - Magneto-Hydro Dynamics

RB - runaway-breakdown (process)

TGB - terrestrial gamma bursts, synonymous of GRF, or

TGF

TGF - terrestrial gamma flash, synonymous of GRF,

or TGB

TLE –Transient Luminous Event

The physics of electrical discharges – II. RB & TGFs

Runaway breakdown – terrestrial gamma flashes – GK effect

Giovanni Pietro Gregori¹, Bruce Allen Leybourne²

¹Former Senior Researcher at IDASC-Institute of Acoustics and Sensors O. M. Corbino (CNR), Rome, now merged into IMM Istituto per la Microelettronica e Microsistemi (CNR) Italy; and ISSO-International Seismic Safety Organization, Italy

²GeoPlasma Research Institute-(GeoPlasmaResearchInstitute.org), Aurora, CO 80014, USA

Corresponding Author:
Giovanni Pietro Gregori
IDASC-Istituto di Acustica e
Sensoristica O. M. Corbino
(CNR), Roma, now merged
into IMM-Istituto per la
Microelettronica e
Microsistemi (CNR) Italy
e-mail:
giovannipgregori38@gmail.com;
leybourneb@iascc.org

Abstract – Compared to the old-fashioned model envisaged by Charles Thomson Rees Wilson in the 1910s, which is here briefly called Wilson’s “cloud generator”, the runaway breakdown (*RB*) process represents a major advance in understanding cloud phenomena and lightning. The Cowling dynamo fills a crucial gap of knowledge in the explanation of these phenomena, as it provides the “seed” electric field E necessary to trigger the *RB* process. Important observational evidence includes narrow bipolar pulses (*NBPs*), and the multiple occurrences of micro-cells. This finding is here called Gurevich and Karashtin effect (or *GK effect*). This important Cowling dynamo contribution clarifies the processes that occur inside a thunderstorm. One byproduct is the explanation of the mysterious deadly terrestrial gamma-ray flashes (*TGFs*). These observations represent a challenge for present understanding in atmospheric physics. *TGFs* are likely behind some unexplained air crashes. Incorporating Cowlings dynamo is a crucial improvement in understanding the atmospheric electrical circuit. And may be key to exploiting a huge reservoir of clean energy from the Sun.

Keywords: cloud physics – thunderstorms – lightning - runaway breakdown – narrow bipolar pulses - *TGF* - atmospheric electrical circuit – atmospheric electrostatic energy

Introduction

The meaning of the term “discharge” is related to the frightening observation of a lightning, and to old-fashioned classical experiments in vacuum tubes, which are the forefathers of plasma physics. Topics are much intricate, and – with the purpose to discuss air-earth currents – a distinction is here made between the following items, concisely discussed in three papers as follows:

- ◇ first paper (small-scale phenomena; Gregori and Leybourne, 2024e)
 - micro Cowling dynamos (fog and atmospheric precipitation)
 - ball lightning (*BLs*)
- ◇ second (present) paper (extreme effects)
 - runaway-breakdown (*RB*) process and *GK*-effect,
 - terrestrial gamma flashes (*TGFs*), also called gamma ray flashes (*GRFs*) or terrestrial gamma bursts (*TGBs*)
- ◇ third paper (large-scale phenomena; Gregori and Leybourne, 2024g)
 - sparks and lightning
 - cloud phenomena, charging of the ionosphere, transient luminous events (*TLEs*)
 - plasma jets collimation and sea-urchin spikes

- solar γ -rays
- stellar and galactic alignments
- formulation through plasma physics, field-aligned currents (*FACs*)
- electrical discharges with no luminous emission.

The present second paper deals with the concept of “runaway breakdown” (*RB*), which is a substantial innovation¹ with respect to the old-fashioned classical approach. *RB* is aimed to explain - by second-quantization effects - the X-ray and γ -ray emissions observed in the sky. The *TGFs* generation was a surprising discovery with serious implication for some unexplained air-crashes - and represents therefore, in several respects, a relevant and often disquieting concern.

Runaway-breakdown (*RB*) process and “*GK effect*”

The first paper in this series (Gregori and Leybourne, 2024e) shows that fog and atmospheric precipitation – being charge carriers - represent significant air-earth currents. The proposed explanation is original. In fact, according to the literature, the physical mechanism is unknown that determines the formation of a water droplet

¹ The very first idea seems to date back to 1961, although its important role was acknowledged only later.

or icelet around a condensation nucleus. In contrast, a large literature is available concerning the physics of a droplet or icelet – i.e., dealing with the droplet or icelet when it already formed. When a droplet or icelet is formed, the physics deals with the competitive role of surface tension and thermal evaporation.

The Cowling micro-dynamo gets rid of the missing explanation, as the atmosphere is dominated by thermal gradients, manifested like micro-phenomena and huge-phenomena, both associated with convection cells that develop at suitable heights. Owing to the Cowling dynamo, convection generates intense e.m. fields (see Gregoti et al., 2024d). Micro-phenomena explain water condensation and precipitation (fog, rain, snow, hail). On the larger scale, the entire enormous thermal energy of the circulation of the neutral and ionized atmosphere is transformed – through huge Cowling dynamos - into e.m. energy, manifested as the observed positive charge of the planetary ionosphere (see Gregori and Leybourne, 2024g). Note that air ionization is essential to transform the motion of air ions into electric currents - and this explains the correlation of atmospheric precipitation with cosmic rays (“Svensmark hypothesis”; see Gregori and Leybourne, 2024e). But cosmic rays alone cannot explain atmospheric precipitations.

Differently stated, a permanent upward flow of positive charge – or, equivalently and more correctly a permanent downward flow of electrons – occurs all over the globe. The process is strongly enhanced by intense meteorological phenomena, such as, e.g., in the Intertropical Convection Zone (ITCZ).

A previous substantial advancement was achieved by the runaway breakdown (RB) process that Gurevich and Zybin (2005) review and illustrate as follows. RB is supposed to be triggered - and sustained - by extensive atmospheric showers (EAS), i.e., by cosmic rays - although some concern exists dealing with the starting process, i.e., with the “seed” E . In contrast, the trigger can be most simply explained by the Cowling dynamo, with no need to appeal to cosmic rays.

Indeed, Gurevich and Zybin (2005) begin and emphasize three “mysteries”.

- (i) *Lightning’s origin.* All measurements of E inside thunderclouds are found to be substantially less than the threshold needed for conventional breakdown intensity (MacGorman and Rust, 1998). Normally the mean electron energy ε at which breakdown occurs is not larger than several electron volts. In air it is $\varepsilon \approx 2 \text{ eV}$, while in a conventional breakdown the threshold field E_{thr} is proportional to the number density of molecules. At atmospheric pressure in air it is $E_{thr} \approx 2 \text{ MV m}^{-1}$.
- (ii) *Narrow bipolar pulses (NBP)s*, which are the most powerful radio pulse observed at Earth’s surface and originated by a natural source. Maybe, they are even more relevant than standard lightning. They are observed during thunderstorms, although not connected to lightning (Le Vine, 1980; Smith et al., 1999a, 2002, 2004). NBP)s last, say, $\sim 5 \mu\text{sec}$ and can have astonishing high powers up to 100 GW. A similar

phenomenon - discovered by Gurevich et al. (2003) - is the lightning-initiation pulse that is always observed when lightning begins, with a typical duration $\sim 0.5 \mu\text{sec}$ and lower power than NBP)s.

- (iii) *Terrestrial gamma flashes (TGFs)* - also called GRBs (gamma ray bursts), or TGBs (terrestrial gamma bursts) - are discussed in a huge literature, with characteristic X-ray energies around $\sim 50 \text{ keV}$, and a duration of $\sim 1 \text{ min}$. They are usually correlated with lightning. Several satellites mapped their frequent occurrence and spatial distribution - mainly in coincidence with the ITCZ, characterized by a permanent particularly intense meteorological activity.

Only a short account can be here given of a conspicuous and learned theoretical development. *The interested reader ought to refer for details to the several original papers.* The purpose of the present synthesis is only to show how the addition of the Cowling dynamo fills the several logical gaps and unexplained facets of this entire remarkable achievement by Gurevich and coworkers.

Runaway breakdown (RB)

Gurevich and Zybin (2005) wonder what can generate a phenomenon of this intensity. The RB mechanism is explained by considering the braking force F that acts on energetic particles that cross through matter, while producing ionization losses (Bethe, 1930).

Scattering of electrons with air molecules

The force F is known to decrease with increasing electron energy ε (Fig. 1). Let us remind about the famous experiments of Ernest Rutherford, who showed that a fast electron interacts with neutral matter, while all electrons and nuclei behave, according to Coulomb’s, like free particles. The Rutherford cross section σ for Coulomb scattering is proportional to $1/\varepsilon^2$. Hence, F is proportional - in the nonrelativistic regime - to the molecular density n_m and inversely proportional to the electron energy - that is, $F \propto \varepsilon \sigma n_m \propto 1/\varepsilon$.

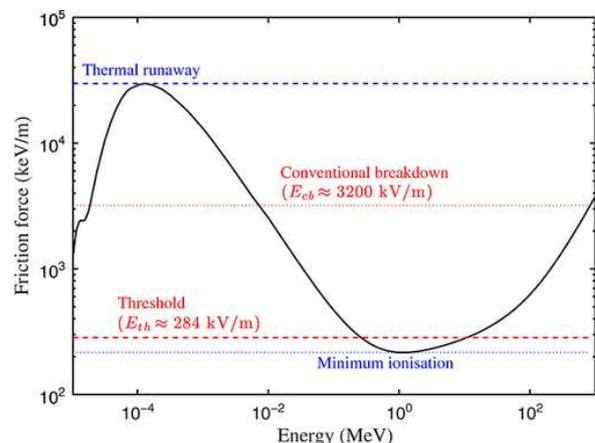


Fig. 1 – Electron scattering with matter. “The friction force experienced by electrons in air at sea level with respect to their kinetic energy (solid black line). The dotted red line indicates the conventional breakdown field, $E_{cb} = 3200 \text{ kV m}^{-1}$. The dashed red line shows the effective

minimum threshold force experienced by runaway electrons and corresponds to $E_{th} = 284 \text{ kV m}^{-1}$ (Dwyer, 2003). The dashed blue line shows the upper threshold for thermal runaway to occur, and the lower dotted blue line indicates the minimum ionization threshold. The data set was obtained from Berger et al. (1984).” That is, the cross-section decreases with increasing electron energy, until relativistic effects are triggered. See text. Figure and captions after Skeltved et al. (2014). See also Gurevich and Zybin (2005). Reproduced with kind permission of AGU copyright free policy

Refer to a given density of matter. It is shown that, with increasing electron energy, the related “Coulomb friction” steadily decreases for about three decades. Owing to relativistic effects, the decrease eventually slows down vs. increasing energy. F reaches a minimum F_{min} for $\varepsilon \geq 1.5 \text{ MeV}$. Then, it starts to increase, slowly and logarithmically. A runaway acceleration occurs whenever a “seed” E accelerates electrons above a certain critical energy ε_c . This happens for $|E| = 2E_c$ where E_c is the critical field. The minimal braking force is $F_{min} = e E_c$. Every electron is efficiently accelerated by E if the electron energy is $\varepsilon > \varepsilon_c \approx m c^2 2E_c / 2E$ (Gurevich and Zybin, 2005).

These electrons were first predicted by Wilson (1924), and were later named runaway electrons, i.e., a 1 MeV electron that crosses through Earth’s atmosphere exhausts all energy within a few meters by ionization, and the electron becomes a runaway when $E > E_c$. For comparison purpose, Fig. 2 is the same as Fig. 1, according to Dwyer (2004) and Dwyer et al. (2013).

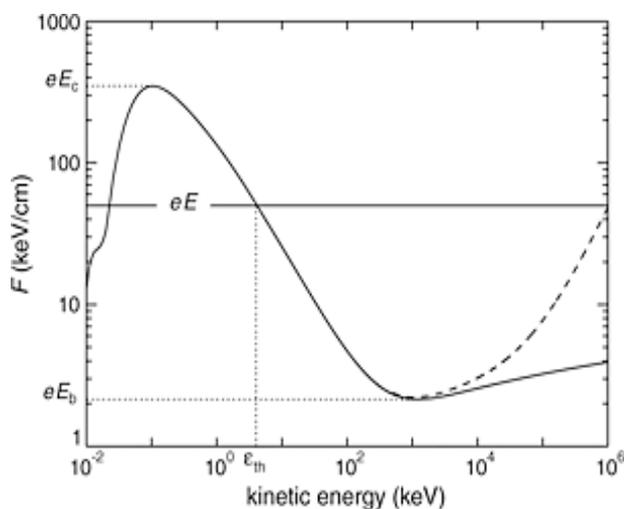


Fig. 2. “Energy loss per unit length experienced by a free electron (or positron) moving through air at STP (standard temperature pressure) as a function of kinetic energy. Figure from Dwyer (2004).” Figure and captions after Dwyer et al. (2013). AGU copyright free policy.

That is, the mechanism can be operative only when two ingredients are available: (i) free electrons with energy sufficiently close to E_c , and (ii) a “seed” E that accelerates these electrons above a suitable threshold. The concern is therefore about finding a source for both these ingredients.

Cosmic rays

Free electrons are available from cosmic radiation (Gurevich et al., 1999), while E was speculated to originate (see below) either by the Wilson’s “cloud generator”, or by electrostatic effects in the ionosphere. The Wilson’s “cloud generator” (we use the term “cloud generator” for simplicity) is a well-known concept since the 1910s, and is generally referred to by every author. It is discussed in Gregori and Leybourne (2024e), and in the present paper is taken for granted. It relies on the different electrification of water droplets inside clouds, depending on droplet radius. In addition, droplets of different size move at different heights due to fluid dynamics, thus causing a charge separation that originates a positive electric charge in the ionosphere. We claim that this process is feeble - if effective at all. In contrast, the Cowling dynamo is much more violent and credible (see Gregori and Leybourne, 2024g). In terms of comparison, only the Cowling dynamo is an efficient converter into e.m. energy of the huge amount of thermal energy in the atmosphere.

The subsequent discussion by Gurevich and Zybin (2005) – who were not aware of the Cowling dynamo - is aimed to envisage the mechanisms that can determine such a violent electron acceleration process, capable to trigger mutual transformations of electrons, positrons, and γ -rays (by Bremsstrahlung) in the atmosphere, i.e., electron-positron pair production, Compton scattering, and ionization. They mention some related historical references. In 1992, Alexander V. Gurevich, together with Gennady Milikh and Robert Roussel-Dupré (Gurevich et al., 1992) predicted the RB phenomenon, while the relativistic theory was implemented by Gurevich and Zybin (1998), Gurevich et al. (2000, 2001), Roussel-Dupré et al. (1994), Symbalysty et al. (1998); Lehtinen et al. (1999), and Babich et al. (1998). Reviews were given by Gurevich and Zybin (2001, 2004).

Lightning vs. laboratory discharges

Gurevich and Zybin (2005) warn about the comparison between laboratory discharges (conventional breakdown at $E \approx 2 \text{ MV m}$), and lightning ($E \sim 200 \text{ kV m}$ in air at standard conditions). That is, in lightning, RB occurs with E that is one order of magnitude smaller than in the laboratory. A few conditions have, however, to be satisfied. In fact, Gurevich and Zybin (2005) stress that “seed” electrons are needed with energy greater than $E_c \approx 0.1 - 1 \text{ MeV}$.

Maybe, some hunch can derive from rocket-triggered lightning discharges, with fair weather and suitable electrostatic state of the overlying ionosphere (see below).

In addition, the space scale of E must be larger than the characteristic distance l_c that is required by the exponential growth of a runaway avalanche. At atmospheric pressure, in air such a characteristic distance is $l_c \approx 50 \text{ m}$, thus explaining why this effect occurs in clouds, and cannot be easily detected in gases in the lab. Gurevich and Zybin (2005) claim that thunderstorms are typically characterized by clouds of a size much greater than l_c , while – they claim - cosmic rays generate plenty of free electrons.

In this respect, remind about the Svensmark effect (see Gregori and Leybourne, 2024e) – by which the time

variation of cosmic ray flux is correlated with rain precipitation. On the other hand, cosmic rays alone do not fully justify the needed condensation nuclei. Hence, additional nuclei are to be originated by friction between wind and Earth's surface.

Gurevich and Zybin (2005) remark that the maximum value of E observed inside thunderclouds (Marshall et al., 1995, 2005) is often found to be greater than E_c , although they envisage no mechanism for such a finding. That is, they just accept the standard explanation in terms of the classical Wilson's "cloud generator". Indeed, the Cowling dynamo is crucial, as it easily provides a great availability of local and intense E .

Gurevich and Zybin (2005) compare - with a laboratory spark (figure not here shown) - four examples of balloon measurements of the vertical component of E in thunderclouds (Marshall et al., 1995, 2005). Gurevich and Zybin (2005) plot the calculated RB critical field E_c that decreases vs. height, depending on air density. In general, the maximum strength of the observed E occurs inside the E_c envelope, while a lightning - that can be observed - often happens when, approximately, the peak field is $\approx E_c$. Sometimes, the maximum E can approach $2E_c$, even though it still remains $< 2 MV m^{-1}$ that is the minimum field needed for conventional breakdown.

Gurevich and Zybin (2005) explain some detail of the cosmic ray interaction with the atmosphere. Primary cosmic rays are highly relativistic. Hence, also the secondary particles of the interaction have a high speed along the impinging particle direction. In addition, the dispersion of velocity is very small along the axis of the *extensive atmospheric showers (EAS)*. A spread occurs, however, in the transversal direction, e.g., due to decay of neutral pions into a couple of γ -rays. Therefore, Gurevich and Zybin (2005) claim that the e.m. cascade of an *EAS* displays a pancake-like structure, with a typical size of a few meters along the original primary direction of the cosmic particle, and $\sim 100 - 150 m$ across. They envisage an n_s (total number of secondary electrons in an *EAS*) proportional to ε_p (primary energy), i.e., for $\varepsilon_p = 10^{15} eV$ it is $n_s \approx 10^6$, and for $\varepsilon_p = 10^{19} eV$ it is $n_s \approx 10^{10}$. The mean energy of secondary electrons in an *EAS* is $\sim 30 MeV$. Therefore, a large flux of energetic electrons is always available, as far as cosmic rays are available with sufficient energy.

A model thunderstorm

Gurevich and Zybin (2005) show the result of a computation, borrowed after Gurevich et al. (2004), which relies on an assumed model of thunderstorm E , and that refers to various ranges of the relativistic factor of the electrons. They show that the electron energy rapidly increases with maximum E , due to the rapid growth of the number of runaway electrons. They find that the energy exceeds by 3 to 5 orders of magnitude the energy ε_p of the triggering particle of cosmic-rays. That is, inside some region of the thundercloud, E is at least close to E_c , while fast secondary electrons grow exponentially in the "pancake" as an avalanche process. Thus, E soon reaches its maximum value E_{cm} inside the thundercloud, and a very

large number is generated of thermal electrons. This is the *RB-EAS* discharge, which also includes positrons and γ -rays. Remark that, as already mentioned, this inference relies on an assumed empirical model of thunderstorm E . Conversely, the Cowling dynamo is needed, due to a theorem, with no empirical input referred to thunderstorms.

γ -ray emission and spectrum vs. height

Gurevich and Zybin (2005) also compute the γ -ray emission and spectrum vs. height. They find two maxima, one near the primary altitude that is reached by the cosmic particles, while another maximum is inside the thundercloud. The secondary maximum, at a higher altitude, is suggestive of a possible self-consistent discharge that is developed inside the thundercloud where $|E| > E_c$. In fact, they claim that the electric discharge can spread through the cloud because of γ -ray diffusion, pair production, and Compton scattering.

It must be pointed out that - independent of Bremsstrahlung occurrence or not - the huge E developed inside nearby clouds is responsible for intra-cloud (*IC*) or cloud-cloud (*CC*) discharges, which are the most frequent occurrence - compared to cloud-ground (*CG*) discharges. This well-known discrepancy - between the frequency of observation of *IC*, *CC* and *CG* discharges - seems to be considered unexplained in a large fraction of the literature. In addition, a lightning can be detected, but a discharge can also occur with no lightning. In any case, the lightning mechanism is clear due to the role of the Cowling dynamo - unlike, as it is generally claimed, the generation of thunder that is poorly understood. See Gregori et al. (2024d).

Narrow bipolar pulses (*NBP*)

Gurevich and Zybin (2005) stress that most part of energy is spent for ionization of air molecules, to generate (in their computed model) $\sim 10^{18} - 10^{21}$ slow thermal electrons. Even though with a short lifetime, they generate a strong unipolar electric current pulse that originates a bipolar radio pulse. This can be detected from a large distance, having even $> 300 GW$, which is the most powerful radio pulse released by a natural source at Earth's surface. Isolated bipolar radio pulses, typical of the lightning initiation process, were observed at altitudes of $4 - 6 km$ (Gurevich et al., 2003). Both positive and negative *NBPs* were observed (Smith et al., 2002), at $13 - 18 km$ height.

An observational campaign

Gurevich and Zybin (2005) looked for observational confirmation that can be inferred from lightning initiation.

According to theory, a bipolar radio pulse at a *few Mhz* is expected to be generated at lightning onset, during a time interval of $\sim 0.5 \mu sec$. Therefore, they operated a radio interferometer (with time resolution up to $10 nsec$, bandwidth $0.1 - 30 MHz$; Gurevich et al., 2003) and detected almost *1200* lightning in different regions of Russia and Kazakhstan.

An isolated *NBP* is always observed at lightning initiation (with pulse width $\sim 0.4 - 0.7 \mu sec$ for a

lightning at 4 – 6 km height, with typical pulse field amplitude $0.05 - 1.0 \text{ V m}^{-1}$). With a source at a typical distance of 10 – 100 km, the electric current pulse is $\sim 0.1 - 1 \text{ kA}$.

The current pulse, consistently with the computed model, can have either negative or positive polarity. The emission is omnidirectional. That is, the current is originated by thermal electrons that move at only $\sim 10^6 \text{ cm sec}^{-1}$ inside the thundercloud.

In addition, the observed radio pulse must be produced by a rapidly increasing density of free electrons, which are generated by the cosmic-ray “ionizer”. Observational data show that the ionizer’s speed is nearly the speed of light, consistently with the model for an *RB* process triggered by cosmic-rays.

On the other hand, the Cowling dynamo process converts thermal energy into e.m. energy and leads to the same result.

That is, cosmic rays can be considered as a potential additional energy supply, added to a phenomenon that can be sustained, through the Cowling dynamo, by thermal convection alone inside the atmosphere. In addition, as already stressed, the skillful model illustrated by Gurevich and Zybin (2005) relies on the input of an empirical model of the observed *E* inside the cloud. In contrast, the role of the Cowling dynamo process is a physical compulsory mechanism, inside an environment where thermal convection is a huge and violent energy source.

Lightning initiation

The following additional comment by Gurevich and Zybin (2005) is relevant for the present discussion, as it deals with the need for a primary trigger - for which, however, Gurevich and Zybin (2005) claim that cosmic rays seem to be (maybe) sufficient.

“Of course, we don’t know what actually initiates lightning, but the recent observations have demonstrated that *RB-EAS discharges could be the trigger*.” Gurevich and Zybin (2005) estimate that a cosmic-ray energy of approximately $10^{16} - 10^{17} \text{ eV}$, and for a maximum thunderstorm $E_m/E_c \sim 1.2 - 1.5$ are needed in order to attain the observed values of the pulse’s maximum electron current. They claim that, according to a “preliminary” analysis of lightning statistics, cosmic-ray particles with $\varepsilon_p \approx 10^{16} \text{ eV}$ are sufficient (Gurevich et al., 2003). This seems certainly very reasonable. The concern is, rather, about the primary cause for the $E_m/E_c \sim 1.2 - 1.5$ starting field.

The sign of NBP

The next concern of Gurevich and Zybin (2005) is about *NBPs* that are observed in two forms, negative and positive, with enormously powerful radio emission that lasts only a few microseconds. A great amount of *NBP* measurements were carried out by the *Los Alamos Sferic Array (LASA)*, across several hundred kilometers, by the *FORTE* satellite, by the *National Lightning Detection Network*, and by other installations (Smith et al., 2002). A typical *NBP* emission has a low frequency (0.2 – 0.5 MHz) and a high amplitude

($E \approx 10 - 100 \text{ V m}^{-1}$), the electric current pulses are unipolar, $\sim 5 \mu\text{s}$ width, and $\sim 30 - 100 \text{ kA}$ maximum amplitude. “... *The data show that, as with the much shorter lightning -initiation pulses, the electric current is generated by thermal electrons and the ionizer moves at a very high speed (Le Vine, 1980; Smith et al., 1999a, 2002, 2004, and Jacobson, 2003)...*” All this is consistent also with the Cowling dynamo process.

NBPs, optical emission, height, coherence

As far the optical emission is concerned, a *NBP* has a very low intensity - at least one order of magnitude less than lightning - while the radio emission power is one order of magnitude higher. This discrepancy shows that the ongoing electric discharge is much different - and much more intense - than what can be perceived by photon emission alone.

The height of the *NBP* source seems to be just above the typical top of the clouds that are associated with violent storms, and it can be assessed with great accuracy, according to studies of radio -pulse propagation and ionospheric reflection. Altitudes are reported mainly in the $\sim 10 - 20 \text{ km}$ range, with a sharp $\sim 18 \text{ km}$ peak for negative *NBPs*, and a $\sim 13 \text{ km}$ peak for positive *NBPs* (Smith et al., 2004). The huge Cowling dynamos that are operative inside large cloud formations imply a height in these same ranges, being thus consistent with the hypothesis that Cowling dynamos are responsible for *NBPs*.

The coherence of the emission process is the reason of the very high power of *NBPs*, because the power increases with the square of the current. On the other hand, the Cowling dynamo has the same coherence as convection inside clouds. Gurevich and Zybin (2005) quote a current pulse of $> 100 \text{ kA}$ that releases a power of $100 - 300 \text{ GW}$ and an energy of $0.2 - 1 \text{ MJ}$. That is, the thunderstorm *E* spends a large amount of work into *NBPs*. Therefore, there is need for some mechanism capable to generate local intense *E* fields. In fact, the Cowling dynamo is the mechanism that transforms thermal energy into e.m. energy, and thus amplifies *E*.

NBPs and RB - A campaign of X-ray

observations According to Abram R. Jacobson (

2003), a possible connection can exist between *NBPs* and *RB*. Gurevich et al. (2004a) shows that a reasonable agreement can be found for $E_m \approx 1.4 - 1.5 E_c$. That is, *NBPs* are generated for $E \approx 1.2 - 1.4 E_c$, and a *TGF* occurs when $E_m \approx 1.4 - 1.5 E_c$.

The Gurevich *RB-EAS* mechanisms was expressively tested by a specifically devoted experiment. Chubenko et al. (2000) carried out passive observations at 3340 m above sea level. They recorded intensive short -time (1 – 5 min) bursts of X-rays during thunderstorms. The bursts resulted highly correlated over a wide area ($\sim 0.5 \text{ km}$). The main energies ranged inside $\sim 50 - 80 \text{ keV}$. They interpreted them like Bremsstrahlung originated by the *RB* effect in the thundercloud *E*.2

A proposed explanation

Chubenko et al. (2000) summarize the rationale as follows. They appeal to Gurevich et al. (1999). Gurevich and Milikh (1999) rely on multiple *RBs* that,³at normal atmospheric pressure, are supposed to develop on a scale-length of tens or hundreds meters. They point out that the critical field for one *RB* is one order of magnitude less than the threshold of conventional air breakdown. Hence, they guess that multiple *RBs* ought to be triggered by cosmic rays during the preconditioning stage of a thunderstorm.

In contrast, the Cowling dynamo *per se* requires no multiple *RBs*, as the effect only relies on the intensity of convection, and on the availability of free electrons – i.e., a large amount of free electrons, which is always available even independent of cosmic rays. In addition, in principle, the multiple *RB* mechanism – and eventually also the Wilson “cloud generator” (see Gregori and Leybourne, 2024g) – can co-exist with the Cowling dynamo, even though the “cloud generator” is optional and can be secondary or negligible.

In addition to the aforementioned role of cosmic rays with their associated time variation, the possible time-variation is to be taken into account of the supply given by the solar wind to the external plate of the atmospheric condenser – i.e., to the local ionosphere – with its spacetime gradient of electrostatic charge-density. This gradient is strongly enhanced by the Cowling dynamo (see Gregori and Leybourne, 2024g). In any case, it must be clearly stressed that the concern is not about favoring one mechanism over another. It is nonsensical to pretend that one mechanism alone can justify all observed features of every case history.

Extensive atmospheric showers (EAS) – An observational campaign

Concerning the role of *EAS* in atmospheric electricity, the *EAS* were considered almost a curiosity before the astute *RB* suggestion. The concern was, rather, about the radio-wave emission that ought to be associated with the generation of an anomalous electrically conducting air column, and/or with possible optical effects (Nishimura, 1969).

Chubenko et al. (2000) exploited a campaign that included simultaneous observations of cosmic ray showers, *RB* emission, and lightning, altogether monitored at a station on a pass in the Tien-Shan Mountains with an effective atmosphere depth of 690 *g cm*⁻².

The Tien-Shan Mountains region is characterized by a great seismic activity, often manifested by strong earthquakes with epicenters widespread over a large region. These mountains are close to the northernmost range of the Himalaya orogenic belt – and Himalaya is characterized

by an anomalous intense geothermal flow (see Gregori et al., 2024h). The Tibet Plateau is associated with a comparatively anomalous – and seemingly more intense – time gradient of soil exhalation, with consequent effects on cloud cover. In addition, according to comparatively recent evidence, cloud cover is believed to be correlated with seismic activity (see Shou, 2024 and Shou et al., 2024, and also Parrot, 2024, Straser et al., 2024, and Wu, 2024). Moreover, the role of topography ought to be considered, due to the corona discharge from mountain peaks. In addition, huge air-earth currents were detected by John M. Quinn in areas characterized by a relevant crustal fracturing (see Gregori and Leybourne, 2024g, and Quinn et al., 2024).

Chubenko et al. (2000) seemingly were not concerned with the seismic activity inside any large area around their recording station. In any case, on a practical ground, such a dependence can be realistically investigated only by means of observations spanning a much longer time interval. Therefore, the present comment is a simple warning about the fact that these Chubenko et al. (2000) measurements are, perhaps, representative only of the state of the Earth’s crust during the specific period of the campaign. Compared to the Chubenko et al. (2000) evidence, eventual similar measurements carried out during a different period of time can give, perhaps, a different result. Indeed, soil exhalation can change, and – in principle – soil exhalation affects air conductivity, hence all phenomena related to the electric discharge through the atmospheric condenser.

This whole concern shows the difficulty of dealing with a set of few phenomena alone inside the natural environment, while the natural system is controlled by several drivers. In addition, the percent role of every driver can change in time, even by some relevant amount.

“The thunderstorm clouds go through the pass at a height of ~ 0.1 – 1 km during three months”. Chubenko et al. (2000) detected *EAS* electrons in the range 0.1 – 10 *MeV*, muons with energy > 5 *GeV*, and neutrons > 100 *MeV*. They installed a system of Geiger counters in an area ~ 500 *m* in size around their station. In addition, antennas for e.m. radiation and directional microphones were used for lightning locations.

In July 1999, until the last days of August 1999, no thunderstorms occurred, and they could assess the zero-reference recording levels. At the end of August 1999 five fronts of thunderstorm clouds crossed at low height over the station, with strong lightning activity. In every case history, a dramatic increase of the records occurred, shortly after the beginning of the thunderstorm. The increase was observed by γ -ray detectors of both low- and high-threshold.

Chubenko et al. (2000) stress the difference of the detectors. One detector had a low-threshold and measured practically a free flux of X-rays. In contrast, the high-threshold detectors were located under a roof having an additional absorption equivalent to 13.6 *g cm*⁻² of carbon.

² Some explanation, alternative to Bremsstrahlung, was also investigated. See, e.g., Medvedev et al. (2011) and references therein. However, these items are outside the general framework of the present discussion.

³ They quote Gurevich et al. (1992, 1997), McCarthy and Parks (1985), Eack et al. (1996), and Gurevich and Milikh (1999).

The correlation between the two detectors resulted quite regular in every thunderstorm. The phenomenon typically lasted $\sim 2 - 3$ hours. At the same time, both neutron monitor and μ detector, which are sensitive only to cosmic radiation, showed no thunderstorm related effect. That is, cosmic rays contribute to ionize air, although they are not the primary driver of thunderstorms. This is consistent with the fact that the Cowling dynamo role is independent of cosmic ray flux.

The three pairs of detectors of the thunderstorm-related radiation displayed no correlation during non-storm conditions. In contrast, a correlation coefficient was found up to ~ 0.8 during storm periods, thus envisaging that the observed X-ray increase involved an area of at least 0.5 km size, or maybe even larger.

Let us point out, however, that, in their measurements, during non-storm conditions the electrostatic state of the overlying ionosphere was unknown.

They also found that, during the characteristic timescale $30 - 60$ min of this prolonged emission variation, a double or triple peak structure was observed in their plots. In addition, they found a new feature, like short-time bursts of X-ray emissions with characteristic burst durations of $1 - 5$ min. The short-time bursts occurred, respectively, at a rate of ~ 0.2 hours (peak 1), ~ 0.4 hours (peak 2), and ~ 1.4 hours (peak 3) after the beginning of thunderstorm. No corresponding increases occurred for neutrons and muons. During short bursts, the energy spectrum of X-rays differed from the spectrum that was observed during the main part of thunderstorm, and the major component had low-energy X-rays of only $\leq 50 - 80$ keV. They estimated an approximate flux of X-ray quanta of $\sim 10 - 20$ photons $cm^{-2}sec^{-1}sterad^{-1}$.

Chubenko et al. (2000) interpreted their data in terms of two main mechanisms of X-ray emission, i.e., γ -ray due to β -decay of *Rn* daughter-ion products, and Bremsstrahlung of electrons that are accelerated by *E*. The *Rn* ought to derive from precipitation of *Rn* and of its products, transported to ground by rainfall, and γ -ray of $\sim 0.2 - 2$ MeV are emitted by *Rn* daughter-ion θ decay. The main time characteristics, $\sim 20 - 30$ min for grow-up and ~ 50 min after washout, are determined by decay processes and rainfall (Suszcynsky et al., 1996; Bhandari and Rama, 1963).

Concerning the mechanism associated to the *E* inside thunderstorms, Chubenko et al. (2000) quote the standard models, i.e., Gurevich et al. (1992), Marshall et al. (1995), and MacGorman and Rust (1998).

Comparison between balloon vs. ground records

Chubenko et al. (2000) review the previous observational evidence inferred from balloon observations and compare ground and balloon records. Balloons seem to detect also some comparatively shorter and higher-energy events. The ranges are:

- ✓ duration (min) $\sim 1 - 5$ (at ground), ≥ 1 (by balloon);
- ✓ characteristic energy (keV) $\sim 50 - 80$ (at ground), $\sim 60 - 90$ (by balloon);

- ✓ characteristic intensity (photons $cm^{-2}sec^{-1}sterad^{-1}$) $\sim 10 - 20$ (at ground), $\sim 40 - 50$ (by balloon);
- ✓ height (m) ~ 3400 (at ground), $\sim 3500 - 4000$ (by balloon).

That is, the characteristic energy is comparable at ground and at balloon height, while the characteristic intensity is twice by balloon. Therefore, they concluded that data seem to agree well with the *Rn* source, including the energy ($\sim 0.2 - 0.5$ MeV). The short-time bursts of X-ray emission were detected for the first time at ground. The major part of their energy spectrum was composed of low energy X-rays ($\leq 50 - 80$ keV) that are characteristic of *RB*. They infer that, since the main features of the observed X-rays bursts are comparable with balloon measurements, short bursts are likely to be originated by *RB* Bremsstrahlung. This is an important inference.

Chubenko et al. (2000) also stress that, according to balloon measurements, the most probable region, in thunderstorm clouds, where high values of *E* can lead to *RB* effect, is located at $\sim 4 - 8$ km height, while the observation of *RB* emission has a much lower probability of occurrence at < 3.5 km.

In addition, Gurevich and Zybin (2005) quote Gurevich et al. (2004b) and specify that they detected pulses of γ emission from *EASs* with energies $\epsilon_p \approx 2 \times 10^{14} - 10^{15}$ eV, with an average time interval of ~ 2.5 sec between *EASs*. They call them "giant electron- γ bursts".

Moreover, the *EAS* antenna triggered the radio receivers. Thus, during two thunderstorms they observed 150 γ and radio pulses, simultaneously to within 50 μ sec. In contrast, during quiet times with no thunderstorms, *EASs* were detected, and no radio pulses.

According to the viewpoint of the present study, they do not specify, however, the time interval of no-thunderstorm monitoring, neither the electrostatic state of the ionosphere. They note that the radio pulses were bipolar with full widths of $0.4 - 0.7$ μ sec, and electric current pulses maximum of a few A. In addition, they found that a reasonable agreement occurs between the radio observations and the prediction according to the *RB-EAS*, by assuming that $E_m \sim 1.2 - 1.4 E_c$.

Summarizing, a synthesis of the estimates of the different physical quantities involved in this entire phenomenon is shown in Fig. 3 based on a Table of Gurevich and Zybin (2005).

Electron current maxima and cosmic-ray energies

The following comments by Gurevich and Zybin (2005) are particularly interesting. "The rough proportionality between electron current maxima and cosmic-ray energies ... To make the comparison, the rather high values of $1.2 - 1.5$ were assumed for E_m/E_c . Direct observations at both low and high altitudes usually give lower values, but the higher values have been seen at altitudes of $4 - 6$ km ... We note that NBPs are seen in the most active storm regions, and some researchers (Le Vine, 1980; Smith et al., 1999a, 2002, 2004) assume that a strong positively charged layer can exist at heights around $15 - 16$ km." [This is

evidently speculative. The dipolar pattern results from the e.m. field that occurs around the convection cell that supplies the Cowling dynamo.]

Concerning this last comment, one wonders whether the trigger can be related to an abrupt electrostatic input from the ionosphere. Also this guess is speculative - although this speculation can be observationally checked by carrying out prolonged monitoring of atmospheric E (see Gregori and Leybourne, 2024d). The purpose of such a check is to exclude, with fair weather, the possible “perturbation” originated by clouds or thunderclouds. Maybe, as mentioned above, even rocket-triggered atmospheric discharges could occur with fair weather, if suitable ionospheric conditions are satisfied.

Gurevich and Zybin (2005) further comment that “... much more has to be done both experimentally and in the theory. For example, it is possible that RB can help solve

yet another lightning mystery: how does the conductivity grow by several orders of magnitude to allow the widely dispersed electric charge in a thundercloud to gather - in what is known as a ‘stepped leader’ - and be transported in a few milliseconds, either to Earth or to another cloud? Recently, Dwyer and his colleagues observed energetic microsecond bursts of γ emission generated by runaway electrons; the bursts were well correlated with the leader steps in CG lightning (Dwyer et al., 2005). According to Dwyer’s suggestion, the runaways arise in a small local region where E could be extremely strong.” [This is, in fact, the role played by the Cowling dynamo.]

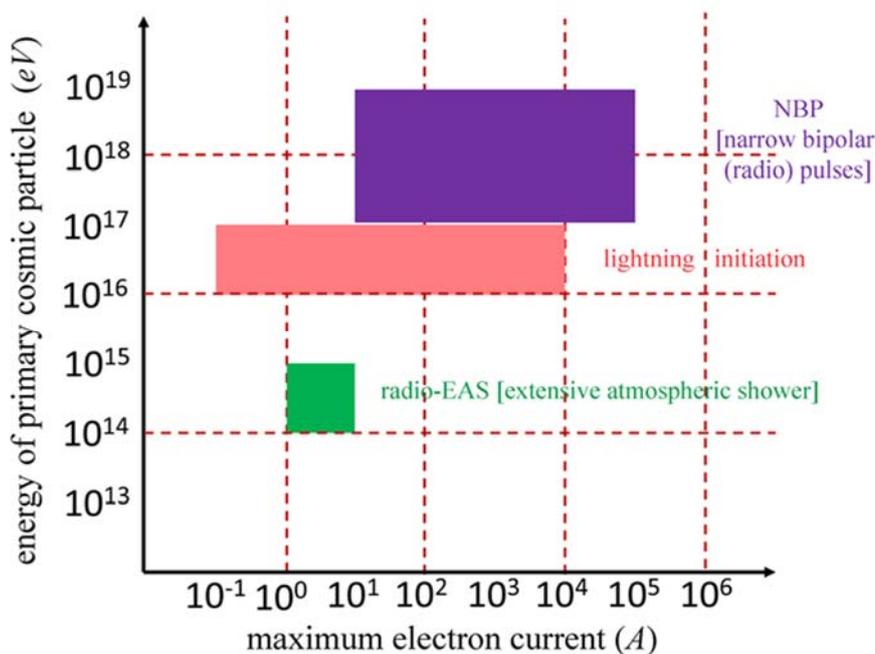


Fig. 3. Energy of primary cosmic particle, and maximum electron current, associated to various atmospheric discharges. The energy and currents are impressive of the mysterious NBP events. Data source Gurevich and Zybin (2005). See text. Unpublished figure.

Concerning the “extremely strong” E in “small local regions”, a warning deals with the aforementioned guess of a possible trigger originated from the electrostatic charges in the ionosphere – such as the QE (quasi-electrostatic) process in TLEs (see Gregori and Leybourne, 2024g). On the other hand, the role is likely to be much more important, which is played by the amplification due to the Cowling dynamo. In fact, the Cowling dynamo is the leading responsible agent for the accumulation of positive charge in the ionosphere, not viceversa.

Applications other than to the physics of lightning

Gurevich and Zybin (2005) also consider a possible application of their findings to studies other than the physics of lightning.

- ✓ The strong growth of the radio-pulse power, attaining cosmic-ray particle energy, can be observed at great distances, up to 1000 km, and this can envisage a way for radio detection of very high-energy cosmic-ray particles ($\epsilon > 10^{17}$ eV).
- ✓ Fundamental physics items can be of concern “... for example, of the 511 keV e^+e^- annihilation line. Of special interest are the extremely strong pulses of γ emission ...” Aircraft security is a serious concern related to TGFs, as discussed by Haines (2010) and Tavani⁴ et al. (2013a).
- ✓ Gurevich and Zybin (2005) also envisage the possibility of using RB in condensed matter, thus making a source of γ and energetic electron radiation. They quote $E_c =$

⁴ We are indebted to Marco Tavani for a stimulating discussion and for providing information about their study.

$1.8 \rho \text{ MeV cm}^{-1}$, the avalanche length $l_a = 6.1 \rho^{-1} \text{ cm}$, with ρ density in $g \text{ cm}^{-3}$ of matter.

- ✓ Gurevich and Zybin (2005) also stress the influence of microphysical effects on large-scale phenomena. They point out that the free path of a thermal electron is measured in microns and lifetime in nanoseconds, and the atmosphere is a comparatively dense medium. In contrast, macroscopic processes occur on the kilometer scale-size, and are triggered by relativistic kinetic effects related to comparatively weak E .

Indeed, this last comment refers to the coalescence of micro-convection cells into convection cells of progressively increasing size. In fact, the Cowling dynamo energy correspondingly increases and supplies a huge amount of electric power for *IC* and *CG* discharges, for thunderstorms, for *NBPs* and *TGFs*, and mostly for producing a large amplification of the electrostatic charge of the ionosphere. That is, the thermal “engine” of the atmosphere - which is powered by solar radiation but also by thermal exchange with ocean and land - sustains convection patterns on a very wide range of scale-sizes. Air is ionized, either by cosmic rays, or by friction electricity due to the flow of air over every kind of surface. The ionization is crucial in applying the Cowling dynamo.

Summary and temporary conclusion

Summarizing, compared to the model implemented by Gurevich and co-workers, the Wilson’s “cloud generator” (see Gregori and Leybourne, 2024g) looks comparatively naïve and *ad hoc*. However, the Gurevich mechanism lacks some process that should generate the “seed” E . The Cowling dynamo is the complementary crucial effect.

Therefore, with reference to electrical phenomena inside the atmospheric condenser, the overall picture is dramatically changed. *RB* is a very effective and fast phenomenon. Air ionization has a twofold origin: relativistic cosmic rays and friction. The Cowling dynamo is an efficient amplifier that transforms into E the entire huge amount of thermal energy that the atmosphere receives from other sources. The final effect is a relevant electrostatic charge of the ionosphere (see Gregori and Leybourne, 2024g). The charge must be positive, as the solar wind has a prevailing positive charge (see Gregori and Leybourne, 2024b).

A final remark is that the energy estimates achieved by means of the Gurevich model are an excellent premise for every attempt to exploit the enormous amount of energy that - in principle - is available from the atmospheric condenser and that exists as long as the Sun shines (Gregori and Leybourne, 2024e, 2024l, and Gregori, 2020).

From the viewpoint of the empirical constraint, these achievements are attained by considering altogether light emission (i.e., lightning), E records, and radio waves. That is, in general all phenomena in the atmospheric condenser look very intricate.

Compared to laboratory discharges, electrical phenomena in the atmosphere are substantially different. The large scale-size cannot be reproduced in the laboratory - and a variety of different inputs are to be considered that can hardly be simulated in any terrella experiment.

The *RB* explanation represents a fundamental progress in the understanding of lightning. However, this *RB* alone cannot explain the nature of the physical process by which a lightning propagates through air. The Cowling dynamo completes this gap of knowledge (see Gregori and Leybourne, 2024g).

Terrestrial gamma flashes (*TGF*)

TGF (terrestrial gamma flashes) is synonymous of *GRB* (gamma ray bursts) or of *TGB* (terrestrial gamma bursts). According to Coulter (2010), *TGFs* are very brief ($\sim 1 - 2 \text{ msec}$) bursts of γ -rays, and are the most energetic atmospheric events. She claims that their origin is a mystery. They are associated with thunderstorms and lightning, although it is not known how this happens.

In contrast, they can be easily explained by Cowling dynamo that generates the “seed” E , plus by *RB* that accelerates electrons to relativistic speeds - and through Bremsstrahlung the electrons release γ -rays. *TGFs* are the object of a huge literature, and they are known to be a comparatively frequent phenomenon, observed mainly in areas with intense meteorological activity, such as in the *ITCZ*. For instance, *TGFs* were observed by several satellites (not here listed), beginning from the *Burst and Transient Source Experiment (BATSE)* detectors, on the *Compton Gamma Ray Observatory (CGRO)* (Fishman et al., 1994). The observed photon energies are $\sim 20 \text{ keV} - 2 \text{ MeV}$. No review can be here given.

When the *TGFs* were discovered, the *RB* mechanism was supposed to be initially triggered by cosmic rays, which produce ionization and electrons. Electrons move due to E , and new electrons are originated by additional air ionization. Most electrons finally thermalize by collisions, while others accelerate and contribute to the avalanche (Lehtinen et al., 1997). Cosmic rays are estimated to produce, at 10 km height, some $\sim 10^{-5} \text{ cm}^{-3} \text{ sec}^{-1}$ electrons with energy $> 1 \text{ MeV}$. Then, most energetic electrons accelerate, because, at certain electron energies, the cross-section - of the interaction of air molecules and electrons - decreases with increasing energy, with a minimum around $\sim 1 \text{ MeV}$ (see Figs 1 and 2, and here below for additional details).

These avalanching relativistic runaway electrons play a role (İnan et al., 1996c; Lehtinen, 2000) in the production of red sprites (see Gregori and Leybourne, 2024g; Bell et al., 1995) and *TGF* (Lehtinen et al., 1996). Red sprites occur at $\sim 50 - 90 \text{ km}$ and are associated with *+CG* discharges (see Gregori and Leybourne, 2024g).

The *RB* electrons were modeled by Monte Carlo technique (Lehtinen et al., 1999) applied to the middle and upper atmosphere above thunderstorms, where E is strong and can accelerate electrons upward. Compared to the emission from thermal electrons in a conventional type of breakdown, the calculated optical emissions associated with runaways are negligible in red sprites. In contrast, the calculated γ -ray flux, due to Bremsstrahlung emissions from relativistic electrons, is of the same order as the *TGFs* observed by the *BATSE* detector on the *CGRO*.

The energetic electrons that leave the atmosphere enter the radiation belts. The electron beam interacts with plasma waves in the ionosphere and magnetosphere, and it precipitates at the geomagnetically conjugate point. Part of the energetic electrons is trapped in the radiation belt, and, as the electrons drift, it originates a longitudinally extended electron "curtain" (Lehtinen et al., 2000).

The Gurevich-Karashtin effect (*GK effect*)

Gurevich and Karashtin (2013) is an interesting study that, altogether with a few recent papers, is decisive in several respects. It deserves a detailed description, although for brevity purpose the related references are not here quoted. It deals with an observational finding, which is here briefly called "Gurevich-Karashtin effect", or briefly "GK effect".

Hydrometeor (HM) discharges vs. Cowling small-dynamos

Gurevich and Karashtin (2013) claim that, during the initial stage of negative *CG* lightning, a radio emission is observed of random and independent bipolar radio pulses, repeated in a long series. According to the mechanism that is here envisaged, these pulses can be interpreted as an ensemble of several Cowling dynamos of comparably small size that, altogether, finally lead to the manifestation of the negative *CG* lightning. The *RB-EAS* discharge modulates the time-dependence and length-scale of every pulse.

Gurevich and Karashtin (2013) claim that the amplitude of the pulse-current is determined by synchronized multiple hydrometeor (*HM*) discharges that are caused by low-energy electrons generated by *RB*, while multiple pulses are supposed to provide the lightning leader preconditioning.

Conversely, the interpretation that is here given refers to every single event – that is called *HM* by Gurevich and Karashtin (2013) – and that is, rather, a Cowling small-dynamo. Altogether, all Cowling small-dynamos produce the final phenomenon. In fact, an integral process occurs that leads to a lightning like final integration phenomenon, as several Cowling small-dynamos sum up altogether into a large-scale photon emission. The leading mechanism is the energy generation that triggers the small-scale convection cells. The energy balance and distribution in space and time is therefore controlled by the *RB* mechanism.⁵

The lightning initiation mechanism

Gurevich and Karashtin (2013) first review the previous state-of-the-art. Lightning initiation within a thunderstorm originally remained largely unknown. A large collection of *E* measurement in thunderclouds gave a maximum value that was about one order of magnitude smaller than the critical $E_k \approx 30 \text{ kV cm}^{-1}$ of conventional air breakdown at

normal atmospheric pressure. The phenomenon looked therefore like a mystery.

"The important role of *HMs* - water droplets or icelets charged and polarized in the thundercloud *E* - has been discussed. Laboratory studies and numerical calculations confirmed the possibility of a streamer discharge formation at *HM* in an *E* much lower than E_k ..."

That is, Gurevich and Karashtin (2013) speculate about water droplets and icelets that move inside clouds and constitute the *HMs* that, in fact - according to the mechanism that is here proposed - ought to be substituted by elementary convection cells that coalesce into Cowling dynamos of increasing size. Note that the focus – both of Gurevich and Karashtin (2013) and of the Cowling mechanism - is always on phenomena that occur inside the cloud, and no contribution is considered that can be eventually originated by any kind of input from the outer environment.

Then, Gurevich and Karashtin (2013) appeal to *RB* aimed to generate an avalanche of runaway electrons. They suppose that the thundercloud *E* is triggered inside a thundercloud by an *RB-EAS*, which acts like initiation of the lightning. In contrast, it is here claimed that the huge thermal convection inside clouds is the source and energy supply for the "seed" *E*.

Gurevich and Karashtin (2013) claim that radio pulses are the cause. But what is the cause of the radio pulses? In fact, they stress that *RB-EASs* are observed like strong radio pulses during lightning events. However, they complain that the role of *RB-EASs* is unclear in the lightning initiation, and the nature was not investigated of the observed series of radio pulses. They refer to measured *E*, while the Cowling dynamo explains how *E* is generated. In any case, Gurevich and Karashtin (2013) point out that the measured *E* inside thunderclouds is sometimes close to - or even higher than - the *E* needed for *RB*. But the evidence is suggestive of the need for some additional driver in order to get lightning initiation.

Gurevich and Karashtin (2013) emphasize the need for some almost stepwise process that dramatically changes the local electrical environment. In any case, they stress the need for the requirement of a preliminary ionization of the *HMs*. That is, they focus on some electric charge accumulation process, aimed to supply the current of the lightning leader. The altitude span of a cloud ranges in the kilometer-size, while the electrical conductivity inside clouds is less than in standard air. Hence, they seek a source for free ions, while conductivity ought to be amplified in order to attain the characteristic leader time scale ($\sim 10 \text{ msec}$). Compared to standard air, there is need for an increase of conductivity up to 4 – 5 orders of magnitude.

⁵ Note that cosmic rays produce ionization that can improve the efficiency of the Cowling dynamo. However, the *RB* process is operative only because the Cowling dynamo provides the "seed" *E*. The Cowling dynamo is related to atmospheric convection, and its impact can be more

effective with a higher cosmic ray flux. However, cosmic rays alone have no direct connection with the *RB* process.

The relationship with NBPs, and an observational campaign

Gurevich and Karashtin (2013) remind about the aforementioned series of NBPs, and guess that the pulse-current amplitude is originated by a synchronized multiple sources – i.e., HM discharges according to their speculated model, and Cowling small-dynamos according to the present proposal.

Gurevich and Karashtin (2013) describe the observational database. A lightning discharge at the initial stage has a duration 10 – 100 msec. They operated a radio interferometer (with time resolution of 16 nsec and wide bandwidth 0.1 – 30 MHz). They collected data for almost 3800 lightning, recorded in Russia (near Nizhny Novgorod, 56° 19' 37" N , 44° 00' 27" E) and in Kazakhstan (Tien-Shan Mountain Station, 43° 15' 0" N , 76° 54' 0" E).

They considered the case history of HF radio emission measurements referring to a somewhat distant one-stroke negative CG lightning, recorded at ~30 km on August 6, 2008, at 12:05:47 local summertime. They point out that we know that the horizontal range of the lightning active region can be several kilometers.⁶ Thus, a comparatively distant lightning decreases the bias that is originated by a possible influence of range variations on the observed intensity of radio emission.

Every lightning radio emission displays an abrupt beginning followed by a series of short bipolar pulses. That is, according to the interpretation that is here given, every short bipolar pulse is a Cowling small-dynamo process of smaller size, which is triggered by a local "small"-convection pattern originated by an energy input – caused by thermodynamic small-scale processes in the atmosphere - of the same spatial scale of the associated Cowling small-dynamo. One can also speculate about micro-scale variations of the cosmic ray modulation of the small-scale Cowling dynamo, although this seems *ad hoc*.

Gurevich and Karashtin (2013) show in detail one record. The parental current pulses are unipolar and have the same negative polarity during the whole series and produces bipolar pulses. The electric current is observed to be directed mainly upward. That is, free electrons move downward under the action of the thundercloud *E*. In fact, the process that increases the positive charge of the ionosphere – and that is caused by the Cowling dynamo mechanism - is related to a downward flux of electrons (see Gregori and Leybourne, 2024g).

Gurevich and Karashtin (2013) consider only events of sufficiently large amplitude > 20 mV. The purpose is to avoid occasional mixing with the low-amplitude background noise. The rms background is ~ 2 mV and the standard deviation is of the same order. The whole discharge released 8373 pulses. Gurevich and Karashtin (2013) chose the first 2100 pulses to focus on the initial stage.

⁶ Recently, it was found, as documented in Texas, that this range can be even larger than several hundred, and even over a thousand, kilometers.

The "GK effect"

Let us stress that Gurevich and Karashtin (2013) monitored some kind of "precursor" phenomenon of lightning, which is structured in time and space. Such a "precursor" is manifested like a sequence of a very large number of small discharges. This unprecedented finding must therefore be explained. This phenomenon is here called "GK effect".

Gurevich and Karashtin (2013) show the distribution of the time intervals between pulses. During the initial stage of the discharge the distribution is close to logarithmic, with a mean time interval ~ 20 – 40 μsec. The distribution reminds about the tail of a lognormal distribution. According to the meaning of a lognormal distribution (Arley and Buch, 1950), the occurrence of a radio pulse is proportional to the number of radio pulses that are already emitted during the same time interval – i.e., much like it typically happens during rush-hour of a public service.

Also the distribution of the pulse growth-time (not here shown) reminds about a lognormal distribution, confirming the expectation according to the same rush-hour argument. The growth time is between 40 – 150 nsec, while no pulses are recorded with growth-time < 30 nsec. These features are related to the physical definition of the parameters of the observed lognormal distribution. The parameters are associated (i) to the typical size of the Cowling small-dynamos, which are the substitute for the HMs speculated by Gurevich and Karashtin (2013), and (ii) to the sensitivity of the recording device in different ranges of pulse growth-time.

The radio emission was found to be stronger when the speed - of the ionization wave that produces free electrons - is close to light speed. That is, the phenomenon is e.m. while the trigger by convection is much slower. Gurevich and Karashtin (2013) conclude that the radio emitting region has a size of ~ 20-50 m, which is an important information, as it gives an observational estimate of the scale-size of the resulting Cowling "macro"-dynamo effect.

Gurevich and Karashtin (2013) plot the distribution of the time-intervals between the peaks of different polarity. As expected according to the aforementioned argument, also this distribution must remind about a lognormal distribution, although the error-bars are somewhat larger, as it is confirmed also by an inset in the original figure (not here shown). The average time interval is 100 nsec, denoting a characteristic width of the emitting region of ~ 30 m. The pulses display a random amplitude, with pulse full width ~ 0.3 – 0.4 μsec.

Summarizing, two features are particularly meaningful for subsequent discussion.

The trends of all these plots by Gurevich and Karashtin (2013), which are not here shown, are suggestive of lognormal distributions. This is consistent with the inference that the occurrence of a case history is proportional to the number of ongoing events of the same

kind - either when dealing with every comparatively longer inter-pulse interval, or with a longer pulse growth-time.

A second related feature deals with the size $\sim 20 - 50$ m of the radio emitting region with a characteristic width ~ 30 m scale. Therefore - independent of the real objective structure and nature of what Gurevich and Karashtin (2013) call "hydrometeor" (*HM*) - they found observational evidence of a large number of small-scale discharges that precede the occurrence of a lightning. Every small-scale discharge is associated to some process that involves a sub-volume of the linear size of $\sim 20 - 50$ m. This is the "GK effect".

The "discharge domain"

Every given small-scale discharge is associated to a given specific sub-volume, which in general is different for different small-scale discharges. Let us shortly denote this sub-volume as "discharge domain" of that given small-scale discharge. Hence, the aforementioned lognormal appearance ought to mean that the probability of occurrence of a small-scale discharge - which is associated with some given "discharge domain" - is proportional to the number of small-scale discharges that are in progress, which are characterized by the same "discharge domain". This is also consistent with the possibility that the occurrence of a small-scale discharge of a given "discharge domain" presumes that a suitable number ought to occur of small-scale discharges of smaller "discharge domain".

In this respect, consider the analogy with the rupture process that occurs in the Earth crust - and that eventually causes an earthquake. A "flaw domain" in the explanation of *AE* (acoustic emission) released at different frequencies (see Gregoti et al., 2024a): higher frequencies are associated to smaller "flaw domains", and smaller "flaw domains" evolve, through coalescence and implosion of flaws, towards increasingly larger "flaw domains". Hence, (higher frequency) *HF AE* must precede (lower frequency) *LF AE*. That is, in the case of fracture phenomena, smaller "flaw domains" experience coalescence and evolve towards larger "flaw domains". Thus, e.g., earthquake precursors are first observed by *HF AE*, and later by *LF AE*.

In a seemingly analogous way, in the case of the small-scale discharges inside thunderstorms, smaller "discharge domains" (i.e., smaller convection cells, whatever is their actual physical structure and meaning) evolve towards larger "discharge domains". Therefore, the process reminds about a coalescence phenomenon: this feature is important for the following discussion.

The explanation of the "GK effect"

Gurevich and Karashtin (2013) comment their findings and attempt to explain observations by means of *EASs*, leading - however - to a fundamental contradiction. In fact, according to their model the pulse amplitude is proportional to the number of secondary electrons. Hence, there is need for some large energy of the primary cosmic ray particle. That is, the *EAS* should be caused by a primary cosmic ray particle with energy $\geq 10^{17}$ eV, which is a rare event. On the characteristic thundercloud scale-size (10 km²), such an event occurs only once a day. This is inconsistent with

the pulse rate $20 - 50$ per msec observed in a thundercloud that corresponds to the shower produced by a primary cosmic ray particle with energy $10^{11} - 10^{12}$ eV. That is, the observed parameters of radio pulses agree with the *RB-EAS* process in the atmosphere, while the pulse amplitude is 5 - 6 orders of magnitude higher.

This contradiction no more exists with the Cowling dynamo mechanism, as the energy budget is just the enormous thermal convection energy inside clouds. This energy can be transformed into e.m. energy only if the medium is ionized. However, several sources of ionization are available, in addition to cosmic rays. Hence, the whole model is self-consistent.

Gurevich and Karashtin (2013) propose an explanation for this paradox, always by appealing to some process internal to the cloud, i.e., of the same kind of the Wilson's "cloud generator". They imagine a large number of electrically charged *HMs* and suppose that *HM* charging, and polarization is correlated in some way with the growth of the ambient *E*. The *E* that accelerates electrons downward usually reaches a maximum value at a height between the main negative and lower positive charge ($\sim 5 - 6$ km). "... As the field becomes equal to or greater than the *RB* critical value $E_{RB} \approx 2.8$ kV cm⁻¹, an avalanche of runaway electrons is generated and, with them, a very large number of thermal electrons and ions." They show a cartoon, not here shown, that is here modified in Fig. 4 (see below):

The aforementioned description of the "GK effect" is all of what is needed for the interpretation that is here proposed. In the ultimate analysis, Gurevich and Karashtin (2013) attempt to explain the "GK effect" by means of some hidden secondary by-product of cosmic rays. They were not aware, however, of the ubiquitous Cowling dynamo, which is certainly operative at every scale-size. Note that, even if cosmic ray eventually play a role, the Cowling dynamo is always present.

Alternative explanations

For completeness sake, also the interpretation has to be reported in some detail that is proposed by Gurevich and Karashtin (2013). As a first item, they estimate the number of thermal electrons and ions. A cosmic ray particle with energy 10^{12} eV originates 10^3 low-energy electrons with mean energy 30 MeV. About 10% of them compose a central beam, where a *RB* avalanche is started if a sufficiently intense thundercloud *E* is available. Let us stress, however, that the Cowling dynamo inside clouds is certainly a source of intense inter-cloud *E*.

When $10 - 12$ avalanches occur with exponential multiplication, the number density of low-energy electrons in the discharge region (50 m \times 30 m) reaches 10^2 cm⁻³. Hence, free electrons are available in close vicinity of every *HM*, and they guess that the *HM* dimension is $D = 1 - 2$ mm. Thus, low-energy particles ought to trigger simultaneously a large number of discharges. Differently stated, *RB* ought to trigger and synchronize multiple *HM* discharges inside a thundercloud. This implies a final strong amplification of the pulse electric current.

Note that Gurevich and Karashtin (2013) speculate that every micro-discharge is associated with a *HM* that they tentatively identify with a droplet or icelet. This is a reasonable, although it is an unproven, assumption. They also estimate the associated current.

They consider that E close to the *HM* ought to be strongly intensified by the E associated to the electric charging and polarization of the *HM*. This E can be even $E_m \approx (2 - 5) \times E_k$. They stress, however, that such a high E value near *HM* cannot endure for a long time, due to the free electrons that are produced by cosmic rays and favor electric discharge. In fact, owing to the great amount of ionization, the medium is prone to react promptly to any kind of E that is eventually generated by any process. Since the ionization rate by cosmic rays at the thundercloud height is $\sim 10 \text{ cm}^{-3} \text{ sec}^{-1}$, and – unlike for the Cowling small-dynamo here envisaged – their guessed *HM* has a millimeter scale, the discharge should have a delay of $\sim 10 \text{ sec}$. Therefore, by a few seconds the E caused by *HM* polarization can become higher than E_k . This seems consistent with the sharp growth of E observed a few seconds before a flash.

Gurevich and Karashtin (2013) also envisage that the growth of the ambient E up to $1 - 2 \text{ kV cm}^{-1}$ is such as to shorten the nonlinear process of icelet growth, consistently with observations in laboratory experiments (see Gregori and Leybourne, 2024e). In addition, the role of E in the process of the droplets and/or icelets growth is consistent with the role of the Cowling dynamo in atmospheric precipitations (see Gregori and Leybourne, 2024e).

Gurevich and Karashtin (2013) quote some estimates of physical quantities, evaluated according to their *HM* model. The observed quantities, however, are the same whether the *HM* or the Cowling dynamo mechanism is considered. A free low-energy electron generates, by $10 - 10^2 \text{ nsec}$, the discharge that ought to be started near a *HM* in a high E , with a maximum number $n \approx W/\varepsilon = 4 \times 10^{12}$ of electron-ion pairs generated in the discharge near the *HM* – where W is the energy $W \approx E^2 D^3$ of E and $\varepsilon = 30 \text{ eV}$ is the energy spent for every electron-ion pair production. The *HM* number density, which is measured directly inside thunderclouds, is $\sim 10^2 \text{ m}^{-3}$, and the volume filled by the pulse discharge is $> 10^4 \text{ m}^3$. Thus, the total number of electron-ion pairs that are generated in the pulse discharge volume close to an *HM* would be $\sim 10^{18} - 10^{19}$. The maximum current caused by the ambient E by the newborn electrons can reach 10^2 A , consistently with observations of maximum pulse current $\sim 100 \text{ A}$ and mean current around 10 A . In addition to *EAS*, also solitary cosmic ray secondary electrons with energy $10^7 - 10^9 \text{ eV}$ can generate low-amplitude pulse discharges. Gurevich and Karashtin (2013) stress that the electric current generated in the *RB-EAS* process with no *HM* is only $\sim 10^{-2} - 10^{-3} \text{ A}$.

Gurevich and Karashtin (2013) also discuss the decay time of the pulses, with a typical observed value of 10^2 nsec , which is determined by electron-ion recombination and free electron attachment either to air O_2 molecules and/or – they claim – to *HM*. Gurevich and Karashtin (2013) point out that, owing to *HM* polarization,

the electric discharge better develops near the positive terminal. They claim that they suppose that it is ambient $E > E_{RB}$ although it is less than the value needed for streamer generation ($E_s = 4.65 - 4.9 \text{ kV cm}^{-1}$). Therefore, no additional source of electrons is available, and – by a few microseconds – a plasma cluster is created near each *HM*, both of positive and negative ions. That is, they envisage a mechanism of agglomeration of positive and negative ions around an *HM* that reminds about the analogous agglomeration of neutral H_2O molecules, although in terms of direct electrostatics, around a condensation nucleus envisaged in Fig. 3 of Gregori and Leybourne (2024e).

Gurevich and Karashtin (2013) further comment that, at the beginning, owing to ion recombination and attachment to *HM*, the number of ions initially decreases in the cluster. However, by $< 1 \text{ msec}$, the positive and negative components are separated by the ambient E . The positive and negative components look therefore like two residual stretched charged clusters that move in opposite directions. Thus, Gurevich and Karashtin (2013) claim that the number of positive and negative charges in the clusters can be different due to *HM* charging. That is, every *HM* is an electric dipole, polarized with negative terminal mainly moving downward, and positive terminal upward. They comment that the resulting charge separation is probably manifested at ground as a gradual decrease of the observed E when a large number of pulses already happened.

Therefore, Gurevich and Karashtin (2013) conclude and state that *“the large number (hundreds or thousands) of pulse discharges observed during the lightning initial stage lead to the formation of a wide region in the thundercloud with a sufficiently high fractal ion conductivity. The estimated number density of ions in the stretched clusters near the HM is not less than 10^7 - 10^8 cm^{-3} , which gives the characteristic charge transport time scale $\sim 10 \text{ msec}$. In that way, a charge drain system can be created, which allows the lightning leader to start.”*

Note that several details – of this whole Gurevich and Karashtin (2013) model and explanation – can fit with the Cowling dynamo mechanism. Hence, all this can be fully shared. In fact, one only needs to substitute the speculated initial trigger by cosmic rays with the role of small convection and Cowling dynamo.

However, Moskvitch (2013), while commenting these findings and interpretation, reports some interview. Clive Saunders *“remains unconvinced that cosmic rays play a role in lightning. ‘They have not shown a correlation between lightning activity and the rate of arrival of cosmic rays at the Earth’ ... If cosmic rays are behind thunderstorms, the incidence of thunderstorms should follow a similar cycle. ‘Until they can prove this correlation, that leaves a fundamental question about the whole concept’.”*

That is, this complaint contends the Svensmark hypothesis (see Gregori and Leybourne, 2024e), although the role must be stressed that is played by the additional ions generated by friction of air at Earth’s surface. In any case, the primary energy source that supplies the Cowling dynamo is other than cosmic rays.

Moskvitch (2013) also state that “most researchers, lean toward another theory: lightning occurs when collisions between ice crystals and hailstones in storm clouds separate enough electric charge to cause a high E . This process alone can ionize the air enough for a lightning bolt to form, no cosmic rays required.” Note that this last comment recalls the present widely shared bias in favor of friction electricity phenomena inside the Wilson’s “cloud generator”, which is a huge “Wimshurst machine” (see Gregori and Leybourne, 2024g). In fact, in several present papers this hypothesis often seems to be considered almost like a paradigm.

In addition, the system is not linear, and the correlation between lightning and cosmic rays might be occasionally biased by some relevant scatter, and the phenomenon is not always the same at different times. Sometimes there can be correlation, sometimes not.

Moskvitch (2013) also states that, according to Joseph Dwyer, “it should be possible to settle the dispute using a detector for cosmic ray air showers known as a Cherenkov telescope. ‘What we really need is to have these air shower arrays that measure the cosmic ray air showers going through, measure the radio waves, measure the pulses, and put it all together’.”

Let us stress that the real primary concern is about the process by which these speculated Gurevich and Karashtin (2013) micro-discharges are generated in the HMs, i.e., inside water droplets or icelets that are charged and polarized inside the thundercloud E . This is a crucial point: what real physical entity must be associated with the speculated emitter of an “elementary” radio emission and/or discharge? Is this what is here called a “hydrometeor” HM , or something different? We envisage Cowling dynamo of suitable size.

Summary: the role of Cowling dynamo

Let us consider the key issue that - unlike what is basically always assumed - phenomena that involve water condensation occur much earlier than at the stage when a droplet or an icelet has already formed (refer to Fig. 3 of Gregori and Leybourne, 2024e). In fact, droplets and icelets are treated by thermodynamics, by surface tension and evaporation, by energy balance, radiation balance, etc. In contrast, the agglomeration of water by a condensation nucleus is a molecular-scale phenomenon, which must be treated by means of quantum mechanics. The “statistical” stage of thermodynamics of a droplet or of an icelet is a much later concern.

Therefore, let us start from a very elementary stage. Suppose to deal with a fluid medium embedded in a gravity field. When the physical system is composed of some minimum needed number of molecules, it happens that an eventual lesser local availability of thermal energy triggers some ordered motion, which can be correctly called a “micro-convection cell”.

Owing to the generalized Cowling theorem (see Gregori et al., 2024d), if the medium is ionized this is a Cowling micro-dynamo. The e.m. field, which is thus generated, can be extremely tiny. It is eventually undetectable. But it exists because the generalized Cowling theorem is a rigorous

consequence of Maxwell’s equations. Therefore, if the physical system is larger than the domain of one atom or one molecule, the Maxwell’s laws apply, hence also the generalized Cowling theorem.

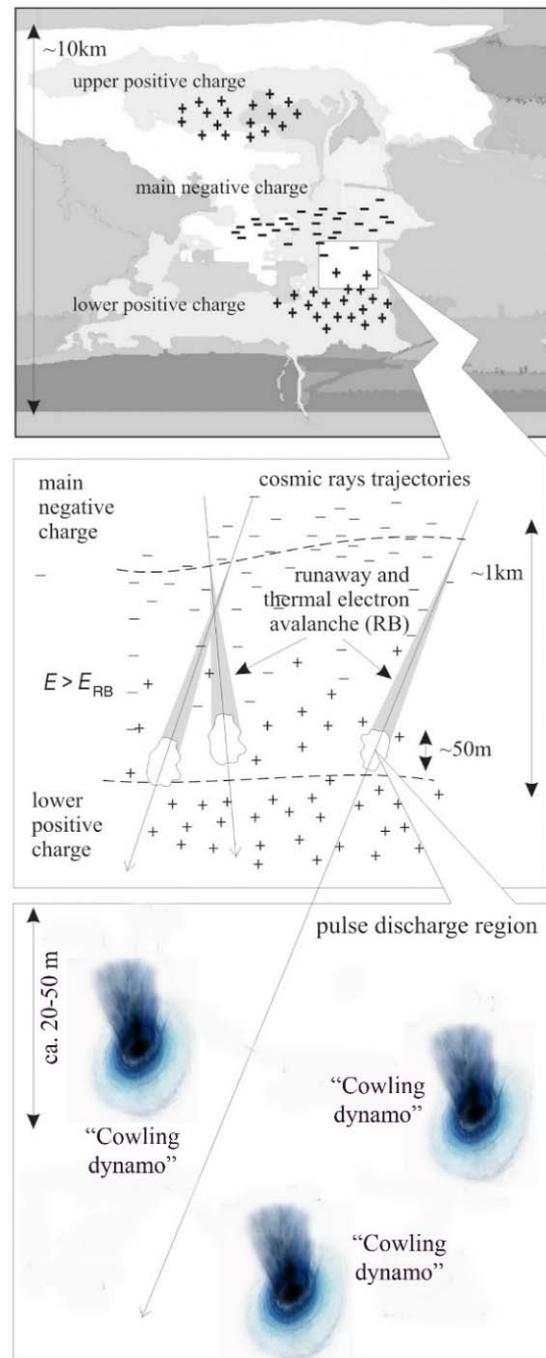


Fig. 4. Modified version of a figure shown by Gurevich and Karashtin (2013). The two upper panels illustrate the process envisaged by Gurevich and Karashtin (2013), while the lower panel represents the “elementary” sources of small-pulses in terms of Cowling small-dynamos. The final result is the observed *GK effect*. A large positive electrostatic charge is located in the overlying ionosphere, at a few to several hundred kilometer height. See text. Unpublished figure.

Note that the possibility to detect a Cowling dynamo can be either by means of some direct instrumental measurement, or more often - and more simply - by means of indirect observable effects. Several micro-Cowling dynamos, which are close to one another, are responsible for water agglomeration around condensation nuclei (see Gregori and Leybourne, 2024e). That is, fog, rain, snow and/or hail are the observable manifestation of Cowling micro-dynamos. Several Cowling micro-dynamos eventually transform, by coalescence, into one larger Cowling micro-dynamo, etc. The process proceeds, until a Cowling dynamo is generated that can be certainly detected, either directly or indirectly. In addition, this process is expected to be in agreement with the aforementioned rush-hour scenario, i.e., it has to imply a lognormal trend.

The *GK effect* can therefore be explained by means of small-discharges that are the instrumentally detectable effect generated by several Cowling small-dynamos, which are active inside a thunderstorm. Every single Cowling small-dynamo is associated to a typical "discharge domain". Cowling dynamos of small "discharge domain" evolve and generate Cowling dynamos characterized larger "discharge domains".

That is, the single source of every small-discharge that partakes to the *GK effect* is not what Gurevich and Karashtin (2013) call a "hydrometeor" (*HM*), i.e., a droplet or an icelet of a few millimeter size. Rather, it is a Cowling small-dynamo associated with a given "discharge domain", which can be even of some much smaller size. In contrast, droplets or icelets are a much later thermodynamic phenomenon, and are associated with friction electricity effects aimed to produce condensation nuclei. However, droplets and icelets are late details that enter into play after a long evolution of the system.

Fig. 4 is a version, modified in the lowest panel, of a cartoon shown by Gurevich and Karashtin (2013). The upper two panels are simply reproduced after Gurevich and Karashtin (2013).

When different models can be envisaged, the correct approach is to search for additional observations capable to discriminate between possible choices. The literature is enormous dealing with *TGFs* and with optical phenomena observed above clouds and thunderstorms, i.e., with the so-called *TLEs* (transient luminous events). A short reminder about *TLEs* is given in Gregori and Leybourne (2024g), including a mention about a few papers that report observations of *TGFs* correlated with *TLEs*. In any case, it should be stressed that, e.g., Dwyer et al. (2013) authoritatively conclude that "at this time, it is not clear which mechanism describes most *TGFs* ...".

That is, the Cowling micro-dynamo process seems crucial in order to explain several unexplained phenomena, beginning from water condensation and precipitation, as explained in Gregori and Leybourne (2024e). A huge number of studies, papers, and experiments were carried out, and a long discussion is needed in order to assess and clarify the final details. In any case, the old-fashioned standard Wilson's approach seems obsolete and incapable of justifying several observations.

Conclusion - Past models and explanations

The nature of electrical discharges deals with phenomena behind the old-fashioned classical treatment of electrical discharges through gases etc. Concerning these items, the interested reader can refer, e.g., to the authoritative and exhaustive review given by Raizer (1991). The term "gas discharge" refers to every phenomenon associated to the motion of ionized matter inside any medium, with or without electrodes. However, unlike arguments that are made in the standard classical treatment, the leading role of B must be considered. In addition, gas interactions with e.m. waves can originate a "gas discharge".

The entire classical theory is mostly concerned with application to gas tubes, such as for light sources etc. In addition, Raizer (1991) specifies that he is not directly concerned with phenomena occurring in presence of a B , such as - he notes - when referring to *MHD* generators (see Gregori and Leybourne, 2024e). Similarly, he does not enter into the realm of plasma physics applied to the investigations on nuclear fusion, etc.

Lightning is to be considered altogether with a spark phenomenon. However, several kinds of less extreme discharge phenomena occur before the onset of the trigger of a spark. This is the main concern of previous theories. On the other hand, this whole scenario is the needed premise for a pertinent physical discussion of the nature of a lightning.

The naïve Wilson model, proposed in the 1910s - and that is still generally appealed to by a huge amount of literature - is to be abandoned after the great achievement and modeling carried out by Gurevich and coworkers in the 1990s, which is now completed by the contribution of the Cowling dynamo.

In addition, the improved and correct understanding - of the physics behind the occurrence of lightning - is likely to be the important forerunner of the future exploitation of the electrostatic energy of the atmosphere (see Gregori and Leybourne, 2024l), which is an enormous free source of clean energy, available everywhere, lasting as long as the Sun shines.

Acknowledgements

We want to acknowledge all co-workers that, in different ways and at different times, contributed to the exploitation of the analyses mentioned in the present study. We like also to thank for the warm encouragement we had from several outstanding scientists.

Funding Information

G.P. Gregori is retired since 2005. B.A. Leybourne is a semi-retired self-funded independent researcher.

Author's Contributions

This study derived from a long-lasting cooperation by both authors. The backbone draft was prepared by the first

author, although a large number of ideas resulted from the emergence of long-lasting discussions.

Ethics

This article is original and contains unpublished material. Authors declare that there are not ethical issues and no conflict of interest that may arise after the publication of this manuscript.

References

- Arley, N., and K.R. Buch, 1950. Introduction to the Theory of Probability and Statistics. Science Editions, John Wiley and Sons, Inc., New York, pp.:1-240
- Babich, L.P., I.M. Kutsyk, E.N. Donskoy, and A.Yu. Kudryavtsov, 1998. New data on space and time scales of relativistic runaway electron avalanche for thunderstorm environment: Monte Carlo calculations, *Physics Letters*, A245 (5): 460-470; DOI:10.1016/S0375-9601(98)00268-0
- Bell, T.F., V.P. Pasko, and U.S. Inan, 1995. Runaway electrons as a source of red sprites in the mesosphere, *Geophysical Research Letters*, 22 (16): 2127-2130; DOI:10.1029/95GL02239
- Berger, M.J., M. Inokuti, H.H. Anderson, H. Bichsel, J.A. Dennis, D. Powers, S.M. Seltzer, and J.E. Turner, 1984. ICRU Report 37, International Commission on Radiation Units and Measurements, os19 (2); DOI:10.1093/jicru/os19.2.Report37
- Bethe, H. A., 1930. Zur Theorie des Durchgangs schneller Korpuskularstrahlen durch Materie, *Annalen der Physik*, 5, 325-400
- Bhandari, N., and Rama, 1963. Study of atmospheric washout processes by means of Radon decay products, *Journal of Geophysical Research*, 68 (7): 3823-3826; DOI:10.1029/JZ068i007p01959
- Chubenko, A.P., V.P. Antonova, S.Yu. Kryukov, V.V. Piskal, M.O. Ptitsyn, A.L. Shepetov, L.I. Vildanova, K.P. Zybin, and A.V. Gurevich, 2000. Intensive X-ray emission bursts during thunderstorms, *Physics Letters*, A275: 90-100; DOI:10.1016/S0375-9601(00)00502-8
- Coulter, D., 2010. Are TGFs hazardous to air travelers? *Science@NASA*, issued 02.10.2010
- Dwyer, J.R., 2003. A fundamental limit on electric fields in air, *Geophysical Research Letters*, 30 (20): 2055; DOI:10.1029/2003GL017781
- Dwyer, J.R., 2004. Implications of X-ray emission from lightning, *Geophysical Research Letters*, 31: L12102; DOI:10.1029/2004GL019795
- Dwyer, J.R., H.K. Rassoul, M. Al-Dayeh, L. Caraway, A. Chrest, B. Wright, E. Kozak, J. Jerauld, M.A. Uman, V.A. Rakov, D.M. Jordan, and K.J. Rambo, 2005. X-ray bursts associated with leader steps in cloud-to-ground lightning, *Geophysical Research Letters*, 32: L01803 [4 pp.]; DOI:10.1029/2004GL021782
- Dwyer, J.R., Ningyu Liu, and H.K. Rassoul, 2013. Properties of the thundercloud discharges responsible for terrestrial gamma-ray flashes, *Geophysical Research Letters*, 40: 4067-4073; DOI:10.1002/grl.50742
- Eack, K.B., W.H. Beasley, W.D. Rust, T.C. Marshall, and M. Stolzenburg, 1996. Initial results from simultaneous observation of X rays and electric fields in a thunderstorm, *Journal of Geophysical Research*, 101 (D23): 29,637-29,640
- Fishman, G.J., P.N. Bhat, R. Mallozzi, J.M. Horack, T. Koshut, C. Kouveliotou, G.N. Pendleton, 1994. Discovery of intense gamma-ray flashes of atmospheric origin, *Science*, 164: 1313
- Gregori, G.P., 2020. Climate change, security, sensors. *Acoustics*, 2: 474-504; DOI:10.3390/acoustics2030026 [<https://www.mdpi.com/2624-599X/2/3/26/html>]
- Gregori, G.P., and B.A. Leybourne, 2024b. The electrostatic Sun, present issue
- Gregori, G.P., and B.A. Leybourne, 2024d. Measuring the electric field at ground, present issue
- Gregori, G.P., and B.A. Leybourne, 2024e. The physics of electrical discharges – 1. Small-scale phenomena - Fog - atmospheric precipitation – BLs, present issue
- Gregori, G.P., and B.A. Leybourne, 2024g. The physics of electrical discharges – 3. Sparks and lightning - electrostatics of the ionosphere – TLEs - plasma jets collimation – Birkeland currents & sea-urchin spikes - stellar and galactic alignments, present issue
- Gregori, G.P., B.A. Leybourne, and J.R. Wright, 2024d. Generalized Cowling theorem and the Cowling dynamo, present issue
- Gregori, G.P., and B.A. Leybourne, 2024l. Conclusion – Exploitation of the electrostatic energy of the atmosphere, present issue
- Gregori, G.P., B.A. Leybourne, Dong Wenjie, and Gao Xaoqing, 2024h. Shallow geotherms, present issue
- Gregori, G.P., B.A. Leybourne, G. Paparo†, and M. Poscolieri, 2024a. The global Sun-Earth circuit, (including a Supplement) present issue
- Gurevich, A. V., and K. P. Zybin, 2004. High energy cosmic ray particles and the most powerful discharges in thunderstorm atmosphere, *Physics Letters A329* (4/5): 341-347
- Gurevich, A.V., A.N. Karashtin, A.P. Chubenko, L.M. Duncan, V.A. Ryabov, A.S. Shepetov, V.P. Antonova, S.V. Kryukov, V.V. Piskal, M.O. Ptitsyn, L.I. Vildanova, Yu.V. Shlyugaev, and K.P. Zybin, 2004b. Experimental evidence of giant electron–gamma bursts generated by extensive atmospheric showers in thunderclouds, *Physics Letters A325* (5/6): 389-402; DOI:10.1016/j.physleta.2004.03.074
- Gurevich, A.V., and A.N. Karashtin, 2013. Runaway breakdown and hydrometeors in lightning initiation, *Physical Review Letters*, 110 (18): 185005, [5 pages]; DOI:10.1103/PhysRevLett.110.185005
- Gurevich, A.V., and G.M. Milikh, 1999. Generation of X-rays due to multiple runaway breakdown inside thunderclouds, *Physics Letters*, A262 (6): 457-463; DOI:10.1016/S0375-9601(99)00695-7
- Gurevich, A.V., and K. P. Zybin, 1998. Kinetic equation for high energy electrons in gases, *Physics Letters A237*, (4/5): 240-246; DOI:10.1016/S0375-9601(97)00868-2

- Gurevich, A.V., and K.P. Zybin, 2001. Runaway breakdown and electric discharges in thunderstorms, *Physics-Uspekh*, 44: 1119-1140
- Gurevich, A.V., and K.P. Zybin, 2005. Runaway breakdown and the mysteries of lightning, *Physics Today*, 58 (5): 37-43
- Gurevich, A.V., G.M. Milikh, and J.A. Valdivia, 1997. Model of X-ray emission and fast preconditioning during a thunderstorm, *Physics Letters A* 231 (5/6): 402-408; DOI:10.1016/S0375-9601(97)00354-X
- Gurevich, A.V., G.M. Milikh, R.A. Rousse1-Dupré, 1992. Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm, *Physics Letters*, A165 (5/6): 463-468; DOI:10.1016/0375-9601(92)90348-P
- Gurevich, A.V., H.C. Carlson, Y.V. Medvedev, and K.P. Zybin, *Physics Letters A* 282, (3): 180-185; DOI:10.1016/S0375-9601(01)00108-6
- Gurevich, A.V., H.C. Carlson, Yu.V. Medvedev, K.P. Zybin, 2000. Generation of electron-positron pairs in runaway breakdown, *Physics Letters A* 275, (1/2): 101-108; DOI:10.1016/S0375-9601(00)00558-2
- Gurevich, A.V., K.P. Zybin, and R. Roussel-Dupré, 1999. Lightning initiation by simultaneous effect of runaway breakdown and cosmic ray showers, *Physics Letters*, A254 (1/2): 79-87; DOI:10.1016/S0375-9601(99)00091-2
- Gurevich, A.V., L.M. Duncan, A.N. Karashtin, and K.P. Zybin, 2003. Radio emission of lightning initiation, *Physics Letters A* 312 (3/4): 228-237; DOI:10.1016/S0375-9601(03)00511-5
- Gurevich, A.V., Y.V. Medvedev, and K.P. Zybin, 2004. New type discharge generated in thunderclouds by joint action of runaway breakdown and extensive atmospheric shower, *Physics Letters A* 329: 348-361; DOI:10.1016/j.physleta.2004.06.099
- Gurevich, A.V., Yu.V. Medvedev, and K.P. Zybin, 2004a. Thermal electrons and electric current generated by runaway breakdown effect, *Physics Letters A* 321 (3): 179-184; DOI:10.1016/j.physleta.2003.10.062
- Haines, R.F., 2010. Ball lightning and earthlights, *NARCAP Project Sphere*, Sect. 4.3, pp: 1-14
- İnan, U.S., S.C. Reising, G.J. Fishman, and J.M. Horack, 1996c. On the association of terrestrial gamma-ray bursts with lightning and implication for sprites, *Geophysical Research Letters*, 23, (9): 1017-1020; DOI:10.1029/96GL00746
- Jacobson, A.R., 2003. How do the strongest radio pulses from thunderstorms relate to lightning flashes?, *Journal of Geophysical Research*, 108 (D24): 4778 [17 pp.]; DOI:10.1029/2003JD003936
- Le Vine, D.M., 1980. Sources of the strongest RF radiation from lightning, *Journal of Geophysical Research*, 85 (C7): 4091-4095; DOI:10.1029/JC085iC07p04091
- Lehtinen, N.G., 2000. Relativistic runaway electrons above thunderstorms, Unpublished dissertation in partial fulfillment of the requirements for the degree of Doctor of Philosophy, Stanford University, Stanford, CA
- Lehtinen, N.G., M. Walt, T.F. Bell, U.S. İnan, and V.P. Pasko, 1996. γ -ray emission produced by a relativistic beam of runaway electrons accelerated by quasi-electrostatic thundercloud fields, *Geophysical Research Letters*, 23 (19): 2645-2648; DOI:10.1029/96GL02573
- Lehtinen, N.G., T.F. Bell, and U.S. İnan, 1999. Monte Carlo simulation of runaway MeV electron breakdown with application to red sprites and terrestrial gamma ray flashes, *Journal of Geophysical Research*, 104 (A11): 24699-24712; DOI:10.1029/1999JA900335.24699
- Lehtinen, N.G., T.F. Bell, V.P. Pasko, and S. İnan, 1997. A two-dimensional model of runaway electron beams driven by quasi-electrostatic thundercloud fields, *Geophysical Research Letters*, 24 (21): 2639-2642; DOI:10.1029/96GL02573
- Lehtinen, N.G., U.S. İnan, and T.F. Bell, 2000. Trapped energetic electron curtains produced by thunderstorm driven relativistic runaway electrons, *Geophysical Research Letters*, 27 (8): 1095-1098; DOI:10.1029/1999GL010765
- MacGorman, D.R., and W.D. Rust, 1998. *The Electrical Nature of Storms*, Oxford University Press, Oxford and New York, pp: 1-422
- Marshall, T.C., M. Stolzenburg, C.R. Maggio, L.M. Coleman, P.R. Krehbiel, T. Hamlin, R.J. Thomas, and W. Rison, 2005. Observed electric fields associated with lightning initiation, *Geophysical Research Letters*, 32: L03813, [5 pp.]; DOI:10.1029/2004GL021802
- Marshall, T.C., M.P. McCarthy, and W.D. Rust, 1995. Electric field magnitudes and lightning initiation in thunderstorms, *Journal of Geophysical Research*, 100 (D4): 7097-7103; DOI:10.1029/95JD00020
- McCarthy, M.P., and G.K. Parks, 1985. Further observations of X-rays inside thunderstorms, *Geophysical Research Letters*, 12 (6): 393-396; DOI:10.1029/GL012i006p00393
- Medvedev, M.V., D. Lazzati, B.C. Morsony, and J.C. Workman, 2011. Jitter radiation as a possible mechanism for gamma-ray burst afterglows: spectra and light curves, *Astrophysical Journal*, 666 (1): 339-349; DOI:10.1086/520701
- Moskvitch, K., 2013. Do cosmic rays grease lightning? *Science now*, (AAAS), issued 3 May 2013.
- Nishimura, J., 1969. Possible effects of an extensive air shower. In *Planetary electrodynamics*, S.C. Coroniti, and J. Hughes, (eds), Gordon & Breach Science Publ., New York, etc. pp: 333-335
- Parrot M., 2024. DEMETER observations of the variations of the global electric circuit under various constraints, present issue
- Quinn, J.M.,† G.P. Gregori, and B.A. Leybourne, 2024. Satellite monitoring of air-earth currents, present issue
- Raizer, Y.P., 1991. *Gas discharge physics*, [Translated from the Russian original published by Nauka, Moscow, in 1987], Springer, Berlin; ISBN 3-540-19462-2, pp: 1-449
- Roussel-Dupré, R., A.V. Gurevich, T. Tunnel, and G.M. Milikh, 1994. Kinetic theory of runaway air breakdown, *Physical Review E*, 49 (3): 2257-2271
- Shou, Zhonghao, 2024. Overview of earthquake clouds, present issue

- Shou, Zhonghao, Yan Fang and Kai Mayhar-Fang, 2024. Use earthquake vapor model to understand the 2009 Australia wildfires, present issue
- Skeltved, B.A., N. Østgaard, B. Carlson, T. Gjesteland, and S. Celestin, 2014. Modeling the relativistic runaway electron avalanche and the feedback mechanism with GEANT4, *Journal of Geophysical Research, Space Physics*, 119 (11): 9174-9191; DOI:10.1002/2014JA020504
- Smith, D.A., K.B. Eack, J. Harlin, M.J. Heavner, A.R. Jacobson, R.S. Massey, X.M. Shao, and K.C. Weins, 2002. The Los Alamos spheric array: a research tool for lightning investigations, *Journal of Geophysical Research*, 107 (D13): 4183, [14 pp.]; DOI:10.1029/2001JD000502
- Smith, D.A., M. J. Heavner, A.R. Jacobson, X.M. Shao, R.S. Massey, R.J. Sheldon, and K.C. Wiens, 2004. A method for determining intracloud lightning and ionospheric heights from VLF/LF electric field records, *Radio Science*, 39: RS1010, [11 pp.]; DOI:10.1029/2002RS002790
- Smith, D.A., X.M. Shao, D.N. Holden, C.T. Rhodes, M. Brook, P.R. Krehbiel, M. Stanley, W. Rison, and R.J. Thomas, 1999a. A distinct class of isolated intracloud lightning discharges and their associated radio emissions, *Journal of Geophysical Research*, 104 (D4): 4189-4212; DOI:10.1029/1998JD200045
- Straser, V., G. Cataldi, and D. Cataldi, 2024. Space weather related to potentially destructive seismic activity, present issue
- Suszcynsky, D.M., R. Roussel-Dupré, and G.E. Shaw, 1996. Ground-based search for X rays generated by thunderstorms and lightning, *Journal of Geophysical Research*, 101 (D18): 23,505-23,516; DOI:10.1029/96JD02134
- Symbalisty, E.M.D., R.A. Roussel-Dupré, and V.A. Yukhimuk, 1998. Finite volume solution of the relativistic Boltzmann equation for electron avalanche studies, *IEEE Transactions Plasma Science*, 26 (5): 1575-1582; DOI:10.1109/27.736065
- Tavani, M., A. Argan, A. Paccagnella, A. Pesoli, F. Palma, S. Gerardin, M. Bagatin, A. Trois, P. Picozza, P. Benvenuti, E. Flamini, M. Marisaldi, C. Pittori, and P. Giommi, 2013a. Possible effects on avionics induced by terrestrial gamma-ray flashes, *Natural Hazards and Earth System Sciences*, 13: 1127-1133; DOI:10.5194/nhess-13-1127-2013
- Wilson, C.T.R., 1924. *Proceedings of the Cambridge Philosophical Society*, 22: 34-
- Wu, Hong-chun, 2024. Jet stream's disturbances as possible precursors of earthquakes, present issue
- CGRO - Compton Gamma Ray Observatory*
EAS - extensive atmospheric showers
FAC - field-aligned current
FORTE - Fast On-orbit Rapid Recording of Transient Events
GK - Gurevich and Karashtin (effect)
GRF - gamma ray flash
HF - high frequency
HM - hydrometeor
IC - intra-cloud (discharge)
ITCZ - Intertropical Convection Zone
LASA - Los Alamos Sferic Array
LF - low frequency
MHD - magneto-hydro dynamics
NBP - narrow bipolar pulse
QE - quasi-electrostatic (process)
RB - runaway-breakdown (process)
STP - standard temperature pressure
TGB - terrestrial gamma bursts
TGF - terrestrial gamma flash
TLE - transient luminous event

Acronyms

- AE -acoustic emissions
 BATSE - Burst and Transient Source Experiment, detectors on CGRO
 BL - ball lightning
 CC - cloud-cloud (discharge)
 CG - cloud-ground (discharge)

The physics of electrical discharges – III. Large-scale phenomena

Sparks and lightning - Electrostatics of the ionosphere – TLEs

Plasma jets collimation – Birkeland currents and sea-urchin spikes - Solar γ -rays - Stellar and galactic alignments

Giovanni Pietro Gregori¹, Bruce Allen Leybourne²

¹Former Senior Researcher at IDASC-Institute of Acoustics and Sensors O. M. Corbino (CNR), Rome, now merged with the IMM-Institute of Marine Engineering "Section of Acoustics and Sensors O.M. Corbino"- (CNR Rome); and ISSO-International Seismic Safety Organization, Italy

²GeoPlasma Research Institute-(GeoPlasmaResearchInstitute.org), Aurora, CO 80014, USA

Corresponding Author:

Giovanni Pietro Gregori
IDASC-Istituto di Acustica e
Sensoristica O. M. Corbino
(CNR), Roma, now merged
into IMM-Istituto per la
Microelettronica e
Microsistemi (CNR) Italy
e-mail:
giovannipgregori38@gmail.com;
leybourneb@iascc.org

Abstract: Two previous papers addressed phenomena associated, respectively, (i) to electrical discharges in the space range, roughly, $\leq n 10$ cm, and (ii) with extreme electromagnetic (e.m.) impulses. The present paper deals with the largely misunderstood realm of electrical discharges on much larger scale sizes, both in space and time. The present literature deals, in general, only with sparks, lightning, and gas tube discharges. In contrast, the focus must be widened, and the whole topic requires an unprecedented detailed discussion. An important gap deals with presently neglected huge air-earth currents, with large cross-section, which play a relevant role, although cannot be monitored by luminous phenomena, and therefore were never considered. However, also the physics of sparks and lightning is partially misunderstood, and can be explained by a domino chain of ball lightning (BLs). Huge convective cells inside clouds are the major supply that accumulates electrostatic charge in the ionosphere, which must be positive because the solar wind has a mean positive charge - hence, the old-fashioned Wilson mechanism still holds although, at most, only as an optional unnecessary process. Transient luminous events (TLEs) represent observational hunches, suited to investigate the microphysics of discharge phenomena above clouds. However, TLEs can be monitored only with suitable conditions, although observations from space provide effective information. In addition, the Cowling dynamo determines several presently otherwise unexplained effects, associated to the self-collimation observed in many physical systems, i.e., either in solar γ -rays, or in the solar wind, or in astrophysical jets, or in star alignments in galaxies, or in galaxy alignments in galactic superclusters, but also in the field-aligned currents (FACs) in the Earth's atmosphere, and in the sea-urchin spikes from the deep Earth interior. Several effects, fully explained by the Cowling dynamo, can also be envisaged - sometimes in some better detail although at the expense of some approximation - by means of the standard algorithms of plasma physics. An unprecedented scenario is thus envisaged of the physics behind a stark or lightning, concerning the relevant impact of huge air-earth currents. This includes the possibility to exploit the electrostatic energy from the ionosphere - which is a free clean basically unlimited source of energy that will last as long as the Sun shines.

Keywords: sparks and lightning - electrostatics of the ionosphere – TLEs - plasma jets collimation – FACs or Birkeland currents and sea-urchin spikes – solar γ -rays - astrophysical jets - stellar and galactic alignments – electrical discharges with no luminous emission – exploitation of the electrostatic energy of the ionosphere

Introduction

The meaning of the term “discharge” is unconsciously related to the frightening observation of lightning and to the

old-fashioned classical experiments in vacuum tubes. However, phenomena are much different, as a key role in several natural phenomena is played by relevant electrical discharges that with no luminous emission. All these topics are intricate, and – with the purpose to discuss air-earth currents – a distinction should be made between the following items, concisely discussed in three papers as follows:

- ◇ first paper (small-scale phenomena)
 - micro Cowling dynamos (fog and atmospheric precipitation)
 - ball lightning (*BLs*)
- ◇ second paper (extreme effects)
 - runaway-breakdown (*RB*) process and *GK-effect*,
 - terrestrial gamma flashes (*TGFs*), also called gamma ray flashes (*GRFs*) or terrestrial gamma bursts (*TGBs*)
- ◇ the present paper (large-scale phenomena)
 - sparks and lightning
 - cloud phenomena, charging of the ionosphere, transient luminous events (*TLEs*)
 - solar γ -rays
 - plasma jets collimation and sea-urchin spikes, astrophysical jets
 - stellar and galactic alignments
 - formulation by plasma physics algorithms, field-aligned currents (*FACs*)
 - electrical discharges with no luminous emission.

The present paper deals with large-scale phenomena observed in the Earth's atmosphere - and also, although only by a few mentions, in some stellar and galactic environment.

The mysterious physics of sparks and lightning can be explained by a domino effect of small-*BLs*.

Cloud phenomena are the source of the electrostatic charge of the ionosphere, with a twofold implication. On the one hand, the obsolete and old-fashioned – although still used – Wilson's hypothesis for the positive charge of the ionospheric can be substituted by a more effective process, thus overcoming several physical perplexities.

Only a brief reminder is given about *TLEs*, which are the object of a huge literature (papers, treatises, and meetings).

The effect of collimation is discussed, both according to the Cowling dynamo viewpoint, and according to the standard algorithms of plasma physics. This applies to field aligned currents (*FACs*), also called Birkeland currents, but it also applies either to solar γ -rays, or to the flow of solar wind, or to the generation of sea-urchin spikes inside the deep Earth's interior - or to astrophysical jets, to star alignments inside galaxies, and to galaxy alignments inside galactic superclusters - but only brief mentions are here given.

Finally, the important role is stressed of large scale, intense, electric currents in our environment associated to several phenomena. Until now, these huge currents have been underestimated, due to the absence of luminous emission, by which these effects were generally considered as irrelevant. In addition, these intense, steady, and large-

scale electrical discharges also include the exploitation of the electric currents between soil and ionosphere, which are a potential source of clean and free energy.

The physics of sparks and lightning. A domino effect of small Cowling dynamos

Cowling "micro-dynamos" make condensation nuclei to collect like "broom" the neutral water molecules in air (see Gregori and Leybourne, 2025e). Thus, they play a crucial role in the presently unexplained water condensation and/or precipitation. Cowling dynamos of larger, although small, size explain the formation of *BLs*. Call "small Cowling dynamos" the Cowling dynamos that are typical of *BLs*.

Refer to the "small-granules" associated to small Cowling dynamos as per Gregori and Leybourne (2025e). If the small-vortex inside the "small-granule" is sufficiently intense, a comparatively strong light emission is triggered, and we can detect the "small-granule". In addition, every "small-granule", like every *BL*, implies a conspicuous large temperature inside a confined volume, and a comparatively much lower temperature at its boundary. The large internal temperature originates an excess heating that must be released as soon as the confinement is over. Thus, a micro-jet of hot gas eventually affords to escape from the "small-granule", and to determine the conditions for the generation of a nearby "small-granule".

In this way, a linear chain of "small-granules" is formed like in a domino play. These "small-granules" constitute a large ensemble of elements aligned along a chain. The lifetime of every "small-granule" can be short - and every single "small-granule" alone is therefore eventually undetected. However, the entire phenomenon has a total energy density, and it can be detected when it lasts for a sufficient time lag - much like, in fact, it occurs in a spark or in a lightning. The phenomenon can be detected - or not - upon considering the visual contrast, i.e., the spatial gradient of the released luminous signal in order to perceive light emission with respect to the background.

A spark or a lightning is a time-ordered occurrence of a large number of small Cowling dynamos associated to "small-granules" that evolve like domino tiles. The spark or lightning is started by one small-convection cell, which is triggered while electrons are violently extracted from one electrode. The first small-dynamo accelerates other electrons inside the surrounding atoms and molecules. The effect generates a local heating, which causes the birth of new small-convective cells, etc. The process thus "rapidly" propagates, and we can finally observe either a corona effect, or a spark, or a lightning, etc. The propagation speed is "rapid", although much slower than light speed. The final appearance is what is generally called the "channel" – but also terms such as "ribbon lightning" are often used (e.g., Uman, 1987).

The domino-propagation speed can be measured by a high-speed camera. The location of the earliest trigger of the discharge can be located everywhere along the "channel", because a domino effect can start at any point along the chain. Unlike it is claimed, the distinction is irrelevant of a lightning that propagates in either one

direction or the other (i.e., top-down or bottom-up). The physics is the same, and the difference is just related to the geometry of the electrodes and of the trigger, to the state of air - such as the ionization of air that depends on the previous history of the electric discharge that occurred through it, or on the time change of the flux and energy of cosmic rays, etc. On the other hand, it is well known that a lightning looks like a damped oscillatory phenomenon, with an alternation of electrical discharges that propagate alternatively in both directions. Hence, observation of the propagation direction of the discharge can be interesting for understanding the details of the evolution of a single lighting, although the direction of the first discharge is an eventually irrelevant physical detail.

Such an explanation in terms of “small-granules” can look speculative, even though it is a reasonable justification of several previously unexplained morphological features. The relation with the standard explanation given in the literature is here briefly reviewed, although only whenever suitable.

As far as the atmospheric condenser is concerned, whenever a simple “discharge” is considered that displays no luminous emission, in principle an alternative and competitive possibility ought to be a discharge-channel of some large cross-section, with an almost uniform mean and widespread charge transport. Therefore, some indirect effects are used to monitor the discharge. For instance, a phenomenon of this kind can be associated to the air-earth currents detected by satellite and associated to soil exhalation from areas of large crustal fracturing (Quinn et al., 2026). However, electrical discharges with large scale cross-section are a phenomenon that plays a paramount role in the environment and that at present is underestimated.

In principle, a discharge with no detectable light emission can happen on several occasions. In such a case no relevant energy density concentration occurs that is comparable with the temperature that is to be expected inside every “small-granule”. The small Cowling dynamo requires an internal energy-source that triggers small-convection. If no small-convection occurs, no small Cowling dynamo can be operative, no luminous phenomenon is detected, i.e., a discharge occurs although with no luminous spark or lightning.

One additional argument deals with the typical appearance of a spark or lightning as a sequence of straight segments. The linear shape is caused by a self-collimation effect, similar to what occurs in solar corpuscular radiation, either while it crosses through interplanetary space (see Gregori and Leybourne, 2025b) or when it impinges on the Earth’s atmosphere (see Gregori et al., 2025u and Gregori and Leybourne, 2021). The effect reminds about a laboratory “Z-pinch” effect, although a “Z-pinch” is physically much different, as it is associated to the input by an applied intense B . In either case, both phenomena, i.e., either a chain of “small-granules” or the “Z-pinch” effect, produce the same effect. The forcing driver is the energy input that can be of various origin and intensity, and the observed effects are commensurate with the energy input.

Both “small-granule” and the “Z-pinch” effects are a formal consequence of Maxwell’s equations. The “small-

granule” addresses to a comparably smaller scale. i.e., to a more “elementary” phenomenon, while the “Z-pinch” refers to some comparably large-scale “average” behavior of the system. The coincidence of their respective conclusion is a reciprocal confirmation, and each explanation is *per se* rigorous.

The straight segment structure is explained by ambient conditions, by which the new BL along the domino chain eventually changes the preferred direction of formation. The process is identical also whenever the domino-chain strikes on water or on ground – or in general on a liquid or solid medium. In fact, the mass density is much larger in water or ground, hence also the electron availability. The spark or lightning can even cross through the medium with no relevant damage to molecular bonds, such as, e.g., when a BL crosses a glass or a metal plate, etc. Hence, in principle, the straight segment structure is the same also when the domino-chain enters into water or ground, although the length of every segment is eventually much shorter than through air. Thus, it is claimed that the whole energy of the spark or lightning is rapidly damped and absorbed by the medium (i.e., either water or ground, like in a fulgurite). In principle, however, also the possibility exists that the spark or lightning - after striking on the surface of water or ground - eventually “jumps” back into air, even though no such an event seems to have been reported. The crucial parameter is the comparable availability of free electrons in different media.

This same concept is used by Salanave (1980, p. 127) to justify the appearance of a “string of sausages” that are displayed by some lightning, called “*bead lightning*”. Compared to a “small-granule”, a “sausage” is a macro-structure. Salanave (1980) refers to the “magnetic pinch effect” that reminds about the “Z-pinch” effect. “*If a heavy current flows across a spark gap, the luminous discharge may take the form of a cylinder, or sheath, whose diameter varies periodically along its length.* [This is the self-collimation effect due to the Cowling dynamo. See Gregori et al., 2026d.] *That is, the column of plasma will appear to be pinched at several places along the spark; hence the analogy to a string of sausages in one theory on the origin of bead lightning.*” [That is, this effects seems to be a rarely occurring condition by which some elements or “rings” of the chain of “small-granules” eventually result to be comparatively less visible. Every spot is visible depending on the local emission of photons. Hence, the appearance of a bead lightning on a given photograph depends on the sensitivity of the film that is used.]

Sausage-strings are sometimes reported, although seldom photographed. One case history occurs, e.g., in one of the three figures (not here reported; see Salanave, 1980, p. 43; also reported by MacGorman and Rust, 1998, p. 85). A different picture - which also refers to an underwater explosion experiment - is shown in Fig. 1, borrowed after Uman (1987).

Maybe, Fig. 2 is the best picture, which refers to a series of 8 frames of a high-speed camera, everyone with $\sim 2 \mu\text{sec}$

exposure.¹ The quality of the photo - and the clear way by which it displays the phenomenon - depends on the high time-resolution of the movie. The first two frames resulted overexposed, and the last three badly underexposed. That is, the phenomenon damps and progressively fades off. This is consistent with the structure of a discharge in terms of a linear zigzag domino chain of small Cowling dynamos - everyone being a miniature *BL*, powered by a residual internal heat source. As long as the internal energy reservoir is sufficient, a nearby small-dynamo is triggered, which emits photons and can be detected. The intensity of the emitted light decreases, altogether with the internal available energy. In addition, perhaps, a stroboscopic effect enters into play. In fact, several phenomena overlap one another that are characterized by a different pace. That is, in addition to the $\sim 2 \mu\text{sec}$ exposure-time of every frame, the pace should be taken into account: of the frames of the movie, of the mean lifetime of a small-granule, of the time required to generate the next granule in the domino chain, and of the decay-time of photons released by excited atoms or molecules. In addition, the speed of small-granules interferes with the sensitivity of the camera. A multiple beat phenomenon can therefore occur, and every frame of the movie shows therefore a varying quality of the image.

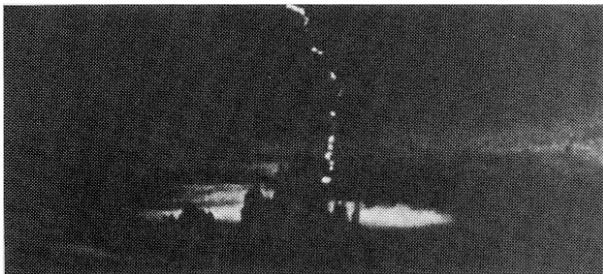


Fig. 1. "Bead lightning as it appears on one frame of a motion picture showing a three-stroke flash striking the top of a depth charge plum. Courtesy, U.S. Naval Ordnance Laboratory." Figure and captions after Uman (1987, p. 25). Reproduced by kind courtesy of the *Naval History and Heritage Command's* photo collections ("Public Domain").

Another somewhat related effect deals with the role played by intense electric fields E associated to the electric discharge, which are sufficient to generate a Stark-Lo Surdo effect. Since motions are random, the effect is a broadening or smearing of spectral lines, rather than a fine-structure splitting (see Salanave, 1980, p. 128).

In any case, the physical argument that is here proposed is a strict and necessary logical consequence of Maxwell's equations, due to two theorems (i.e., Chandrasekhar and Fermi's, and generalized Cowling's; see Gregori et al., 2026d). This statement applies either to the classical

historical pioneering experiments in gas tubes, or to every environmental phenomenon. In terms of analogy, it is like a dust devil and a large hurricane, i.e., both phenomena are related to the same physics, although on a different scale.

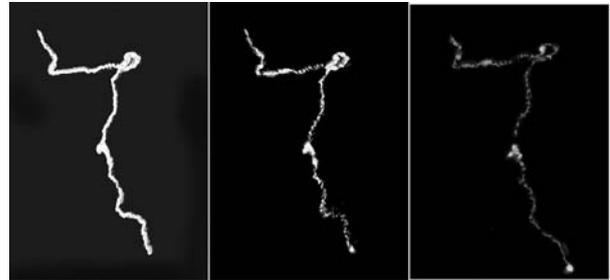


Fig. 2. Three consecutive frames of a high-speed camera (13,000 frames per second; 100 mm lens focused on, and 8 m above, the tip of a tower atop Mount Bigelow near Tucson, Arizona; every frame has a $\sim 2 \mu\text{sec}$ exposure). The bright spot at the bottom is the tip of the lightning rod on the tower, located at 112 m from the camera. The 3rd, 4th, and 5th frames are shown of an 8-frame sequence. The "interval between frames is not quite 80 μsec ". The 1st and 2nd frames where overexposed, and the 6th, 7th, and 8th underexposed. The total extension of the flash, projected on a plane, is ~ 12 m. Only few centimeter features can be resolved, in agreement with the generally accepted estimate of $\sim 1 - 2$ cm for the diameter of the lightning channel. The detection of lesser details largely depends on the time resolution of images, and on exposure time. Adapted - and slightly improved - artwork based on three photos published in Salanave (1980, p. 44). The hand-made sketch aims to correct for possible reproduction bias. See text. Credit of the original photographs: *University of Arizona, Institute of Atmospheric Physics* (Louis Battan, Walter Evans, E. Philip Krider, Clyde Richards, Leon Salanave). Unpublished figure.

The structure of every "small-granule" - which is an *MHD* small Cowling dynamo - derives from a motion of conduction charges. The driver is a thermodynamic phenomenon, i.e., a convection cell inside an ionized medium. The leading response relies on *MHD*, i.e., motion of electrons with no need for motion of molecules and atoms. This justifies the possibility - as already stressed (see Gregori and Leybourne, 2025e) concerning a *BL* - of crossing undisturbed different media, such as, e.g., the glass of a window, as sometimes the crossed medium is seemingly almost undisturbed by *BL*. In fact, the electrons that determine the dynamo are borrowed from the medium (i.e., air, or glass, or metal, or other material) while the "solid" or crystalline bonds of the medium are eventually almost undisturbed. The unique consequence is thermal, rather than structural. No fracture occurs of crystalline

shown contain therefore some subjectivity, aimed to show the features of concern for the present discussion. Every quantitative photometric evidence should, however, rely on objective measurements carried out on the original frames, rather than on printed reproductions, which could satisfy printing optimization requirement.

¹ We made and show here three pencil hand-drawings. The printed copy of these pictures is published in Salanave (1980), maybe with a copyright. The print quality is good, although - when comparing the three pictures - the level of the dark (black) background is different. Every single picture had an independent treatment in order to improve the printing quality. The hand-drawings here

bonds, except - at most - a local transient thermal melt process.

Hence, the small Cowling dynamo has a former thermodynamic trigger, then it becomes electrodynamic, and thus it can cross through different media, eventually not affecting their respective crystalline structure. The destruction - or not - of the solid material depends on the intensity of the small Cowling dynamo, i.e., on its spatial energy-density, or on the capability to melt the crystalline bonds. Similarly, when the small Cowling dynamo enters into water, it will cause a different amount of evaporation depending on its intensity. The same holds when dealing with a fulgurite, which can or cannot form depending on various circumstances. A fulgurite, however, is not a necessary occurrence related to every air-earth current in the ground.

The electric discharges observed in volcanic plumes can be fully justified as per Gregori et al. (2025t). They are likely to be among the electric discharges with the greatest power that occur inside the atmospheric condenser. They are an extreme phenomenon directly observed by naked eye. The conventional lightning - with their whole well-known and impressive morphology - display some "intermediate" intensity compared to lab discharges and to volcanic plumes. For instance, refer to the atlas by Salanave (1980).

The present concise review cannot report the learned morphological distinction of these phenomena. Only a reminder of some notable (generally unnoticed) features is here given. Horizontal lightning discharge are often - though not very frequently - observed. Fig. 3 is one example. Several similar photos are often found in the literature.

According to seemingly generally shared feelings, it is guessed that the dynamics is a feedback of meteorology, being the cause of this phenomenon. However, a meteorological phenomenon should require, perhaps, a friction - caused by an air wind-speed - comparable with the propagation speed of a lightning along the linear "channel". This seems unlikely. Another possibility is, perhaps, to speculate about a horizontal electrically more conducting channel, etc. However, these explanations look *ad hoc*. A more credible possibility is in terms of a preferential direction in the e.m. coupling between the ionospheric plate and subsoil. This can depend, in general, either on the distribution of the electrostatic charge on the upper plate, or on anisotropy of atmospheric conductivity, or on the geometry of the lower plate, i.e., on the sea-urchin spike distribution underground (Gregori, 2002; Gregori and Leybourne, 2021). Several different drivers can contribute.

Note that this case history is associated to a conspicuous flow of electrons between soil and ionosphere. This is opposite to the mean trend that transfers positive charges to the ionosphere, hence electrons to ground. In any case, a lightning looks like a damped oscillation with an alternation

of the direction of the current flow, while an intense air-earth current occurs.



Fig. 3. Looped upward flash from a tower atop Mount San Salvatore above Lake Lugano (Switzerland). The flash "was initiated by an upward propagating leader from a tower with negative polarity. It looped around to within ~ 600 m of the tower and then continued along a nearly horizontal path for approximately ~ 2 km before moving out of the camera's field of view. This photograph was taken with a 50 mm lens on 35 mm film, from a distance of ~ 6.5 km, so the trajectory in a horizontal plane with its origin at the tower could be approximately plotted (see Orville and Berger, 1973). Simultaneous electrical measurements at the research station atop Mount Salvatore showed that current flowed for at least ~ 100 msec but did not exceed ~ 1600 A at any time. The positive charge transferred to ground (electrons moving upward effectively transfer positive charge downward) was estimated to be between ~ 30 - 40 C." The branching of the discharge is from the tower towards the ionosphere. Artwork, ink and pencil sketch based on an image by Salanave (1980). Description after Salanave (1980, p. 28). Unpublished figure.

The geometry of the lower plate of the atmospheric condenser is responsible for the preferential occurrence of lightning that strikes on tall trees, or on towers, etc. or at some sites better than at others, depending on the underground conductivity structure. In addition, also a comparatively higher or lower conductivity of the soil-cover can play an important role. Figs 4 and 5 are remarkable examples. The lightning does not strike the mountain, which is several hundred meters higher than water in the lake. Rather, the lightning strikes water in the lake, because water is more conductive than mountain soil and rocks.²

Another curious feature is that - in general - all photos of lightning display a preferential top-down branching, rather than viceversa. That is, the dielectric of the atmospheric condenser appears to yield due to a trigger that begins in its higher section, and at a comparatively spatially less extended area. This may be due to either one of two different causes.

² The σ of (salted) water and the σ of dry rocks differ by a factor ~ 40,000 (Lanzerotti and Gregori, 1986). However, the Lake Lugano water is not salted.

The top-down branching can derive from an ionospheric trigger, i.e., from an increased transient electrostatic charge-concentration that occurs on the upper plate of the condenser. In contrast, the lower plate ought to respond depending on the more or less irregular distribution, both of sea-urchin spikes and of the conductivity σ of the upper soil-cover. Differently stated, compared to some mean spatial extension that is involved in the lower plate of the condenser, the spatial scale of the ionospheric anomaly seems smaller - even if in principle the discharge occurs on every single conductivity anomaly underground (sea-urchin spike or other). That is, the ionospheric anomaly originates discharges that strike over several point-like anomalies at ground. In fact, an alternative possibility is that the discharge occurs between one unique comparatively less extended electrode (in the ionosphere), and several electrodes that are spread through the Earth's surface on a wide spatial extension.



Fig. 4. View of the Lake Lugano (Switzerland) from Mount San Salvatore, 640 m high above lake water. The lightning does not strike Mount San Salvatore, rather the lake water and Mount San Giorgio, seen at the right. Artwork, ink and pencil sketch based on an image by Salanave (1980, p. 17). Unpublished figure.

However, this curious effect perhaps can derive also from atmospheric dynamics, i.e., from a comparatively larger turbulence in the upper layers. The turbulence ought to be capable of affecting the local dielectric constant in the upper layers better than in the lower layers. In addition, the entire effect can derive from a combination of both causes.

The discharges from volcanic plumes (see Gregori et al., 2025t) represent a likely intermediate situation. In fact, in general the size is comparable to each other - of the region of the upper and lower plate, respectively, of the condenser. However, in the case of Icelandic volcanoes, the anomaly has a comparably larger extension, as it is associated with the auroral electrojet (see Figs 5-9 of Gregori et al., 2025t, and Figs. 1-2 of Gregori et al., 2025t).

An opposite example (bottom-up branching) is shown in Figs. 6, 7 and 8. The ground electrode is a tower, and the spatially more widespread electrode is located in the ionosphere. The tower is the small electrode also shown in Fig. 3.

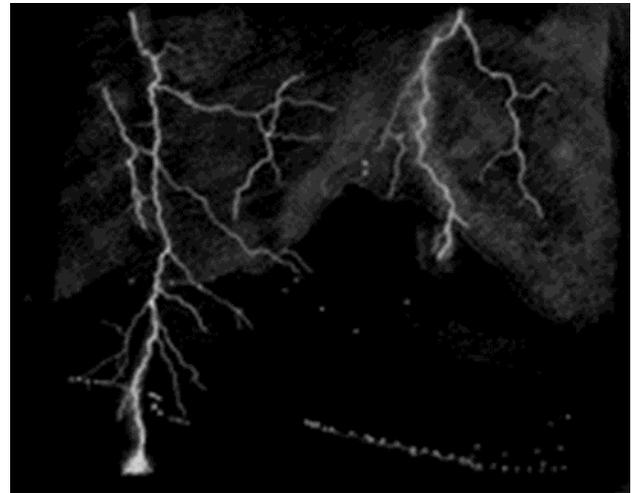


Fig. 5. Lightning striking the water of a lake and a nearby mountain. No details are given. Artwork, ink and pencil sketch based on an image by Salanave (1980, p. 18). Unpublished figure.



Fig. 6. Lightning strikes the Eiffel Tower, France on June 3rd, 1902. After Wikipedia, "Lightning", with "Public Domain" Mark 1.0 Wikimedia Commons kind permission.

As far as the phenomenon is concerned with *QE* (quasi-electrostatic) fields associated to *TGF* or *GRFs* (see below), note that the *QEs* can hardly be conceived to derive from atmospheric dynamics.

Lightning are fascinating, though awful phenomena.³ The physics is, however, difficult. Extensive investigations

³ The ancients were frightened by lightning that looked to them one of the most violent manifestations of nature. Lucius Annaeus Seneca (often known simply as Seneca,

or Seneca the Younger; ~3 BC - 65 AD) describes their effects in his famous *Naturales Quaestiones*. Titus Lucretius Carus (~99 BC - ~55 BC), in "*De rerum*

were concerned with the observed morphology, mostly based on high-speed movies that afford to distinguish the up-and-down evolution of a lightning. In contrast, the physical model still seems inadequate. Indeed, the physics deals with huge convection cells that supply intense Cowling dynamos that push – as a mean effect - positive charges to the ionosphere and negative charges towards ground.



Fig. 7. A clear event of lightning striking a tower in Banská Bystrica, Slovakia. After *Wikipedia*, “Lightning”, with *Wikimedia Commons* kind permission by free copyright policy of *Wikipedia*, retrieved on August 14, 2010.

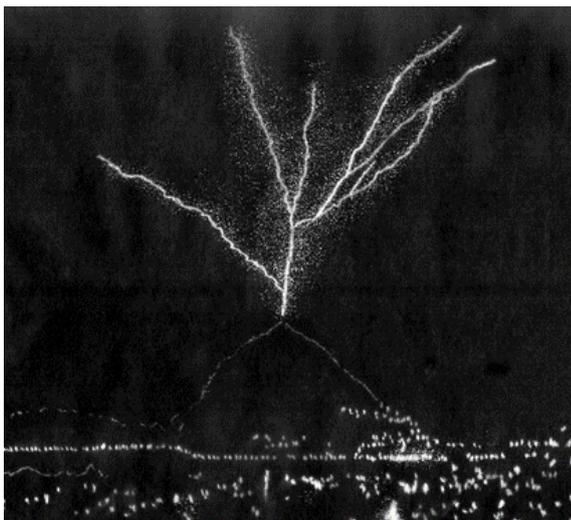


Fig. 8. Upward flash from a tower on Mount San Salvatore, Lake Lugano, Switzerland. Artwork, ink and pencil sketch based on an image by Salanave (1980, p. 26). Unpublished figure.

An additional distinction is between cloud-ground (*CG*) lightning, and the much more frequent cloud-cloud (*CC*) lightning. *CC* is synonymous of *IC* (intra -cloud), depending on the distinction, or not, of separate clouds. The standard explanation for lightning can hardly justify why *CC* discharges are more frequent than *CG* lightning. Conversely, this is what can be expected by the Cowling dynamo

process, as contiguous clouds have more chance to trigger a discharge between their respective convection cells, than with ground.

In addition, a lightning displays an alternation of discharges that – almost like in a damped oscillation - bounce up-and-down, with intensity that depends on the temporal changes of ionization along the “channel”, according to the previous stages of the development of lightning.

A community of scientists developed a specialized lexicon, suited to describe details of observations. We mention a few entries - from the short glossary by Salanave (1980) - which seem to be uncommon and less easily understandable. The information here given relies on Uman (1987) who gives a comparatively more extensive description. No additional details are needed for the present discussion. It should be stressed, however, that the observed direction of propagation of a lightning simply denotes where the domino-effect is triggered, while the physics of the almost oscillatory trend is independent of the location of the trigger. The definitions are as follows, and Fig. 9 is a concise visual reminder.

- ◇ “*Dart leader*” is called a column of electrical charge, with a smooth motion, which precedes the second and subsequent strokes of a lightning flash that is characterized by multi-stroke. The propagation speed of a dart leader is approximately ten times the speed of stepped leaders. The reason is the residual ionization - hence the higher conductivity - of air along the channel, originated and maintained by the preceding return stroke. That is, the domino effect is much faster.
- ◇ “*Return stroke*” - or “*ground flash*” - is called an intense luminous lightning streamer that moves upward from ground to the base of the cloud. It may evolve either as stepped leader or as dart leader. A lightning flash is composed of one or more consecutive strokes. The electric current in a return stroke may be $\sim 10 - 20 \text{ kA}$ or higher, and it lasts only $\sim 50 \mu\text{sec}$. That is, a *return stroke* has a direction consistent with the mean behavior that determines a conspicuous increase of the positive charge of the ionosphere.
- ◇ “*Stepped leader*” is defined an intermittent column of ionized air that moves and determines the formation of the path, or channel, for a subsequent lightning stroke. In the common case of a flash, the leader moves downward, and different sections (called steps) are recognized. Every step is $\sim 50 \text{ m}$ long, and carries a negative charge. That is, the huge Cowling dynamo inside a thunderstorm cloud pushes, as a mean, positive charge into the ionosphere and negative charge towards ground.
- ◇ “*Telluric band*” means - in general - all complex structures of the light spectrum observed at Earth’s surface, whether the radiation refers (*i*) to the whole downward light, such as sunlight that crosses through

natura”, devotes to lightning and storms a large percent of his sixth book (chapter) of “*Phenomena*”. He even mentions (VI, 231-235) that sometimes wine is evaporated inside earthen wine-jars while the jars

remained intact. Then, he deals, although with less emphasis, with tornados, clouds and rain, earthquakes, Etna, and epidemic diseases.

the entire atmosphere, or (ii) only to the radiation released in the lower atmospheric layers, such as in a lightning. The deep red and IR spectral bands are particularly conspicuous, as O_2 and H_2O are the strongest absorbers (and greenhouse gases). The use of the adjective “telluric” ought not to be confused with the more frequent use, applied almost exclusively, to the induced electric currents underground, either at shallow or at large depth.

“Upward connecting streamer” is called a positive spark channel, which moves from ground up to several tens of meters and that finally contacts the negative stepped layer

that begins the first return stroke of a lightning flash. “It may be thought of as the discharge that short-circuits the electrical charge from the leader to the ground - rather like connecting both terminals of a storage battery with a heavy wire ... The word streamer has several connotations in discussions of lightning discharge theory; these should not be confused with specific descriptions” (Uman,1987). That is, this reminds about the case history of Fig. 7a of Gregori and Leybourne (2025e), being representative of a transient condition when the huge Cowling dynamo inside the cloud is temporarily unconnected with ground.

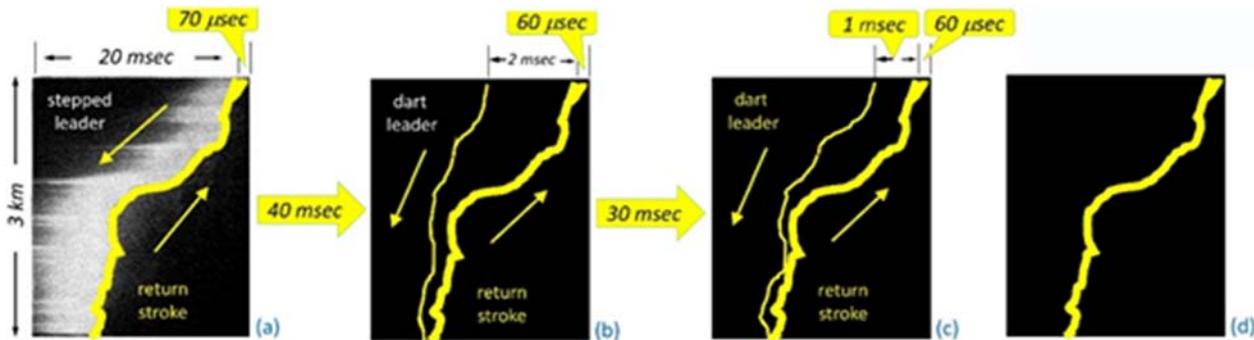


Fig. 9. Scheme of time sequence of luminous features of a lightning. For clarity, the time scale has been distorted. Panel (d) shows the same flash as it looks when recorded by a time-integrated camera picture. Information borrowed from, or according to, Schonland (1956), Uman (1969), Volland (1984), Uman (1987, p. 14), and Raizer (1991, p. 373). Unpublished figure.

Lightning observation from space is likely to provide additional relevant information. For instance, a remarkable picture is shown in Fig. 10.



Fig. 10. “This image of lightning over Kuwait was taken by an astronaut aboard the ISS on December 12, 2013. Credit: NASA Earth Observatory.” Figure and captions after Poppick (2014). NASA copyright free policy.

It shows a lightning observed from above clouds, from the *International Space Station (ISS)*. No photometric information is given. Hence, this picture is a curiosity that can be only intuitively interpreted. Compared to lightning discharges observed below clouds, the light intensity above clouds looks much larger. This might be a consequence of light diffusion from water inside clouds. The lightning is observed at a spot where clouds seem to be comparatively denser and thicker. Alternatively, one can guess that, perhaps, the spatial size of the large-scale convective cell inside the cloud is particularly wide, hence convection

supplies a comparatively more intense and extended Cowling dynamo etc. This is, however, speculative.

However, this rare picture shows that, perhaps, also optical observations of lightning discharges from space platforms can provide with additional information for a better understanding of atmospheric electricity. In fact, they get observations integrated over large areas and through a large atmospheric depth, reminding in some respect, e.g., about “Andes lights” or “hot water flashes” that can be observed only when seen from a large distance in order to have optical thickness and suitable bright contrast (see below).

Fig. 11 shows how a thunderstorm is perceived from space. The associated Cowling dynamo originates effects that can be more or less easily observed by luminous phenomena. Eventually, these violent processes generate a TGF, although in general a wide variety of phenomena of different energy can occur.

Anonymous (2011n) synthesizes the present state of the art by Fig. 12, including geomagnetic conjugacy effects.

Upon considering the definition of these phenomena – which are observed in a rapid time-sequence during a lightning - the physical details look very complicated. These details, however, are often concerned with the temporary state of the dielectric inside the condenser. The discussion here given is, rather, focused on the physics of drivers that trigger a “discharge” in the widest sense. The availability of additional observational parameters will certainly help to achieve a better assessment. For instance, some unprecedented evidence is also related to the specific e.m. emission associated to different kinds of lightning

(Hare et al., 2019).



Fig. 11. “A lightning storm over the Pacific Ocean as seen from the ISS at night. Credit: NASA.” Figure and captions after Mathewson (2017c). NASA copyright free policy.

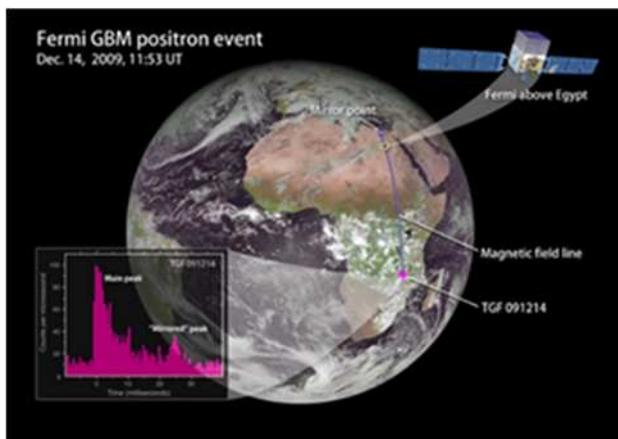


Fig. 12. “On December 14, 2009, while NASA’s Fermi flew over Egypt, the spacecraft intercepted a particle beam from a TGF that occurred over its horizon. Fermi’s Gamma-ray Burst Monitor detected the signal of positrons annihilating on the spacecraft – not once, but twice. After passing Fermi, some of the particles reflected off of a magnetic ‘mirror’ point and returned.” Figure and captions after Anonymous (2011n). NASA copyright free policy.

Cloud phenomena, charging of the ionosphere, and the Wilson’s “cloud generator”

The previous paper Gregori and Leybourne (2025e) shows that fog and atmospheric precipitation are air-earth currents, i.e., an electrical discharge between air and ground, as they are charge carriers. According to the literature, the physical mechanism is unknown that determines the formation around a condensation nucleus either of a water droplet or of an icelet. That is, the explanation that is here envisaged is original. In contrast, the physics of a droplet or icelet is extensively investigated in a wide literature - and the phenomenon is the balance of the competitive role of surface tension and thermal evaporation. However, the earliest process is unexplained of the formation of a droplet or icelet. The Cowling micro-dynamo gets rid of this drawback.

Consider a much larger scale-size. The atmosphere is dominated by thermal gradients, due to several causes that

are manifested like violent convection cells at suitable heights. Owing to the Cowling dynamo, convection cells generate intense e.m. fields - and the associated enormous MHD effects were never considered.

The solar wind particles precipitate on top of the atmosphere, and penetrate until the height of the “Chapman layer”. That is, a photon or a charged particle crosses through air with almost no interaction with air, which has a feeble density. At a suitable low altitude, the photon or charged particle abruptly experiences an increased atmospheric density. Thus, photons and particles rapidly stop inside a comparatively thin layer. As an analogy, consider, e.g., a stone falling on a sofa: the stone crosses through some large distance until the fall subsides on a pillow of limited vertical extension. Similarly, solar wind particles stop inside the “Chapman layer” - e.g., remind about a polar aurora. For comparison, consider, e.g., the pancake pattern, mentioned in Gregori and Leybourne (2025f), of an EAS a few meter thick and $\sim 100 - 150 m$ across generated by a cosmic ray particle.

However, as a standard, the solar wind transports a mean positive electric charge (see Gregori and Leybourne, 2025b). The positive electric charge of the solar wind eventually redistributes all over the Earth, spreading from the original precipitation site - although requesting a suitable time delay, because the Earth’s ionosphere has a very low electrical conductivity.

In any case - as a mean planetary trend - the ionosphere gets a positive charge from the solar wind. The positive charge is therefore either locally resulting from particle precipitation - or also indirectly due to charge redistribution through the whole planetary ionosphere. The Cowling dynamo - like every other dynamo - works in either one sense or another - e.g., consider an electric citrus-juicer that is triggered by pressure, and can randomly rotate sometimes clockwise, sometimes counterclockwise. Since the upper atmosphere, i.e., the ionosphere, has a mean positive charges, the huge Cowling dynamos supplied by cloud convection must have an obligatory sense. Therefore, the ultimate effect is a great amplification of the positive charge of the ionosphere.

Thus, the entire enormous thermal energy of the circulation of the neutral atmosphere is transformed - through huge Cowling dynamos - into e.m. energy, manifested as the ever-increasing planetary positive charge of the ionosphere. Differently stated, a permanent upward flow of positive charge - or, equivalently and more correctly a permanent downward flow of electrons - occurs all over the globe. The phenomenon is enhanced by intense meteorological phenomena associated to stronger convection, such as inside the ITCZ (intertropical convection zone).

The proposal here envisaged is original, concerning the mechanism for the amplification of the electrostatic charge of the ionosphere. It substitutes the currently generally accepted - and outdated - mechanism that was formerly proposed in the 1910s by the Nobel laureate Charles Thomson Rees Wilson (1869-1959). In fact, the old-fashioned Wilson’s “cloud generator” mechanism can be likened to a huge natural “Wimshurst machine” or “van de

Graaff generator". In suitable circumstances, the Wilson's "cloud generator" can eventually operate, although only like an optional additional effect. In contrast, the Cowling dynamo is a ubiquitous and always existing, associated to convection processes in the atmosphere at every altitude and scale-size.

The Wilson "cloud generator" can be briefly illustrated as follows. Wilson appealed to convection inside clouds (e.g., see Rycroft et al., 2000 and references therein). He envisaged a mechanism that should explain how convection can transfer a positive charge to the ionosphere. The leading hypothesis was that water droplets, depending on the droplet radius, respond differently to the fluid dynamics of convection, and thus keep a different total electrostatic charge while they move up and down due to local convection. This Wilson hypothesis is still reported, and still seems to be, generally agreed. This Wilson argument, however, is vague.

In 1939, the most authoritative and acknowledged specialists of that time seemingly did not fully understand this process. At present, it is unbelievable that - at least to our knowledge - no critical concern is generally found in the literature. In contrast, the mechanism, which is here proposed, relies on the rigorous generalization of the classical Cowling theorem. Wilson was not aware of the Cowling dynamo. The Wilson viewpoint was certainly reasonable in the 1910s, while, at present, his working hypothesis looks one-sided, partial, and understating.

Some old related discussion can be highlighted relying on a few authoritative reviews. For instance, the review by Gish (1939, p. 155 and fl.) is an article inside the very authoritative 794-page volume by Fleming (1939). Owing to the lack of any comparably detailed discussion being seemingly reported by other authors, the Gish discussion clarifies the logical framework within which air-earth currents - and the entire related concern of atmospheric electricity - were historically investigated and finally assessed.

Remind about Schonland (1939, p. 657), who illustrates as follows the "cloud generator" or "thunderstorm generator". "*That a thunder-cloud is an electrostatic generator was shown in 1752 by the celebrated experiments by Franklin, D'Alibard, and de Romans, and some further characteristics of this generator can be simply stated. The seat of the generation of electricity being with the cloud itself; the machine separates out equal quantities of electricity of opposite sign from one another and places them - though now not necessarily equal, for their rates of dissipation may differ (Wilson, 1916, 1920, 1923) - in different parts of the cloud. [Note the reference to Wilson.] As the process of separation proceeds, the E between these 'poles', or sometimes between one of them and the Earth, growth until breakdown occurs. [The concern is about the E intensity and the breakdown threshold, see below and Gregori and Leybourne (2025f). In addition, no distinction seems to separate CC from CG processes.] A conducting channel is then produced which leads to the disappearance of part at least of the charges originally separated.*"

That is, the perfect electrical neutrality of the cloud is taken for granted, and a mechanism is envisaged that should

be capable to justify, in some way, a charge separation. The "principle of sufficient reason" is applied - i.e., since a speculated mechanism seems sufficient for the scope, there is no need to search for other processes.

Subsequent reviews were, e.g., Malone (1951) or Krider and Roble (1986) or MacGorman and Rust (1998). The older Gish (1939) source helps, however, to get a better assessment of the origin of the interpretation.

An authoritative discussion is given by Moore and Vonnegut (1977), who state that "*at the present time there is no consensus on the mechanisms by which thunderclouds become electrified.*" Moore and Vonnegut (1977) refer to Vonnegut (1963, 1965), Mason (1971, 1972, 1976) and Moore (1974, 1976), and distinguish, at least, between two categories of explanations. One category appeals to particles that fall and separate charges inside clouds. The other relies on convection inside clouds and transport of charges according to some organized pattern. "*It has long been widely assumed, without evidence, that negative charge is selectively separated and transported downwards in thunderclouds by falling precipitation particles ...*" i.e., this is the Wilson "cloud generator". They also mention some speculated mechanism generated by contact potentials between different molecules, etc., although these explanations seem to be somewhat controversial.

Concerning cloud electrification, Moore and Vonnegut (1977) stress that - unlike assuming that one mechanism alone can be responsible for the effect - many scientists agree with Schonland, with Chalmers (1954) and with others, who favor the hypothesis of several concurrent processes. Thus, Moore and Vonnegut (1977) conclude that these electrical phenomena are "*a major meteorological mystery*" and complain about an insufficient amount of observational input. That is, nobody knows what electric current is caused by motion either of free electrons, or by positive or negative and more or less heavy ions.

Additional discussion is given below while discussing *TLEs*. In any case, according to the discussion here given, the uncertainty is crucial dealing with particle precipitation phenomena, and their associated electrical effects (see Gregori et al., 2025t). In fact, this can be likened, e.g., to what occurs inside a volcanic plume, where the scale-size is much smaller - in terms of particle and charge concentration, and of dynamics, etc. - although the processes are identical.

The starting point, which is presently reported in the literature, unconsciously relies on an unmotivated paradigm: the entire Earth is treated like a uniform system, independent of whether it is a flat landscape or a mountain or a volcano. It is assumed that all phenomena of atmospheric electricity can be explained in a similar way everywhere, by means of atmospheric phenomena alone.

In addition, the Earth is always conceived like an "isolated" object having a total zero electric charge and moving through a vacuum interplanetary space (see Gregori and Leybourne, 2025b). Thus, whenever some charge separation occurs, it must be assumed that somewhere some charge are located of one sign, and somewhere else some charge of the opposite sign. Hence, since the ionosphere is observed to have a positive charge, it should be assumed

that solid Earth should have a negative charge, with consequent implications on air-earth currents, etc. Therefore, one should envisage a mechanism for sustaining the charge separation between ground and ionosphere.

After over half a century of Space Age, this paradigm is evidently untenable, according to the present well assessed knowledge of the solar wind and of the state of interplanetary environment (see Gregori and Leybourne, 2025b). In addition, no physical reason supports any speculative assumption of a generator that is exclusively “internal” to the system, i.e., either inside clouds or elsewhere.

The plates of the atmospheric condenser, the dielectric, and the twofold energy supply, are here considered as a premise for the interpretation of available observations. That is, the previous standard explanation appeals to atmospheric convection as the primary cause of the electrification of the ionosphere. Convection inside clouds is very likely to play a relevant role in the atmospheric electrical circuit. However, several observational evidences of Space Age are not taken into account - and in some respects, maybe, also the achievements of quantum mechanics.

The literature is often concerned with several extremely clever experiments, aimed to monitor micro-details of the spacetime structure and evolution of a lightning etc. In contrast, according to the rationale of the present study, these aspects are secondary details, which are directly related to some local time-varying features of the dielectric between the plates of the condenser. These details are irrelevant for the discussion of the primary physical drivers that rely on the positive charge of the solar wind, on atmospheric convection cells, and on the rigorous implication of the Cowling dynamo.

During recent decades, several improvements were achieved. On the other hand, the general feeling is that the primary logical scheme and physical model remains always the same. Thus, also recent formulations encounter the same previous relevant difficulties in the interpretation of the scant available observational information. The present literature is biased in favor of the Wilson “cloud generator”.

In comparably more recent studies, the quantum effects were included of the “runaway breakdown” (RB) process (see Gregori and Leybourne, 2025f). In addition, also the role is sometimes explicitly considered of the ionization by cosmic rays, and/or the influence by trapped and quasi-trapped radiation with magnetic conjugacy effects.

The Cowling dynamo explanation is original, also in terms of a non-uniform electrostatic charge distribution in the ionosphere. In addition, only in some respect the interpretation of a lightning can be vaguely likened to a spark observed in the lab.

Some indicative powers are listed in Table 1. They are borrowed⁴ after Roble and Tzur (1986). These powers synthesize the present state-of-the-art, although these

estimates are the result of a difficult discussion of interplanetary environment, magnetosphere, and ionosphere (see some items in Gregori and Leybourne, 2025b and in Gregori and Leybourne, 2021). The scatter and great variability of different phenomena is such that it is often awkward - if possible at all - to guess any kind of “mean” value. The endogenous energy entry in Table 1 is after Table 1 of Gregori and Leybourne (2021).

Remark the power of the *TD* dynamo. The endogenous energy of the Earth is a relevant energy supply for huge convection cells in the atmosphere that, through Cowling dynamo, transform the immense reservoir of thermal energy into e.m. energy supplied to the ionosphere, up to the magnetosphere and outward to the solar wind. The endogenous energy is therefore a main energy supply for the atmospheric condenser, including the dramatic changes vs. time associated to the Earth’s electrocardiogram, hence to climate change (see Gregori and Leybourne, 2021).

Table 1. Generators in the global electrical circuit

description	power (<i>W</i>)
<i>Thunderstorms</i> - current output maintains a vertical potential difference of 300,000 <i>V</i> between ground and ionosphere. Current $\sim 10^3$ <i>A</i>	$\sim 3 \times 10^8$
<i>Ionospheric dynamo</i> - tides at ionospheric heights maintain horizontal potential difference 5,000 – 15,000 <i>V</i> between high and low latitudes. Current $\sim 10^5$ <i>A</i>	$\sim 5 - 15 \times 10^8$
<i>Magnetospheric dynamo</i> - interaction of solar wind with Earth’s geomagnetic field maintains a horizontal dawn-to-dusk potential drop of 40,000 – 100,000 <i>V</i> across polar caps. Current $\sim 10^6$ <i>A</i>	$\sim 4 - 10 \times 10^{10}$
<i>Endogenous energy</i> of the Earth during the last few <i>Ma</i> supplied, either exclusively or mostly, by the <i>TD</i> dynamo	$\sim 5.56 \times 10^{13}$
<i>Total solar radiation</i> captured by the Earth (6370 + 100 <i>km</i> radius) ⁵	$\sim 1.8 \times 10^{17}$

The thunderstorm power should be considered altogether with the total number of simultaneous thunderstorms. This number is very likely to change very much, depending on the variation of the global release of endogenous energy, according to the Earth’s electrocardiogram (Gregori and Leybourne, 2021). The power of the ionosphere/magnetosphere all over the globe is important, as this is the potential reservoir of clean energy that, in principle, can be exploited (see Gregori, 2020; Gregori and Leybourne, 2025f).

Summarizing, compared to the model implemented by Gurevich and co-workers (see Gregori and Leybourne, 2025f), the Wilson “cloud generator” looks naïve and *ad*

fourth of the total solar irradiance, or $\sim 340 \text{ W m}^{-2}$. (NASA, Earth Observatory, retrieved February 16, 2022).

⁴ Reproduced with kind permission of the *National Academy of Sciences*.

⁵ “Averaged over the entire planet, the amount of sunlight arriving at the top of Earth’s atmosphere is only one-

hoc. The *RB* Gurevich's mechanism misses, however, some process that ought to generate the "seed" *E*. The Cowling dynamo is the complementary crucial effect.

Therefore, we must change the overall picture of electrical phenomena in the atmospheric condenser. *RB* is a crucial effective and fast phenomenon. Air ionization has a twofold origin: relativistic cosmic rays and friction at Earth's surface. The Cowling dynamo is an efficient amplifier that transforms into *E* the thermal energy that the atmosphere receives from other sources. The final effect is a relevant electrostatic charge of the ionosphere. The charge must be positive, as the solar wind has a prevailing positive charge (see Gregori and Leybourne, 2025b).

From the viewpoint of the limitation by the empirical constraint, these achievements were attained by considering altogether light emission (i.e., lightning), *E* records, and radio waves. Even the motion of one electron alone is a "discharge", but in general all phenomena inside the atmospheric condenser look very intricate. Compared to lab discharges, electrical phenomena in the atmosphere are substantially different, as the atmospheric scale-size cannot be reproduced in the lab. In particular, intense air-earth currents - with large cross-section and no luminous emission - are a generally unnoticed phenomenon that play a most relevant role inside the atmospheric condenser (see Quinn et al. (2026)). In addition, a variety of different inputs are to be considered that can hardly be simulated in any terrella experiment. The *RB* explanation represented a fundamental progress in the understanding of lightning. However, *RB* alone cannot explain the nature of the physical process by which a lightning propagates through air. The Cowling dynamo fills the gap.

Transient luminous events (*TLEs*)

Photon emission is an important witness for monitoring electrical discharges in the atmosphere. Polar auroras are the best known phenomena - the first observational evidence of the magnetosphere monitored by humankind (see, e.g., Petrie, 1963, and Eather, 1980). Auroras result from the precipitation of field aligned currents (*FACs*) that are specifically discussed in Gregori et al. (2025u). The self-collimation due to the Cowling dynamo (see Gregori et al., 2026d) plays a key role in *FACs*. The most spectacular polar auroras are generated by precipitating electrons, which are the electron clouds released by the Sun, on a ~11 year cycle, in order to compensate the electrostatic balance of the Sun (see Gregori and Leybourne, 2025b).

Much fainter phenomena are less known and were investigated only in comparably more recent time. For several years, several pilots reported strange flashes of light above thunderstorms (Vaughan and Vonnegut, 1989; Lyons, 1997). Nobody, however, dared to tell these stories that could raise some doubt about the eye efficiency of the pilot. During the 1970s and 1980s, several reports were gradually collected from a number of pilots about observation of sprites and jets during night flights. It wasn't until the late 1980s that scientists began taking these reports seriously. Then, researchers discovered a number of new phenomena.

The "*Sprites*" campaign (in 1994) and a video titled "*Red Sprites and Blue Jets*" popularized the name sprite and gave a dictionary of terms, to describe visual attributes. So far the main classes are:

- ✓ "*Red sprites*" which are diffuse blobs of red light that stretch through ~ 40 – 90 km of altitude.
- ✓ "*Elves*" that occur at altitudes ranging from ~ 90 – 100 km, and can expand horizontally to sizes > 250 km across.
- ✓ "*Blue jets*" which are streamers of blue light that stretch horizontally as far as ~ 50 km just above the cloud tops.

These new forms of "lightning" can be quite bright, but they are subliminally brief, existing for only ~a few msec. *Elves* are the shortest-lived events, lasting significantly < 1 msec.

According to the model here envisaged, in general every phenomenon of this kind ought to be interpreted in terms of a domino effect displayed like contiguous *BLs*, thus looking like a comparatively slowly moving flash. The direction of every respective development has no particular implication, as it is determined by the ambient condition that should be suited for the domino-effect trigger-and-propagation in every given direction.

An almost endless number of papers and reviews is now available on these phenomena generally denoted as *TLEs* (transient luminous events). They are observed only whenever a sufficient contrast exists with the background. In addition, the detection depends on the source height that sometimes has a wide spatial extension, thus affecting the optical contrast that is eventually low. On the other hand, the involved total energy sometimes can be remarkable.

Therefore, the distinction between different phenomena depends only on the visibility, better than on the primary physical process, which are the same although characterized by a different capability of detection. Only *ELVES* (acronym for *Emission of Light and Very Low Frequency perturbations due to Electromagnetic Pulse Sources*, described also like stratospheric/mesospheric perturbations resulting from intense thunderstorm electrification), which are shorter lived (< 1 msec) than others (~ a few msec), are a different phenomenon, associated to a perturbation that is projected from a lightning at low altitude up to the ionosphere.

Also much fainter electric discharges are sometimes reported. They include the St. Elmo fire, the "*Andes lights*" or "*hot weather flashes*", the Caronia phenomenon, and the presently unexplained "*Hessdalen lights*". See Gregori et al. (2025b). Only for completeness sake, a few mentions are as follows.

St. Elmo fire is a well-known corona discharge formerly observed at the points of ship masts.

The "*Andes lights*" – that in the western Po Valley are reasonably common and are known by farmers like "*hot weather flashes*" – are due to large-scale convection that, after a hot and dry day, raises by night from a mountain massif. If the sky is observed from a few hundred kilometer distance, one detects very frequent rapid flashes, reminding about lightning below the horizon. These flashes cannot be observed by the inhabitants of the area close to the mountain

massif, as the phenomenon is diffuse and they lack the needed luminous contrast. Formerly reported from the Andes, they are associated in the Po Valley with the massifs of Mont Blanc and Monte Rosa, i.e., with the highest Alps.

The Caronia phenomenon refers to an event of comparatively negligible intensity, observed in January 2004 at the site Canneto di Caronia - in the province of Messina, along the coast of Sicily, approximately halfway between Messina and Palermo. Canneto di Caronia is a small fraction, with only ~ 40 inhabitants, of the town of Caronia. The local inhabitants were the unwilling - though very accurate - “detectors”, with no consequence for their safety. Abruptly, large fires simultaneously spread out from all plug-ins of the electrical circuit of one house. A few other nearby houses had similar, though less violent, anomalies. For several weeks or for a few months (or maybe longer), these phenomena occurred - more or less continuously - with a variety of morphologies, even with a likely change of the frequency-band of the leading e.m. perturbation. Analogous effects continued in the subsequent years, until mass media no more reported news. All these occurrences - including also some repeated beaching of dead marine fauna - seemingly fit into the rationale of anomalous soil exhalation. Unfortunately the phenomenon was exploited for sensationalistic and non-scientific purposes. Therefore, it has not been the object of attention from the scientific world. In addition, exactly in those same days, marine circulation reversed direction in the Adriatic Sea - from the normal counterclockwise state to clockwise direction - denoting an abrupt anomalous increase of geothermal heat flow released from the sea floor. Moreover, a strong Stromboli paroxysm shortly preceded this Caronia phenomenon, denoting a generalized anomalous increase of endogenous heat release during those several months in the central Mediterranean area.

A still unexplained phenomenon deals with the so-called “Hessdalen lights”, and is the object of investigation by professional research teams. Hessdalen is a small valley (~

12 km long) in Norway, roughly ~ 120 km south of Trondheim, and ~ 35 km North of Roros. In 1981-1984 the inhabitants (~ 200 people) begun to report about this very unusual phenomenon (~ 15 – 20 events per week, later ~ 20 per year). The Hessdalen lights look like luminous structures of various shapes that may appear steady for over one hour or may move up to ~ 8500 m sec⁻¹, while displaying sudden accelerations and zigzag tracks. The maximum measured speed is ~ 30,000 km hour⁻¹. The color varies between yellow, red and blue, and their more common color is white or yellow-white. They can appear pulsating. They can be equally observed close to ground or above Earth’s surface. The possible forms can be spherical, ellipsoidal, or much more fanciful. No correlation was found with the local seismic activity. When a laser beam hits one of these objects, in 8 cases among 9 their pulsation period changed. The hypotheses for their explanation are either a plasmoid triggered in some way, or some exotic and unknown “radiating matter”. A workshop was held in June 2006 (Cabassi and Conti, 2007). It seems that air humidity > 85% favors their appearance, but the mystery remains. On a very speculative basis, one can guess that, maybe, according to the plasmoid hypothesis, the Hessdalen lights are a phenomenon similar (?) to BL, even though on some much smaller spatial scale. The dependence on humidity ought to be associated with the electrical conductivity of air. If this speculation is correct, one should justify the presence of some lesser heat sources. This is, however, mere speculation. In addition, one wonders whether some fog or atmospheric precipitation occurs, as per Gregori and Leybourne (2025e).

With reference to all TLEs, an attempt to synthesize the present state-of-the-art is shown in Fig. 13. The reference is to processes above a thunderstorm, with trigger associated to the so-called runaway electrons (see Gregori and Leybourne, 2025f).

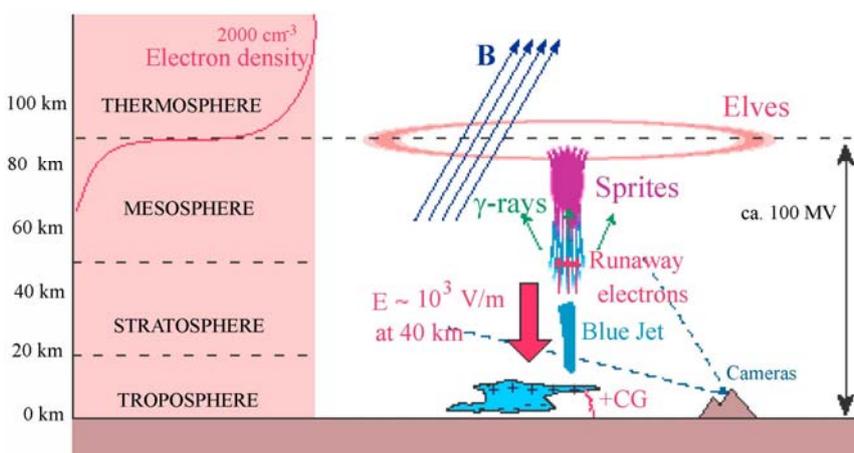


Fig. 13. A cartoon sketch of E and B fields in a thunderstorm and some of the phenomena they produce. TGFs may be just one aspect of thunderstorm activity in addition to ELVES, sprites, blue jets and ordinary lightning. Credit: Stanford University. After Coulter (2010). NASA copyright free policy.

Another synthesis is given by Siingh et al. (2010) who report Fig. 14, and rely on data after Chern et al. (2003), while Siingh et al. (2008) review TLEs including whistler association in the Earth’s magnetosphere etc. They complain that the microphysics is not fully understood of

phenomena that determine charge separation in thunderclouds with various meteorological conditions – in fact, they do not know the role of the Cowling dynamo - and they conclude as follows. “... The observations of sprites have revealed that many processes are involved.

Observations show an asymmetry in CG discharges which generate sprites; negative CG discharges are rarely associated with sprites ... [That is, the visibility of sprites

depend on the direction of the electric current in the damped-oscillating lighting.]

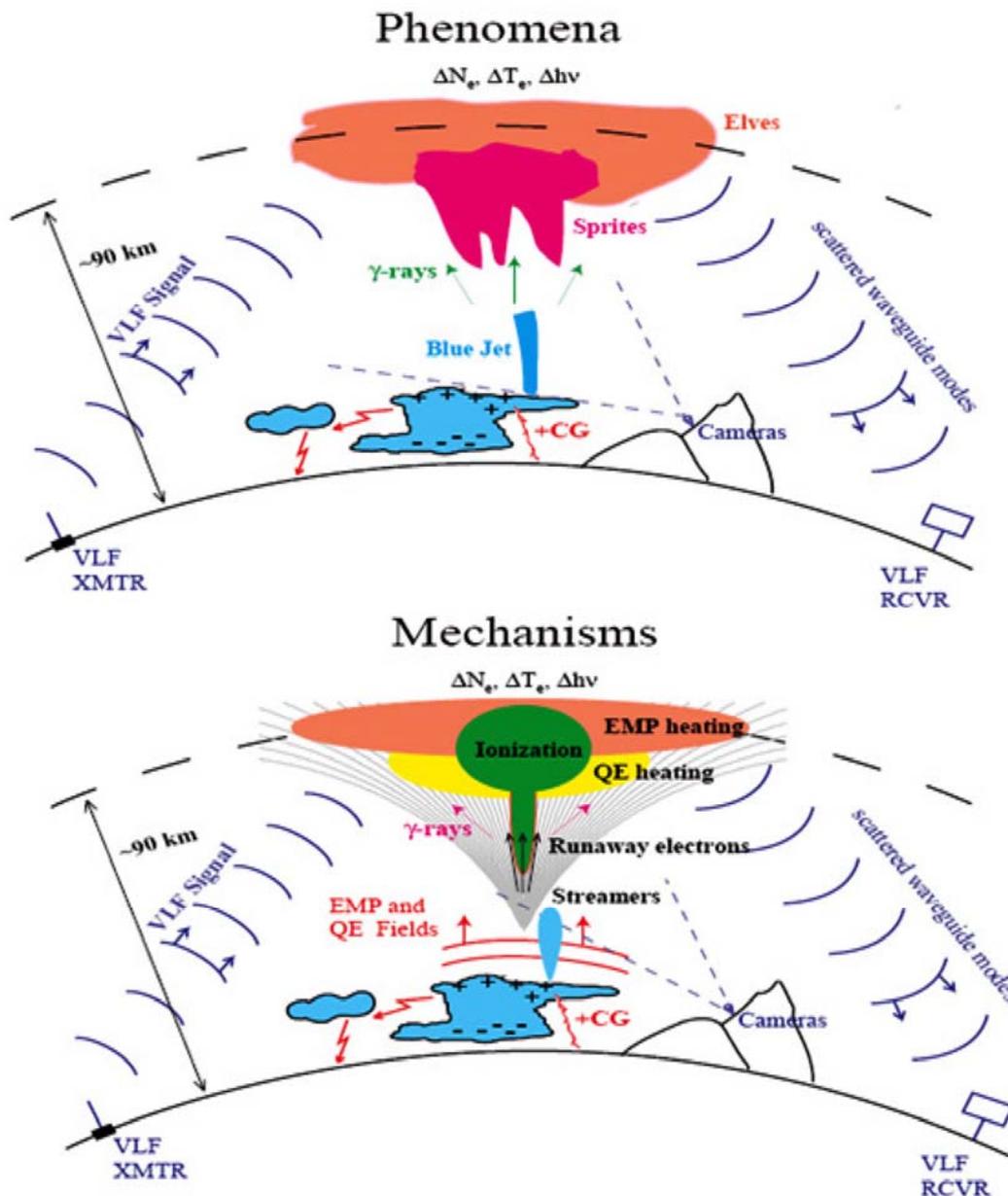


Fig. 14. “Illustration of different phenomena (top panel) and theoretical mechanisms (bottom panel) of lightning-ionsphere interactions operating at different altitudes and producing optical emissions observed as sprites, blue jets and ELVES, as well as heating and ionization changes detected as VLF signal changes (Chern et al., 2003).” Figure and captions after Siingh et al. (2010). Reproduced from an “Open Access” e-journal.

The infrasound observations show that the energy input during sprites is quite high, $\sim 0.4 - 40$ GJ (Farges et al., 2005), and this energy would produce perturbations in the atmosphere. This speculation has to be explored further. The infrasound can propagate to long distances and hence the perturbations might also be over a wide area ... [However, the mechanism that determines thunder is generally claimed to be poorly understood.]

The electric fields E established in the mesosphere following a lightning discharge are not properly understood, and the relaxation time scale of QE fields and its dependence on the ambient parameters of the medium are not well-known. A complete understanding of the

E generated during IC, CG and cloud-to-ionsphere discharges remain a problem, which requires both experimental and theoretical modeling efforts ... “[In fact, the Cowling dynamo gets rid of difficulties of this kind.]

In any case, these authors do not know the Cowling dynamo, and are therefore biased in favor of the old-fashioned “cloud generator” deriving from friction between air molecules etc. In fact, they state that “the electrical processes acting in thunderstorms control the flow of vertical current, which near the cloud surface create space charges which rapidly attach to droplets, aerosol particles and ice forming nuclei and affect storm dynamics. The charging time constant ranges from minutes to hours, which

are comparable to typical convection and turbulence characteristics times ...”

For comparison purposes, we give a concise review of the present theoretical models and interpretations of TLEs that are reported in the literature. The scope is to show the need to appeal to some intricate mechanism, compared to the more straightforward explanation by the Cowling dynamo.

Modeling TLE mechanisms

The following discussion of sprites is borrowed, e.g., after Savtchenko and Mitzeva (2007).⁶ Only a few mentions are here given, while the interested reader ought to refer to the original paper. They try to interpret the physics of the discharge inside and above thunderstorm clouds, according to the standard approach. Savtchenko and Mitzeva (2007) first remind about Wilson (1925) who stated that “while the electric force due to the thundercloud falls off rapidly as r increases, the electric force required to causing sparkling (which for a given composition of the air is proportional to its density) falls off still more rapidly. Thus, if the electric moment of a cloud is not too small, there will be a height above which the electric force due to the cloud exceeds the sparkling limit.” Savtchenko and Mitzeva (2007) illustrate his idea in detail in Fig. 15. They explain that the E (bold line) associated to thunderstorm electricity decreases with altitude proportional to r^{-3} , while as a standard (Raizer, 1991) the conventional breakdown threshold E_k is defined by the equality of the ionization and dissociative attachment coefficient. It happens that E_k decreases with height more rapidly than r^{-3} . Hence, the discharge spontaneously occurs at height where $E > E_k$.

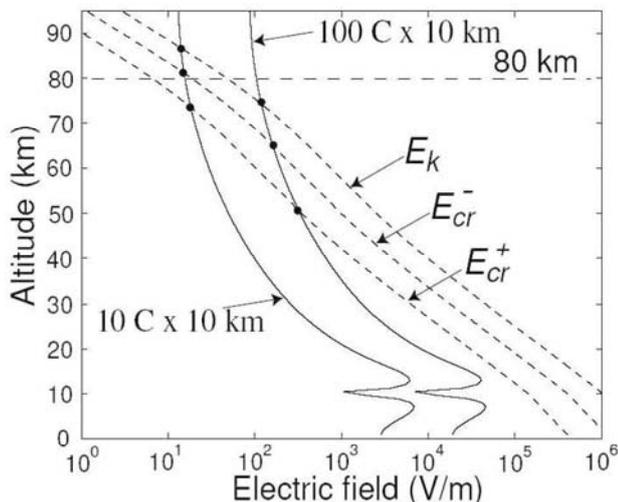


Fig. 15. “The development of E with height above an active thunderstorm.” Figure and captions after Savtchenko and Mitzeva (2007).

The reference fields E_{cr}^+ and E_{cr}^- in Fig. 15 are, respectively, the minimum field required for the

propagation of positive and negative streamer (Raizer, 1991; Allen and Ghaffar, 1995; Babaeva and Naidis, 1997). However, Savtchenko and Mitzeva (2007) point out several other reference fields, described with reference to the so-called dynamic friction force F of electrons in air (Gurevich et al., 1992; Babich, 2003). “There is a maximum in F at ~ 150 eV, which is called the thermal runaway threshold ($E_c \sim 260$ kV cm⁻¹) and a minimum around ~ 1 MeV, called the relativistic runaway threshold ($E_{rt} \sim 2$ kV cm⁻¹).” The maximum is a consequence of a combined action of N_2 and O_2 molecules that are ionized and excited at different electronic states. The friction force F decreases with increasing electron energy at higher energies > 150 eV. Coulter (2010) illustrates the same concept by referring to Fig. 1 of Gregori and Leybourne (2025f).

Savtchenko and Mitzeva (2007) further remind about the first observations of sprites and about the related theoretical models that several groups⁷ developed for modeling the response of the upper atmosphere to thunderstorm fields and to lightning – in terms of both electrostatic and more general e.m. interaction. The models look for a solution of Maxwell’s equations by looking for self-consistency inside a model-atmosphere with a given conductivity profile. The aim of most studies was focused on: (1) how CG lightning triggers sprites; (2) the critical parameters needed for sprite initialization; (3) the factors that determine the height of sprite initialization; (4) sprite propagation to and through the ionosphere.

Summarizing, the conclusion was that the energy source for sprites is the energy associated to lightning, which can result either like the QE field depending on the charge distribution inside a thunderstorm, or like the e.m. pulse from a lightning (Rycroft, 2007).

In contrast, note that the Cowling dynamo implies a substantial change of perspective, as the huge thermal convection inside the lower atmosphere – which is supplied by the fluid dynamics of ocean/atmosphere – combined with the ionized component of air masses (cosmic rays and friction), ensures a large input of e.m. energy, which amplifies the electrostatic charge of the ionosphere through huge vertical currents. In addition, under suitable conditions, some photon emission occurs and – whenever the contrast is sufficient – TLEs are observed. The energy of TLEs is, in any case, a lesser concern, as it is a negligible fraction of the total energy of the whole process.

Savtchenko and Mitzeva (2007) remind about two basic theories for sprite formation above thunderstorms, i.e., the conventional (thermal) theory, and the runaway (relativistic) electron discharge physics. “According to the conventional theory, sprites are generated by the E pulse ($E > E_k$) that travels upward toward the ionosphere from a +CG stroke of lightning (Neubert, 2003). The +CG discharges can involve transfer (to the ground) of up to 300 C in several msec (Brook et al., 1982), resulting in large (up to ~ 1000 V m⁻¹ at 50 km altitude) QE fields

⁶ No reply was received to permission application, either from Bulgarian institutions, or from the authors.

⁷ Pasko et al. (1995, 1997a,b, 2002); Bell et al. (1995); İnan et al. (1996, 1996a, 1996b, 1996c); Huang et al. (1999); Thomas et al. (2005b); and others.

due to the uncompensated negative charge left in and above the cloud.”

As already stressed, the direction of the current is pertinent to the damped oscillatory lightning. Note that reference is always made to an internal process inside the cloud, i.e., of the kind of the Wilson’s “cloud generator”. That is, large QE fields at all heights above the cloud warm - and excite - the ambient electrons and ions, leading to optical emissions. Red sprites are observed that persist during *several to tens of msec*, consistently with the characteristic relaxation time of QE fields, and depending on the finite conductivity of the medium (Dejnakarintra and Park, 1974; Baginski et al., 1988).

High-speed optical imaging showed that the sprite discharge propagates downward from a starting height of ~ 75 km, and then shoots upward as a recoil (Stenbaek-Nielsen et al., 2000). That is, the oscillatory character of a lightning is observed also inside *TLEs*. Remind, however, about the distinction between a discharge propagation and optical photon emission. They are different phenomena, although connected to each other.

Sprites seem to be weakly ionized, unlike conventional lightning that have fully ionized channels. That is, compared to the dramatic events associated with a lightning, sprites are a less violent discharge. On the other hand, electron energies of *a few eV* or 20,000 – 30,000 K (Morrill et al., 2002) are observed inside both normal lightning returns strokes and sprites. Sprites are considered a peculiar form of lightning and are sometimes called “*high-altitude lightning*”. In any case, the bulk of energy conversion by Cowling dynamo occurs inside thunderclouds, while *TLEs* are only lesser fringe effects manifested at a greater height, inside a less dense medium. The air-earth current is conspicuous, but the effect on the medium is less pronounced.

The *RB* mechanism is discussed in Gregori and Leybourne (2025f). The discharge starts when the applied E is greater than the runaway threshold. According to the theory, an electrical breakdown mechanism associated to relativistic electrons is operative also inside sprites ($E > E_t$) (Roussel-Dupré and Gurevich, 1996). Cosmic rays are supposed to provide free relativistic “seed” electrons, and to start an upward ionization avalanche that generates additional high-energy electrons. In contrast, it is suggested in Gregori and Leybourne (2025f) that the Cowling dynamo mechanism is the leading cause for the generation of these “seed” electrons.

Observations (by *CGRO*) of X- and γ -radiation from the atmosphere, which are originated above thunderstorms, support the existence of this process that is related to Bremsstrahlung by electron beams with *MeV* energy in the upper atmosphere (Fishman et al., 1994).

However, Savtchenko and Mitzeva (2007) emphasize the ongoing present intensive research on the role of relativistic breakdown in sprites. They also remind about studies concerning either the source of sprite initiation and propagation, or the models of small-scale sprite-streamer processes and photoionization effects (Babaeva and Naidis, 1997; Kulikovskiy 2000), or the optical emission associated to sprite streamers (Liu and Pasko, 2004).

In contrast, according to the interpretation that is here proposed, both conventional (thermal) and runaway (relativistic) electron discharge coexist altogether, due to two additional processes, i.e., due to the role (i) of the non-uniform instant electrostatic charge distribution in the ionosphere, and mostly (ii) of the role of the Cowling dynamo at all space-sizes, beginning from micro-convection (see Gregori and Leybourne, 2025e).

Bhattacharya and Nag (2012) implemented another model for giving a unifying picture of all *TLEs*. They claim having made a QE “*model of sprites with the formation of a giant parallel plate capacitor by positive ionosphere and negative shielding layer.*” They consider a scheme which is illustrated by the cartoons of Figs. 16, 17, and 18. These figures are here reproduced - only for comparison purpose with the straightforward criterion expressed by Fig. 7 of Gregori and Leybourne (2025e). Figs. 16, 17, and 18 show a feeling about the different observed morphologies, although - as already stressed - the basic physics is eventually the same, although different conditions of visibility determine different aspects. Only *ELVES* are representative of a different phenomenon.

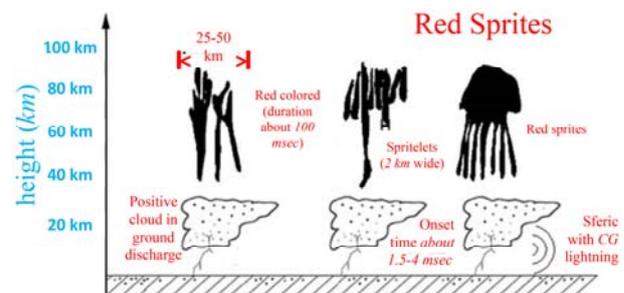


Fig. 16. “Schematic diagram of sprite production.” Figure and captions after Bhattacharya and Nag (2012). Reproduced with kind permission of the *International Journal of Engineering Science Technology*, “Open Access”.

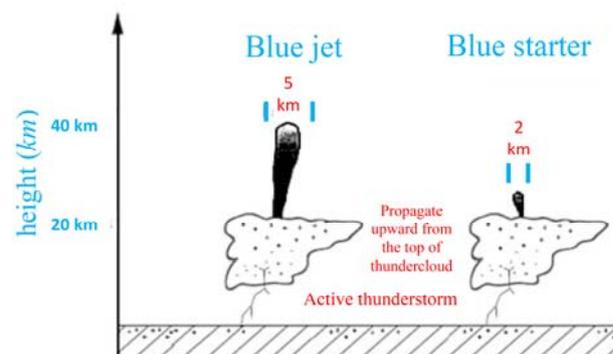


Fig. 17. “Schematic diagrams of blue jet and blue starter.” Figure and captions after Bhattacharya and Nag (2012). Reproduced with kind permission of the *International Journal of Engineering Science Technology*, “Open Access”.

In addition, Bhattacharya and Nag (2012) – always for comparison with Fig. 7 of Gregori and Leybourne (2025e) - describe the QE model of sprites and state that “*Fig. 19a describes that the cloud charges up before the lightning discharge including a negative shielding layer, while Fig.*

19b describes how the positive charge is removed by +CG discharges, which in turn keep the negative shielding layer for a long time. The negative shielding layer persists even after the discharge causing polarization in the atmosphere and a quasi-static E -field [i.e., the QE field]. This can be compared to a giant parallel plate capacitor as illustrated in Fig. 20. This strong E -field is responsible for the electrical breakdown and eventually produces the sprites.” [Compare Fig. 19a with Fig. 7a of Gregori and Leybourne (2025e). This is representative of the initial stage when electrostatic induction and polarization occurs, originated by the electrostatic charge of the ionosphere. Fig. 19b represents the beginning of the subsequent discharge process due to the voltage difference between ground and the base of the cloud, as in Fig. 19a or in Fig. 7a of Gregori and Leybourne (2025e). Fig. 7 of Gregori and Leybourne (2025e) ought to be integrated with the concept of damped-oscillation of the atmospheric discharge. Fig. 20 represents the general concept of the atmospheric condenser.]

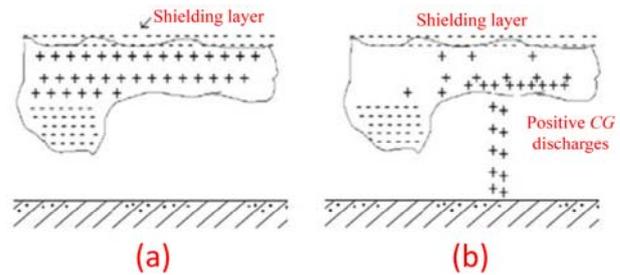


Fig. 19. “(a) The cloud charges up before the lightning discharge including a negative shielding layer and (b) the +CG removes positive charge, keeping the negative shielding layer for a longer time.” See text. Figure and captions after Bhattacharya and Nag (2012). Reproduced with kind permission of the *International Journal of Engineering Science Technology*, “Open Access”.

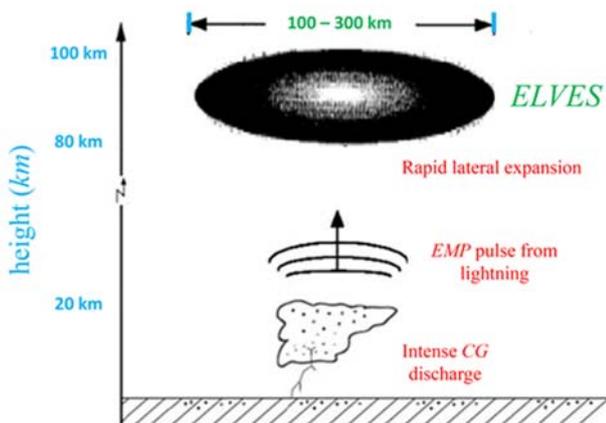


Fig. 18. “Schematic diagrams of ELVES.” Figure and captions after Bhattacharya and Nag (2012). Reproduced with kind permission of the *International Journal of Engineering Science Technology*, “Open Access”.

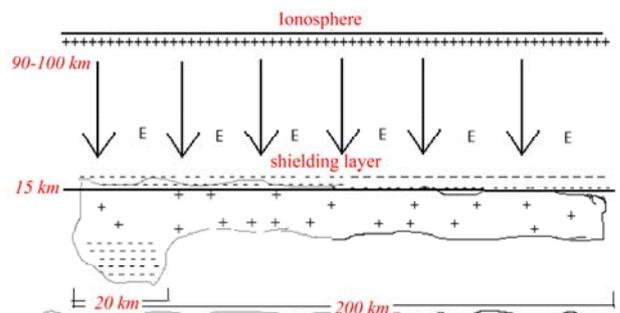


Fig. 20. “Giant parallel plate capacitor with positive ionosphere and negative shielding layer.” See text. Figure and captions after Bhattacharya and Nag (2012). Reproduced with kind permission of the *International Journal of Engineering Science Technology*, “Open Access”.

In this respect, note that – unlike what is often reported - it is impossible to define any standard mean charge distribution inside a cloud, as the charge distribution is a transient phenomenon that depends on the applied external voltage, and on the oscillatory damping of the lightning. Rather, the physics ought to be specified in terms of the Cowling dynamo that generates strong QE fields, both above violent thunderstorms and inside intense convection cells. An observer who is suitably located – with sufficient luminous contrast with the background – can observe the luminous emissions released by the excited air atoms and molecules that scatter with the upward flux of positive charges (or downward flux of electrons) that connect clouds to the ionosphere. In addition, the electron (or positive charge) flux can be eventually temporarily reversed, due to the oscillatory discharge of the lightning. That is, visibility conditions are critical, much like, e.g., in “Andes lights”.

Bhattacharya and Nag (2012) summarize the main mechanisms of sprite formations as: (i) lightning e.m. pulse (EMP), (ii) thunderstorm QE fields, and (iii) air RB . Note that the first two mechanisms are implicit in the Cowling dynamo, and RB is the violent quantum effect (see Gregori and Leybourne, 2025f) that amplifies the previously generated “seed” E .

According to Bhattacharya and Nag (2012), “out of the three, the first mechanism, the e.m. pulse from large lightning discharges, causes electrical breakdown of the upper-lying atmosphere over the thunderstorms (Wescott et al., 1996; Inan et al., 1997). In the second mechanism the thundercloud charges up before the lightning discharges and those charges are rapidly disappeared after the discharges, leaving the shielding charge and producing a large QE field over the thunderstorm. By the E the heated electrons cause ionization changes, producing optical emissions referred to as red sprites. If the accelerating field is high enough, the number of energetic electrons increases rapidly causing RB and thus generating optical emissions produced by collisional excitation with the relativistic electrons and the low-energy secondary electrons (Barrington-Leigh and Inan, 1999; Brundell et al., 1996; Inan et al., 1996, 1996a, 1996b, 1996c; Sukhorukov et al., 1996).”

These remarks show how a learned distinction of different processes can result into an intricate picture. In fact, these three mechanisms are taken for granted and interact one another, although one should explain what originates every mechanism.

In contrast, the process is just one and much simpler, i.e., the Cowling dynamo alone, to be integrated, whenever suitable, with the *RB* quantum effect, concerned with the scattering of electrons with air molecules. One additional physical complication is only related to the damped-oscillatory trend of a lighting, by which a time-varying voltage-difference occurs with the ionosphere, and different *TLEs* are therefore eventually observed.

TLEs statistics

Bhattacharya and Nag (2012) show some statistics of *TLEs*. They first consider association, occurrence rate, and timing. Red sprites are reported to be associated in time and position with *CG* or *IC* (i.e., *CC*) stroke (Fisher, 1990; Sentman and Wescott, 1993). It is confirmed that red sprites occur after large-amplitude +*CG* strokes (Winckler et al., 1994). “The lightning associated with red sprites occurs in large nocturnal mesoscale convective system (*MCS*) class thunderstorms, although the red sprites tend to occur over a relatively small region of the storm (Lyons, 1994).” *MCS* storms are called some large and isolated storms, 20 – 500 km wide, characterized by intense convection. However, red sprites are clearly associated to +*CG* strokes and to intense currents, although red sprites are not necessarily observed directly over +*CG* strokes. Note that the visibility conditions (nocturnal) are crucial for the observation of *TLEs*.

“The occurrence rate of red sprites is now accepted to be between 1 in every 2 and 1 in every 40 +*CG* discharges (Sentman and Wescott, 1993; Lyons, 1994). The higher occurrence rate (44% of +*CGs*) is incompatible with the threshold return stroke peak current of 50 kA (Boccippio et al., 1995). Such a threshold corresponds to the upper 15% of return stroke peak currents observed by the National Lightning Detection Network (NLDN), while a 44% occurrence rate would imply a return stroke peak current of ~ 30 kA. At this stage it is difficult to determine a correct representative occurrence rate for red sprites.” These estimates, however, rely on the assumption of an internal mechanism. Other than thermodynamic convection that support an intense Cowling dynamo.

Bhattacharya and Nag (2012) show statistics based on the first four years, i.e., July 2004 - June 2008 (Figs 21 and 22), and stress that *ELVES* are the most abundant (~ 80%) *TLEs*, while sprites and halos altogether are ~ 20%. In fact, in principle *ELVES* are associated to all lightning. In contrast, other *TLEs* require specific conditions in order to be detected. It is reasonable to guess that these phenomena are very frequent, although only seldom observed. Then, Bhattacharya and Nag (2012) state that red sprites last between 5 – 300 msec, with a mean duration of ~ 98 msec (Lyons, 1994), and comment that “differences between measurements may be due to differing thresholds and spectral responses of observing equipment. It was reported that red sprite discharges began with an intense

flash over both blue and red parts of the spectrum, with a weaker lingering tail that was mainly red (Winckler et al., 1994).”

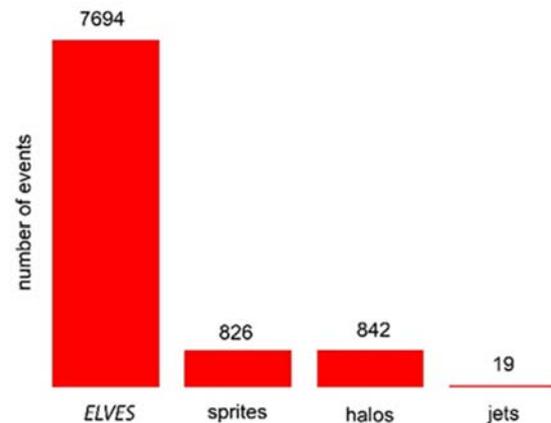


Fig. 21. “Number of *TLEs* ... between July 2004-June 2008.” Figure redrawn and captions after Bhattacharya and Nag (2012). Reproduced with kind permission of the *International Journal of Engineering Science Technology*, “Open Access”.

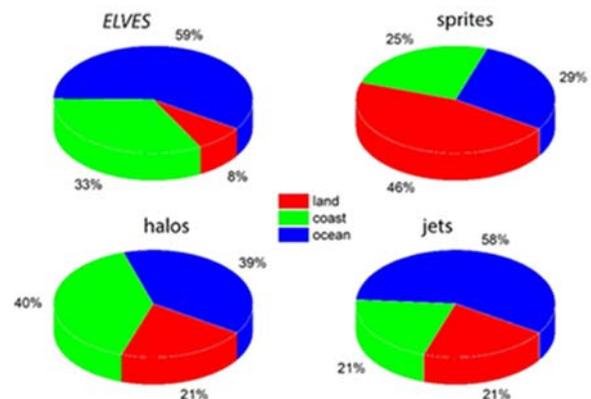


Fig. 22. “Percentage abundances for *TLEs* (*ELVES*, sprites, halos and jets) ... between July 2004-June 2008.” Figure redrawn and captions after Bhattacharya and Nag (2012). Reproduced with kind permission of the *International Journal of Engineering Science Technology*, “Open Access”.

Then, Bhattacharya and Nag (2012) discuss energy items, and give Table 2. They also discuss the impact of *TLEs* on the upper atmosphere, and on the chemistry and ionization of the ionosphere.

They also consider the asymmetries associated to the up-or-down direction of the lightning current – that, in fact, can be important in terms of mechanism for ion excitation. They conclude that “observations show an asymmetry in *CG* discharges which generate sprites; -*CG* discharges are rarely associated with sprites. The upward discharge creates a conducting path in the upper atmosphere so that the role of sprites and *TLEs* in the global electric circuit becomes important. [In fact, an upward discharge is associated to an intense downward flux of electrons underneath the cloud. This means that, symmetrically above

the cloud, an intense current exists with the ionosphere, with greater ion excitation.]

Table 2.⁸ Average energy, global occurrence rate and energy deposition rate of TLEs

type	avg. energy/event (MJ)	global occurrence rate (events min ⁻¹)	energy deposition rate (MJ min ⁻¹)
sprites	22	~ 1	22
halos	14	3.7	52
ELVES	19	72	1370

The electric fields E established in the mesosphere following a lightning discharge are not properly understood, and the relaxation time scale of QE fields and its dependence on the ambient parameters of the medium are not well-known. [In fact, a great variety exists of convection cells of different size and intensity. Hence, the associated QE fields and related temporal evolution can hardly be represented by any “mean” behavior.]

A complete understanding of the E generated during IC, CG and cloud-to-ionosphere discharges remain a problem which requires both experimental and theoretical modeling efforts.” [In fact, the huge variety of convection cells corresponds to an equivalent variety of E generation, and consequent impact on lightning and TLEs morphology. If any regularity is found, one should explain while such a regularity is connected with a corresponding regularity of convection patterns. This seems, however, hardly tenable.]

Bhattacharya and Nag (2012) also comment that “thunderstorm electrification process ... couple the troposphere to higher regions of the atmosphere and to the ionosphere and magnetosphere. The most promising option, which is approved by broadband VLF recordings of sferics and lightning detection data, refers to a gradual buildup of secondary ionization production at higher D region heights where free electrons have longer lifetimes and can attain ionizing energies more easily.” That is, the focus enters into the realm of ionospheric physics, which is outside the perspective of the present study.

Summarizing, several details of air-earth currents can be inferred from a correct interpretation of TLEs. This seems to be, however, a challenge for every Earth scientist, and several additional observations and discussion are needed before achieving complete understanding of the lesser details of these several faint phenomena.

The large scale-sizes: plasma jets collimation, Birkeland currents and sea-urchin spikes, solar γ -rays, astrophysical jets, stellar and galactic alignments

The self-collimation of a plasma jet is responsible for field-aligned currents (FACs) that are also known as Birkeland currents. The mechanism is according to the

Cowling dynamo. The process is through the generation of toroidal B , identically to what occurs in the confinement of a BL. Refer, e.g., to Gregori et al. (2025u) for a detailed discussion.

The same collimation process is responsible for thinning and coalescence of sea-urchin spikes inside the deep Earth interior, and also for the interaction between different sea-urchin spikes, which leads to explain the mechanism that is likely to be responsible for the geographical distribution of MORs (Gregori and Leybourne, 2021).

The leading topic of the present paper is the nature of an electrical discharge in the Earth environment. However, for completeness sake, space phenomena deserve a few mentions.

The solar wind collimation is briefly discussed in Gregori and Leybourn (2025b). The presently unexplained observed properties of the γ -ray emission from the Sun (Nisa et al, 2019; Wolchover, 2022) can be explained by considering RB plus “seed” Cowling dynamo. In addition, the same physical argument applies to violent poloidal jets, along the E field-lines, which are roughly perpendicular to the toroidal B of several astrophysical objects. This applies to observed huge plasma jets (see Gregori et al., 2025w), or to star alignments (either during star formation, or during supernova catastrophe; see, e.g., Fukui et al., 2006, or also Morris, 2006), or the filamentary pattern of interstellar dust inside the Milky Way (e.g., Miville-Deschênes, 2014), or to galaxy alignments in galactic superclusters (e.g., Tully et al., 2014), etc. The formal MHD theory for jet-launching is discussed in detail, e.g., by Rüdiger and Hollerbach (2004, p. 209), and plasma collimation by Scott (2015; see below).

Several case histories are often observed in fascinating telescope images (see Gregori et al., 2025w), beginning from the Active Galactic Nuclei (AGNs), which are believed to surround a black hole, through galaxies, through stellar dynamos.

The e.m. confinement results particularly effective inside a star. It confines the huge endogenous energy generated by thermonuclear processes (see Gregori and Leybourne, 2025b), thus leading to the Biermann’s blocking of the entire system. On the other hand, owing to such an extreme condition of total confinement - and with no possibility to avoid it - the mere MHD requirement is incompatible with the energy balance of the system. Hence, a thermonuclear and thermodynamic process ensures, through a permanent explosive state, the energy balance paradox that is implied by Biermann’s blocking.

For comparison purpose – and as far as a planetary object is concerned when no thermonuclear source is available (see Gregori, 2002; Gregori and Leybourne, 2021; Gregori et al., 2025a) - a TD can be considered. The tidal interaction is the leading energy source. The energy balance is always attained by the Hamilton’s principle. Energy must propagate outward, according to same e.m. processes, and leads to the so-called sea-urchin structure, and to the behavior of the system reminding about a car battery, etc.

⁸ Reproduced with kind permission of the *International Journal of Engineering Science Technology*, “Open Access”.

(see Gregori, 2002; Gregori and Leybourne, 2021; Gregori et al., 2025a).

Therefore, one can claim that the rigorous Cowling dynamo is a “universal” process. It is like a “theorem” that applies everywhere and at every space- and time-scale outside the atomic and molecular interior.

The FACs plasma model

The identical inference of the collimation process – which is inferred from the Cowling dynamo - can be proven by means of standard plasma physics algorithms. Whenever a result can be derived by independent procedures, this helps to check the correctness of every computation, and, in addition, one can explore different facets and details of the same phenomenon. A summary is here given of some remarkable results of two papers, Scott (2015) and Burn (2015), including a few essential highlights of the computations. The interested reader ought to refer for a more exhaustive account to the original papers.

The Cowling dynamo approach relies on the proof of the generalized Cowling theorem, which is a straight and rigorous result that requires no approximation, derived from the Maxwell equations. In contrast, the formal treatment by means of standard plasma algorithms is computationally heavier. Therefore, it requires suitable approximations, while sometimes interesting details can be evidenced. Such a comparison of the two derivations has some advantages. (i) The approximations required by the plasma model can be accepted as far as they do not contradict the rigorous inferences. (ii) Hence, one can suppose that also the better details are meaningful, independent of approximations. (iii) On the other hand, the plasma computation can eventually miss some inference of the rigorous approach.

The detailed paper by Scott (2015) [Quotes reproduced with kind permission of *Progress in Physics* (“Open Access” academic journal)] contains all needed computational specifications. Scott (2015) begins and briefly reviews the historical development of concepts. Then, he clarifies the implications of his approximations.

A basic concept is the so-called “force-free field-aligned current”. This means that it is assumed that - compared to the magnetic energy density - the plasma kinetic energy density is negligible. That is, this approximation holds in space-domains either close to stars, or when dealing with trapped radiation, while it does not apply inside the solar wind. This explains why the present formal treatment of the solar wind by means of *MHD* cannot explain the observed self-collimation effect, which – in contrast - is foreseen by the Cowling dynamo approach that is independent of the *MHD* approximations.

Scott (2015) refers to usual cylindrical coordinates (r , θ , z). He deals with a physical current density \mathbf{j} , which is a vector field that creates an overall average current vector \mathbf{I} that, by definition determines the direction of the z -axis. The magnitude of \mathbf{I} is assumed to be everywhere independent of the z coordinate. Therefore, \mathbf{I} the integral of \mathbf{j} over the full cross-section of the plasma bundle.

The starting equation is the momentum equation of ideal *MHD*

$$(\nabla \times \mathbf{B}) \times \mathbf{B} = \mu_0 \nabla p \quad (1)$$

where μ_0 is the permeability of free space. [In terms of different symbols (see some mentions in Gregori et al., 2025e) - and apart eventual constants depending on the unit system used - this equation is the same as (where $\text{curl } \mathbf{B} \propto \mathbf{j}$)

$$(\text{curl } \mathbf{B}) \wedge \mathbf{B} = \mu_0 \text{grad } p \quad (1')$$

The left hand side of (1) is the compressive magnetic (Lorentz) force. The right side is the expansive force (pressure gradient multiplied by the permeability of the plasma). Force-free fields have $\nabla p = 0$ and pressure balanced fields have $\nabla p \neq 0$.

Define the parameter β that is the ratio between the plasma pressure p and the magnetic pressure

$$\beta = 2 \mu_0 \frac{p}{B^2} \quad (2)$$

Close to the Sun, i.e., on the photosphere and within the lower chromosphere, and inside some large portion of the solar wind, a high- β plasma occurs, i.e., the energy of the plasma motion dominates the magnetic energy. Thus, \mathbf{B} is swept passively along with the plasma. “Higher up in the corona, in interplanetary and in cosmic space, a lower pressure (lower ion and electron densities), low- β plasma often exists depending on local field pressure. Here the plasma can take on a force-free character ... However, care must be exercised in assuming low- β properties ...”

Every charged particle with velocity \mathbf{v} inside the plasma experiences an e.m. force (called Lorentz force)

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad (3)$$

where $q\mathbf{E}$, is the electric force and $q(\mathbf{v} \times \mathbf{B})$ is the magnetic force. In cylindrical symmetry computation, plasma is a cylindrical current stream. No requirements are assumed for the distribution of the current density \mathbf{j} across the cross-section.

According to standard college physics, locally a charge particle q is associated to the magnetic field \mathbf{B} and to a current density $\mathbf{j} = q\mathbf{v}$, related by the relation

$$\nabla \times \mathbf{B} = \mu \left(\mathbf{j} + \epsilon \frac{\partial \mathbf{E}}{\partial t} \right) \quad (4)$$

In addition, according to the former historical formulation, the symbol \mathbf{H} denotes the magnetic intensity

$$\mathbf{H} = \frac{\mathbf{B}}{\mu} = \frac{NI}{l} \quad (5)$$

where the dimensions of \mathbf{H} are $A m^{-1}$. The number of turns, N , is dimensionless, and \mathbf{H} is often called magnetic field strength, or magnetizing force.

Then, Scott (2015) introduces the Hamilton’s variation principle (see Gregori et al., 2025e), i.e., the plasma searches for a minimum internally stored potential energy, resulting from magnetic Lorentz forces. The energy content is controlled by the fixed quantity \mathbf{I} , while the Lorentz energies can be minimized and are independent of \mathbf{I} . Whenever steady-state equilibrium occurs, this is called a force-free current, and the relation holds

$$q(\mathbf{v} \times \mathbf{B}) = \mathbf{j} \times \mathbf{B} = 0 \quad (6)$$

Therefore, in a force-free current every \mathbf{j} is collinear with \mathbf{B} , and the Lorentz forces vanish everywhere. This is the reason of the name “FAC” that - in more elementary although somewhat understating terms - is commonly

illustrated by claiming that particles, in a high- β environment, spiral along \mathbf{B} field lines.

Owing to (4), when no time-varying \mathbf{E} is operative, (6) is just

$$(\nabla \times \mathbf{B}) \times \mathbf{B} = 0 \quad (7)$$

which is identical to (1) when $\nabla p = 0$. This is the basic defining property of a “force-free FAC”.

These FACs are identified with the lowest state of stored magnetic energy. We need to compute the $\mathbf{B}(r, \theta, z)$ that we can expect inside such a current/field structure.

Owing to (7), \mathbf{j} has the same direction (except for sign) as \mathbf{B} with no requirements on magnitude. Hence, Lundquist (1950, 1951) and others suggested that

$$\nabla \times \mathbf{B} = \alpha \mathbf{B} \quad (8)$$

that, owing to (4), is equivalent to

$$\mu \mathbf{j} = \alpha \mathbf{B} \quad (9)$$

The parameter α plays a crucial role within this whole theory.

Scott (2015) stresses that a formal solution can be found, although he warns about a related physical approximation. In fact, he comments that while accepting (9) instead of (7) one assumes *a priori* that, at any point, for every non-zero α and non-zero \mathbf{B} one always finds a $\mathbf{j} \neq 0$ at that same point. “This is in general, an unwarranted presumption. This is especially so in light of the well-known tendency of plasmas to form filaments.” In fact, the rigorous Cowling dynamo causes the self-collimation through the action of a local toroidal \mathbf{B} , i.e., the same as the *BL* process (see Gregori et al., 2025d). That is, owing a physical

requirement, regions occur where $\mathbf{j} = 0$ and $\mathbf{B} \neq 0$. “There are many examples in the study of electromagnetism ... However, most investigators start unhesitatingly with (8) and therefore (9) as givens. (This rules out applying the solution to a filamented plasma ...)”

The whole discussion is here omitted of the final equation - and of the different more or less approximate solutions that were proposed in the literature. Scott (2015) writes and solves the equation (a Bessel equation). The solution can be computed either by the formal mathematical analysis or by an iteration procedure (by Euler’s method). The result is here directly shown, mainly in terms of figures displayed by Scott (2015), who also adds comments. Owing to brevity purpose, the following description highlights only a few essential aspects.

Fig. 23 shows the classical trends of the Bessel functions J_0 and J_1 displayed by the axial component $B_z(r)$, and by the azimuthal component $B_\theta(r)$. In addition, the plot includes the total magnetic field strength $|\mathbf{B}|$, which decreases monotonically with r as $(\alpha r^{-1/2})$ that is also plotted in Fig. 23 as a green line.

In addition to the obvious decreasing trend vs. r , note the remarkable oscillating trend of B_θ that implies an alternation of concentric cylindrical layers with B_θ oriented clockwise or counterclockwise along the z -axis. In addition, note that the \mathbf{B} of a simple electric current in a straight-wire extends outward in space with a $1/r$ trend, while this self-confined \mathbf{B} decays vs. r as $\sim 1/\sqrt{r}$.

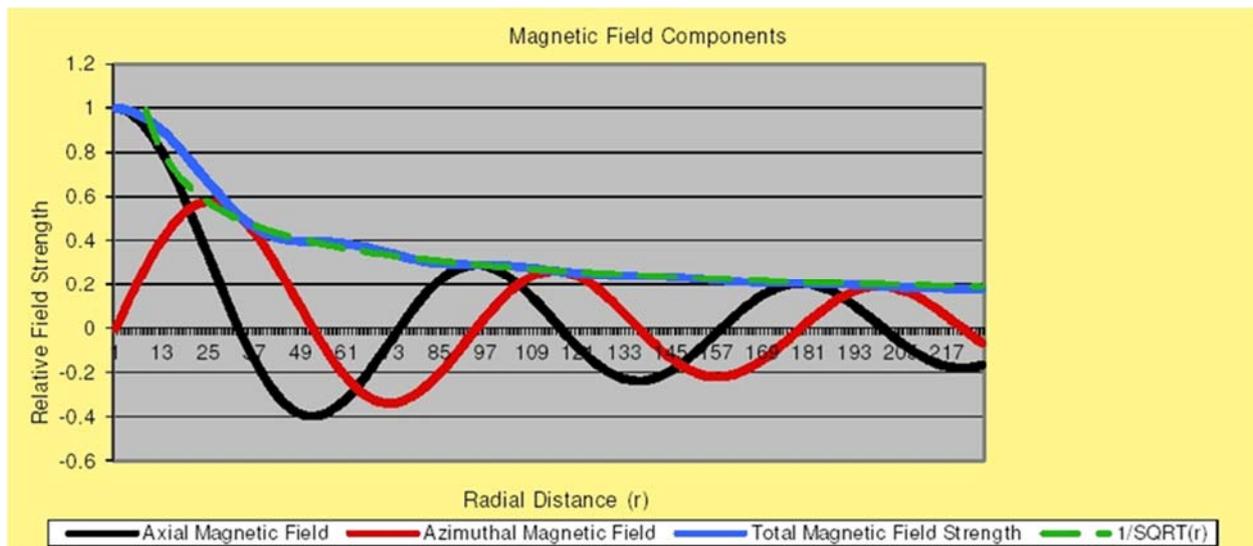


Fig. 23. “Axial magnetic field component B_z , the azimuthal magnetic field component B_θ , the magnitude of the total \mathbf{B} ; and, for reference, a plot of $(1/\sqrt{r})$ - all vs. radial distance quantized to integer multiples of the step-size $h = 0.1$. The value of α arbitrarily selected ... to achieve adequate resolution of the Bessel functions with this step-size is 0.075. The horizontal axis in this plot is the radius r -axis. Note ... that in every case ... the inherently dimensionless Bessel function argument, $x = \alpha r$, thus demonstrating the scale factor utility of α ... “ Figure and captions (simplified) after Scott (2015). With kind permission of *Progress in Physics* (“Open Access” academic journal).

Note the role of the scaling parameter α , arbitrarily chosen in Fig. 23 to be $\alpha = 0.075$, while the horizontal axis is in units of r . For instance, the first zero of $J_0(x)$ is at $x = 2.4048$, which corresponds to $r = x / \alpha = 2.4048 / 0.075 = 32$,

defining how the non-dimensional argument x of the Bessel functions is related to the scaled variable r , i.e. $x = \alpha r$. In addition, at this stage no evaluation is concerned with the current density \mathbf{j} .

Scott (2015) shows that the choice of the assumption of (8) or (9) is not critical for the validity of the solution, which is

$$B_z(r) = B_z(0) J_0(\alpha r) \quad (10)$$

$$B_\theta(r) = B_z(0) J_1(\alpha r) \quad (11)$$

$$j_z(r) = \frac{\alpha B_z(0)}{\mu} J_0(\alpha r) \quad (12)$$

$$j_\theta(r) = \frac{\alpha B_z(0)}{\mu} J_1(\alpha r) \quad (13)$$

Scott (2015) illustrates as follows the characteristics of the solutions.

“Expressions (10)-(13) fully describe the structure of the model of a minimum (Lorentz force) energy, cylindrical, force-free, FAC under the assumption of equation (9). Thus:

1. There are no points within the plasma where $\mathbf{B} = 0$. A non-zero valued \mathbf{B} exists at every point ... (12) and (13) now express that spatial distribution of \mathbf{j} .
2. At every point in the plasma, \mathbf{j} and \mathbf{B} are collinear.
3. At every point in the plasma $\mu \mathbf{j} = \alpha \mathbf{B}$ (assumption, as discussed above).
4. The model expressions (10)-(13) remain valid only over the range $0 < r < R$. Farther out from the z-axis than $r = R$, $\mathbf{j} = 0$. From that point outward, the cylindrical plasma appears more and more like a single straight, isolated current-carrying wire. So beyond radius R , the \mathbf{B} strength will decay approaching $1/r$. This is shown directly using (9): for $r > R$, $\mathbf{j} = 0$, $\alpha = 0$. Then ... [it can be formally shown]

$$B_\theta(r) = \frac{k_z}{r} \quad \dots \quad (14)$$

Thus, it is found that, at increasing r , both \mathbf{B} and \mathbf{j} wrap the axis of the current stream \mathbf{I} with a continuously increasing helical pitch angle. The plasma is self-confined, consistently with the expectation of the Cowling theorem. That is, no outward radiation of \mathbf{B} and no collinear \mathbf{j} is found from inside the plasma where $\alpha \neq 0$. No non-zero B_r or j_r component is found anywhere. No matter escapes from the plasma. Self-confinement applies.

Both solutions (closed-form and Euler) display the aforementioned repeated clockwise and counterclockwise reversals in the directions of both the axial and the azimuthal \mathbf{B} components vs. increasing r (Fig. 24), as expected by Fig. 23. Another expressive representation is shown in Fig. 25.

Fig. 23 shows that B_z and B_θ are in quadrature: when one \mathbf{B} component attains a maximum or minimum value, the other vanishes. As a result, \mathbf{B} wraps the current stream \mathbf{I} , with pitch angle rotating (with increasing r) in a clockwise direction when viewed looking inward in a radial direction (see Fig. 26).

Scott (2015) also compares his treatment with the generally better known standard Lundquist-Alfvén formalism that is synthesized in Fig. 27.

After this entire critical discussion, Scott (2015) mentions several applications for the interpretation of observations. The twofold viewpoint ought to be stressed.

The Cowling dynamo implication is the main aspect that is here emphasized. It applies to every physical system that

evolves according to its respective endogenous energy source while it seeks a better final equilibrium (Gregori et al., 2022, 2022a). This approach illustrates the general overall perspective of phenomena in a fully rigorous way, although it provides with less specific details.

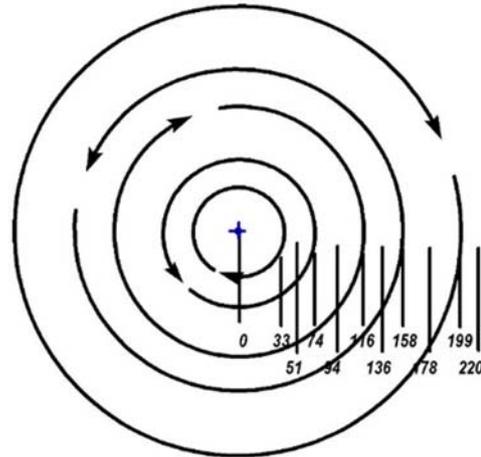


Fig. 24. “Cross-section of a FAC. In this view the reader is looking in the +z-direction, in the direction of main current flow. The radius values shown are plotted as values of $r = x/\alpha$ ($\alpha = 0.075$) ... At the radius values shown, the axial \mathbf{B} -field is zero-valued so the total field is only azimuthal (either clockwise or counterclockwise circles).” Figure and captions (simplified) after Scott (2015). With kind permission of *Progress in Physics* (“Open Access”).

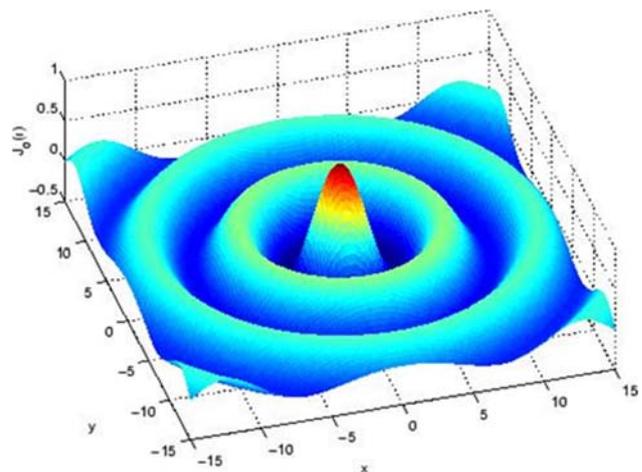


Fig. 25. “3D plot of the magnitude of $B_z(r)$ and the current density $j_z(r)$. This demonstrates the relative strength of both those central (on-axis) fields. The magnitude scale of the horizontal axes used in this figure are both x , the dimensionless arguments of the Bessel $J_0(x)$ and $J_1(x)$ functions.” Figure and captions (simplified) after Scott (2015). With kind permission of *Progress in Physics* (“Open Access”).

The most common description of Birkeland’s currents is Fig. 27, in agreement with (10)-(13). However, this description only explains the morphology for small values of r . In fact, when r is beyond what is shown in Fig. 27, the trend of Fig. 26 is not shown.

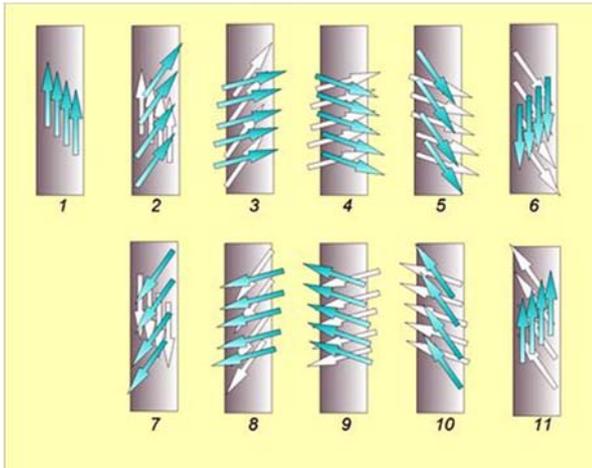


Fig. 26. “The pitch angle of the helical total \mathbf{B} that encircles a FAC changes continuously with increasing radial distance from the central axis of the current. There are no abrupt quantum jumps or breaks in this angle’s change or in the field’s magnitude. One cycle (0° - 360°) of the pitch angle is shown. The cycle is sketched at eleven incrementally increasing sample values of radius. The shaded arrows show the total \mathbf{B} direction at each value of radius, r , and the white arrows show the field direction at an increment just below each of those values of radius.” Figure and captions (simplified) after Scott (2015). With kind permission of *Progress in Physics* (“Open Access”).

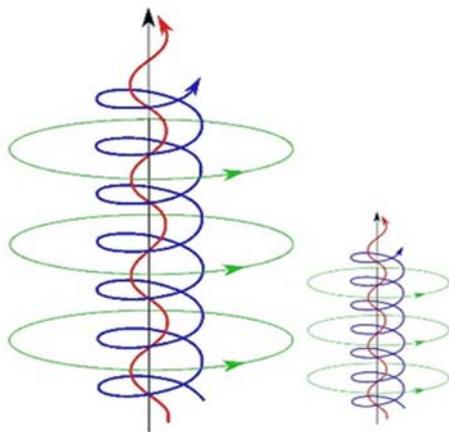


Fig. 27. “Two different sized scale models of a FAC. These are both Lundquist-Alfvén-type images showing the helical structure of the collinear \mathbf{j} and \mathbf{B} vectors for small values of radius, r . ([Left]: Using $\alpha = \alpha_0$. [Right]: Using $\alpha = 2 \alpha_0$.) This demonstrates why some investigators say that α controls the ‘tightness of twist’. It only appears to do that as a secondary effect, because its primary effect is as a scale factor on the overall dimensional size (r , z) of the model’s structure.” Figure and captions (simplified) after Scott (2015). With kind permission of *Progress in Physics* (“Open Access”).

When the total \mathbf{B} is orthogonal to the direction of z , the field rotation does not abruptly stop at 90° , as might be inferred from Fig. 27. Rather, the helical wrapping of \mathbf{j} and \mathbf{B} continues vs. r . At any r , the tangent of the helical angle is

$$\frac{B_z(r)}{B_\theta(r)} = \frac{J_0(\alpha r)}{J_1(\alpha r)} = \frac{J_0(x)}{J_1(x)} \quad (15)$$

“Therefore if $\alpha = x/r$ is, say, doubled, then that same pitch angle will occur at a value of r at half the original radius (x value unchanged). Thus the scale of the entire model will be halved (see Fig. 27).”

In contrast, the Scott (2105) approach is focused on partial subsystems of the whole natural system, and discusses the details of the interaction of the given subsystem with some forcing action that is imposed by some intense perturbation.

That is, the two approaches are complementary to each other. The Scott (2015) analysis relies on some approximations. His astute and authoritative critical discussion is therefore fundamental in order to evaluate the accuracy of the interpretation of observations. The comparison between the two approaches is important for a correct understanding and for avoiding eventual misconception and senseless debates.

Scott (2015) stresses that the scope of his whole study is to reduce - or to eliminate - through the Hamilton principle, the Lorentz force in (3). However, in addition to j_z derived above, the $q\mathbf{E}$ term in (3) contributes an independent conduction term to the current density. This additional term can be expressed as

$$\mathbf{j}_{cond} = q\mathbf{E} \left(\sum_k n_k \mu_{ions}^{(k)} + n_e \mu_e \right) \quad (16)$$

where n_k is the ion density, k denotes the ionization number of the various ions, n_e is the electron density, while $\mu_{ions}^{(k)}$ and μ_e are the respective ion and electron mobility in the plasma. In fact, (16) is the point form of Ohm’s law. Therefore, in general, the cross-sectional area of the Birkeland current is squeezed by two effects, (i) by the convergence of geomagnetic field-lines while approaching the Earth, and (ii) by the self-collimation effect caused by the toroidal \mathbf{B} associated to the Cowling dynamo.

Scott (2015) considers whether, and when, a real natural system agrees with the assumptions of his computation. “It is not known if any actual, observed cosmic currents are in the complete minimum (Lorentz force) energy, field-aligned state. Several apparently show evidence of near-force-free behavior ...” When all Lorentz forces are eliminated, charges simply follow the geometry of \mathbf{B} and look for the steady-state minimum energy FAC configuration, with concentric layers of alternating direction as in Fig. 24.

Scott (2015) shows a laboratory image (not here shown)⁹ after Peratt et al. (2007) of the cross-section of a dense plasma that is focused into a Birkeland current carrying $I = 174,000 \text{ A}$. The spiral structure is visible.

⁹ Peratt A. L., image: Penumbra from a dense plasma focus device. Available online: http://www.academia.edu/9156605/Neolithic_rock_art

associated with intense auroral currents, figure 51, 4 February 2015.

Scott (2015) also discusses in some detail the effects – and how they are observed in the image - of the perturbation originated by the injection of a low intensity stream of charged particles infused into the entire cross-section in the z direction. Refer to the original paper.

Another case history is the well-known hexagon pattern of the Saturn’s North Pole (Fig. 28). Scott (2015) warns, however, that neither the aforementioned laboratory image, nor the image of Saturn’s North Pole, are case histories of true force-free currents, as they both represent collisions of currents with material objects.

Scott (2015) comments on three pictures derived from astronomical observations, i.e., Figs. 28, 29 and 30.

According to Scott (2025), Fig. 28 “is consistent with the hypothesis that Saturn is receiving a flow of electric charge via a Birkeland current directed into its North Pole much as Earth is known to be experiencing.” Hence, consistently with Fig. 24 one should observe clockwise and counter-clockwise counterrotating currents. “But for years it has been unknown whether the spiraling/circular paths appearing [in the Peratt et al. (2007) laboratory image] and in Figs. 28 and 29 are really counter-rotating. It would require a video to reveal that relative motion.”

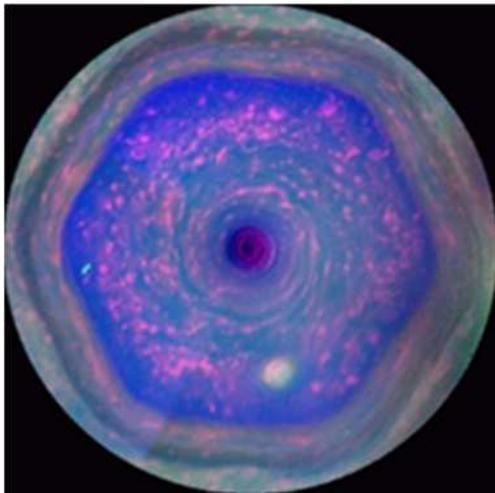


Fig. 28. “In full view: Saturn’s streaming hexagon. This colorful view from NASA’s Cassini mission is the highest-resolution view of the unique six-sided jet stream at Saturn’s North Pole known as ‘the hexagon’. Image obtained on December 10, 2012 and released December 4, 2013. Credit: NASA/JPL-Caltech/SSI/Hampton.” Figure and captions after Anonymous (2018f). NASA copyright free policy.

In fact, NASA produced a video that shows exactly clear counter-rotating (plasma) clouds in the hexagonal shape at Saturn’s North Pole. Scott (2025) emphasizes that the narrator of the video repeatedly uses the term hurricane, and comments that the “storm” is fixed on the North Pole, even though no ocean can justify it – but he does not mention the counter-rotating feature. In fact, a “storm” or a “hurricane” in a planetary atmosphere are conceived like a

thermodynamic phenomenon that involves the whole atmosphere (ionized and non-ionized components). In contrast, the Scott (2015) process is electrodynamic, and the consequence is the curious rotating and counter-rotating alternation of concentric fixed-latitude stripes associated to precipitating charged particles.

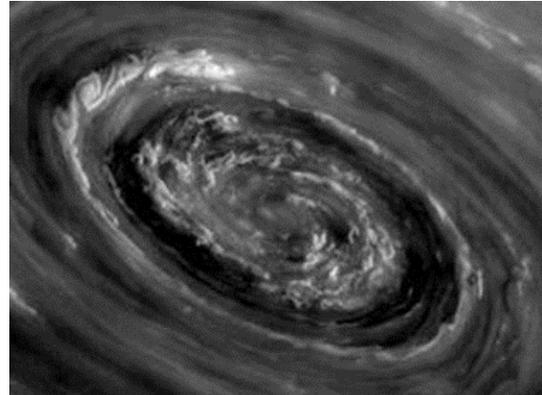


Fig. 29. “Series of diocotron (shear) instabilities, especially obvious in the upper left of this image. This was taken from the NASA video¹⁰ which clearly shows counter-rotation. From NASA Cassini mission video of Saturn’s North Pole. Courtesy of NASA/JPLCaltech/University of Arizona.” Figure and captions (simplified) after Scott (2015). NASA copyright free policy.

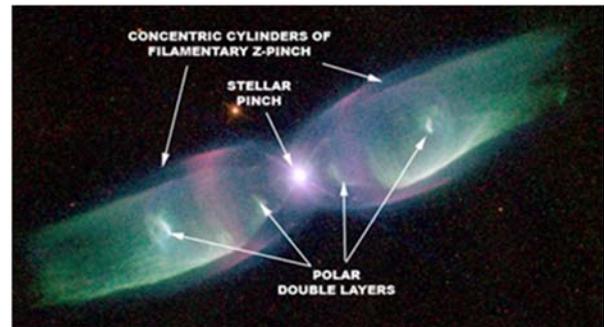


Fig. 30. “The Hourglass (or Butterfly) planetary nebula, M2-9. In this image the separate hollow, cylindrical tubes of matter are clearly visible. The cross-sectional area of the structure diminishes near the center of the pinch. Since the total current is the same at every cross-section, this means regions near the central pinch have increased current density ($A m^{-2}$) and corresponding greater visual brightness. Courtesy of the Hubble Legacy Archive (HLA), NASA, ESA Processing Judy Schmidt ... “ The interpretation that is here given is substantially different. See text. Figure and captions (simplified) after Scott (2015). NASA and ESA copyright free policy.

Therefore, such a NASA video is crucial, as it clearly displays this curious counter-rotating concentric layers. “Without NASA’s video, the counter-rotational motions of these areas in the Saturnian surface would not be observed and therefore their existence would go undiscovered. ... Many other edited versions of the original NASA video

¹⁰ NASA video Saturn hurricane. Available online: <http://www.jpl.nasa.gov/video/details.php?id=1213>, 4 February 2015.

exist that do not show counter-rotation taking place. The uncut original does.”

Fig. 30 highlights the difference between the Cowling dynamo and the plasma model interpretation. Scott (2015) interprets this picture in terms of a poloidal stellar \mathbf{B} (i.e., analogous to the Earth geomagnetic field) and trapped radiation focused along \mathbf{B} -field lines. Scott (2015) claims that “we suggest that the narrowing of the plasma FAC channel due to the Z-pinch creates an increased current density which causes a transition of the plasma from the dark mode into the visible glow and arc modes. The observed dual, concentric cylinders of excited plasma are consistent with the counter-rotation, matter scavenging, and reversing flows described in this paper.”

The interpretation according to the Cowling dynamo is substantially different. According to the aforementioned plasma model, FACs are located along \mathbf{B} -field lines of a huge stellar *poloidal* \mathbf{B} . However, the reason is unexplained of the generation of such a poloidal \mathbf{B} . Conversely, according to the Cowling dynamo (see Gregori et al., 2025d) the cylindrical glow in Fig. 30 is a huge *toroidal* \mathbf{B} . Therefore, additional observational evidences ought to discriminate between these two controversial interpretations. That is, the morphological features that in

Fig. 30 are called “polar double layers” ought to be explained by a different mechanism. In fact, particles are not trapped along poloidal \mathbf{B} -field lines, rather they are trapped along toroidal \mathbf{B} -field lines. The Cowling dynamo process ought to apply also to every bundle of particles, thus ensuring a self-collimation along a circle internal to the toroidal image displayed in Fig. 30. In addition, the entire process is other than a Z-pitch phenomenon.

An almost endless number of fascinating images of several nebulae display such a pattern, and all available \mathbf{B} measurements are consistent with a toroidal \mathbf{B} , not with a poloidal \mathbf{B} . In addition, the Cowling dynamo implies a toroidal \mathbf{B} and a poloidal \mathbf{E} . Therefore, one should expect that violent current jets eventually emerge (due to \mathbf{E}) from the poles of the observed toroidal \mathbf{B} patterns. In fact, this feature is often observed. Moreover, jets look quite collimated, consistently with the self-confinement and collimation required by the Cowling dynamo. A set of a few pictures is shown in Gregori et al. (2025w).

A study by Fletcher et al. (2018) deserves a special mention, being, maybe, the most complete investigation on the hexagonal pattern on the Saturn’s North Pole. Only Fig. 31¹¹ is here shown. Several figures and modelling are given and explained in their long paper.

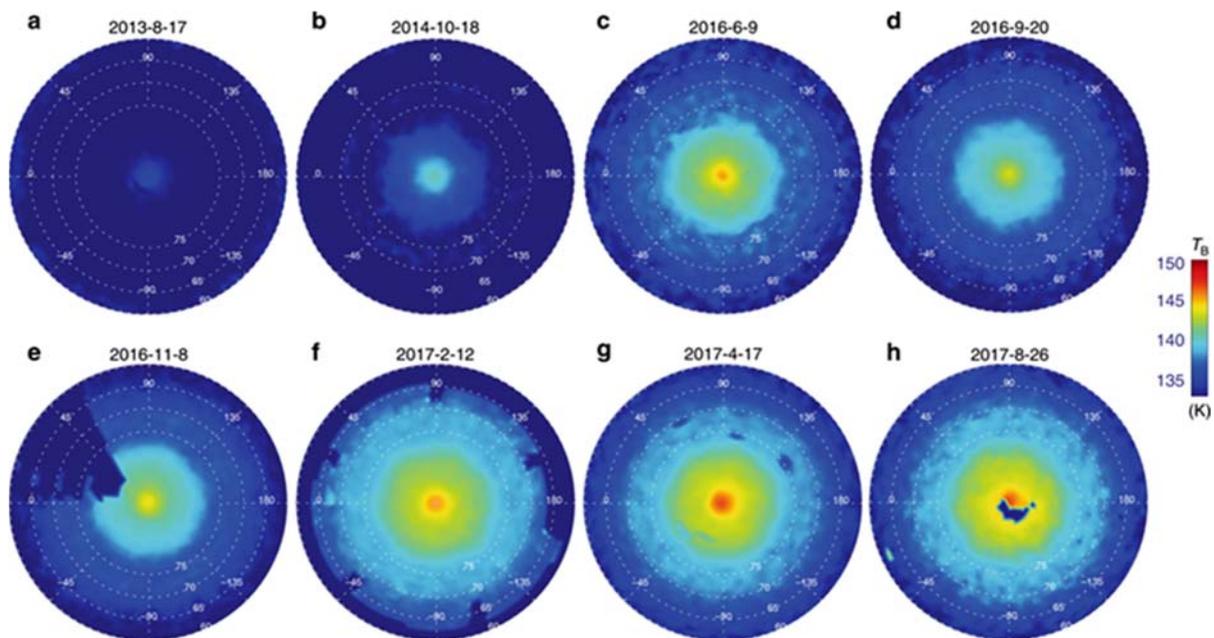


Fig. 31. “These eight frames show Saturn’s northern pole as it appeared between the years of 2013 and 2017, as seen by Composite Infrared Spectrometer (CIRS) on the international Cassini mission. From left to right, the panels date to 17 August 2013, 18 October 2014, 9 June 2016, 20 September 2016 (top row) and 8 November 2016, 12 February 2017, 17 April 2017, 26 August 2017 (bottom row).” See text. Figure and captions after Anonymous (2018v). ESA copyright free policy.

Fletcher et al. (2018) shows this figure with the following captions.¹² “Brightness temperature maps of the north polar stratosphere from 2013-2017. Brightness temperatures were averaged over the 1280 – 1320 cm^{-1} range sensing 0.5 – 5.0 mbar, and each map has the same temperature scale. The figure indicates the hexagonal

boundary to the polar stratospheric hood. ... Maps with spectral resolutions of 2.5 cm^{-1} (REGMAPs) and 15.0 cm^{-1} (FIRMAPs) were used here, spanning Cassini’s solstice mission and proximal orbits. These data were obtained from a relatively high orbital inclination to facilitate views of the North Pole. Spectra have been

¹¹ Quotes reproduced by CC BY 4.0 licence of *Nature Communications*.

¹² Reproduced with kind permission of *Nature Communications*, (CC BY 4.0).

averaged on an equal area projection to reduce noise. Regions of dark blue represent missing data and defects - in particular, the central polar cyclone was partially obscured in the final FIRMAP of the mission acquired in August 2017 (h). The hexagonal boundary near 78 – 80° latitude is clearer in the October 2014 (b), November 2016 (e) and February 2017 (f) data ... “

Fletcher et al. (2018) briefly synthesize their findings, pointing out the seasonal growth and dissipation of warm and broad vortices above ~ 75° latitude. Vortices are more intense in summer and absent in winter. *Cassini* collected a sufficient data base to explore the longevity of this phenomenon by means of IR spectroscopy. Thus, they traced the formation of the North Polar Stratospheric Vortex (*NPSV*), which is a region of comparatively larger temperature and high hydrocarbon abundances at millibar pressures.

According to the available observations, the *NPSV* appeared during late northern spring. *Cassini*'s data ended shortly after northern summer solstice. However, data still did not show the contrasts in temperature and composition that during southern summer were clearly seen at the South Pole. A boundary of the newly formed *NPSV* was characterized by a strengthening of the stratospheric thermal gradient near 78°N. This new boundary was hexagonal. Fletcher et al. (2018) envisage that the Rossby wave – formerly believed to be trapped in the troposphere – ought to influence stratospheric temperatures some 300 km above Saturn's clouds, being thus responsible for the Saturn's long-lived polar hexagon.

That is, the Scott (2012) *FAC* mechanism is to be fitted with the requirements of atmospheric circulation. Several other details are given by Fletcher et al. (2018), although they are not directly pertinent for the discussion carried out in the present study. Hence, they are here omitted.

The Scott (2015) analysis is supported by the impressive dodecahedron pattern, with pentagonal faces, displayed by polar aurora in Fig. 11 of Gregori et al. (2025u). Scott (2015) summarizes and emphasizes the main features of his results. A few comments are to be remembered. He stresses that the skew-pattern of Fig. 26 explains the “*structural stability of the spiraling fascies-like wrapping of B*” by means of the “*enigmatic stability of Birkeland currents over long interplanetary, inter-stellar, and inter-galactic distances.*” In fact, this “enigmatic” feature is rigorously explained by the self-collimation effect caused by the Cowling dynamo through confinement by a local toroidal **B**. Scott (2015) points out that the cosmic jet that emanates from galaxy M87 looks still collimated over a distance > 5000 LY. “*The stability of the flux-rope connecting the Sun and Earth is now better understood.*” That is, the collimation of the solar wind is better understood.

Scott (2015) also points out the relevance of the evidence associated to the counter-rotating layers implied by the oscillatory trend of the solutions of the Bessel equation (Fig. 23). “*The major difference between a FAC and a Birkeland current is that in a FAC the total current, I, is a minimum. When the current density at any point, j, increases for any reason above its minimal value, non-zero Lorentz forces begin to occur and the matter scavenging ...*

takes place.” That is, the Scott (2015) analysis refers to a detail of the evolution of the transient phenomenon, while the final reset is represented by the Cowling dynamo that expresses the actual observed phenomenon, i.e. the Birkeland current.

Scott (2015) also clearly emphasizes and warns about the assumption (8) and (9), by which his theory cannot apply to filamentary plasmas.

A recent finding deals with a new instability that also contributes to a self-collimation of plasma (see Shalaby et al., 2021, 2022, 2023, illustrated by *Leibniz Institute for Astrophysics Potsdam*, 2023). This finding stresses the key role of self-collimation of space plasmas, and self-collimation is, indeed, a very common feature in nature (Gregori et al., 2025w).

The Burn (2015) interpretation of the Scott (2015) plasma model

Burn (2015) proposes an intuitive explanation of several inferences of the Scott (2015) model. A brief summary is here reported.

A premise deals with the reference to a Z-pinch often made by both Scott (2015) and by Burn (2015). The structure is analogous of a Z-pinch and of a *FAC*, although the prime driver and energy source is different. In fact, in the Z-pinch the energy source is an externally applied impulse by an intense **B**. In contrast, in natural phenomena - such as in Birkeland currents that impinge on the atmosphere - the **B** pattern is the dominating geometrical constraint, while particles precipitate due to some driver that is independent of the local **B**. In general, the Cowling dynamo process relies on the endogenous kinetic energy (3D convection cells) applied to an ionized medium that, owing to the generalized Cowling theorem, generates a toroidal **B** that confines the discharge causing self-collimation. The analogy with a Z-pinch is, however, pertinent in the case of exceptionally violent energy precipitation on the Earth (see below).

Burns (2015) considers a bunch of elementary **j** components. For instance, one can even imagine single precipitating particles (Fig. 32a) that arrange their geometry according to either a hexagonal (Fig. 32b) or a cubic (Fig. 32c) pattern.

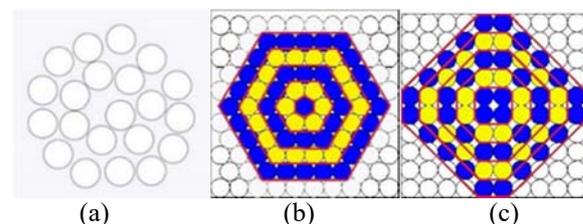


Fig. 32 – (a) Horizontal cross section of current filaments. (b) Hexagonal close packing (HCP). (c) Cubic close packing (CCP). After Burn (2015). With kind permission of *New Concepts in Global Tectonics*.

The choice of a hexagonal - and not an octagonal - discharge is not strictly compulsory. In general, one can consider an economy criterion of the structure (see Gregori

et al., 2025u). In every case, the process occurs through quasi-equilibrium states (Gregori et al., 2022, 2022a), as every observed state is a transient pattern during the everlasting search for final equilibrium by the natural system, equilibrium that is never attained. In fact, owing to self-collimation, small j bundles coalesce into progressively larger j bundles (Fig. 33). In fact, consider two filaments (Fig. 33[left]a) and suppose that, owing to some environmental action, they can experience deformation. If the deformation occurs as in Fig. 33[left]b, the result is that two filaments coalesce into a unique filament. Note that the currents flow only on the outer surface of the unique resulting filament or bundle of particles, consistently with the requirements of the Hamilton's variation principle. This is the same process that occurs either in a spark or lightning discharge, or – inside deep Earth - in the coalescence of two sea-urchin spikes into a unique spike (see Gregori et al., 2025d).

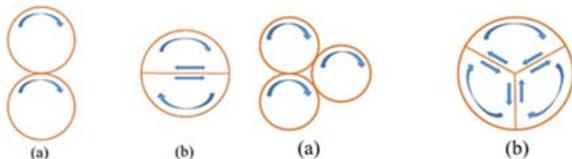


Fig. 33 – [left] Coalescence of two filaments; [right] Coalescence of three filaments. See text. Unpublished figure.

The analogous case history of three filaments is shown in Fig. 33[right], etc. In every case, the key item is the quasi-equilibrium state, i.e., the need for a physical driver capable to push - or to permit that - the system evolves towards a better equilibrium. In fact, a better equilibrium condition is attained after coalescence, and this is according to the requirements by the Hamilton's principle.

However, in general coalescence must be considered in the framework of the transition through states of quasi-equilibrium towards better equilibrium (Gregori et al., 2022, 2022a). Burn (2015) addresses to this case history, and intuitively justifies the Scott (2015) counter-rotating layers.

“From established work on Birkeland currents we know that they exhibit both long range attraction via their axial component, and short range repulsion due to their radial component. “ In fact, long-range attraction is just the compulsory requirement by the Cowling dynamo. The radial B component is an eventual, though unessential, additional local feature. Since the radial components of two contiguous Birkeland currents are approximately equal and opposite (at the “contact” point of the contiguous elements), they are in unstable equilibrium. Thus, they attempt to reverse the direction of every respective radial component, in order to fit with the radial component of the next element.

“Their short range repulsion will cause the current filaments to space themselves out (Fig. 34), but still be restrained by their limited spatial geometries into an arrangement of concentric polygonal layers.” That is, in any case, a self-confinement always occurs that compresses several filaments altogether, consistently with the picture that is rigorously inferred by the Cowling dynamo and by the Scott (2015) inference.

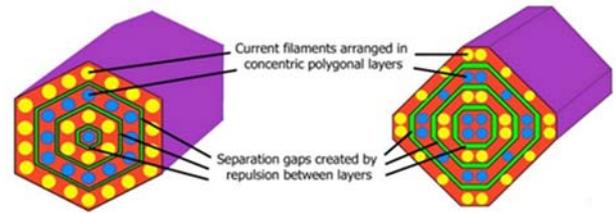


Fig. 34. “Extended cross sections of hexagonal and octagonal lightning bolts showing the arrangement of current filaments after separation by repulsion.” Figure and captions after Burn (2015). With kind permission of *New Concepts in Global Tectonics*.

Note, however, that Burn (2015) considers the case of a Z-pinch, where the driver is the electric current that is injected by a powerful external generator. Hence, it is reasonable to guess that a repulsion occurs between different filaments. In contrast, in the Cowling dynamo the process is totally endogenous. The e.m. field that is generated causes a self-confinement of the filament, and, maybe - compared to a Z-pinch - it causes also a less efficient repulsion. However, it is difficult, if possible at all, to assess the role of this repulsion. Repulsion has to be considered as a reasonable possibility that can apply at least in some case histories. There is need to seek observational evidence, dealing with every case history, which is either in favor or against such a feature.

“By separating into concentric layers, the current filaments gain a degree of freedom in that they can rotate as a unit. This enables the filaments shown in white (Fig. 35a) to repel each other in the only way possible i.e. by spinning in opposite directions. This automatically creates the counter-rotational effect (Fig. 35b) predicted by Scott (2015).” Indeed, this is an intuitive justification, or physical interpretation, of the formal result shown by Scott (2015).

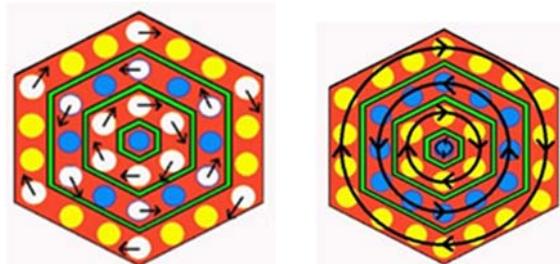


Fig. 35. (a) “Repulsion between layers.” (b) “Counter-rotation of layers.” Figure and captions after Burn (2015). With kind permission of *New Concepts in Global Tectonics*.

A basic physical distinction can be made for solving the dilemma concerned with the role of repulsion. In this respect, we should distinguish two different and competing extreme physical case histories.

The “quietest” phenomenon occurs whenever a gentle local convection triggers a Cowling dynamo that locally confines plasma, like inside a ball lightning (BL). When the BL exhausts its internal energy, it breaks down, and it transfers thermal energy to a new convection cell close to

it. A new *BL* is thus eventually activated next to the previous one, etc. The process propagates like a domino effect. This model seems to apply to every spark or lightning (or other) discharge. As already stressed, it is indifferent whether the discharge moves from higher to lower height, or viceversa, because the starting trigger can occur at any location along the lightning (or other) discharge, and the *BL*'s domino propagates either upward and/or downward. The physics is the same, while a lightning is a damped oscillatory discharge. Summarizing, in this "quiet" case a lightning discharge is a chain of *BL*s and the speed of propagation of the discharge is low compared to light speed.

A different case history occurs when a violent external *E* field is abruptly applied to the system. This occurs e.g. in a *Z*-pinch. However, some analogous condition sometimes can occur also in natural phenomena. In fact, e.g., the largest number of lightning discharges is *IC* (or *CC*). This means that violent convection cells are operative inside huge cumuli and generate intense e.m. fields. An intense *E* triggers therefore the discharge that is always composed of a domino sequence of *BL*s. The physical process, however, is different whether the dominating driver is an externally applied *E*, or an endogenous heat-source that slowly propagates through a domino chain of local *BL*s.

Note that no sharp distinction exists between the two extremes. Rather, a continuum is to be considered. The distinction derives from the arbitrary choice to consider one given subvolume of the whole physical system. In fact, the reduced portion of physical system - i.e., the subsystem which is considered - is such that the system considers the effect of the remaining fraction of the whole system as an "externally applied" perturbation. The role of the repulsion - between concentric layers inside the electric discharge - is therefore varying and different in every case, a transient quasi-equilibrium state, and it depends - in some way - on the arbitrary definition of the subsystem that is arbitrarily considered.

Burn (2015) considers the case of a *Z*-pinch, i.e., of an intense external driver. He also speculates about the possible occurrence in the past of anomalous and exceptional events.

"Both close packing arrangements [i.e., HCP and CCP] produce an infinite series of concentric polygonal layers of current filaments, indicating that the underlying formation process of a lightning bolt is infinitely scalable. Therefore I submit that this establishes the possibility of lightning bolts on a colossal scale which, though not witnessed in recent recorded history, may have occurred in the distant past."

According to some general present intuitive feeling, this working hypothesis can appear "exotic" and fanciful. In reality, the aforementioned alternation of the circulation patterns in the Saturn's North Pole atmosphere (see Figs 28 and 29, and Fig. 12 of Gregori et al., 2025u) show that an intuitive feeling can be incorrect. In addition, violent - and large cross-section - air-earth currents events seemingly occurred (see Quinn et al., 2026; Gregori et al., 2025v, 2025x). Note that this concept is also close to the "Stellar Transformer" approach (see and Leybourne et al., 2025).

Thus, Burn (2015) considers the case of an intense external driver. He envisages a coaxial structure of the discharge with the inner layers that ought to propagate faster than the external layers. The intuitive physical explanation, however, is not clear. A justification is given here below.

He refers to the lightning bolt model of Fig. 36a. *"Each layer has been extended to emphasize its freedom of movement within the bolt due to repulsion between layers; [i.e., stated in this way, the different elongation of the coaxial structure seems to be adopted only for representation purpose; but, consider the following discussion ...] the repulsion gaps are shown in yellow and the white arrows indicate direction of rotation."* He refers only to a hexagonal pattern, although the same argument applies also to other geometries.

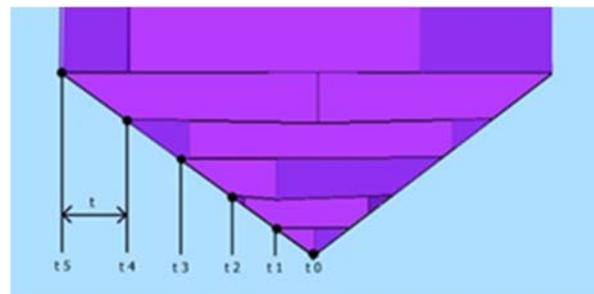
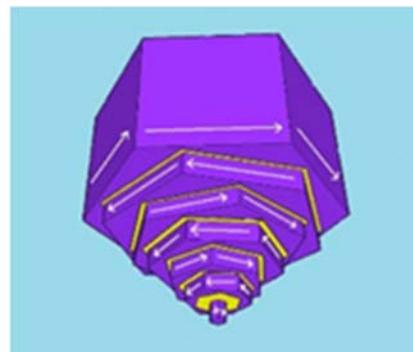


Fig. 36. (a) "Lightning bolt model." (b) "Time intervals between contacts of successive layers." Figure and captions after Burn (2015). With kind permission of *New Concepts in Global Tectonics*.

Burn (2015) comments that the high current levels ensure an effective self-confinement (this is consistent with Cowling's dynamo). *"Just before contact with the surface, the high current levels surging towards the bolt's tip will induce a Z-pinch."*

*As the current density decreases from the center to the outer edge of the bolt, then each successive layer ... will be progressively less constricted by their radial *B*, which decrease in strength as current density falls. The effect this has on the profile of the bolt's tip (Fig. 36b) indicates there will be a succession of contacts with the surface."*

That is, the strongest *Z*-pinch effect is supposed to occur along the central axis of the discharge, where - owing to a more effective confinement - a comparatively higher density of electric charge is found. Therefore, Burn (2015) guesses a different arrival time of the tip of the discharge.

The argument may seem mostly intuitive, i.e., the innermost axial Z-pinch effect “pulls” the outer layers. That is, the energy source of the Z-pinch effect is supposed to be mostly active along the axis of the discharge – where the bulk of the intense current flows, while all other concentric layers are progressively less affected. In fact, the rigorous support for this whole inference is the aforementioned Scott (2015) analysis.

Consider, however, also a different viewpoint, i.e., the upward penetration of a sea-urchin spike. Owing to Hamilton’s principle, the electric currents flow on the outer surface of the spike and their highest density occurs right at the tip of the spike. Owing to the *ESI* (electric soldering iron; see Gregori et al., 2025a) mechanism, the tip of the spike propagates upward at a speed of the order of, say, $\sim 10 \text{ cm year}^{-1}$. That is, even though compared to a Z-pinch the propagation speed is much slower, the axis of the spike penetrates upward prior to the outer layers of the spike.

Therefore, one can state that the effect is similar both in a Z-pinch process in the atmosphere triggered by an external effect - and also in a sea-urchin spike that propagates due to the energy supply by the endogenous electric currents of the *TD* dynamo. That is, the axis of the electric phenomenon penetrates faster than its surrounding layers: the outer layers are “pulled” by the process along the axis.

Thus, Burn (2015) claims that “*this process is illustrated in Fig. 37a, where each layer has a different color with a matching discharge pattern.*” He warns, however, that “*the discharge patterns have been simplified to illustrate the principle of successive discharges separated by the time interval between successive layers making contact. The tip profile has also been exaggerated for the same purpose.*”

Fig. 37a is aimed to emphasize that different layers of the coaxial discharge can be associated with different discharges in soil. Note that, if the effect can be actually recognized in soil of different concentric layers of discharge, the observed distance between these layers is related to the physical size r of every elementary circle that composes Figs 32 etc. That is, this size r is a physically significant parameter, of some given finite size.

In fact, Burn (2015) comments that “*taking into account that each layer is rotating in a counter direction to adjacent layers, the resulting pattern of discharges will more closely resemble those in Figs 37b and 37c ...*”

Note that in this case the analogy cannot be simply applied with the sea-urchin spike’s penetration. In fact, one should be able to justify a twist of the spike during its slow upward penetration. However, also in this respect, note that also in case of a sea-urchin spike one should distinguish between two extreme phenomena as follows.

In a comparatively “quiet” configuration, the *ESI* mechanism occurs by simple push, which is passively derived from the Hamilton’s principle that is applied to the electric currents that flow on the *CMB*. Thus, the “push” is caused by the *TD* dynamo, which is powered by the tidal action by Moon plus Sun.

However, an electric discharge between a sea-urchin spike and the atmosphere (ionosphere plus magnetosphere) occurs whenever an electric potential difference occurs

between the two electrodes. If the externally imposed E field is large, the Z-pinch condition occurs, with the leading action played by the axial currents etc. In this case, also a sea-urchin spike behaves according to the Burn’s (2015) picture of concentric radial layers of electric currents. Hence, also in this case, one can envisage a twist of the sea-urchin spike.

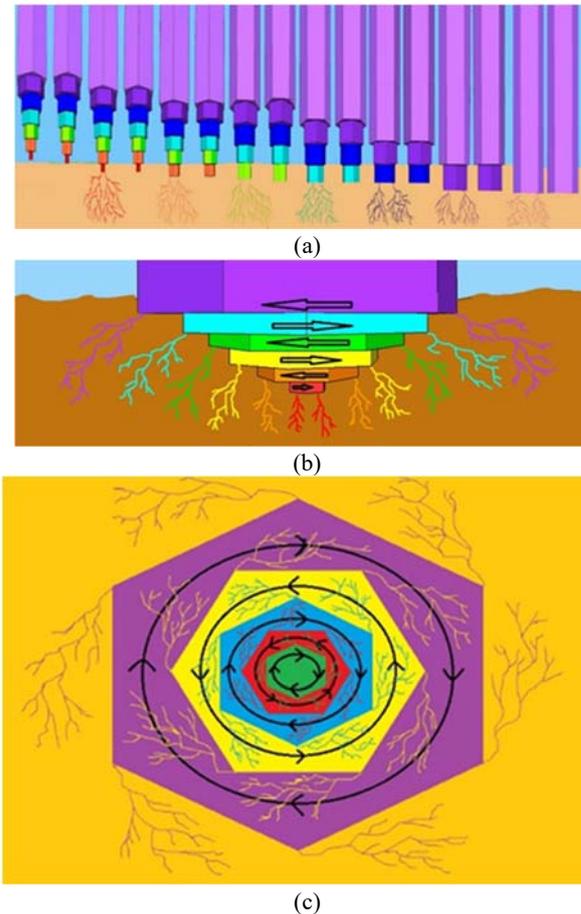


Fig. 37. (a) “Contact and resulting discharge of successive layers of filaments.” (b) “Cross sectional view of counter-rotating layers and their discharges.” (c) “Underside view of counter-rotating layers and their discharges.” Figure and captions after Burn (2015). With kind permission of *New Concepts in Global Tectonics*.

Differently stated, the electric discharge is one unique phenomenon, from deep Earth (i.e., from the *CMB*) through the ionosphere and magnetosphere. That is, one can expect either a twist of sea-urchin spikes or not, depending on the intensity of the externally applied E .

Finally, Burn (2012) states that “*I submit that the lightning bolt model outlined here is a complete and accurate model of the lightning bolt process, and that every aspect of it will be justified by directly linking it to clearly observable features in the respective morphologies of the two polygonal craters discussed in this paper.*”

That is, he assumes that his argument is correct and realistic. His conclusion has therefore to be validated by observations, i.e., it has to be either confirmed, or denied, or it might hold only in some case histories, etc. The

comparison with observations is discussed in Gregori et al. (2025u, 2025v, 2025x) and in Leybourne et al. (2025). Burn (2015) considers, however, also case histories of twisted structures inside rocks, consistently with the twisting pattern of sea-urchin spikes. These details are not here reported.

One should consider two additional key concepts, which give a physical justification of the Burn's intuition. As already mentioned, every physical system, including the Jupiter or Saturn system, never attains a state of final equilibrium. Rather, it evolves through states of quasi-equilibrium during a steady attempt to reach the final equilibrium that is never achieved (Gregori et al., 2022, 2022a). Thus, every polygonal pattern is just one transient quasi-equilibrium state during the evolution of the system.

The second concept reminds about the justification of the pattern of the Earth's MORs that can be described by a tetrahedron (Gregori and Leybourne, 2021).

In the case of a large gaseous planet (such as Jupiter¹³ or Saturn¹⁴), consider the extremely intricate pattern of FACs that precipitate from the magnetosphere on top the atmosphere. Different FACs tend to coalesce, due to the identical e.m. laws that apply to the Earth's sea-urchin spikes. The FACs system is much intricate, compared to the much simpler case history of the Earth. The focus is therefore on a subsystem of a bunch of FACs that precipitate on top of one pole. The precipitating FACs must organize their pattern searching for a better reciprocal equilibrium state. That is, they should precipitate according to an equidistant pattern. That is, when the FACs are projected on the "detector" represented by the planetary atmosphere, one should always observe a regular polygonal pattern.

The FACs pattern, however, is a temporary quasi-equilibrium state that – more or less slowly according to the Earth's time - evolves into new quasi-equilibrium states etc.

Summarizing, the phenomenon is MHD and the e.m. interaction is fully prevailing over fluid-dynamic or thermodynamic drivers. The atmosphere is only a detector, while atmospheric or meteorological dynamics are definitely other than - and cannot be compared with - the case history of the Earth.

Differently stated, Earth, Jupiter and Saturn are different natural laboratories where the identical e.m. (or MHD) interaction applies. However, their respective case histories can be compared including the Earth's sea-urchin spikes (and MORs pattern), and the Saturn's or Jupiter's FACs that precipitate on top the Jovian atmosphere. In every case, phenomena should display regular polygonal patterns, everyone representing one quasi-equilibrium state.

Summarizing, the Cowling dynamo approach is the fully rigorous derivation. Scott (2015) explains better details, although at the expense of some approximation, by which he misses, however, some inference. Burn (2015) is an intuitive and expressive, approximate illustration of the physical processes that characterize either bundles of

precipitating particles, or the upward propagation of sea-urchin spikes. Burn (2015) envisages no specific physical explanation, although he intuitively guesses the correct final solution. Thus, Burn (2015) reports several case histories of craters observed either on Mars or on the Earth that display polygonal patterns, although eventually perturbed by a various amount of erosion and weathering (see Gregori et al., 2025u).

Conclusion

The old-fashioned classical treatment of electrical discharge phenomena does not reveal the true physics behind sparks, lightning, and electric currents through gases etc. Refer, e.g., to the authoritative review by the Raizer (1991) where the standard concepts are extensively reviewed.

The term "gas discharge" can refer to every phenomenon associated with the motion of ionized matter inside any medium, with or without electrodes. However, unlike the standard classical treatment, the leading role of **B** should be considered or accounted for. In addition, also the interaction with e.m. waves can originate a "gas discharge". Raizer (1991) specifies that he is not directly concerned with phenomena occurring in presence of a **B**, such as - he notes - referring to MHD generators, and he does not enter into the realm of plasma physics applied to the investigations on nuclear fusion, etc.

Electrical discharges should be identified with every kind of motion of charged matter. In addition, the perspective is behind the concept of bundles with a comparably limited cross-section. Rather, electric currents flow with a huge cross-section, which at present are generally unrecognized (see *passim* through the present set of accompanying papers). This unconscious bias relies on the absence of detectable photon emission, thus the modern concept of dark matter is intricately related to this bias (Gregori et al., 2025w).

Owing to an important historical drawback, in general, the leading concern is about gravitation, while e.m. interaction is considered an additional, almost optional, component that plays no role in the case of electrically neutral matter (Gregori et al., 2025a). In fact, almost three centuries¹⁵ elapsed between Newton's gravitation, through Maxwell's formulation, to Alfvén's inclusion (MHD) of e.m. interaction into the neutral fluid dynamics. This drawback originated, e.g., a bias of cosmologists in favor of gravitation. This entire scenario, however, is likely to be still strongly biased. Fig. 38 shows an indicative state-of-the-art, with no presumption for completeness. When dealing with a cloud of ionized matter, the algorithms often seem to deal with a matter of semantics, but also with the need for new methodological approaches.

The standard homogeneous dynamo (for the Earth's interior or for a star) is essentially always supposed to be

Electromagnetic Field, 1865; Alfvén's *Cosmical Electrodynamics*, 1950.

¹³ See Figs 12 and 13 of Gregori et al. (2023u).

¹⁴ See Figs 28, 29, 31.

¹⁵ Newton's *Philosophiæ Naturalis Principia Mathematica*, 1687; Maxwell's *A Dynamical Theory of the*

composed of an incompressible fluid, hence it relies on *MHD*. In the case of a compressible fluid (e.g., for the ionospheric dynamo) the dynamo should rely on *MGD* (magneto-gasdynamics). The case of control by an

externally applied electric field E seems to be of no concern, likewise *EHD* and *EGD* (electrohydro-dynamics or electro-gas-dynamics).

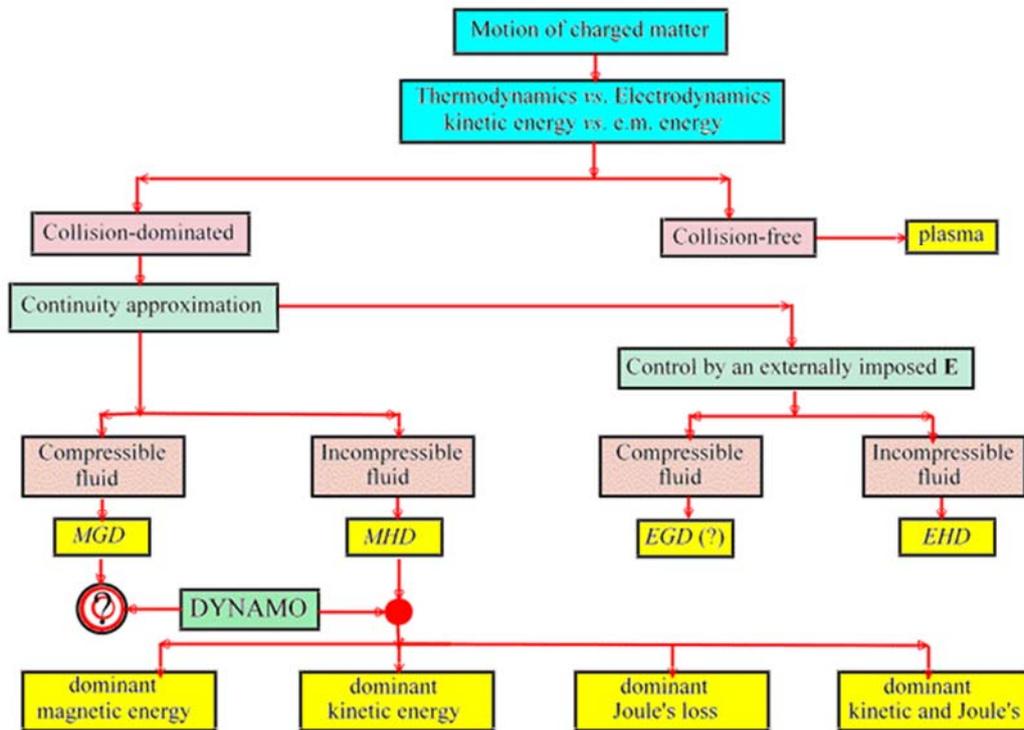


Fig. 38 – Different conventional definitions dealing with the motion of charged particles, and four possible dynamo scenarios. They depend on the kind of the dominating energy. See text. After Gregori (2002). With kind permission of the late Wilfried Schröder.

According to Shercliff (1965),¹⁶ the term “plasma” is often improperly used. Fig. 38 summarizes a few formal distinctions. It highlights also the four possible and substantially different scenarios of dynamo that can be prompted, depending both on the dominating type of energy, and on its primary source. The motion of ionized matter is dominated by thermodynamics or by electro-dynamics depending on the prevailing energy density. In the case of dominating electro-dynamics, the system is said to be either collision-dominated or collision-free, depending on the mean free path of the charged particles. When, the mean free path is small compared to the size that is considered of the elementary space-cell, the so-called collision-dominated situation occurs (like in a liquid or in a gas). The opposite case, called collision-free condition, is the concern of plasma physics. The term “plasma” should be used only for the collision-free case histories.

In the collision-dominated case, in general the continuity approximation is used. A distinction can be made depending on whether E is applied from its exterior or not. If it is applied, the physical system has some additional component, which should be specified. In the case of no

external E -control, a distinction is made between *MHD* in the case of incompressible fluids, compared to *MGD* (magneto-gas-dynamics) in the case of compressible fluids. By analogy, in the case of an external E -control, one might define *EHD* (electro-hydro-dynamics) and *EGD* (electro-gas-dynamics), depending on whether incompressible or compressible fluids are considered, respectively.

The literature is always concerned only with *MHD*. To our knowledge, the literature very often reports about *MHD*, which was formerly called “hydro-magnetic theory” etc., while no mention seem to be given about either *MGD*, or *EHD*, or *EGD*. On the other hand, the formal *MHD* treatment of the expanding solar corona can be exploited only by assuming a compressible solar wind. That is, one should claim that *MGD* ought to be used rather than *MHD*. On the other hand, the term *MHD* can be applied also to a compressible solar wind. It is only a matter of semantics and of convention. Hence, every different specific application always must be suitably considered in detail.

As far as a lightning considered, it cannot be likened to a spark, which is a similar, although substantially different, phenomenon. In addition, the naïve Wilson’s model, proposed in the 1910s - and that is still generally applied

¹⁶ See also Gregori (2002, sections I-3.1 and I-12) that contains a more exhaustive discussion, and from which the following mentions are borrowed.

and considered fashionable - should be abandoned after the great achievement and modeling carried out by Gurevich and coworkers in the 1990s, which is now completed by the contribution of the Cowling dynamo (see Gregori and Leybourne, 2025e).

The electrical phenomena inside the atmospheric condenser should take into account the huge undetected air-earth currents (see Quinn et al., 2026). In addition, one can consider the combined action (i) of the old fashioned classical processes (such as corona discharge, and “Townsend discharge”), and also (ii) *RB* processes, and (iii) Cowling dynamo. These processes are intermingled with one another, and the trigger derives from the uneven electrostatic charge distribution in the ionosphere - in addition to the ionization that is more or less occasionally produced by cosmic rays of high energy, and friction at Earth’s surface.

In any case, the largest part of air-earth currents is not related to lightning, or to visible discharges in air (see e.g. Quinn et al., 2026). The largest associated phenomena were almost unnoticed in the past, as science was strongly biased in favor of luminous phenomena, and of gravitational, rather than of e.m. interaction. In addition, air-earth currents are part of huge circuits that cross through the Solar System, from the Sun to all planetary interiors, and even farther away.

It is impossible to simulate atmospheric phenomena by any laboratory experiment. For instance, the classical gas tube experiments can simulate corona effects and Townsend discharge, but they can hardly reproduce the conditions either for *RB* or for Cowling dynamo. The Cowling dynamo can be rather reproduced in the laboratory by means of experiments focused on specific phenomena, e.g., to mimic the *BL* phenomenon. The Cowling dynamo process is the process that co-exists with every kind of *RB* mechanism. It is well-known that the *RB* mechanism needs a starting \mathbf{E} , and the Cowling dynamo originates an almost ubiquitous “seed”, which is eventually violently amplified by the *RB* process.

This whole improved understanding is likely to be the important forerunner of the exploitation of the electrostatic energy of the atmosphere, which is a free enormous source of clean energy, available everywhere, and that will last as long as the Sun will shine (see Gregori and Leybourne, 2025l).

In any case, the three-century evolution from Newton’s *Principia* (in 1687) through Alfvén’s *MHD* (in 1950) is not completed, and much harder thinking is needed before exploiting algorithms, and approximations, required to deal with e.m. phenomena in the universe, which play a role of paramount relevance, compared to gravitation alone.

Summarizing, the Cowling dynamo explains the filamentary structure of galactic superclusters, and also the observed \mathbf{B} of *AGNs* (active galactic nuclei), of galaxies, and of stars – although not of planetary objects where the *TD* dynamo applies (see Gregori et al., 2025a). The Cowling dynamo seemingly also explains the behavior of sungrazing comets (a study is in preparation). The Cowling dynamo applies inside clouds, on their typical space-scale, and it explains the huge electrostatic charge of the

ionosphere. In addition, the Cowling dynamo applies on several smaller scale sizes within the internal processes that occur inside a cloud. In the case of thunderstorm clouds, this is manifested as *GK effect* (see Gregori and Leybourne, 2025f). In addition, it applies also on the few tens of centimeter scale, being the explanation of *BLs* and perhaps of the orb effect (see Gregori and Leybourne, 2025e). Also the micro-structure and detailed micro-process that determines a spark discharge is interpreted as a chain deriving from a domino effect of several *BLs*. Even on a micro-space, the Cowling dynamo explains water agglomeration around a condensation nucleus leading to the initial formation of a droplet or icelet.

That is, the generalized Cowling theorem (see Gregori et al., 2025d) – which is the primary motivation of the Cowling dynamo - is a strictly rigorous implication of the Maxwell’s laws. Hence, it must apply everywhere, on every spacetime scale (see also Gregori et al., 2025w). The unique limitation deals with the problem that the role of the empirical constraint depends on our objectivity in detecting, either directly or indirectly, its effects.

Let us summarize how this entire scenario fits with Alfvén’s “frozen-in” concept and with Birkeland currents (or *FACs*).

Consider a convection cell of any size. Nothing happens if the medium is neutral. When the medium is ionized the Cowling dynamo generates a toroidal \mathbf{B} that confines the convection cell into a “ball”. In the case of a few ten centimeter scale-size, one gets the *BL*. In the case of micro-convection cells, the effect depends on the amount of ionization. This explains why atmospheric precipitation is controlled by cosmic rays (Svensmark effect), although cosmic rays alone do not completely explain the phenomenon, which depends on the thermal input from the atmospheric dynamics generating convection cells.

Consider a flow of an ionized fluid, such as the solar wind. It contains some small convection cells due to thermal heterogeneities. These heterogeneities are responsible for an extra amount of self-confinement – that is not explained by standard *MHD* models of the corona expansion.

When the electrical conductivity σ of the solar wind is approximated as infinite, one gets the Alfvén’s “frozen-in” concept. In fact, the kinetic energy overwhelms the magnetic field energy. Thus, the magnetic field is dominated by the kinetic energy. You need no Cowling dynamo, because the confinement is total, much like when the convection cell gets a zero radius.

The same alignment effect is operative, and explains the mysterious solar γ -rays, stellar alignments inside galaxies, and the analogous impressive alignments of galaxies inside galactic superclusters.

Consider a different scenario, where the magnetic field energy density overwhelms the kinetic energy density. This typically occurs inside radiation belts. In this case, one considers *FACs* (or Birkeland currents). One cannot talk about *FACs* inside the solar wind, where \mathbf{B} is passive and transported by the solar wind. *FACs* precipitate on top of the atmosphere, like spiraling electrons with their gyration radii. Here, a new phenomenon happens, because the

thermal heterogeneities - on the micro-scale - determine micro-Cowling dynamos. Thus, a large beam of *FACs* splits into several micro-beams. These interact one another and finally attain an equilibrium that can be attained only when the cross-sections of the micro-*FACs* are aligned along the edges and at the vertices of an exact polygon. The phenomenon is similar to what happens inside the Earth, where sea-urchin spikes interact one another and finally determine the exact tetrahedron pattern (Gregori and Leybourne, 2021). The Earth's surface signature is represented by the planetary patterns of *MORs*, while the rotation of South America – and the Scotia arc - are likely to be caused by the kingpin in the Gulf of Mexico.

An additional effect is the rotation in opposite directions of co-axial polygons inside *FACs*. It is difficult to prove this by means of the Cowling dynamo alone, although this looks quite reasonable. The formal proof is the Don Scott (2015) treatment by means of plasma physics algorithms and Bessel functions. The Burn (2015) treatment is a pictorial representation of the Scott's finding.

Summarizing, the Cowling dynamo is a universal theorem that applies everywhere on every scale-size (from the micro-scale where it explains fog, rain, and the Svensmark effect), through the galactic superclusters. It is as universal as, say, the Pythagoras theorem. In contrast, *FACs* occur inside a specific environment, and the Cowling dynamo explains some observed features of *FACs*. However, self-confinement, filamentary structures, spiral pattern, and chirality (i.e., the symmetry between clockwise and counterclockwise spirals) are common features in the universe (see Gregori et al., 2025w).

Acknowledgements

We want to acknowledge all co-workers that, in different ways and at different times, contributed to the exploitation of the analyses mentioned in the present study. We like also to thank for the warm encouragement we had from several outstanding scientists.

Funding information

G.P. Gregori is retired since 2005. B.A. Leybourne is a semi-retired self-funded independent researcher.

Author's contributions

This study derived from a long-lasting cooperation by both authors. The backbone draft was prepared by the first author, although a large number of ideas resulted from the emergence of long lasting discussions.

Ethics

This article is original, and contains unpublished material. Authors declare that there are not ethical issues and no conflict of interest that may arise after the publication of this manuscript.

References

Allen, N.L., and A. Ghaffar, 1995. The conditions required for the propagation of a cathode-directed positive

streamer in air, *Journal of Physics, D: Applied Physics*, 28: 331–337

Anonymous, 2011n. Terrestrial gamma-ray flashes create antimatter, NASA, Goddard Media Studios, issued Jan 10, 2011

Anonymous, 2018f. Amazing Saturn photos from NASA's Cassini orbiter, Space.com, issued Apr 25, 2018

Anonymous, 2018v. First experimental evidence for superionic ice, Lawrence Livermore National Laboratory, issued Feb 6, 2018

Babaeva, N.Y., and G.V. Naidis, 1997. Dynamics of positive and negative streamers in air in weak uniform electric fields, *IEEE Transactions, Plasma Science*, 25: 375–379

Babich, L.P., 2003. High-Energy Phenomena in Electric Discharges in Dense Gases: Theory, Experiment and Natural Phenomena, vol. 2 of *ISTC Science and Technology Series*, Futurepast, Arlington, VA

Baginski, M.E., C.L. Hale, and J.J. Olivero, 1988. Lightning-related fields in the ionosphere, *Geophysical Research Letters*, 15: 764–767

Barrington-Leigh, C.P., and U.S. Inan, 1999. Elves triggered by positive and negative lightning discharges, *Geophysical Research Letters*, 26 (6): 683-686; DOI:10.1029/1999GL900059

Bell, T.F., V.P. Pasko, and U.S. Inan, 1995. Runaway electrons as a source of red sprites in the mesosphere, *Geophysical Research Letters*, 22 (16): 2127-2130; DOI:10.1029/95GL02239

Bhattacharya, A.B. and A. Nag, 2012. Influence of luminous structure on the lower ionosphere as derived from the responses of lightning activity, *International Journal of Engineering, Science and Technology*, 4 (06): 2510-2521

Boccippio, D.J., E.R. Williams, S.J. Heckman, W.A. Lyons, I.T. Baker, and R. Boldi, 1995. Sprites, ELF transients, and positive ground strokes. *Science*, 269 (5227), 1088-1091; DOI:10.1126/science.269.5227.1088

Brook, M., M. Nakano, P. Krehbiel, and T. Takeuti, 1982. The electrical structure of the Hokuriku winter thunderstorms, *Journal of Geophysical Research*, 87: 1207–1215

Brundell, J.B., R.L. Dowden, and C.J. Rodger, 1996. VLF emission associated with cloud-ionosphere discharges (CID), paper presented at 25th General Assembly, URSI, Lille, France

Burn, W., 2015. Polygonal crater formation by electrical discharges, *New Concepts in Global Tectonics, Journal*, 3 (2): 158-186

Cabassi, R., and N. Conti, (eds), 2007. International project Hessdalen Workshop 2006 (Proceedings), Lo Scarabeo Editrice, Bologna, pp: 1-192

Chalmers, J.A., 1954. Atmospheric electricity, *Reports on Progress in Physics*, 17 (1): 101-; DOI:10.1088/0034-4885/17/1/303

Chern, J.L., R.R. Hsu, H.T. Su, S.B. Mende, H. Fukunishi, Y. Takahashi, and L.C. Lee, 2003. Global survey of upper atmospheric Transient Luminous Events on the ROCSAT-2 satellite. Coulter, Dauna, 2010. Are TGFs

- hazardous to air travelers? *Science@NASA*, issued 02/10/2010
- Dejnakarintra, M., and C.G. Park, 1974. Lightning-induced electric fields in the ionosphere, *Journal of Geophysical Research*, 79: 1903–1910
- Eather, R.H., 1980. Majestic lights. *The Aurora in Science, History, and the Arts*. American Geophysical Union, Washington, D.C., pp: 1-323
- Farges, T., E. Blanc, A. Le Pichon, T. Neubert, and T.H. Allin, 2005. Identification of infrasound produced by sprites during the Sprite2003 campaign, *Geophysical Research Letters*, 32: L01813; doi:10.1029/2004GL021212
- Fisher, J.R., 1990. Upward electrical discharge above thunderstorms, *Weather*, 45: 451–452
- Fishman, G.J., P.N. Bhat, R. Mallozzi, J.M. Horack, T. Koshut, C. Kouveliotou, G.N. Pendleton, 1994. Discovery of intense gamma-ray flashes of atmospheric origin, *Science*, 164: 1313
- Fleming, J. A. (ed.), 1939. *Terrestrial Magnetism and Electricity*, McGraw-Hill Book Co., New York and London; pp: 1-794
- Fletcher, L.N., G.S. Orton, J.A. Sinclair, S. Guerlet, P.L. Read, A. Antuñano, R.K. Achterberg, F.M. Flasar, P.G.J. Irwin, G.L. Bjoraker, J. Hurley, B.E. Hesman, M. Segura, N. Gorius, A. Mamoutkine, and S.B. Calcutt, 2018. A hexagon in Saturn’s northern stratosphere surrounding the emerging summertime polar vortex, *Nature Communications*, 9 (1): article number 3564; DOI:10.1038/s41467-018-06017-3
- Fukui, Y., H. Yamamoto, M. Fujishita, N. Kudo, K. Torii, S. Nozawa, K. Takahashi, R. Matsumoto, M. Machida, A. Kawamura, Y. Yonekura, N. Mizuno, T. Onishi, and A. Mizuno, 2006. Molecular loops in the galactic center: evidence for magnetic flotation, *Science*, 314 (5796): 106-109; DOI:10.1126/science.1130425
- Gish, O.H., 1939. Atmospheric electricity. In J.A. Fleming, (ed.), *Terrestrial Magnetism and Electricity*, McGraw-Hill Book Co., New York and London, pp.: 149-230
- Gregori, G.P., 2002. Galaxy – Sun – Earth relations. The origin of the magnetic field and of the endogenous energy of the Earth, with implications for volcanism, geodynamics and climate control, and related items of concern for stars, planets, satellites, and other planetary objects. A discussion in a prologue and two parts. *Beiträge zur Geschichte der Geophysik und Kosmischen Physik*, 3 (3), 471 pp. [Available at <http://nctjournal.com/additional-resources.html>]
- Gregori, G.P., 2020. Climate change, security, sensors. *Acoustics*, 2: 474-504; DOI:10.3390/acoustics2030026 [<https://www.mdpi.com/2624-599X/2/3/26/html>]
- Gregori, G.P., and B.A. Leybourne, 2021. An unprecedented challenge for humankind survival. Energy exploitation from the atmospheric electrical circuit, *American Journal of Engineering and Applied Sciences*, 14 (2): 258-291; DOI:10.3844/ajeassp.2021.258.291
- Gregori, G. P., and B. A. Leybourne, 2025b. The electrostatic Sun. In press in *New Concepts in Global Tectonics, Journal*
- Gregori, G.P., and B.A. Leybourne, 2025e. The physics of electrical discharges – 1. Small-scale phenomena - Fog - atmospheric precipitation – BLs, present issue
- Gregori, G.P., and B.A. Leybourne, 2025f. The physics of electrical discharges – 2. RB & TGFs - Runaway breakdown – terrestrial gamma flashes – GK effect, present issue
- Gregori, G. P., and B. A. Leybourne, 2025l. Conclusion – Exploitation of the electrostatic energy of the atmosphere, *New Concepts in Global Tectonics, Journal*, 13, (2): 336-343
- Gregori, G.P., and S. Martellucci, 1992. MHD pulsed generators in Antarctica: man-made production of magnetospheric substorms, and underground surveying-proposals and perspectives. In M. Colacino, G. Giovannelli, and L. Stefanutti, (eds), 4th Workshop-Italian Research on Antarctic Atmosphere. *Conference Proceedings*, 35, Società Italiana di Fisica, Bologna, pp: 351-359
- Gregori, G. P., B. A. Leybourne, and F. F. Bonavia, 2025u. Symmetries and polygonal patterns: a reminder, *New Concepts in Global Tectonics, Journal*, 13, (5): 711-730
- Gregori, G. P., B. A. Leybourne, and F. F. Bonavia, 2025v. The origin of lavakas. *New Concepts in Global Tectonics, Journal*, 13, (5): 787-811
- Gregori, G. P., B. A. Leybourne, and G. Paparo†, 2025b. Introduction – Anomalous lesser air-earth phenomena. In press in *New Concepts in Global Tectonics, Journal*
- Gregori, G. P., B. A. Leybourne, and J. R. Wright, 2026d. Generalized Cowling theorem and the Cowling dynamo. In press in *New Concepts in Global Tectonics, Journal*
- Gregori, G. P., B. A. Leybourne, G. Paparo†, and M. Poscolieri, 2025a. The global Sun-Earth circuit. In press in *New Concepts in Global Tectonics, Journal*
- Gregori, G. P., B. A. Leybourne, U. Coppa, and G. Luongo, 2025t. Lightning and volcanic plumes. *New Concept of Global Tectonics*, 13, (6): 920-967
- Gregori, G. P., B. A. Leybourne, W. Soon, and V. Straser, 2025e. The heuristic meaning of variational principles. In press in *New Concepts in Global Tectonics, Journal*, 13, (6): 920-967
- Gregori, G. P., C. W. Monckton of Brenchley, W. Soon, R. Tattersall, A. D'Amico†, G. Zimatore, V. M. Velasco Herrera, B. A. Leybourne, and Z. A. Oziewicz†, 2022. The golden Ratio, variational principles, cyclic and wave phenomena, and Quanta. In H. M. Colin Garcia, J-de-J. Cruz Guzman, L. H. Kauffman, and H. Makaruk, (eds), *Scientific Legacy of Professor Oziewicz, selected papers from the International Conference “Applied Category Theory Graph-Operated-Logic”* held in honor of Professor Zbigniew Oziewicz in Memoriam (August 25th to 27th, 2021), World Scientific, Series on Knots and Everything; DOI:10.1142/9789811271151.0018: 363-389; <http://nctjournal.com/additional-resources.html>
- Gregori, G. P., F.F. Bonavia, and B. A. Leybourne, 2025x. Geoelectrical geology in North America, *New Concepts in Global Tectonics, Journal*, 13, (2): 252-269
- Gregori, G. P., M. T. Hovland, B. A. Leybourne, S. Pellis, V. Straser, B. G. Gregori, G. M. Gregori, and A. R.

- Simonelli, 2025w. Air-earth currents and a universal “law”: filamentary and spiral structures - Repetitiveness, fractality, golden ratio, fine-structure constant, antifragility and “statistics” - The origin of life, *New Concepts in Global Tectonics, Journal*, 3, (1): 106-225
- Gregori, G. P., W. Soon, V. Straser, and B. A. Leybourne, 2022a. Golden ratio, fractals, and the arrow of time. Irreversibility vs. reversibility - Space, time, antitime - The foundations of physics. *New Concepts in Global Tectonics, Journal*, 10 (3): 158-201
- Gurevich, A.V., G.M. Milikh, R.A. Rousse1-Dupré, 1992. Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm, *Physics Letters*, A165 (5/6): 463-468; DOI:10.1016/0375-9601(92)90348-P
- Hare, B.M., O. Scholten, J. Dwyer, T.N.G. Trinh, S. Buitink, S. ter Veen, A. Bonardi, A. Corstanje, H. Falcke, J.R. Hörandel, T. Huege, P. Mitra, K. Mulrey, A. Nelles, J.P. Rachen, L. Rossetto, P. Schellart, T. Winchen, J. Anderson, I.M. Avruch, M.J. Bentum, R. Blaauw, J.W. Broderick, W.N. Brouw, M. Brügger, H.R. Butcher, B. Ciardi, R.A. Fallows, E. de Geus, S. Duscha, J. Eislöffel, M.A. Garrett, J.M. Grießmeier, A.W. Gunst, M.P. van Haarlem, J.W.T. Hessels, M. Hoefl, A.J. van der Horst, M. Iacobelli, L.V.E. Koopmans, A. Krankowski, P. Maat, M.J. Norden, H. Paas, M. Pandey-Pommier, V.N. Pandey, R. Pekal, R. Pizzo, W. Reich, H. Rothkaehl, H.J.A. Röttgering, A. Rowlinson, D.J. Schwarz, A. Shulevski, J. Sluman, O. Smirnov, M. Soida, M. Tagger, M.C. Toribio, A. van Ardenne, R.A.M.J. Wijers, R.J. van Weeren, O. Wucknitz, P. Zarka, and P. Zucca, 2019. Needle-like structures discovered on positively charged lightning branches, *Nature*, 568 (7752): 360–363; DOI:10.1038/s41586-019-1086-6
- Huang, E., E. Williams, R. Boldi, S. Heckman, W. Lyons, M. Taylor, T. Nelson, and C. Wong, 1999. Criteria for sprites and ELVES based on Schumann resonance observations, *Journal of Geophysical Research*, 104: 16,943-16,964
- İnan, U. S., A. Slingeland, V.P. Pasko, and J. Rodriguez, 1996b. VLF and LF signatures of mesospheric/lower ionospheric response to lightning discharges, *Journal of Geophysical Research*, 101: 5219-5238
- İnan, U.S., C. Barrington-Leigh, S. Hansen, V.S. Glukhov, and T.F. Bell, 1997. Rapid lateral expansion of optical luminosity in lightning-induced ionospheric flashes referred to as 'Elves', *Geophysical Research Letters*, 24 (5): 583-586
- İnan, U.S., S.C. Reising, G.J. Fishman, and J.M. Horack, 1996c. On the association of terrestrial gamma-ray bursts with lightning and implication for sprites, *Geophysical Research Letters*, 23 (9): 1017-1020; DOI:10.1029/96GL00746
- İnan, U.S., V.P. Pasko, and T.F. Bell, 1996a. Sustained heating of the ionosphere above thunderstorms as evidenced in “early/fast” events. *Geophysical Research Letters*, 23 (10): 1067-1070
- İnan, U.S., W.A. Sampson, and Y.N. Taranenko, 1996. Space-time structure of optical flashes and ionization changes produced by lightning-EMP, *Geophysical Research Letters*, 23: 133–136
- Krider, E.P., and R.G. Roble, (eds), 1986. *The Earth's Electrical Environment*. National Academy Press, Washington, D.C.; DOI:10.17226/898, pp.:1-263
- Kulikovskiy, A.A., 2000. The role of photoionization in positive streamer dynamics, *Journal of Physics D: Applied Physics*, 33: 1514–1524
- Leibniz Institute for Astrophysics Potsdam*, 2023. Riding the cosmic wave: how plasma instability is changing our view of the universe, *SciTechDaily*, issued December 15, 2023
- Leybourne, B. A., D. W. Johnson, and G. P. Gregori, 2025. Arc-blast as static electricity or interplanetary lightning short circuits in Stellar Transformers. A plausible North American scenario, *New Concepts in Global Tectonics, Journal*, 13, (2): 229-251
- Liu, N., and V.P. Pasko, 2004. Effects of photoionization on propagation and branching of positive and negative streamers in sprites, *Journal of Geophysical Research*, 109: A04301; DOI:10.1029/2003JA010064
- Lundquist, S., 1950. Magneto-hydrostatic fields. *Arkiv för fysik*, 2: 361-365
- Lundquist, S., 1951. On the stability of magneto-hydrostatic fields. *Physical Review*, 83 (2): 307–311; DOI:10.1103/PhysRev.83.307
- Lyons, W.A., 1994. Characteristics of luminous structures in the stratosphere above thunderstorms as imaged by low-light video, *Geophysical Research Letters*, 21 (10): 875-878
- Lyons, W.A., 1997. Sprites, ELVES, and blue jets, *Weatherwise*, 50 (4): 19-23; DOI:10.1080/00431672.1997.9926060
- MacGorman, D.R., and W.D. Rust, 1998. *The Electrical Nature of Storms*, Oxford University Press, Oxford and New York, pp.:1-422
- Malone, T.F., (ed.), 1951. *Compendium of Meteorology*, American Meteorological Society, Boston, pp.: 1-1334
- Mason, B.J., 1971. *The Physics of Clouds*, II ed., Clarendon Press, Oxford, pp.: 1-688
- Mason, B.J., 1972. The Bakerian lecture, 1971. The physics of thunderstorm, *Proceedings of the Royal Society*, A327: 433-466
- Mason, B.J., 1976. In reply to a critique of precipitation theories of thunderstorm electrification by C.B. Moore, *Quarterly Journal of the Royal Meteorological Society*, 102: 219-240
- Mathewson, S., 2017c. Backup lightning imaging sensor to finally get its day in space, *Space.com*, issued February 17, 2017
- Miville-Deschênes, M.-A. (ESA/Planck Collaboration), 2014. The magnetic field along the Galactic plane, *ESA, Space in images*, issued 15/12/2014, retrieved March 13, 2015
- Moore, C.B., 1974. An assessment of thundercloud electrification mechanisms. Fifth International Conference on Atmospheric Electricity Garmisch-Partenkirchen, September 2-7, 1974, pp.: 1–21+ill.

- Moore, C.B., 1976. Reply to B.J. Mason "In reply to a critique of precipitation theories of thunderstorm electrification by C.B. Moore", *Quarterly Journal of the Royal Meteorological Society*, 102: 219-240
- Moore, C.B., and B. Vonnegut, 1977. The thundercloud. In R. H. Golde, (ed.), *Lightning I: Physics of Lightning*, Academic Press, London, pp. 51-98
- Morrill, J., E. Bucseila, C. Sierfing, M. Heavner, S. Berg, D. Moudry, S. Slinker, R. Fernsler, E. Wescott, D. Sentman, and D. Osborne, 2002. Electron energy and electric field estimates in sprites derived from ionized and neutral N₂ emissions, *Geophysical Research Letters*, 29: 1462; DOI:10.1029/2001GL014018
- Morris, M., 2006. Galactic prominences on the rise, *Science*, 314 (5796): 70-71; [DOI:10.1126/science.1133500]
- Neubert, T., 2003. On sprites and their exotic kin, *Science*, 300: 747-749
- Nisa, M.U., J.F. Beacom, S.Y. BenZvi, R.K. Leane, T. Linden, K.C.Y. Ng, A.H.G. Peter, and B. Zhou, 2019. The Sun at GeV-TeV energies: a new laboratory for astroparticle physics, arXiv:1903.06349 [astro-ph.HE]
- Orville, R.E., and K. Berger, 1973. An unusual lightning flash initiated by an upward-propagating leader, *Journal of Geophysical Research*, 78: 4520-4525
- Pasko, V.E., M.A. Stanley, J.D. Mathews, U.S. Inan, and T.G. Woods, 2002. Electrical discharge from a thunderstorm top to the lower ionosphere. *Nature*, 416:152-154
- Pasko, V.P., U.S. Inan, and T.F. Bell, 1997a. Sprites as evidence of vertical gravity wave structures above mesoscale thunderstorms, *Geophysical Research Letters*, 24: 1735-1738
- Pasko, V.P., U.S. Inan, and Y.N. Taranenko, 1997. Sprites produced by quasi-electrostatic heating and ionization in the lower ionosphere. *Journal of Geophysical Research*, 102 (3): 4529-4562
- Pasko, V.P., U.S. Inan, Y.N. Taranenko, and T.F. Bell, 1995. Heating, ionization and upward discharges in the mesosphere due to intense quasi-electrostatic thundercloud fields. *Geophysical Research Letters*, 22 (4): 365-368
- Peratt, A.L., J. McGovern, A.H. Qoyawayma, M.A. Van der Sluijs, and M.G. Peratt, 2007. Characteristics of a high-current, Z-Pinch aurora as recorded in antiquity, Part II, Directionality and source. *IEEE Transactions Plasma Science*, 35, (4), 778 - 807; DOI:10.1109/TPS.2007.902630
- Petrie, W., 1963. *Keoeit, The Story of the Aurora Borealis*, Pergamon Press, Oxford, etc. pp.: 1-134
- Poppick, L., 2014. Stunning lightning above Mideast seen from space (photo), *Space.com*, issued March 24, 2014
- Quinn, J. M.,† G. P. Gregori, and B. A. Leybourne, 2026. Satellite monitoring of air-earth currents. In press in *New Concepts in Global Tectonics, Journal*
- Raizer, Y.P., 1991. *Gas discharge physics*, [Translated from the Russian original published by Nauka, Moscow, in 1987], Springer, Berlin; ISBN 3-540-19462-2. pp.: 1-449
- Roble, R.G., and I. Tzur, 1986. The global atmospheric-electrical circuit. In E.P. Krider, and R.G. Roble, (eds), *The Earth's electrical environment*, National Academy Press, Washington, D.C.; DOI:10.17226/898, pp.: 206-231
- Roussel-Dupré, R., and A.V. Gurevich, 1996. On runaway breakdown and upward propagating discharges, *Journal of Geophysical Research*, 101, 2297-2312
- Rüdiger, G., and R. Hollerbach, 2004. *The Magnetic Universe – Geophysical and Astrophysical Dynamo Theory*, Wiley-VHC Verlag GmbH & Co. KGaA, pp.: 1-332
- Rycroft, M.J., 2007. Introduction to the physics of sprites, ELVES and intense lightning discharges. In M. Füllekrug, E.A. Mareev, and M.J. Rycroft (eds), *Sprites, ELVES and Intense Lightning Discharges*, Proceedings of the NATO Advanced Study Institute, Corte, Corsica, France, 24-31 July 2004, Springer, Berlin; DOI:10.1007/1-4020-4629-4 2007, pp.: 1-13
- Salanave, L.E., 1980. *Lightning and Its Spectrum. An Atlas of Photographs*. The University of Arizona Press, Tucson, Arizona, pp.: 1-136
- Savtchenko, A., and R. Mitzeva, 2007. Sprites and parent thunderstorms. In *Proceedings of the Black Sea School on Plasma Physics, Kiten, July 1-9, 2006 [Bulgarian Summer School on Plasma Physics]* I. Zhelyazkov (ed.), BSSPP Proceedings, Series No. 1, pp.: 115-128
- Schonland, B.F.J., 1937. The diameter of the lightning channel, *Philosophical Magazine*, 23: 503-508
- Schonland, B.F.J., 1939. Thunder-clouds, shower-clouds, and their electrical effects. In J.A. Fleming, (ed.), *Terrestrial Magnetism and Electricity*, McGraw-Hill Book Co., New York and London, pp.: 657-678
- Schonland, B.F.J., 1956. The lightning discharge, *Handbuch der Physik*, 22: 576-628
- Scott, D.E., 2015. Birkeland currents: a force-free field-aligned model. *Progress in Physics*, 11 (2): 167-179
- Sentman, D.D., and E.M. Wescott, 1993. Video observations of upper atmospheric optical flashes recorded from an aircraft. *Geophysical Research Letters*, 20 (24): 2857-2860
- Shalaby, M., R. Lemmerz, T. Thomas, and C. Pfrommer, 2022. The mechanism of efficient electron acceleration at parallel non-relativistic shocks. arXiv:2202.05288
- Shalaby, M., T. Thomas, and C. Pfrommer, 2021. A new cosmic-ray-driven instability, *The Astrophysical Journal*; DOI:10.3847/1538-4357/abd02d
- Shalaby, M., T. Thomas, C. Pfrommer, R. Lemmerz, and V. Bresci, 2023. Deciphering the physical basis of the intermediate-scale instability, *Journal of Plasma Physics*; DOI:10.1017/S0022377823001289
- Shercliff, J.A., 1965. *A Textbook of Magneto-hydrodynamics*, Pergamon Press, Oxford, pp.: 1-265
- Siingh, D., A.K. Singh, R.P. Patel, R. Singh, R.P. Singh, B. Veenadhari, and M. Mukherjee, 2008. Thunderstorms, lightning, sprites and magnetospheric whistler-mode radio waves, *Surveys in Geophysics*, 29 (6): 499-551; DOI:10.1007/s10712-008-9053-z
- Siingh, D., and R.P. Singh, 2010. The role of cosmic rays in the Earth's atmospheric processes, *PRAMANA*,

- Indian Academy of Science, Journal of Physics, 74 (1): 153-168
- Stenbaek-Nielsen, H.C., D.R. Moudry, E.M. Wescott, D. D. Sentman, and F.T. Sao Sabbas, 2000. Sprites and possible mesospheric effects, *Geophysical Research Letters*, 27: 3829–3832
- Sukhorukov, A.I., E.A. Rudenichik, and P. Stubbe, 1996. Simulation of the strong lightning pulse penetration into the lower ionosphere, *Geophysical Research Letters*, 23: 2911–2914
- Thomas, J.N., R.H. Holzworth, M.P. McCarthy, and O. Pinto Jr., 2005b. Predicting lightning driven quasi-electrostatic fields at sprite altitudes using in situ measurements and a numerical model, *Geophysical Research Letters*, 32: L10809; DOI:10.1029/2005GL022693
- Tully, R.B., H. Courtois, Y. Hoffman, and D. Pomarède, 2014. The Laniakea supercluster of galaxies, *Nature*, 513: 71–73; DOI:10.1038/nature13674
- Uman, M.A., 1969. *Lightning*, McGraw-Hill, New York, pp: xvi + 272
- Uman, M.A., 1987. *The Lightning Discharge*. Academic Press, Orlando, etc., pp.: 1-377
- Volland, H., 1984. *Atmospheric Electrodynamics*, Springer-Verlag, Berlin, etc.; DOI:10.1007/978-3-642-69813-2, pp.: 1-193
- Vonnegut, B., 1963. Some facts and speculations concerning the origin and role of thunderstorm electricity, *Meteorological Monographs*, 5 (27): 224-241
- Vonnegut, B., 1965. Thunderstorm electricity, *Discovery*, 26: 12-17
- Wescott, E.M., D.D. Sentman, M.J. Heavner, D.L. Hampton, D.L. Osborne, and O.H. Vaughan, 1996. Blue starters: brief upward discharges from an intense Arkansas thunderstorm, *Geophysical Research Letters*, 23: 2153–2156
- Wilson, C.T.R., 1925. The electric field of a thundercloud and some of its effects, *Proceedings of the Physical Society of London*, 37: 32D-37D
- Wilson, C.T.R., 1916. On some determinations of the sign and magnitude of electric discharges in lightning flashes, *Proceedings of the Royal Society, London*, A92: 555-574
- Wilson, C.T.R., 1920. Investigations on lightning discharges and on the electric field of thunderstorms, *Philosophical Transactions of the Royal Society of London*, A221: 73-115
- Wilson, C.T.R., 1923. Atmospheric Electricity. In Sir R. Glazebrook, (ed.), *Dictionary of Applied Physics*, (5 vol.), III. Meteorology, Metrology; Macmillan, London, pp.: 84-117
- Wilson, C.T.R., 1924. *Proceedings of the Cambridge Philosophical Society*, 22: 34-
- Winckler, J.R., W.A. Lyons, T.E. Nelson, and R.J. Nemzek, 1994. New high-resolution ground-based studies of sprites, *Journal of Geophysical Research*, 101: 6997–7004
- Wolchover, N., 2022. The Sun is Stranger than Astrophysicists Imagined, *Quanta Magazine*

Acronyms

- AGN - Active Galactic Nucleus
- BL - ball lightning
- CC - cloud-cloud, synonymous of IC (lightning or discharge)
- CCP - cubic close packing
- CG - cloud-ground (lightning or discharge)
- CGRO - Compton Gamma Ray Observatory
- CIRS - Composite Infrared Spectrometer
- CMB - core-mantle boundary
- EAS - extensive atmospheric showers
- EGD - electro-gas-dynamics
- EHD - electrohydro-dynamics
- ELVES - Emission of Light and Very Low Frequency perturbations due to Electromagnetic Pulse Sources
- EMP - lightning e.m. pulse
- ESI - electric soldering iron (mechanism)
- FAC - field-aligned current, also known as Birkeland currents
- GK - Gurevich and Karashtin (effect)
- GRF - gamma ray flash (also known as TGF or TGB)
- HCP - hexagonal close packing
- HLA - Hubble Legacy Archive
- IC - intra-cloud, synonymous of CC (lightning or discharge)
- ISS - International Space Station
- ITCZ - Intertropical Convection Zone
- MCS - mesoscale convective system
- MGD - magneto-gas-dynamics
- MHD - magneto-hydro-dynamics
- MOR - Mid-Ocean Ridge
- NLDN - National Lightning Detection Network
- NPSV - North polar stratospheric vortex (on Saturn)
- QE - quasi-electrostatic (field)
- RB - runaway-breakdown (process)
- TD - tide-driven (dynamo)
- TGB - terrestrial gamma burst (also known as TGF or GRF)
- TGF - terrestrial gamma flash (also known as GRF or TGB)
- TLE - transient luminous event

The Fukushima theorem

Giovanni Pietro Gregori¹, Bruce Allen Leybourne²

¹ IDASC-Istituto di Acustica e Sensoristica O. M. Corbino (CNR), Roma, now merged into IMM-Istituto per la Microelettronica e Microsistemi (CNR), Italy, and ISSO-International Seismic Safety Organization, Italy

²GeoPlasma Research Institute-(GeoPlasmaResearchInstitute.org), Aurora, CO 80014, USA

Corresponding Author:

Giovanni Pietro Gregori
IDASC-Istituto di Acustica e Sensoristica O. M. Corbino (CNR), Roma, now merged into IMM-Istituto per la Microelettronica e Microsistemi (CNR) Italy

e-mail:

giovannipgregori38@gmail.com;
leybourneb@iascc.org

Abstract: Since the end of the 19th century, a dichotomy existed about the pattern of electric currents \mathbf{j} that originate the transient variations of the geomagnetic field. The most fashionable model - now called Chapman-Vestine's \mathbf{j} -system - envisaged \mathbf{j} flowing only inside the ionosphere. The alternate model relied on \mathbf{j} aligned with the field-lines of the geomagnetic field \mathbf{B} . In 1967 the Fukushima theorem proved that it is impossible to distinguish the two systems by means of ground-based records alone. *In situ* measurements are required, while the two systems can coexist.

Keywords: Chapman-Vestine currents - Birkeland-Alfvén currents – field aligned currents in space – currents in the Earth's interior

Introduction

The concern is about the pattern of the electric currents \mathbf{j} that are responsible for the variations of the geomagnetic field, observed either at Earth's surface or in the atmosphere and/or in outer space. Owing to the Fukushima theorem, this topic has now a mainly historical interest. Since the time of earliest discussion, a basic dichotomy existed between \mathbf{j} -loops flowing over approximately spherical geocentric shells in the ionosphere (Chapman-Vestine's \mathbf{j} -system) vs. \mathbf{j} that are aligned along geomagnetic field-lines, i.e., FACs (Birkeland-Alfvén's \mathbf{j} -system).

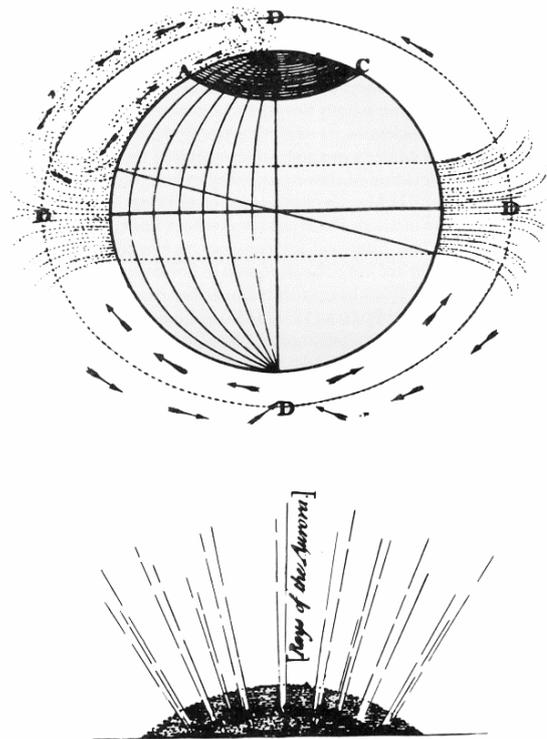
The early speculations favored Birkeland-Alfvén's (Fig. 1). Balfour Stewart (1882) is reported as the classical precursory reference to Chapman-Vestine's.

Interplanetary space was believed to be empty (see Gregori and Leybourne, 2025b). Hence, the Chapman-Vestine system seemed more credible, because no hypothesis could be envisaged capable to close eventual circuits that included field-aligned \mathbf{j} . Thus, Chapman-Vestine's was considered more credible, as it is extensively reviewed, e.g., by the classical Chapman and Bartels (1940). However, after the formulation in 1958 – and proof of correctness by *in situ* records – of the expanding solar corona and of the Parker spiral structure of the interplanetary magnetic field (*IMF* or \mathbf{B}_{int}), the Birkeland-Alfvén's \mathbf{j} -system became relevant again.

In September 1967 a vivid debate characterized a meeting at Sandefjord, in the Oslo fjord. Shortly afterwards Naoshi Fukushima (1925-2003) showed what was later called the "*Fukushima theorem*".

He proved that, when we can rely on ground-based magnetic records alone, it is conceptually impossible to distinguish either one kind of \mathbf{j} -system from the other. That is, both kinds of speculated \mathbf{j} -patterns are equally valid. Therefore, we need for space-borne measurements in order to envisage the rationale that is better suited to describe every given natural occurrence. The references

papers are Fukushima (1972, 1989), while a detailed account of the early generation of this achievement is given in Fukushima (1976a, 1976b).



Benjamin Franklin, *Philosophical Pieces*. London 1779

Fig. 1. In April 1779, Benjamin Franklin (1706-1790) presented in Paris, before the *Académie Française*, a theory of polar aurorae (which had already been anticipated in the treatise by Dortous de Mairan; it had been published in 1749). But, a similar idea dated back to Sir Edmond Halley (1656-1742). A "remarkably similar" theory had been presented in 1753 at the *St. Petersburg Academy* by Mikhail Vasil'evich Lomonosov (1711-1765), who was much involved in studying polar aurorae and had planned a three volume set on them. The idea of an ionized medium in the upper atmosphere arose much later. See Chapman (1967), Silverman (1970), and Eather (1980). The image is original by Benjamin Franklin, who died in 1790. Hence, the copyright decayed.

The original proof relied on some simplifying assumptions. Several details are given below, including additional related historical items. Instead, the discussion is here made in terms of a generalized approach. A separate section illustrates the historical development of the entire argument.

An unprecedented application of the Fukushima theorem deals with the j -systems inside deep Earth. This item is discussed in some detail, and a short final section summarizes the conclusions.

The general proof

Approach the problem in an abstract way. Compared to its original formulation - which is illustrated below - the argument is here tackled in a generalized form. G. P. Gregori discussed it, while spending several hours on a nice Sunday in Exeter (UK) in 1989 with the late Professor Naoshi Fukushima, an absolutely most pleasant and very kind friend and gentleman. He definitely liked this argument, and he made one astute additional remark, which however G. P. Gregori later unduly forgot. More recently, with deep sorrow, we knew that Professor Naoshi Fukushima (1925-2003) had passed away on 25 June 2003 (Kamide, 2006).

G. P. Gregori considers Professor Fukushima as one of the most brilliant minds of entire Space Age. It should be stressed that he very modestly liked to emphasize that he had a comparatively limited number of published papers. Maybe, owing to this reason, his papers are always stimulating. G. P. Gregori always learned true genuine and astute physics from reading his understating discussions. The modern "publish or perish" rush - complained by Einstein - should probably be reconsidered upon reflecting on the way the Fukushima theorem was understood and accepted vs. several present uncritical references to consensus science that seemingly has no concern while accepting paradoxes.

A surface Σ (Fig. 2) divides space into two parts, which can be arbitrarily called, respectively, "external" or "e" and "internal" or "i". In addition, suppose that no j crosses Σ . Every Σ of this kind is, however, unrealistic, as every real physical surface must always deal with a finite space domain. Hence, Σ cannot be extended up to infinity.



Fig. 2. A surface Σ divides space in two parts, conventionally denoted as "external" $[e]$ and "internal" $[i]$, respectively. The choice is arbitrary while defining what is "external" and what "internal". Unpublished figure.

Since the system must contain closed j -loops, it is reasonable to refer to a closed Σ .¹ In addition, there is no physical reason to hypothesize any kind of complicated topological structure. Hence, we should consider rather Fig. 3, where the notion of "e" and "i" is obvious. However, in the following a perfect symmetry exists. Hence, with no loss of generality, one can indifferently exchange the location of "e" and "i". In any case, it is supposed that it is impossible to connect any point of "e" with any point of "i", unless the track crosses Σ at least once. Let me just claim that the side "e", unlike the side "i", contains the point at infinity.²



Fig. 3. Every surface Σ must be closed as no part of it can be at infinity. The notion of "external" and "internal" is obvious. Unpublished figure.

Consider Fig. 4. We observe $B(t)$ at some given point that is located somewhere on the surface Σ . We know that $B(t)$ is the result of the vector sum of a $B^{(e)}(t)$ originated by all $j^{(e)}$ -systems that flow inside "e", plus the field $B^{(i)}(t)$ generated by all $j^{(i)}$ -systems that flow inside "i", i.e., it is $B(t) = B^{(e)}(t) + B^{(i)}(t)$.

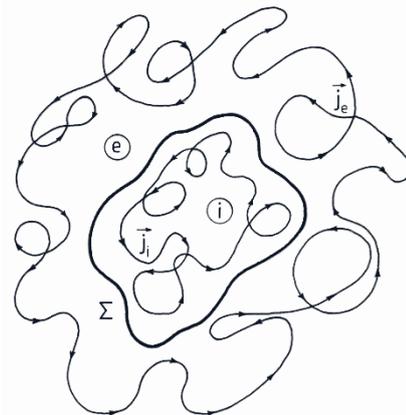


Fig. 4. Two ensembles of j -loops flow either inside the "external" or inside the "internal" subdomain of space. No j can cross through Σ . Hence, every j -loop must entirely flow inside one subdomain. For simplicity, the figure shows only one arbitrary and general j -loop of either one subdomain. The observed B is the sum of an internal and an external origin part, i.e., $B(t) = B^{(e)}(t) + B^{(i)}(t)$. Unpublished figure.

In the following, when dealing with any kind of $B(t)$, we suppose that reference is made only to a $B(t)$ that varies in time with one given pre-assigned frequency ν . However, for brevity purpose, in the following the frequency ν is not explicitly indicated in mathematical symbols.

Since no j crosses Σ , every $j^{(e)}$ -loop can be connected with no $j^{(i)}$ -loop. For simplicity, Fig. 4 shows only one $j^{(e)}$ -

¹ In reality, the following argument can also be adapted to the case history of an open Σ covered by closed j -loops, although the case history of a closed Σ is more expressive in terms of analogy with the Earth.

² Note that, in the case of an open Σ , one could connect j -loops in "e" with j -loops in "i", although by some line that gets out of the border of Σ . This refers to a condition that, even approximately, can never be applied to the real Earth.

loop and one $\mathbf{j}^{(i)}$ -loop, while in reality one should consider some very large number of mutually non-connected loops on either side of Σ .

In addition, owing to \mathbf{j} conservation, i.e., owing to $\text{div } \mathbf{j} = 0$, all \mathbf{j} -loops contained inside "e" (or analogously all \mathbf{j} -loops inside "i") can never intersect one another. Every \mathbf{j} -loop, either inside "e" or inside "i", can have any general shape, although the system must satisfy Maxwell's equations - and, in particular, the role of the Hamilton's variational principle (see Gregori et al., 2025e), i.e., every \mathbf{j} -loop must expand in space as much as possible, compatibly with the interaction with other \mathbf{j} -loops.

In general, the only one $\mathbf{j}^{(e)}$ -loop and only one $\mathbf{j}^{(i)}$ -loop that are drawn in Fig. 4 are not stationary. Rather, they can even very rapidly change morphology vs. time. The change can involve both shape and cross-section, where - according to a representation in terms of continuous functions - the "cross-section" of a \mathbf{j} -loop conventionally indicates the \mathbf{j} intensity.

Suppose that we afford to separate $\mathbf{B}^{(e)}(t)$ and $\mathbf{B}^{(i)}(t)$ at every point on Σ . The concern is about the uniqueness of the inferred \mathbf{j} -loops that - either on the "e" side or on the "i" side - originate the observed $\mathbf{B}^{(e)}(t)$ and $\mathbf{B}^{(i)}(t)$, respectively. This problem is called the "inversion problem". It is well-known that the main concern of every classical inversion problem is about the non-uniqueness of the solution, unless some very special circumstances are satisfied.

Identify Σ with the Earth's surface, which is supposed - at least for the time being (see Gregori et al., 2025a) - to be crossed by no \mathbf{j} . The field $\mathbf{B}^{(e)}(t)$ is generated by \mathbf{j} -loops that flow in the solar wind, and/or in the magnetosphere, and/or in the ionosphere. The field $\mathbf{B}^{(i)}(t)$ is generated by the currents \mathbf{j} underground, originated by electromagnetic (e.m.) induction and called "telluric currents", plus by the \mathbf{j} -loops of the deep geodynamo (refer to Gregori, 2002 or Gregori and Leybourne, 2021 or Gregori et al., 2025a).

The induced telluric currents \mathbf{j} flow only inside some shallow layer of limited thickness. The thickness depends on frequency. In fact, all currents - which are induced underground and that flow above some given depth - quench the impinging signal that is thus progressively weakened vs. depth. This is the classical skin depth effect, by which higher frequencies are comparatively more rapidly quenched while crossing the shallower layers. The skin depth is defined as the depth at which the inducing external signal is damped by a factor $1/e$ (where e is the Euler's constant).

Consider first (as it is usually done) an Earth's model composed of concentric layers, i.e., a model that reminds about an onion. Only signals of some very low frequency - corresponding to periods, say, $T \gg 22 \text{ years}$ - afford to penetrate through the mantle, and in this way they afford to control the efficiency of the tide driven (TD) dynamo, which originates a large fraction of (or maybe even entirely) the endogenous energy budget of the Earth (see Gregori, 2002, Gregori and Leybourne, 2021 or Gregori et al., 2025a).

However, also the crucial role must be considered of the sea-urchin spikes, because they act like antennas that ensure an effective e.m. coupling between the external \mathbf{j} and the deep Earth's structures. The e.m. coupling is quite effective, therefore, even at comparatively much higher frequency than the frequency permitted by skin depth inside the "onion" Earth.

The discussion, which is here of concern, deals with comparatively high frequencies (say with $T < a \text{ few days}$), and with the telluric currents \mathbf{j} that flow within some comparatively shallow layer of Earth. Differently stated, for these frequencies the $\mathbf{B}(t) = \mathbf{B}^{(e)}(t) + \mathbf{B}^{(i)}(t)$ penetrates only into some limited outer layer of the Earth. In addition, the role of the aforementioned sea-urchin spikes ought to be taken into account, and it can result to play a different role at different sites at Earth's surface, depending on the location of the spikes (see Gregori, 2002, Gregori and Leybourne, 2021, or Gregori et al., 2025a).

Consider the $\mathbf{j}^{(e)}$ -system, and represent the ionosphere by a 2D sheet formally defined by a surface Σ' that envelops the Earth (Fig. 5). For a moment, first suppose that the ionosphere is not penetrated by $\mathbf{B}(t) = \mathbf{B}^{(e)}(t) + \mathbf{B}^{(i)}(t)$. For simplicity - and with no loss of generality - let us refer to one unique $\mathbf{j}^{(e)}$ -loop that drops on top of Σ' at a point A, and it leaves it at a point B.

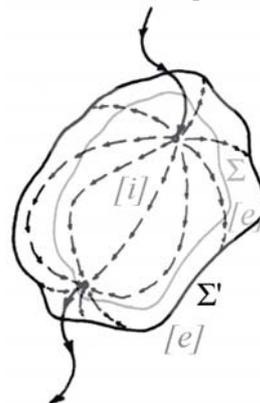


Fig. 5. A surface Σ' envelops the Earth, and it has some given finite and eventually inhomogeneous electrical conductivity σ . Only one external \mathbf{j} is here indicated that drops on Σ' at a point A (upper side), and leaves it at a point B (lower side). Unpublished figure.

Consider Fig. 6, which is identical to Fig. 5, except that the ionosphere is now represented by a surface Σ'' that has an electrical conductivity $\sigma \rightarrow \infty$. Equivalently, as it is often unrealistically done, the ionosphere is supposed to be a perfect equipotential surface. For the time being, suppose that these assumptions are reasonably close to natural reality, although this physically compulsory assumption must be dropped at a subsequent step of the present proof.

The pattern of Fig. 6, which is briefly called (a)-system, is identically repeated in Figs 7a and 7b. Add to this (a)-system the null pattern represented by Fig. 7c, which is called (c)-system. The sum of the two patterns $[(b) + (c)]$ -system can be formally represented as the sum $[(d) + (e)]$ -system, represented in Figs 7d and 7e, respectively. In addition, if a (g)-system is formally defined by reversing every \mathbf{j} within the (e)-system, i.e., if $[(g)\text{-system}] = - [(e)\text{-system}]$, it is inferred that (see Figs 7f and 7g)

$$\begin{aligned} (a)\text{-system} &\equiv [(b)+(c)]\text{-system} \equiv & (1) \\ &\equiv [(d)+(e)]\text{-system} \equiv [(f)-(g)]\text{-} \\ &\text{system} \end{aligned}$$

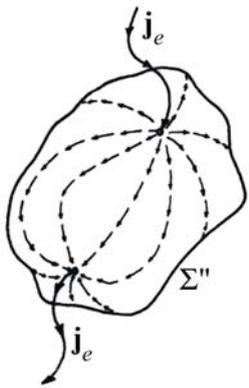


Fig. 6. The same as Fig. 5 except that the surface Σ'' is identical to Σ' having, however and unlike in Fig. 5, everywhere $\sigma \rightarrow \infty$. Unpublished figure.

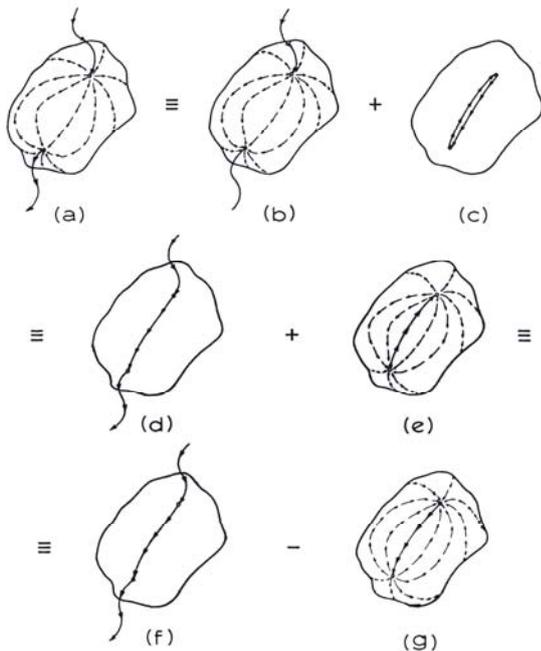


Fig. 7. All systems flow on Σ'' with $\sigma \rightarrow \infty$. Both Figs (a) and (b) are identical to Fig. 6, while (c) is a null \mathbf{j} -system, always flowing over Σ'' . Hence, the \mathbf{j} -system (a) can be represented as the sum of the (b) and (c) systems, or as the difference between the (f) and (g) systems. See text. Unpublished figure.

However, suppose that we carry out measurements of $\mathbf{B}(t) = \mathbf{B}^{(e)}(t) + \mathbf{B}^{(i)}(t) \equiv \mathbf{B}^{(e)}(t)$ at Earth's surface. In fact, if we suppose that the Earth's surface is an ideal perfect conductor, the Earth's surface is an efficient Faraday's screen. Hence, for an observer located at Earth's surface, it is $\mathbf{B}^{(i)}(t) = 0$. It should be stressed that, as already mentioned, we refer only of a \mathbf{B} associated to one given and prechosen frequency alone.

Alternatively, one can suppose that the observer at Earth's surface has carried out the separation between $\mathbf{B}^{(i)}(t) = 0$ and $\mathbf{B}^{(e)}(t)$, and thus the observer can refer only to $\mathbf{B}^{(e)}(t)$ alone.

In the following identify $\mathbf{B}(t) = \mathbf{B}^{(e)}(t) + \mathbf{B}^{(i)}(t) \equiv \mathbf{B}^{(e)}(t)$ with $\mathbf{B}^{(a)}(t) = \mathbf{B}^{(a,e)}(t) + \mathbf{B}^{(a,i)}(t) \equiv \mathbf{B}^{(a,e)}(t)$ where (a) has the same meaning as in

Fig. 7a. Since we supposed that Σ'' is an ideal conductor, i.e., a perfect e.m. screen, it must be $\mathbf{B}^{(a)}(t) = \mathbf{B}^{(a,e)}(t) + \mathbf{B}^{(a,i)}(t) \equiv \mathbf{B}^{(a,e)}(t)$. Hence, equivalently

$$\mathbf{B}^{(a)}(t) = \mathbf{B}^{(b,e)}(t) + \mathbf{B}^{(c,e)}(t) \equiv \mathbf{B}^{(b,e)}(t) + \mathbf{B}^{(e,e)}(t) \equiv \mathbf{B}^{(f,e)}(t) - \mathbf{B}^{(g,i)}(t) \equiv 0 \quad (2)$$

$$\mathbf{B}^{(f,e)}(t) \equiv \mathbf{B}^{(g,i)}(t) \quad (3)$$

In fact (3) proves the Fukushima theorem, although in the case of an ionosphere that is an equipotential surface, i.e., with $\sigma \rightarrow \infty$.

Consider, instead of Fig. 5, the case of Fig. 6, i.e., consider an ionosphere having a finite σ . Hence, we deal with the surface Σ'' rather than with Σ' . The previous argument applies if the observed $\mathbf{B}^{(a)}(t) = \mathbf{B}^{(a,e)}(t) + \mathbf{B}^{(a,i)}(t) \equiv 0$.

In contrast, suppose that the measured $\mathbf{B}^{(a)}(t) = \mathbf{B}^{(a,e)}(t) + \mathbf{B}^{(a,i)}(t) \neq 0$. Suppose for a moment that we know the actual \mathbf{j} -system that impinges on Σ' and flows over it. That is, suppose that we know - and we can draw - the (h)-system shown in Fig. 8h, where for simplicity only a few \mathbf{j} -lines have been represented, which either drop on or leave from Σ' . Similarly to (2) we can state

$$\mathbf{B}^{(h)}(t) \equiv \mathbf{B}^{(i,e)}(t) + \mathbf{B}^{(j,e)}(t) \quad (4)$$

where the (h)-system and the (i)-system (shown in Figs 8h and 8i, respectively) have the identical \mathbf{j} -pattern dropping on, or leaving from, Σ' . In addition, the (j)-system is defined by assuming that Σ' has $\sigma \rightarrow \infty$, i.e. that Σ' is temporarily substituted by an ideal Σ'' . That is, the (h)-system and the (i)-system differ due to \mathbf{j} -patterns flowing over their respective identical geometrical surfaces Σ' and Σ'' . The (j)-system is defined by means of a formal vector subtraction of the (i)-system from the (h)-system. The result is that an observer located at Earth's surface interprets his observations as being originated by the (j)-system.

Symmetrically, the (h)-system can be represented as

$$\mathbf{B}^{(h)}(t) \equiv \mathbf{B}^{(k,e)}(t) + \mathbf{B}^{(l,e)}(t) \quad (5)$$

where the (h)-system and the (k)-system have the identical \mathbf{j} -pattern over Σ' , while the pattern of the currents \mathbf{j} that drop on, or leave from, Σ' is suitably changed in order that the (k)-system represents the \mathbf{j} -pattern that must be observed whenever Σ' is substituted by an ideal Σ'' with $\sigma \rightarrow \infty$.

This is possible, because - for every given \mathbf{j} -pattern that drops on, or leaves from, Σ' - a unique solution exists ("forward problem") for the induced currents \mathbf{j} that flow on the infinitely thin Σ'' characterized by $\sigma \rightarrow \infty$.³ Hence, by a trial-and-check procedure, one can iteratively change the \mathbf{j} -pattern that drops on, or leaves from, Σ' . In principle, it is possible to repeat the whole procedure as many times as needed until getting over Σ'' the same identical \mathbf{j} -pattern that is actually observed over the real Σ' that is characterized by a finite σ .

The (l)-system (of Fig. 8l) is defined by computing the vector difference between the \mathbf{j} -patterns that drop on, or

³ The "forward problem" is a classical topic, and the unique solution derives from the deterministic implication of Maxwell's laws.

leave from, Σ' in the (h) -system and in the (k) -system, respectively. In this case, the same aforementioned observer

located at Earth's surface will interpret his geomagnetic records as being originated by the (l) -system.

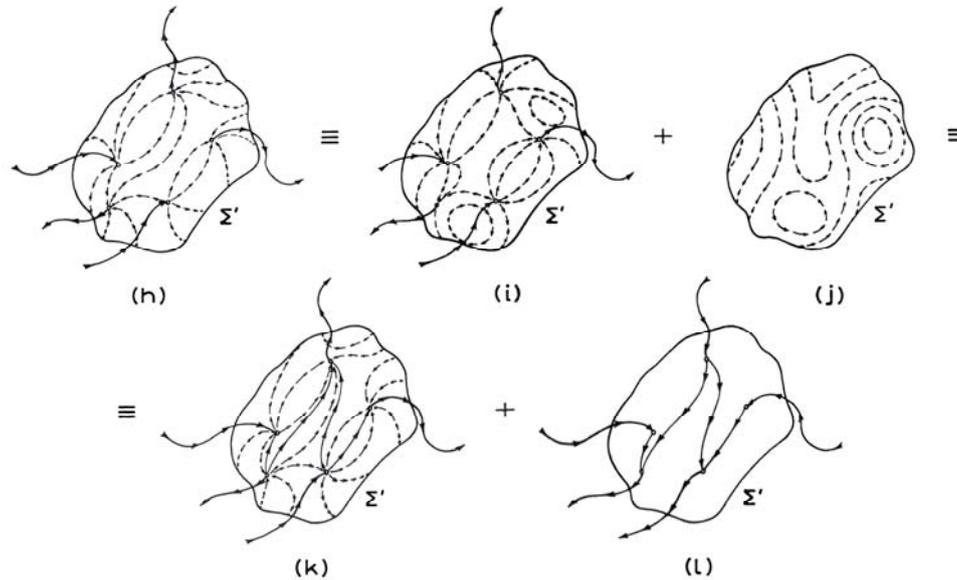


Fig. 8. This is the analogous case of Fig. 7, except that the surface is Σ' with finite σ . Every given general (h) -system can be likened to the case history of an identical geometrical surface, being however Σ'' i.e., with $\sigma \rightarrow \infty$. The system (i) has identical currents \mathbf{j} that either drop on or outgo from Σ'' . The consequent physical difference is formally represented by the system (j) . In contrast, the part of the system (k) that flows over Σ'' is identical to the part of the system (h) that flows over Σ' . Some physical change must be introduced in the currents \mathbf{j} that either drop on or leave from Σ'' . The formal difference is represented by the (l) system. See text. Unpublished figure.

This proves the Fukushima theorem also for the more realistic case that the ionosphere is not a perfect conductor, hence that it is not an equipotential surface (unlike what is presently generally assumed by the community of ionospheric physicists; see Gregori, 2002, 2020, Gregori and Leybourne, 2021, and Gregori et al., 2025a).

Differently stated, the indeterminacy that is evidenced by the Fukushima theorem is generated because the ionosphere (or the surface Σ') behaves like a Faraday shield. If the ionosphere is a perfect conductor, i.e., $\sigma \rightarrow \infty$, the e.m. screening is total, and both (j) -system and the (l) -system identically vanish. An observer located at Earth's surface can detect no \mathbf{j} that either impinges on, or leaves from, the ionosphere.

Instead, if the ionosphere has a finite σ , the observer concludes that the inversion problem, i.e., inferring the \mathbf{j} -system causing his observed $\mathbf{B}(t)$, is indeterminate. Indeed, the observer can detect only - and strictly only - that part of $\mathbf{B}(t)$ that is not screened by the ionosphere and that affords to cross it.

The conclusion is that, compared to what was formerly generally expected, all ground-based \mathbf{B} records are definitely useless for the determination of the general pattern of the magnetospheric \mathbf{j} -system. The reason is that the ionosphere, compatibly with the amount of ionization, cancels as much as possible the external signal.

Differently stated, the ionosphere played a fundamental role in the history of radio communications as it represented a natural mirror for radio waves. However, owing to the identical reason, the ionosphere works like an effective mirror, and it reflects backward, also as much $\mathbf{B}^{(e)}(t)$ as possible originated in the magnetosphere and in the solar wind.

The historical development

This entire conceptual and basic theorem is crucial. Hence, it deserves some historical illustration. Fukushima (1976a, 1976b) gives a detailed account of the way his theorem was derived, in terms of a step-by-step consideration of physical case-histories of increasing complication. For instance, Figs 9 and 10 are two simple examples of this kind, while for brevity purpose others are not here reported. These figures are self-explanatory, and they refer to very specific case histories of the general proof that is here given above.

Birkeland (1908) and Alfvén (1939, 1940) attempted to explain geomagnetic storms and auroræ by a \mathbf{j} -system of the kind of the (l) -system (Fig. 8l). Chapman (1935) and Vestine and Chapman (1938) proposed a \mathbf{j} -pattern of the kind of the (j) -system (Fig. 8j), and their system was seemingly generally accepted, until the Alfvén school re-insisted on the Birkeland-Alfvén system.

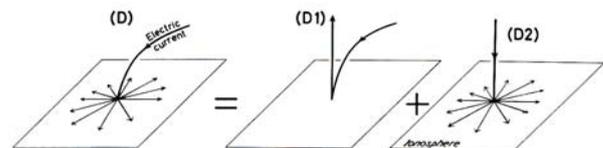


Fig. 9. Correction of the argument in the case of \mathbf{B} field-lines deviating from simple radial direction. After Fukushima (1976a). Unpublished figure, private communication of the author.

Fukushima (private communication) synthesized the problem in a transparency that is here readapted as Table 1.

Fig. 11 shows the standard system proposed by Chapman for disturbed days (characterized by the scheme

that is conventionally called *SD*). Fig. 12 shows the Birkeland-Alfvén system. Fig. 13 shows the expected east-west component of \mathbf{B} to be observed at Earth's surface for different intensity of the auroral electrojet. Figs 14a and 14b show the presentation of the idea according to Fukushima (1991). Fig. 15 is a re-handling according to Kirkpatrick (1952).

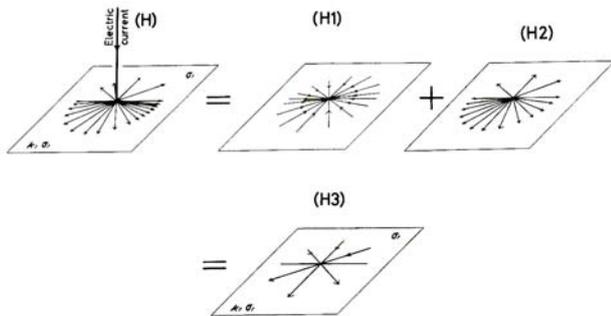


Fig. 10. Correction of the argument in the case of inhomogeneities in the ionosphere. After Fukushima (1976a). Unpublished figure, private communication of the author.

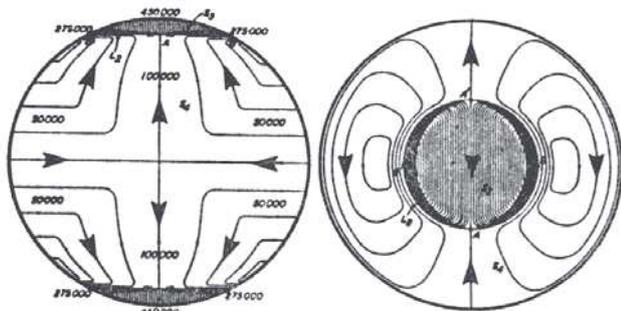


Fig. 11. "Current-system for geomagnetic *SD*-field (diurnally varying part of ground \mathbf{B} observed on disturbed days) proposed by Chapman, viewed from the Sun (left) and from above the North Pole of the Earth (right) (taken from Fig. 1 of Vestine and Chapman, 1938)." Figure and captions after Fukushima (1991). The original figure is after Chapman (1935), and is reported by Akasofu and Chapman (1972). Reproduced with kind permission of *AGU* and of *NiPR*.

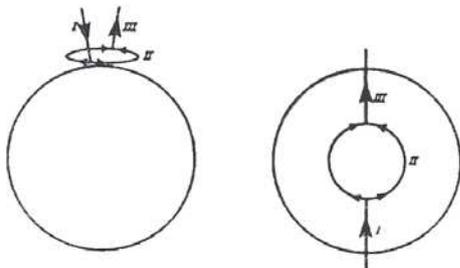


Fig. 12. "Birkeland's current-system for *SD*-field (not his own, but presented by Vestine and Chapman as Fig. 17 in their 1938 paper to compare its ground \mathbf{B} with that of Fig. 11 current-system), viewed from the early afternoon side (left) and above the North Pole (right)." Figure and captions after Fukushima (1991). Reproduced with kind permission of *NiPR*.

This culminated, as already mentioned, into the strong debate held at the meeting at Sandefjord in September 1967.

For completeness sake, the remarkable formal computation deserves a special mention, by Rolph Boström who evaluated the spherical harmonic expansion (*SHE*) formulas⁴ for various 3D patterns of Birkeland-Alfvén systems. The scope was to detect these systems by ground-based \mathbf{B} records. The Fukushima theorem showed that this is impossible.

Table 1. Historical background of the debate on the typical \mathbf{j} -system of substorms

<i>British school (Chapman-Vestine)</i>	<i>Scandinavian school (Birkeland-Alfvén)</i>
Prediction of the existence of a conductive layer in the conductive higher atmosphere (Balfour Stewart, 1882)	Reports of the Norwegian Auroral Polar expedition, and terrella experiment (Kr. Birkeland, 1908, 1913, 1913a)
Emphasis on approximately horizontal \mathbf{j} in the ionosphere, and on average disturbances	Emphasis on field-aligned \mathbf{j} in the Earth environmental space, and on individual disturbances
An individual disturbance will be deviated only slightly from the average disturbance	Individual disturbances, compared to each other, are usually so much different, that the average disturbance has practically almost no physical meaning, if any

Quoting Kamide (2006), "according to Fukushima, it was during a flight from Norway to Tokyo in 1967 when Fukushima suddenly hit upon a solution of this riddle. This was the genesis of the so-called 'Fukushima's theorem'."

By the end of 1967, Fukushima circulated a very short preprint with his proof referring to a plane ionosphere, and to \mathbf{j} -lines dropping on it, or leaving it, while being perpendicular to it (Fig. 16). Maybe, Boström (1969) refers to it by mentioning a "private communication". This Fukushima's proof later appeared in Fukushima (1969) - and in Fukushima (1972) as a short appendix of an article for *Hand. Phys.*, by Professor H. Poeverlein (1972), who had participated to the Sandefjord symposium while collecting updated information for preparing his article. The Fukushima theorem is mentioned, e.g., by Berdichevskiy et al. (1972).

The Fukushima proof was extended (according to Fukushima, 1972) by Vytėnis M. Vasyliūnas to a spherical ionosphere, by considering some radial incoming or outgoing currents \mathbf{j} . The average planetary distribution of the two kinds of \mathbf{j} -systems is synthesized in Fig. 17.

The very astute intuition should be emphasized by Naoshi Fukushima, who, by his theorem, got rid of a dichotomy that lasted since several decades. He has been one of the most brilliant minds of the 20th century in the study of solar-terrestrial relations.

Anderson et al. (2014) investigated the details of the observational evidence of Birkeland-Alfvén \mathbf{j} -systems. They stress that "the average Birkeland current distribution during geomagnetically active conditions has been known

⁴ Boström (1968, 1969, 1971, 1974), and also Alfvén (1977).

for more than 35 years (Iijima and Potemra, 1976)" and they display, e.g., "an instance of this system determined with 10 min of data acquired under the Active

Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) ...

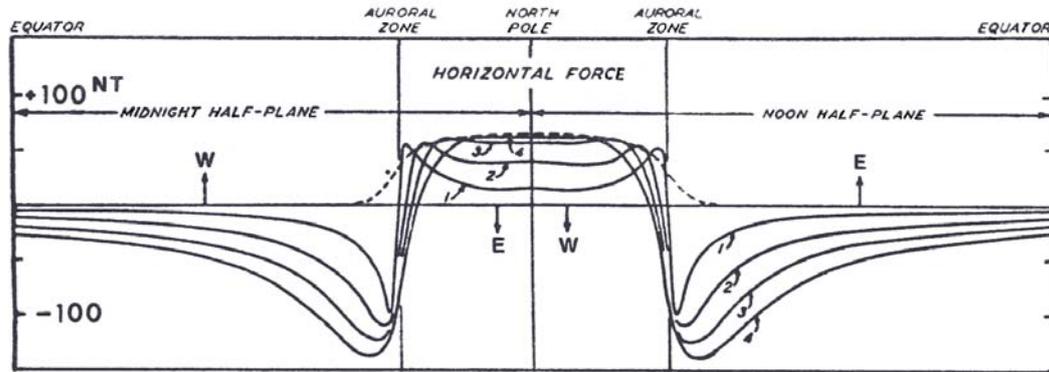


Fig. 13. "East-west B on the ground produced by the current-system of Chapman (with dotted lines) and of Birkeland (full lines; 1, 2, 3, and 4 refer respectively to assumed height of the auroral zone current, 100, 300, 500 and 700 km above the Earth). This diagram is taken from Fig. 18 of Vestine and Chapman (1938) paper." Figure and captions after Fukushima (1991). Reproduced with kind permission of AGU and of NiPR.

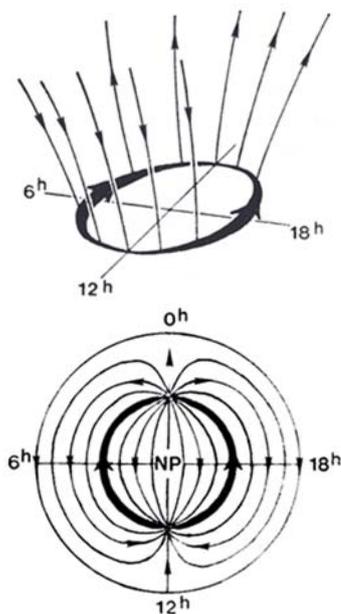


Fig. 14. [upper] "Birkeland's j -system that should have been compared with Chapman's Fig. 11 j -system. Field-aligned currents flow to all longitudes, downward on the dayside and upward on the night side." [lower] "Equivalent overhead current-system of Fig. 12, which produces an intense east-west B on the ground near the noon-midnight meridian, especially in the region immediately outside the auroral oval." Figure and captions after Fukushima (1991). Reproduced with kind permission of NiPR.

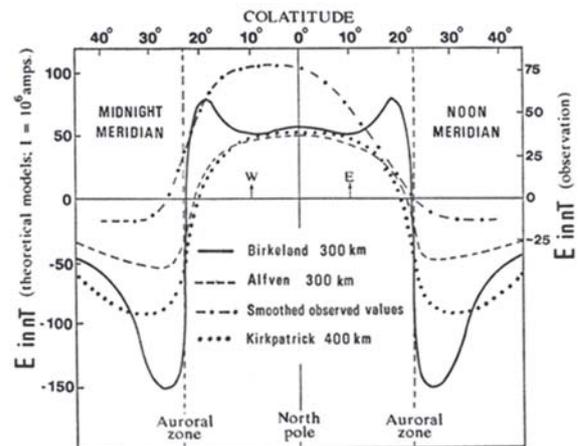


Fig. 15. "East-west B on the ground produced by Birkeland's-Alfvén's and Kirkpatrick's j -systems over the Earth (the heights of horizontal currents in their models are indicated in this diagram) and smoothed observed values, reproduced from Kirkpatrick's (1952) paper. For the calculated curves the current intensity is given so as to produce the ground B of 50 nT at the North Pole of the Earth, and the auroral zone is assumed to be fixed at 23° colatitude circle. The noteworthy deviation of the 'Birkeland 300 km' curve from the other two calculated curves must have originated from the misrepresentation of Birkeland's current-system by Vestine and Chapman ... ". Figure and captions after Fukushima (1991). Reproduced with kind permission of AGU and of NiPR.

AMPERE provides global, continuous sampling of the B perturbations at low Earth orbit from the Iridium Communications constellation of 70 near-polar orbiting satellites ... "

By this, Anderson et al. (2014) afford to plot the global Birkeland-Alfvén j -distribution every 10 min. They also consider the correlation with the vertical component B_z of B_{int} and interpret their records by means of the presently very fashionable Dungey (1963, 1967) open model of the magnetosphere and of the related speculated "convection" in the magnetosphere.

This model, however, cannot be shared and included inside the rationale that is here supported. In fact, the dependence on B_z is here contended as being approximate and sometimes invalid, as B_{int} is always recorded to lie in the heliocentric equatorial plane (with at most very few degrees scatter). Furthermore, the open Dungey model, altogether with "convection" in the magnetosphere, are shown to be inconsistent with observations, as the magnetosphere cannot be considered a closed system. Rather, the magnetosphere is a continuously changing system, depending on the varying instant flux of the solar

wind. Hence, no reason requires that any return-flux of plasma ought to exist inside the magnetosphere. Conversely, all available observations can be explained in a straightforward way, with reference to no *ad hoc*

assumption (Gregori and Leybourne, 2021, and 2025b). . In any case, the observations by Anderson et al. (2014) are physically significant, and can be fully re-interpreted according to the logical framework that is here proposed.

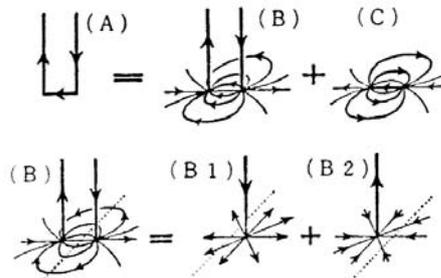


Fig. 16. Fukushima circulated a very short preprint with its proof referring to a plane ionosphere and to *j*-lines dropping on it, or leaving it, while being perpendicular to it. After Fukushima (1969). See text. With kind permission of the *Journal of the Radio Research Laboratories (NICT)*.

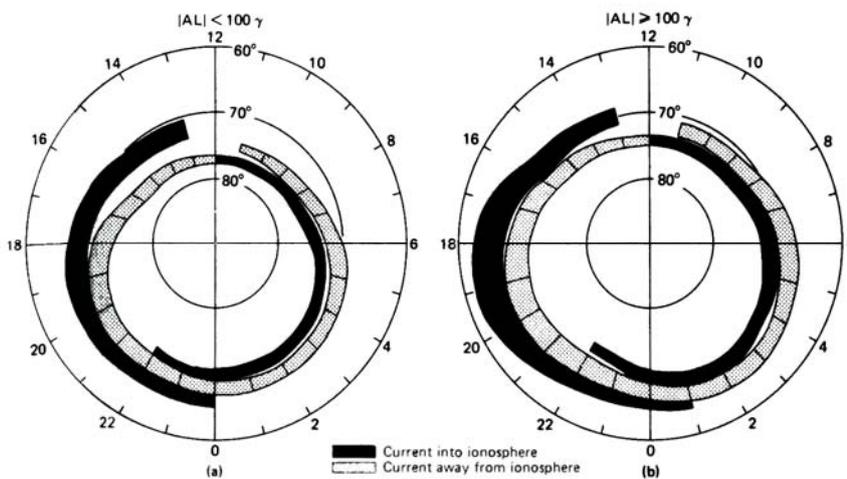


Fig. 17. View from above the Northern Hemisphere of the distribution and direction of Birkeland-Alfvén's currents: (a) during quite periods, with auroral electrojet index *AL* of geomagnetic activity < 100 γ [this *AL* index denotes some kind of average *B* generated by some *j* that is supposed to flow approximately along the auroral oval]; (b) when *AL* > 100 γ. After Iijima and Potemra (1978), and Crooker and Siscoe (1986) or McPherron (1991).

The Fukushima theorem and the Earth's interior

Owing to the similarity - or identity - of the primary rationale, the implications can be considered of the Fukushima theorem also for the investigation of the electrical structure of deep Earth. In fact, the Fukushima theorem resulted determinant in order to clarify what can - or cannot - be inferred by means of observations carried out at Earth's surface. Similarly, it is reasonable to enquire whether similar inferences can be attained concerning the exploration of the Earth's interior.

The problem of concern - when dealing with the Fukushima theorem - is the inversion of $\mathbf{B}^{(i)}(t)$, i.e., not just of $\mathbf{B}^{(e)}(t)$ as above. The problem is perfectly symmetrical between $\mathbf{B}^{(e)}(t)$ and $\mathbf{B}^{(i)}(t)$. In the Earth's interior, the Chapman-Vestine style represents currents *j* flowing over some closed - and approximately geocentric - surface underground, while the Birkeland-Alfvén style refers to currents *j* that flow along some approximately radial direction inside the Earth etc. This arbitrariness, however, is just formal and mathematical, as - owing to Hamilton's (see Gregori et al., 2025e) - every *j* must attempt to expand in space as much as possible, and is responsible for the formation of sea-urchin spikes. Hence, inside deep Earth, the Chapman-Vestine's system has to be definitely preferred. In fact, the *j* that flow along the sea-

urchin spikes have a radial component that reminds (at least partially) about Birkeland-Alfvén's. Some better details are as follows.

The Fukushima theorem is a mathematical fact, and we can get rid of its logical constraints only by appealing to some additional physical implication derived from observational inferences. The items here recalled are much more extensively and formally discussed in Gregori (2002), Gregori and Leybourne (2021) and Gregori et al. (2025a). The following short synthesis aims only to focus on the essential logical content, which is crucial in order to provide some new physical input into the modeling that is here of concern. These new physical facts can be synthesized as follows.

Remind about the Lowes-Nevanlinna's (*LN*) law that plots the "space density spectrum" of the geomagnetic *B*. That is, it refers to the planetary mean of the square of *B* computed at Earth's surface. Every *B* contribution is, however, distinguished that is associated to different degree *n* of the *SHE* of the potential. Such a separate contribution is plotted vs. *n* and this is the *LN* plot. Three lines can be clearly recognized, corresponding, respectively, to the *n* = 1, 2 components *B*, to the *B* originated inside mantle and lithosphere (*n* ≤ 14), and to the *B* originated in the crust (*n* ≥ 14). See Gregori (2002), Gregori and Leybourne (2021) and Gregori et al. (2025a).

These 3 sources can be formally treated in terms of 3 conventional spherical shells (*ss*). The energy can be

computed of the \mathbf{j} -distribution on every such a respective ss that generates the corresponding observed \mathbf{B} . The energy depends on the radius of the ss . The radius of every ss is thus found to have an asymptotic lower value (Gregori, 2002, Gregori and Leybourne, 2021, and Gregori et al., 2025a) that can be compared with seismological derived data.

The seismological evidence shows a surprising correspondence between the aforementioned asymptotic radius - derived from energy balance of \mathbf{j} -systems on every given ss - and the radius, respectively, either of the *ICB* (inner core boundary), or of the *CMB* (core mantle boundary), or of the *ALB* (asthenosphere-lithosphere boundary). That is, this is a way to determine the radii *vs.* time, respectively, of the *ICB*, *CMB* and *ALB* by means of the \mathbf{B} records at Earth's surface. The geomagnetically determined estimate is found to be only a very few percent smaller than the seismically determined value.

According to the Hamilton principle, every \mathbf{j} -loop must expand in space as much as possible (see Gregori et al., 2025e). Whenever one step-like drop of σ occurs, the \mathbf{j} do concentrate on it, thus originating the structure that, according to the aforementioned ss simplifying model, can be described - as a first order approximation - as a 2D surface of \mathbf{j} -distribution that is therefore simply approximated by a ss having some given mean radius.

The energy propagation through the Earth's body occurs, due to Hamilton's, along spikes, and the Earth's interior reminds, therefore, about an ensemble of sea-urchin spikes of electrical conductors (Gregori, 2002, Gregori and Leybourne, 2021 and Gregori et al., 2025a). The surface manifestation of this morphology is the uneven distribution of geothermal flow, including its extreme quasi-point-like singularities represented by several volcanoes, although several volcanoes are directly supplied by local friction-heat released at the *ALB*.

The tidal pull by the Moon and by the Sun operates - by different amount - on several disjoint components of the planet Earth. Since the components are ionized, this is quite an effective dynamo, i.e., the *TD* dynamo, which is the leading enormous source of endogenous energy, either inside the Earth or inside several planetary objects (Gregori, 2002, 2020, Gregori and Leybourne, 2021, and Gregori et al., 2025a).

The Earth behaves like a battery that accumulates and releases energy at different times. A battery can store energy either chemically (like in car battery), or like inside a condenser, or by means of transformation of the state-of-matter, such as it happens inside the Earth. This effect is documented by the change *vs.* time of the *ICB*, as determined since AD 1400 by means of the geomagnetic secular variation (*SV*) (Gregori, 2002, Gregori and Leybourne, 2021, and Gregori et al., 2025a). The trend *vs.* time is confirmed in recent times also by means of seismological determinations.

It should be stressed that the old fashioned - and observationally unsupported - model appears completely obsolete, which relied on an Earth supposedly cooling in space since the time of its planetary accretion (see Gregori, 2006e, 2009 and Gregori et al., 2025a).

It is possible to get rid of the assumption of the perfect spherical shape of the ss , although at the expense of some heavy mathematics. In fact, one can compute the formal \mathbf{j} -distribution that ought to flow on every spherical ss in order to generate the observed \mathbf{B} , which is associated to every given ss . In reality, no such a given and general \mathbf{j} -distribution could be stable inside any Gedankenexperiment, because, owing to Hamilton's, the \mathbf{j} -distribution would immediately redistribute in some uniform way. However, in principle it is possible to compute the shape of a deformed ss in order that the needed \mathbf{j} -distribution is stable on such a deformed ss . The whole procedure is certainly computationally lengthy, although it is expected to provide with unprecedented information of the state of matter inside deep Earth.

Summarizing, the substantial logical constraints imposed by the Fukushima theorem raise some serious conceptual limit to the capability to infer the internal structure of the Earth. However, after combining several different additional physical constraints and features, plus some reasonable assumption, it is found that it is possible to carry out a geomagnetic tomography of the Earth's interior. Hence, the Fukushima theorem has no devastating consequence for the internal \mathbf{B} , comparable to what occurs for the external \mathbf{B} source.

For the sake of completeness, a mention is needed about the possibility to compute - apart an arbitrary multiplicative constant - the Joule heat released on either one of the aforementioned three ss , i.e., on *ICB*, *CMB*, and *ALB*, respectively. A computation was carried out by Gao Xiao-Quin, though only dealing with spherical shells (Gregori et al., 2025k, 2025l, 2025m, 2025n, 2025o). The Joule heat released at the *ICB* reveals the classical westward drift (*WD*) of the geomagnetic *SV*. In contrast, Joule heat, released since AD 1400 at the *CMB*, denotes just 30 hotspots that occasionally display a main and intense activity only during a few decades (see Gregori et al., 2025k, 2025l, 2025m, 2025n, 2025o).

Conclusion

In the ultimate analysis, concerning the Fukushima theorem, the path toward understanding was historically biased by several paradigms that can be concisely listed as follows.

1. A first paradigm was the assumption of an empty interplanetary space that only sporadically is crossed by isolated clouds of solar particles, thus leading to the Chapman-Ferraro magnetosphere etc. (see Gregori and Leybourne, 2025b). This favored the concept of ionosphere represented as a simple outward expansion of the Earth's atmosphere. The ionosphere was thus considered from the viewpoint of a meteorologist. The Chapman-Vestine \mathbf{j} -system appeared the most obvious model, consistently with the former classical Balfour Stewart "dynamo" model of the *Encyclopaedia Britannica*.

The classical Chapman-Vestine 2D \mathbf{j} -sheet model still survives in the literature as a conventional way to represent and to depict ground based geomagnetic records. The

Fukushima theorem finally proved that the controversy is nonsensical between the supporters of Chapman-Vestine's and the supporters of the Birkeland-Alfvén's *j*-pattern. Satellite *in situ* measurement of Birkeland-Alfvén *j* finally proved that the old-fashioned classical way to conceive solar-terrestrial phenomena is now "*almost obsolete*" (Kristian Schlegel, private communication, 2012).

2. Another closely related paradigm is the assumption of the total neutral charge of the solar corpuscular radiation that impinges on the Earth. Only in the 1960s, when spectroscopic observations of auroræ detected simultaneous occurrence of electron auroræ and protons auroræ, it was realized that positive and negative electric charges simultaneously precipitate at sites even very far from each other.

The remaining still surviving part of the paradigm assumes an instant space-integrated charge neutrality. Instead, this neutrality can be achieved only when averaging in time, over some suitable time-lag that, however, has to be suitably assessed (see Gregori and Leybourne, 2025b). However, also this paradigm has been implicitly challenged and actually denied by several investigations, and the best opposing evidence is given by the straight explanation of the solar sunspot cycle.

3. An additional paradigm is the (still surviving) aforementioned assumption that the ionosphere is an equipotential surface, because it is claimed that the ionosphere is an electrical conductor. In contrast, it is not considered that, whenever an uneven distribution occurs of the total electric charge of precipitating particles, the poor conductivity of the ionosphere is such that charge re-distribution requires a conspicuous time-delay. That is, the tenuously ionized ionospheric medium behaves quite differently - as it is other than an ideal conductor that ought to be needed in order to ensure an equipotential state.

4. Another paradigm deals with the assumption of an electrostatic charging of the ionosphere caused - according to the classical Wilson hypothesis - by thermodynamic convection inside clouds (see Gregori et al., 2025e, Gregori and Leybourne, 2025e, 2025g). This paradigm originated some confusion, in terms of the real physical processes that occur within the ionosphere. At present, this paradigm - which is partially correct in terms of an optional lesser contribution - is seriously challenged by several *TLEs* (transient luminous events), and mostly by the deadly *TGF* (Terrestrial Gamma Flashes) [or Gamma Ray Bursts (*GRB*) or Terrestrial Gamma Bursts] originated by Bremsstrahlung at some very low height (below ~ 30 km, in fact in the troposphere, and the phenomenon is due to the Cowling dynamo within clouds; see Gregori et al., 2025e, Gregori and Leybourne, 2025e).

5. An additional misleading approximation was always concerned with the assumption of a negligible (at least, as a planetary average) role of air-earth currents, which is the leading topic of the present issue. This forbade a correct investigation of the e.m. coupling between subsoil and atmosphere. This paradigm is presently being questioned, following the investigation

both of *CHAMP* records by means of the Quinn's inversion technique (see Quinn et al., 2025), or of the correlation between ionospheric phenomena and seismic activity (see Parrot et al., 2025; Straser et al., 2025; Wu, 2024). In addition, several other effects deny such a paradigm, as extensively discussed in the present special issue on air-earth currents.

Acknowledgement

The results here outlined derived from astute stimulating discussions with several friends and colleagues, and it is impossible to list all inputs we had during several decades. A particular thank is deserved for the late Professor Naoshi Fukushima who regularly mailed to GPG his preprints and reprints, and later extensively contributed by a long-lasting friendly discussion. GPG misses a dear friend and gentleman.

Funding Information

G. P. Gregori retired since 2005. B. A. Leybourne is a semi-retired self-funded independent researcher.

Author's Contributions

This study is a lesser detail of a long-lasting cooperation by both authors and resulted from the emergence of suitable discussions.

Ethics

This article is original and contains unpublished material. Authors declare that there are not ethical issues and no conflict of interest that may arise after the publication of this manuscript.

References

- Akasofu, S.-I., and Chapman, S., 1972. Solar-terrestrial Physics-An Account of the Wave and Particle Radiations from the Quiet and the Active Sun, and of the Consequent Terrestrial Phenomena. Oxford, at the Clarendon Press, pp: 901
- Alfvén, H.O.G., 1939. A theory of magnetic storms and of the aurorae, Kungl. Svenska vetenskapsakademiens handlingar, Stockholm, Ser. III, 18 (3). (Reprinted in part with comments in Dessler, A., and J. Wilcox, 1970. EOS, Transactions of the American Geophysical Union, 51: 180-194
- Alfvén, H.O.G., 1940. A theory of magnetic storms and of the aurorae, Kungl. Svenska vetenskapsakademiens handlingar, Stockholm, Ser. III, 18 (9)
- Alfvén, H.O.G., 1977. Electric currents in cosmic plasmas, Reviews of. Geophysics and Space Physics, 15: 271-284; DOI: 10.1029/RG015i003p00271
- Anderson, B.J., H. Korth, C.L. Waters, D.L. Green, V.G. Merkin, R.J. Barnes, and L.P. Dyrud, 2014. Development of large-scale Birkeland currents

- determined from the Active Magnetosphere and Planetary Electrodynamics Response Experiment, *Geophysical Research Letters*, 41 (9): 3017–3025; DOI: 10.1002/2014GL059941.
- Birkeland, K., 1908, 1913. The Norwegian Auroral Polaris expedition, 1902-1903, H. Archebourg Co., Christiania, pp: 801
- Birkeland, K., 1913a. Sur la conservation et l'origine du magnétisme terrestre, *Comptes rendus de l'Académie des Sciences*, 157: 272-277. The separate copies contain a printed "Remarque" of two pages added in July 1913. Sur le magnétisme générale du Soleil, *Comptes rendus de l'Académie des Sciences*, 157: 104-106.
- Bostrøm, R., 1967. Currents in the ionosphere and magnetosphere. In *The Birkeland Symposium on Aurora and Magnetic Storms*, Egeland, A., and J. Holtet (eds.), Centre National de la Recherche Scientifique, pp: 445-458. Several papers appeared in *Annales de Géophysique*
- Bostrøm, R., 1968. *Annales de Géophysique*, 24: 681
- Bostrøm, R., 1969. Auroral current system. In *Atmospheric Emissions*, McCormac, B.M., and A. Omholt, (eds), Van Nostrand Reinhold Company, New York etc., pp: 277-284
- Bostrøm, R., 1971. Polar magnetic storms. In *The Radiating Atmosphere*, McCormac, B.M., (ed.), D. Reidel Publ. Co., Dordrecht, pp: 357-365
- Bostrøm, R., 1974. Ionosphere-magnetosphere coupling. In *Magnetospheric Physics*, McCormac, B.M., (ed.), D. Reidel Publ. Co., Dordrecht, pp: 45-59
- Chapman, S. and Bartels, J., 1940. *Geomagnetism*. 2 vol., Oxford Univ. Press, (Clarendon): London and New York. pp: 1049
- Chapman, S., 1935. The electric current system of magnetic storms. *Terrestrial Magnetism and Atmospheric Electricity*, 40: 349-370; DOI: 10.1029/TE040i004p00349
- Chapman, S., 1967. History of aurora and airglow. In *Aurora and airglow*, McCormac, B.M., (ed.), Reinhold Publ. Corp., New York etc., pp: 15-28
- Crooker, N.U., and G.L. Siscoe, 1986. The effect of the solar wind on the terrestrial environment. In *Physics of the Sun – Vol. 3: Astrophysics and solar-terrestrial relations*, Sturrock, P.A., T.E. Holzer, D.M. Mihalas, and R.K. Ulrich, (eds.), D. Reidel Publ. Co., Dordrecht, etc., pp: 193-249
- Dungey, J.W., 1963. The structure of the exosphere or adventures in velocity space. In *Géophysique Extérieur - Geophysics, The Earth's Environment*, deWitt, C., J. Hieblot, and A. Lebeau, (eds), Gordon and Breach, Science Publ., New York and London, pp: 503-550
- Dungey, J.W., 1967. Magnetohydrodynamics in the magnetosphere. In *The Birkeland Symposium on Aurora and Magnetic Storms*, Egeland, A., and J. Holtet (eds.), Centre National de la Recherche Scientifique, pp: 431-438. Several papers appeared in *Annales de Géophysique*
- Eather, R.H., 1980. *Majestic Lights. The Aurora in Science, History, and the Arts*, American Geophysical Union, Washington, D.C., pp: 323
- Fukushima, N., 1969. Equivalence of ground magnetic effect of Chapman-Vestine's and Birkeland-Alfvén's current-systems for polar magnetic storms, *Reports on Ionospheric Space Research in Japan*, 23 (3): 219-227
- Fukushima, N., 1972. Remarks on plasmopause and current systems. *Handbuch der Physik*, 49/4: 103-109, being inserted in the article by H. Poeverlein, *The Earth's magnetosphere*, at page 1-113
- Fukushima, N., 1976b. Generalized theorem for no ground magnetic effect of vertical currents connected with Pedersen currents in the uniform-conductivity ionosphere, *Reports on Ionospheric Space Research in Japan*, 30: 35–40
- Fukushima, N., 1989. Memorandum on non-curl-free geomagnetic field. *Il Nuovo Cimento*, 12C (5): 541-546
- Fukushima, N., 1991. Unreasonable discrimination of Birkeland's current-system in the history of magnetic storm studies, *Proceedings of the NIPR Symposium on Upper Atmospheric Physics*, 4: 108-115
- Fukushima, N., 1976a. Ground magnetic effect of field-aligned currents connected with ionospheric currents – Fundamental theorems and their applications, *Preprint UT-GRL-76-01*, 23 pp., a 24th page was added in 1980
- Gregori, G.P., 2002. *Galaxy – Sun – Earth relations. The Origin of the Magnetic Field and of the Endogenous Energy of the Earth, with Implications for Volcanism, Geodynamics and Climate Control, and Related Items of Concern for Stars, Planets, Satellites, and Other Planetary Objects. A Discussion in a Prologue and Two Parts. Beiträge zur Geschichte der Geophysik und Kosmischen Physik*, Band 3, Heft 3, pp. 471 [Available at <http://ncgtjournal.com/additional-resources.html>]
- Gregori, G.P., 2009. The Earth's interior – Myth and science, *New Concepts in Global Tectonics, Newsletters*, (53): 57-75. [Revised edition of Gregori (2006e).]
- Gregori, G.P., 2006e. The Earth's interior-Myth and science. In *Case studies in physics and geophysics*. W. Schröder, (ed.), *Beiträge zur Geschichte der Geophysik und Kosmischen Physik*, special issue (2006/2), (*Journal for the history of Geophysics and Cosmical Physics*), Science Editions, AKGG, Bremen-Roennebeck; pp: 108-126
- Gregori, G.P., 2020. Climate change, security, sensors. *Acoustics*, 2: 474-504; DOI:10.3390/acoustics2030026 [https://www.mdpi.com/2624-599X/2/3/26/html]
- Gregori, G.P., and B.A. Leybourne, 2021. An unprecedented challenge for humankind survival. Energy exploitation from the atmospheric electrical circuit, *American Journal of Engineering and Applied Science*, 14 (2): 258-291, DOI:10.3844/ajeassp.2021.258.291
- Gregori, G. P., and B. A. Leybourne, 2025b. The electrostatic Sun. In press in *New Concepts in Global Tectonics, Journal*
- Gregori, G.P., and B.A. Leybourne, 2025e. The physics of electrical discharges – 1. Small-scale phenomena, present issue

- Gregori, G.P., and B.A. Leybourne, 2025g. The physics of electrical discharges – 3. Sparks and lightning - electrostatics of the ionosphere – TLEs - plasma jets collimation – Birkeland currents & sea-urchin spikes - stellar and galactic alignments, present issue
- Gregori, G. P., B. A. Leybourne, and Gao Xiaoqing, 2025q. Atlas of the Joule heat released at the *ALB*, *CMB* and *ICB* during AD 1400 through present, *New Concepts in Global Tectonics, Journal*, 13, (3): 460-472
- Gregori, G. P., B. A. Leybourne, Dong Wenjie, and Gao Xiaoqing, 2025l. Energy release from *ALB*, *CMB* and *ICB* and secular variation. II – Methods: the “principle of magnetic energy variation” & Joule heat on a spherical shell of currents *New Concepts in Global Tectonics, Journal*, 13, (3): 350-377
- Gregori, G. P., B. A. Leybourne, Dong Wenjie, and Gao Xiaoqing, 2025m. Energy release from *ALB*, *CMB* and *ICB* and secular variation. III – A physical analysis - Estimate of self-energies and radii & the *LN* law and related secular variation *New Concepts in Global Tectonics, Journal*, 13, (3): 378-409
- Gregori, G. P., B. A. Leybourne, Dong Wenjie, and Gao Xiaoqing, 2025n. Energy release from *ALB*, *CMB* and *ICB* and secular variation. IV – A physical analysis - The Poynting theorem and the estimate of s/σ , separating the roles of terms with different degree n , and a tentative physical explanation concerning the role of the “magpol” *IC* in the *TD* dynamo, *New Concepts in Global Tectonics, Journal*, 13, (3): 410-432
- Gregori, G. P., B. A. Leybourne, Dong Wenjie, and Gao Xiaoqing, 2025o. Energy release from *ALB*, *CMB* and *ICB* and secular variation. V – Results, *New Concepts in Global Tectonics, Journal*, 13, (3): 433-459
- Gregori, G. P., B. A. Leybourne, Dong Wenjie, and Gao Xiaoqing, 2025o. Energy release from *ALB*, *CMB* and *ICB* and secular variation. V – Results, *New Concepts in Global Tectonics, Journal*, 13, (3): 433-459
- Gregori, G. P., B. A. Leybourne, F. T. Gizzi, Dong Wenjie, and Gao Xiaoqing, 2025k. Energy release from *ALB*, *CMB* and *ICB* and secular variation. I – The observational database, *New Concepts in Global Tectonics, Journal*, 13, (3): 341-349
- Gregori, G. P., B. A. Leybourne, G. Paparo†, and M. Poscolieri, 2025a. The global Sun-Earth circuit. In press in *New Concepts in Global Tectonics, Journal*
- Gregori, G. P., B. A. Leybourne, W. Soon, and V. Straser, 2025e. The heuristic meaning of variational principles. In press in *New Concepts in Global Tectonics, Journal*, 13, (6): 920-967
- Iijima, T. and T.A. Potemra, 1978. Large-scale characteristics of field-aligned currents associated with substorms, *Journal of Geophysical Research, Space Physics*, 83: 599-615; DOI:10.1029/JA083iA02p00599
- Kamide, Y., 2006. Fukushima’s theorem. In *Historical events and people in aeronomy, geomagnetism and solar-terrestrial*, Schröder, W., (ed.), *Beiträge zur Geschichte der Geophysik und Kosmischen Physik ; Bremen-Roennebeck : Science Ed. AGGKP*, 7 (1): 28-32
- Kirkpatrick, C.B., 1952. On current systems proposed for S_D in the theory of magnetic storms, *Journal of Geophysical Research*, 57: 511-526; DOI:10.1029/JZ057i004p00511
- McPherron, R.L., 1991. Physical processes producing magnetospheric substorms and magnetic storms. In *Geomagnetism*, Vol. 4, Jacobs, J.A., (ed.), Academic Press, Harcourt Brace, pp: 593-739
- Parrot, M., 2025. DEMETER observations of the variations of the global electric circuit under various constraints, *New Concepts in Global Tectonics, Journal*, 13, (2): 355-366; ID 530865; DOI:10.1155/2013/530865
- Poevlerlein, H., 1972. The Earth’s magnetosphere, *Handbuch der Physik*, XLIX/4: 1-113
- Quinn, J. M.,† G. P. Gregori, and B. A. Leybourne, 2025. Satellite monitoring of air-earth currents. In press in *New Concepts in Global Tectonics, Journal*
- Silverman, S.M., 1970. Franklin’s theory of the aurora, *Journal of The Franklin Institute*, 290 (3): 177-178
- Stewart, B., 1882. *Encyclopedia Britannica*, 9th Edition, 16: 181
- Straser, V., G. Cataldi, and D. Cataldi, 2025. Space weather related to potentially destructive seismic activity, In press in *New Concepts in Global Tectonics, Journal*
- Vestine, E.H., and S. Chapman, 1938. The electric current-system of geomagnetic disturbance. *Terrestrial Magnetism and Atmospheric Electricity*, 43: 351-382; DOI:10.1029/TE043i004p00351
- Wu, Hong-chun, 2025. Jet stream’s disturbances as possible precursors of earthquakes, preprint

Acronyms

- AGU* – American Geophysical Union
ALB - asthenosphere lithosphere boundary
AMPERE - Active Magnetosphere and Planetary Electrodynamics Response Experiment
CHAMP - Challenging Minisatellite Payload, German satellite
CMB - core mantle boundary
e.m. - electromagnetic
FAC – field aligned current
GRB - Gamma Ray Burst, or Terrestrial Gamma Burst
ICB - inner core boundary
IMF- interplanetary magnetic field
LN - Lowes-Nevanlinna (law and/or plot)
NICT - National Institute of Information and Communications Technology
NiPR - National Institute of Polar Research
SHE –spherical harmonic expansion
ss - spherical shell
SV - secular variation
TD - tide-driven (dynamo)
TGF –terrestrial gamma flash
TLE - transient luminous event
WD - westward drift

Space weather related to potentially destructive seismic activity

Valentino Straser¹, Gabriele Cataldi², Daniele Cataldi³

¹ University of Makeni, Sierra Leone & Department of Science and Environment UPKL Brussel (B)

²Radio Emissions Project, Rome, Italy

³Fondazione Permanente G. Giuliani - Onlus, Rome, Italy

Corresponding Author:

Valentino Straser, University of Makeni, Sierra Leone & Department of Science and Environment UPKL Brussel (B)

Email:

valentino.straser@gmail.com

ltpaobserverproject@gmail.com

daniele77c@gmail.com

Abstract: This study examines the potential coupling between solar ion flux and more than 1,300 earthquakes of magnitude 6 or greater that have occurred on a global scale. The study, initiated in 2012 by the authors, highlights the non-randomness of seismic events with increases in the proton density of the solar wind entering a collision course with the Earth's magnetosphere. The result has, at present, statistical value, as a convincing and rigorously proven scientific theory has not yet been formulated and proposed. The triggering mechanism of tectonic earthquakes, in fact, has not yet been fully elucidated because of the multitude of factors that can affect the equilibrium in a fault. Included among the variables involved is solar activity due to solar wind energy transfer with the geosphere and potential circuits that may occur on a global scale. A determining factor in establishing the potential relationship between solar activity and earthquakes is particular values of the solar wind ion flux.

Keywords: space weather - proton density - seismic precursors - potentially destructive seismic events - solar ion flux

Introduction

The study of earthquakes and their triggering mechanisms, especially for destructive ones, is an ever-present topic, both for the better understanding of crustal stresses that act relentlessly and to arrive, in the near future, at the prediction of potentially destructive events.

For the past century or so, there has been a proliferation of studies on the periodicity of solar activity in relation to global seismic release and, more recently, on the electromagnetic (e.m.) interaction of the solar wind with the geosphere, in areas periodically affected by violent earthquakes [Anagnostopoulos et al. (2021), Duma and Ruzhin (2003), Hajra (2022), Homola et al. (2015), Kovalyov and Kovalyov (2014), Odintsov et al. (2006), Simpson (1968), Sytinskii (1989), Tavares and Azevedo (2011), Urata et al. (2018), Vargas and Kastle (2012)].

Between January 1, 2012, and May 12, 2022, 1360 potentially destructive earthquake events of magnitude (M_w) 6 or greater were recorded on our planet. On average, about 131 seismic events were recorded per year, but the number of recorded seismic events on a global scale may vary slightly over several weeks due to more precise analysis of the energy released by seismic activity.

Studies conducted by the authors since 2011 have established that potentially destructive seismic activity recorded on a global scale is always preceded by an increase in solar activity [Straser and Cataldi (2014; 2015), Cataldi et al. (2013; 2017; 2019; 2020), Rabeh et al. (2014)].

Methods and data

This study analyzed 1360 destructive seismic events recorded on a global scale between January 1, 2012 and May 13, 2022. The catalog used on potentially destructive seismic activity ($M6+$) is that provided by the USGS (United States Geological Survey) and the data on the $M6+$ activity to carry out this study were collected almost in real time: it is however possible that in the course of longer time frames, some data have undergone updates or the number of potentially destructive seismic events has changed due to more precise analyzes carried out on the energy released by the seismic events.

To understand if a single potentially destructive seismic event or if a potentially destructive seismic train is related to solar activity, the authors examined in detail the solar activity in the time frame that precedes and exceeds one or more $M6+$ seismic events recorded on a global scale. To proceed in this direction, the authors used the data provided by:

- Advanced Composition Explorer (ACE) satellite;
- Deep Space Climate Observatory (DSCOVR) satellite.

Both satellites are located in the $L1$ Lagrangian orbit. More specifically, the data examined by the authors were the following:

- ACE Satellite:
 - differential proton flux 1060 – 1900 keV ;
 - differential proton flux 761 – 1220 keV ;
 - differential proton flux 310 – 580 keV
- DSCOVR Satellite:
 - proton density ($p \cdot cm^{-3}$).

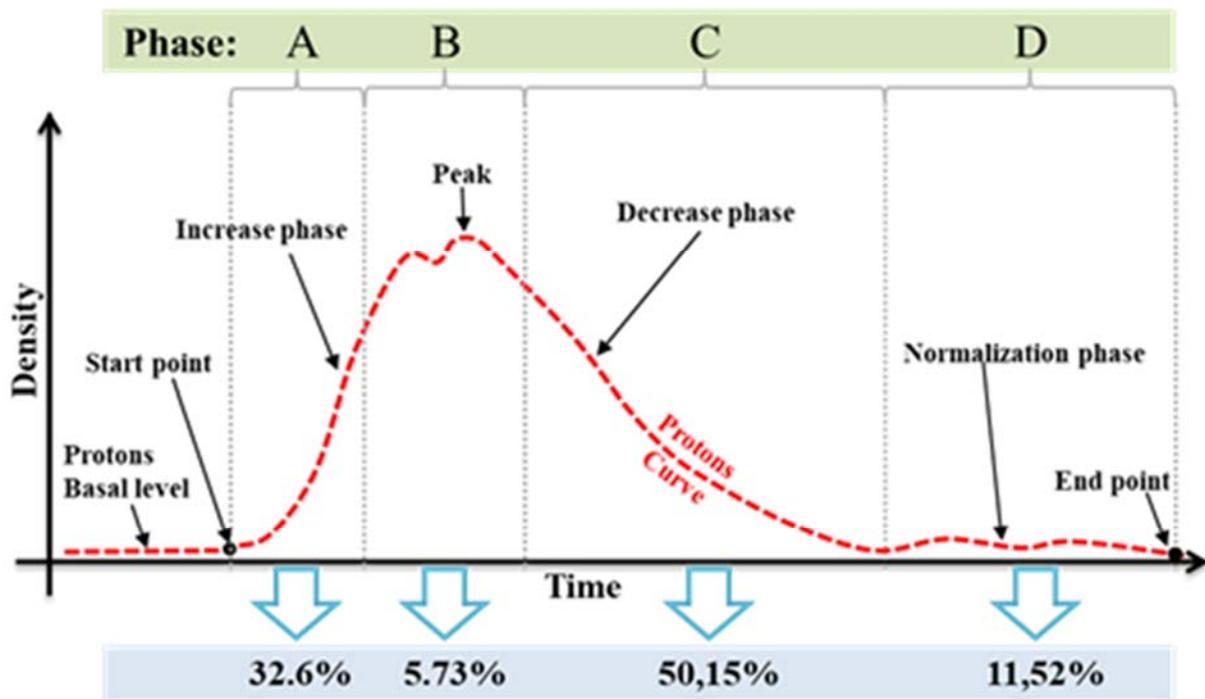
Discussion

The selection of data to discuss in this research fell on solar proton flux density, solar proton flux density variations being the only solar-derived phenomena closely related to global $M6+$ seismic activity [Straser and Cataldi (2015)]. In practice, potentially destructive seismic activity recorded on a global scale is always preceded by an increase in solar proton flux density [Straser and Cataldi (2014)].

The authors, in a study conducted between 2012 and 2021, showed that potentially destructive seismic events on a global scale are distributed in different percentages along the proton change curve (Fig. 1). Most earthquakes (50.15%) are recorded during the decreasing phase (C phase) of proton density, while another large percentage (32.6%) occur during the initial phase of increasing proton density (A phase). Therefore, more than 82% of potentially destructive seismic events are recorded during the increase or decrease of the solar proton flux density. This distribution remains stable even considering the number of $M6+$ seismic events recorded monthly.

Scientific Research Project For
Solar, Interplanetary And Geomagnetic
Seismic Precursors Monitoring  Radio
Emissions
Project

Percentage of occurrence of potentially destructive seismic events ($M6+$) recorded on a global scale between 2012 and 2021 related to solar wind proton density phases curve



Data sample: 1310 potentially destructive seismic events ($M6+$) recorded between 2012 and 2021

Fig. 1. Distribution of potentially destructive seismic events ($M6+$) recorded on a global scale with respect to the proton variation curve. In the graph above the typical proton curve of a “gradual” type event has been reproduced. The authors divided the variation curve into four distinct phases to simplify the description in relation to the correlation data with the $M6+$ global seismic activity provided by the study. Credit: *Radio Emissions Project*.

Based on the preliminary data obtained from the correlation study carried out in 2022 (from January 1, 2022 to May 13, 2022) and incorporating these data with those already in the authors' possession obtained between 2012 and 2021, the average number of $M6+$ seismic

events occurring during a single proton increase was calculated: this value is 2.87. In contrast, the average time interval measured between the onset of proton increase and a given potentially destructive seismic event is 4.29 days (103.07 hours) (Fig. 2).

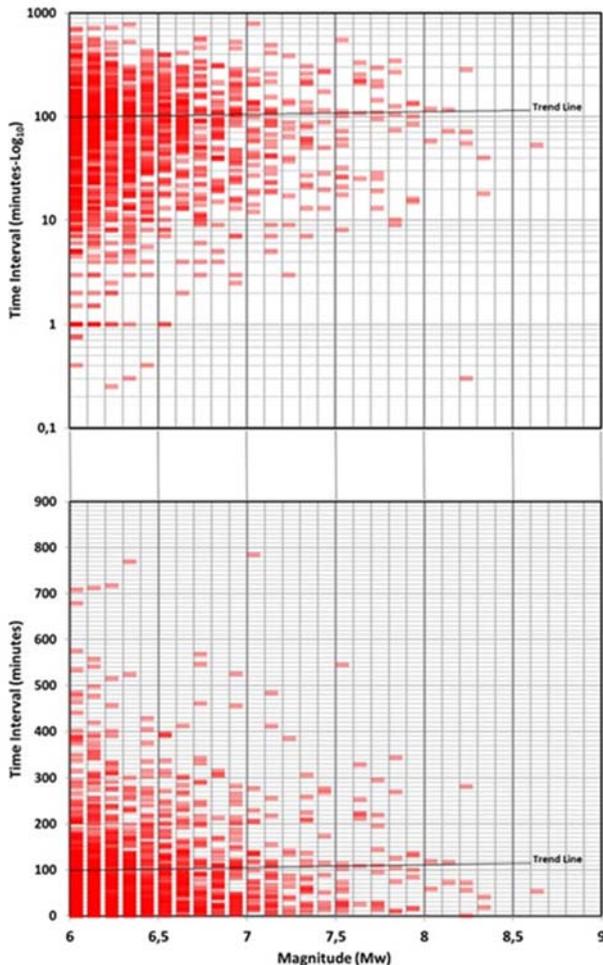


Fig. 2. Distribution of time intervals. The graph shows the distribution of time intervals associated with 1300 potentially destructive seismic events ($M6+$) recorded on a global scale between January 1, 2012 and May 13, 2022. Credit: *Radio Emission Project*.

Considering these trends, it means that by analyzing solar activity it would be possible, with an average notice of 4.29 days, to make an estimate of potentially destructive seismic activity on a global scale. Another finding that emerges by analyzing all time intervals is the average of the time intervals increases as the magnitude of the seismic event increases. In this case, the hourly increase is greater than 15 hours if one goes from magnitude $Mw6$ to magnitude $Mw8.6$. This finding suggests to the authors that the time interval associated with an extremely high magnitude seismic event is on average > 15 hours compared to the average time interval associated with a destructive seismic event of magnitude $Mw6$.

By measuring the value of the increase in proton density in the hours prior to a given seismic event, it is inferred that the rate of increase (expressed in $p/cm^3 \text{ hour}^{-1}$) increases with increasing earthquake magnitude; as does the maximum increase achieved by proton density in the hours prior to a strong seismic event, which in some cases may coincide with the time marker of the earthquake.

Conclusion

We conclude that the analysis of solar activity allows us to understand with an average notice of about 103 hours (Fig. 2) the resumption of potentially destructive seismic activity ($M6$) on our planet. Time analysis has proven to be very convenient compared to other parameters that will allow, in the future, to develop a new method of seismic prediction on a global scale. At the present state of knowledge, although the mechanism the physical mechanism that correlates solar activity with potentially destructive global seismic activity is not yet precisely understood, some hypotheses can be made. Among the various theories considered by the authors, it is believed that an electromagnetic interaction phenomenon could concur with other events to alter the static balance of faults and trigger an earthquake.

Acknowledgement

We would like to express our sincere thanks to all the collaborators of Radio Emission Project for the success of this study.

Funding Information

No funding was sought or implemented in this original work by Radio Emission Project for publishing in the NCGT Journal.

Author's Contributions

Valentino Straser is responsible for this study, while co-authors contributed to the data processing and discussion.

Ethics

This article is original and contains unpublished material. Authors declare that there are not ethical issues and no conflict of interest that may arise after the publication of this manuscript.

References

- Anagnostopoulos G., I. Spyroglou, A. Rigas, and I. Kiosses, 2021. The sun as a significant agent provoking earthquakes. *European Physical Journal Special Topics*, 230: 287–333; DOI:10.1140/epjst/e2020-000266-2
- Cataldi G., D. Cataldi, V. Straser, 2013. Variations of terrestrial geomagnetic activity correlated to $M6+$ global seismic activity. EGU (European Geosciences Union) 2013, General Assembly, Geophysical Research Abstracts, 15: EGU2013-2617, Vienna, Austria
- Cataldi G., D. Cataldi, V. Straser, 2017. Solar wind proton density increase that preceded Central Italy earthquakes occurred between 26 and 30 October 2016. *Geophysical Research Abstracts*, 19: EGU2017-3774, Vienna, Austria
- Cataldi G., D. Cataldi, V. Straser, 2019. Solar wind ionic density variations related to $M6+$ global seismic activity

- between 2012 and 2018. Geophysical Research Abstract, 21: EGU2019-3067, Vienna, Austria
- Cataldi G., V. Straser, D. Cataldi, 2020. Space weather related to potentially destructive seismic activity recorded on a global scale. New Concepts in Global Tectonics, Journal. 8 (3): 233-253
- Duma G. and Y. Ruzhin, 2003. Diurnal changes of earthquake activity and geomagnetic Sq-variations. Natural Hazards and Earth System Sciences, 3: 171–177, DOI:10.5194/nhess-3-171-2003
- Hajra R., 2022. Intense Geomagnetically Induced Currents (GICs): association with solar and geomagnetic activities, Solar Physics, 297:1, DOI:10.1007/s11207-021-01945-8
- Homola P., V. Marchenko, A. Napolitano, R. Damian, R. Guzik, D. Alvarez-Castillo, S. Stuglik, O. Ruimi, O. Skorenok, J. Zamora-Saa, J.M. Vaquero, T. Wibig, M. Knap, K. Dziadkowiec, M. Karpel, O. Sushchov, J. W. Mietelski, K. Gorzkiewicz, N. Zabari, K. Almeida Cheminant, B. Idzkowski, T. Bulik, G. Bhatta, N. Budnev, R. Kamiński, M.V. Medvedev, K. Kozak, O. Bar, Ł. Bibrzycki, M. Bielewicz, M. Frontczak, P. Kovács, B. Łozowski, J. Miszczyk, M. Niedźwiecki, L. del Peral, M. Piekarczyk, M. D. Rodriguez Frias, K. Rzecki, K. Smelcerz, T. Sośnicki, J. Stasielak, A. A. Tursunov, 2015. Observation of large scale precursor correlations between cosmic rays and earthquakes, arXiv:2204.12310v1 [physics.geo-ph], DOI:10.48550/arXiv.1403.5728
- Kovalyov, M. and S. Kovalyov, 2014. On the relationship between cosmic rays, solar activity and powerful earthquakes. arXiv:1403.5728v2 [physics.gen-ph], <https://doi.org/10.48550/arXiv.1403.5728>
- Odintsov, S., K. Boyarchuk, B. Georgieva, B. Kirov, and D. Antanasov, 2006. Long-period trends in global seismic and geomagnetic activity and their relation to solar activity. Physics and Chemistry of the Earth. Parts A/B/C 31.1-3: 88-93
- Rabeh T., G. Cataldi, V. Straser, 2014. Possibility of coupling the magnetosphere–ionosphere during the time of earthquakes. European Geosciences Union (EGU) General Assembly 2014, Geophysical Research Abstract, 16: EGU2014-1067, Vienna, Austria
- Simpson, J.F., 1968. Solar activity as a triggering mechanism for earthquakes. Earth and Planetary Science Letters. 3: 417-425, DOI:10.1016/0012-821X(67)90071-4
- Straser V. and G. Cataldi, 2014. Solar wind proton density increase and geomagnetic background anomalies before strong M6+ earthquakes. Space Research Institute of Moscow, Russian Academy of Sciences, MSS-14: 280-286, Moscow, Russia
- Straser V. and G. Cataldi, 2015. Solar wind ionic variation associated with earthquakes greater than magnitude M6.0. New Concepts in Global Tectonics Journal, 3 (2): 140-154
- Sytinskii A.D., 1989. Correlation of earthquakes with solar activity, Izvestiya, Physics of the Solid Earth, 25 (2): 86 – 98
- Tavares, M. and A. Azevedo, 2011. Influences of solar cycles on earthquakes. Natural Sciences, 3: 436-443, DOI:10.4236/ns.2011.36060
- Urata, N., G. Duma, and F. Freund, 2018. Geomagnetic Kp Index and Earthquakes. Open Journal of Earthquake Research. 7: 39-52, DOI:10.4236/ojer.2018.71003.
- Vargas, C. and E. Kastle, 2012. Does the sun trigger earthquakes? Natural Sciences, 4: 595-600, DOI:10.4236/ns.2012.428079

Acronyms

- ACE* - Advanced Composition Explorer (satellite)
DSCOVR - Deep Space Climate Observatory (satellite)
USGS -United States Geological Survey

ABOUT THE NCGT JOURNAL

The NCGT Newsletter, the predecessor of the NCGT Journal, was begun as a result of discussions at the symposium “Alternative Theories to Plate Tectonics” held at the 30th International Geological Congress in Beijing in August 1996. The name is taken from an earlier symposium held in association with the 28th International Geological Congress in Washington, D. C. in 1989. The first issue of the NCGT Newsletter was December 1996. The NCGT Newsletter changed its name in 2013 to the NCGT Journal. Aims of the NCGT Journal include:

1. Providing an international forum for the open exchange of new ideas and approaches in the fields of geology, geophysics, solar and planetary physics, cosmology, climatology, oceanography, electric universe, and other fields that affect or are closely related to physical processes occurring on Earth from its core to the top of its atmosphere.
2. Forming an organizational focus for creative ideas not fitting readily within the scope of dominant tectonic models.
3. Forming the basis for the reproduction and publication of such work, especially where there has been censorship or discrimination.

