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Editors

Planetary Atmospheric Electricity

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Foreword

Roger-Maurice Bonnet · Michel Blanc

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"Planetary Atmospheric Electricity" is the first publication of its kind in the Space Science Series of ISSI. It is the result of a new and successful joint venture between ISSI and Europlanet.

Europlanet is a network of over 110 European and U.S. laboratories deeply involved in the development of planetary sciences and support to the European planetary space exploration programme. In 2004, the Europlanet consortium obtained support from the European Commission to strengthen the planetary science community worldwide, and to amplify the scientific output, impact and visibility of the European space programme, essentially the European Space Agency's Horizon 2000, Cosmic Vision programmes and their successors. Its present contract with the Commission extends from 2005 to 2008, and includes 7 networking activities, including discipline-based working groups covering the main areas of planetary sciences. A new contract with the Commission, presently under negotiation, will extend Europlanet's activities into the period 2009–2012. With the broad community connection made through its Discipline Working Groups and other activities, Europlanet offers an ideal base from which to identify new fields of research for planetary sciences and to stimulate collaborative work among its member laboratories. For Europlanet, developing collaboration with ISSI in holding workshops and producing books on these new and emerging subjects is both natural and extremely stimulating, considering the high profile, international standing and proven success of ISSI. For ISSI, collaboration with Europlanet offers a very interesting opportunity to extend its successful series of workshops and books within the area of planetary sciences and to deepen its links with this community.

Working from this clear convergence of interests, in 2006 ISSI and Europlanet initiated implementation of a series of joint workshops, soon after the establishment of Europlanet's

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Discipline Working Groups. Each of Europlanet's nine Discipline Working Groups were invited to select one or two promising subjects for ISSI workshops, which were presented and discussed at a working group meeting at ESAC, Villafranca, Spain, April 24th–26th. The Board of Coordinators of Europlanet then selected a shortlist. Finally, on May 18th, 2006, the Science Committee of ISSI, chaired by Prof. Len Culhane, selected the "Planetary Atmospheric Electricity" proposal, initially formulated by Jean-Pierre Lebreton and François Leblanc, to become the first joint ISSI-Europlanet workshop.

In retrospect, the choice of this subject has indeed been particularly good. As this volume nicely illustrates, Planetary Atmospheric Electricity happened to be an outstanding theme to stimulate the dialogue between a "traditional" field of geosciences—atmospheric electricity was initiated as a science by Benjamin Franklin—and the emerging field of planetary electricity, a promising development of comparative planetology. Once again, the synergistic alchemy of ISSI operated beautifully between these two communities, leading to many exciting scientific exchanges and finally to a fundamentally interdisciplinary book, merging the expertise and prospects of the two communities.

Electrical phenomena have been studied for centuries in the Earth's atmosphere, leading to a progressively better understanding of electrification sources (galactic cosmic rays, deep cloud convection, etc.), their manifestations (lightning, discharges and electromagnetic emissions…) and their hazards. Atmospheric electricity still offers outstanding challenges to modern environmental research. For example, the very mechanism of charging of cloud droplets is only partly understood, and understanding the complex 3-D geometry of thunderstorm convection cells is only beginning. Even more, a significant fraction of electrostatic discharges, those which occur between the cloud tops and the ionosphere base and manifest themselves through spectacular optical phenomena such as sprites, elves, coronae, have only recently been discovered. Taranis, the first European in-depth global study of these phenomena from space is still only in its preparation phase. Many discoveries are ahead of us!

While terrestrial atmospheric electricity is well established yet rapidly evolving, its planetary counterpart is in its infancy. One of the major merits of this book is to show the *universality*, the *diversity* and the *importance* of atmospheric electrical phenomena across the solar system.

Standing as a good example of a *universal process*, lightning is common and currently observed at Jupiter and Saturn, it is likely at Uranus and Neptune, and evidence of its existence in the atmosphere of Venus accumulates from Venus Express data. But many basic questions about its generation and occurrence are open: does cloud convection need water to generate electrification and lightning? Is there a global electrical circuit at any other planet than Earth?

Space exploration of the solar system has also illustrated the broad *diversity* of charging and discharge phenomena, in Martian dust storms or on planetary rings and dust particles, for instance, or through levitation processes at the surfaces of airless bodies.

Finally, the *importance* of electrical phenomena in the history of solar system evolution is also emerging more and more as research progresses. Did atmospheric discharges play a role in the dynamics and chemical activity of the primordial solar nebula? Or in the synthesis of the first prebiotic molecules of early Earth as suggested by Miller and Urey more than fifty years ago? Or in the growth and dynamics of atmospheric aerosol?

Based on this first inventory of electrical phenomena in the solar system, the next phase of detailed investigations of these phenomena by future planetary missions can be expected to be planned with great effectiveness, through taking advantage of the terrestrial experience both to design the best possible diagnostic instruments and to anticipate and better understand what they will observe. We are convinced that this first ISSI-Europlanet volume on

Planetary Atmospheric Electricity will become and remain a key reference for the planning of future missions.

In achieving this goal, all credit must be given to those whose hard work and dedication made this first joint workshop and publication of ISSI and Europlanet possible. Many thanks, first, to the leadership of ISSI and Europlanet who designed this collaborative project, and to the leaders of the Discipline Working Groups of Europlanet, Norbert Krupp and Ari-Matti Harri, who managed and inspired their working groups to produce challenging new subjects for future planetary science workshops. Many thanks to the Science Committee of ISSI, chaired by Prof. Len Culhane, who did the selection and made useful suggestions on the workshop contents. Our special gratitude goes to François Leblanc and Jean-Pierre Lebreton, who originally proposed the workshop's topic, and to François for masterly leadership of the whole process, from the first Conveners Meeting to book production. The team of conveners and editors did a fantastic job in defining the structure of the workshop and of the book, in managing the writing and the overall review process: as usual, all chapters were carefully reviewed by independent experts to whom we would also like to extend our gratitude.

Last, but not least, our warmest appreciation goes to the wonderful staff of ISSI, Andrea Fischer, Vittorio Manno, Saliba Saliba, Brigitte Schutte, Irmela Schweizer, Silvia Wenger, and all their colleagues whose kindness and dedication make ISSI such a nice place for a visit and for work. They are the greatest asset on which this new and promising collaboration between ISSI and Europlanet will continue to develop and flourish in the years to come.

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Preface

Planetary Atmospheric Electricity

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Abstract Electrification is a fundamental process in planetary atmospheres, found widely in the solar system. It is most evident through lightning discharges, which can influence an atmosphere's chemical composition, but electrification also affects the physical behaviour of aerosols and cloud droplets that determine an atmosphere's radiative balance. In the terrestrial atmosphere, lightning has been implicated in the origin of life.

Keywords Charge · Lightning · Electrostatic discharge · Comparative planetology · Primordial atmosphere · Cosmic rays · Electromagnetic radiation

1 Electrification in Atmospheres

Electrification occurs commonly in planetary atmospheres, although it is present in different forms. The most direct evidence to remote observers is presented by lightning, which is definitively known to occur on Earth, Jupiter, Saturn and, most probably, Venus, with lightning on Mars thought very likely but as yet undetected. In addition, Uranus and Neptune have yielded possible signals of lightning discharges. Taken across the solar system, the probability of lightning occurring in a planetary atmosphere (Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune, but neglecting moons) is therefore confidently at least (4 ± 1) in 7. Thus, as lightning can also result from volcanic activity, it is reasonable to expect electrical discharges in a solar system atmosphere, with odds considerably better than evens.

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Planetary electrification has generally been explained by analogy with terrestrial processes. Lightning on both Saturn and Jupiter is thought to originate from water clouds deep in their atmospheres, with temperatures ~300 K (Fischer et al. 2008) where water is likely to exist in more than one phase. Charge separation is therefore expected to develop in a similar way to terrestrial thunderclouds (Saunders 2008). Martian lightning, though not yet measured, is likely to originate in dust storms. These storms are probably directly analogous to terrestrial dust devils, in which high electric fields are generated by triboelectric charge separation[1] (Farrell and Desch 2001). There is, however, no terrestrial analogue for the sulphuric acid clouds on Venus. Observations of lightning on Venus are increasingly convincing (e.g. Russell et al. 2007), but a scientific consensus on the existence of Venusian lightning has been slow to develop, probably because of the clear differences between Venusian and other solar system lightning (Gurnett et al. 2001). This illustrates that much of our acceptance of planetary atmospheric electricity is rooted in comparison with terrestrial models.

Lightning highlights atmospheric electrification localised in space and time. Charge released by high-energy particles, such as Galactic Cosmic Rays (GCR) is, however, spatially and temporally widespread in an atmosphere. The incessant GCR flux sweeping across the solar system from stellar and galactic sources ensures that planetary atmospheres are constantly permeated by energetic particles. Their arrival rate is modulated by solar activity (with the 11-year Schwabe cycle, though this effect decreases with distance from the Sun), and by the planetary magnetic field (Bazilevskaya et al. 2008). Together with the ultraviolet part of the solar spectrum, GCRs constitute energetic ionisation agents, although the depth of penetration and the nature of ionisation products are specific to each planetary atmosphere.

2 Ion Production, Clouds and Atmospheric Discharges

As well as GCR ionisation, rocky planetary bodies have a low-altitude ionisation source from the radioactive minerals contained within the surface rocks, whose decay products emanate and ionise the air immediately above it. Charging of aerosols generated mechanically from the planet's surface is expected to be a direct consequence. In the presence of condensable compounds, varying in composition between atmospheres, ion production may affect the nucleation of ultra-fine aerosol particles (Arnold 2008; Kazil et al. 2008) or droplet condensation, thus providing a link between ionisation and cloud formation. The connection between ions and clouds is especially important in Earth's atmosphere because of the central role clouds play in the climate system, now studied more intensively than ever because of the challenging context presented by climate change.

The presence of ionisation in cloud-forming atmospheric regions indicates that charging can affect many microphysical processes in clouds (e.g. ion-droplet attachment, droplet activation, droplet coalescence and aerosol-droplet scavenging) which determine cloud lifetime, cloud thickness and ultimately precipitation, and also the complex charging processes leading to electric field growth. Cloud microphysical processes and charging occur simultaneously as thunderclouds mature, and are intricately inter-related. Modern theories suggest that GCR-induced free electrons within a developing thundercloud are actually responsible for triggering the breakdown process, which culminates in an avalanche, propagating between charge centres or to the ground as a lightning flash. Electrons and ions also exist

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[1] On Earth, however, the breakdown voltage is sufficiently large that discharges in dust devils generally do not occur.

above cloud tops, where they are subjected to transient electric fields following lightning discharges; acceleration of electrons and ions upwards above terrestrial cloud tops creates spectacular transient luminous events (TLEs), known as sprites and elves. Terrestrial gamma flashes (TGFs) may also result from lightning's aftermath.

When a lightning channel passes through an atmosphere (N_2 or CO_2 based), it initiates chains of chemical reactions whose long-lived products can be remotely detected, permitting elucidation of the atmospheric composition. On Earth, NO_x from lightning is transported over large distances in the anvils of thunderstorms; the chemical effects are prolonged, ultimately providing a source of dissolved solutions at the surface.

3 Evidence for Planetary Atmospheric Electrification

Non-terrestrial electricity in upper atmospheres has generally been studied by ion and electron spectrometers, electric and magnetic field measurements and plasma wave instruments, as well as remotely, from earth, by radio-occultation, optical spectrometry, electromagnetic and radar measurements (Aplin et al. 2008). Upper atmosphere measurements characterise the ionospheres produced by energetic ultra-violet ionisation but, in some cases, a secondary peak in electron concentration due to meteors has been discovered, below the ionospheric electron region (Molina-Cuberos et al. 2008).

Considering lower atmospheres, no definitive evidence for lightning has yet emerged from the *Huygens* descent through the atmosphere of Saturn's satellite Titan. No Martian lightning activity has ever been measured but, so far, no electrical instrument has deployed at its surface and therefore scope for its detection remains. Very recently, *Venus Express* magnetic measurements have strongly suggested lightning on Venus, although without a coincident optical observation, a small ambiguity over the precise source remains. Ground-based observations of NO abundance in the Venusian atmosphere also suggest lightning activity (Krasnopolsky 2006). *Voyager 1* first detected optical lightning and the electromagnetic signatures of whistlers[2] at Jupiter. It subsequently detected sferics[3] and whistlers at Saturn, a discovery recently confirmed by the *Cassini* mission (Fischer et al. 2008). *Voyager 2* measured sferics at Neptune and Uranus, interpreted as the signatures of lightning activity (Yair et al. 2008; Zarka et al. 2008).

As an alternative to direct optical detection (Takahashi et al. 2008), electromagnetic emissions have assumed to present clear signatures of lightning activity in planetary atmospheres (Zarka et al. 2008). However recent work arising from terrestrial atmospheric electricity has suggested some new approaches to studying planetary atmospheric electricity. Very low frequency measurements (3 Hz–3 kHz) can indicate the Schumann resonance, which is caused by lightning and its presence presents an important clue to the existence of a global circuit (Aplin et al. 2008; Simoes et al. 2008). The uppermost ultra low frequency present in the spectrum may be associated with lightning activity (Bosinger and Shalimov 2008). Transient luminous events discovered above active thunderstorms provide a further possibility for characterising lightning activity optically, even on planets completely covered by clouds (Yair et al. 2008). Terrestrial gamma and X-ray flashes associated with intra-cloud discharges are other potentially detectable

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[2] *Whistlers* are radio signals below $f \sim 30$ kHz. In physical terms they propagate in the frequency interval between the ion and electron cyclotron frequencies $f_{\mathrm{ci}} \ll f < f_{\mathrm{ce}}$.

[3] *Sferics* (a word derived originally from "atmospherics" in radio work) describes high frequency electromagnetic emissions.

phenomena which may occur more widely in the solar system (Lefeuvre et al. 2008; Roussel-Dupré et al. 2008).

4 Atmospheric Current Flow and Global Electrical Circuits

The balance between charge generation, lightning and local ionisation results, on earth at least, in a planetary scale current flow between disturbed and fair weather regions. More generally, this conceptual circuit model provides a framework unifying atmospheric electrical processes operating in disturbed weather regions (e.g. thunderclouds, dust devils, volcanic plumes) and the ionisation processes occurring throughout the atmosphere. Conceived by CTR Wilson, the terrestrial global circuit model is based on the generation of a global potential difference between conducting upper and lower regions, separated by a poorly conducting atmosphere (Rycroft et al. 2008). This potential difference drives a current of cluster ions (and/or electrons) created by cosmic rays and natural radioactivity between the two conducting layers. Through the global circuit current, the source energy from thunderstorms is globally dissipated by the transport of trace species, and a steady flow of ions is maintained throughout the widespread non-thunderstorm regions.

As the study of terrestrial atmospheric electricity is long established, there is much that can be learnt from its history (Aplin et al. 2008). Understanding the terrestrial concepts, and synthesising them to produce the global circuit model was protracted, taking two centuries. Identifying the key stages in the synthesis could be used to optimise future measurements of extraterrestrial environments. For example, the Schumann resonance (low frequency radiation caused by the lightning excitation of the cavity formed between the atmosphere's lower and upper conducting layers) is one of the more recently discovered aspects of the terrestrial global circuit (1950s). It has been identified as the most informative single measurement to make (Aplin et al. 2008), and therefore deserves priority when proposing future planetary atmospheric electrical instrumentation.

5 Significance of Atmospheric Electrification

Clearly, our knowledge of terrestrial lightning can be applied in mitigating electrostatic hazards. This is put to very practical application when designing lightning protection systems for spacecraft. All spacecraft are under threat from lightning after launch, or sometimes before (Lorenz 2008), particularly because the tropical locations where spacecraft are launched are also where lightning is most common. Planetary probes need additional protection against electrostatic discharge (ESD) hazards when passing through atmospheres or landing on other planets. For the *Huygens* and *Galileo* probes, ESD protection technology was directly borrowed from the aircraft industry (Lorenz 2008).

There are, however, two broader scientific issues extending well beyond the essential protection of spacecraft. Firstly, fossil evidence confirms that terrestrial lightning has existed for at least 250 million years (Harland and Hacker 1966), so, as well as being abundant in the solar system, electrification is probably a long-lived phenomenon extending to geological timescales. The abundance and longevity of terrestrial lightning has caused it to be suggested as a possible factor in the formation of molecules central to the origin of life (Miller 1953). Secondly, as outlined above, charge can modify cloud formation processes and the collision rates between droplets, crystals and aerosols. Although the effect of electrification on individual aerosols and droplets may be small, it can also be widespread, acting, in total, to influence an atmosphere's radiative balance.[4]

Beyond lightning in planetary atmospheres, aspects in their infancy include the role of electrical forces in lifting dust (Renno and Kok 2008), as well as the importance of cluster ions and charged aerosols (Tripathi et al. 2008; Harrison and Tammet 2008; Aplin 2008), Some further aspects of non-terrestrial planetary electricity have also hardly been characterised, such as the charging of planetary rings (Graps et al. 2008), volcanic electrical activity on Io (James et al. 2008) and the charge carried by asteroids.

6 Conclusions

Atmospheric electricity can originate from many different causes, specific to the kind of atmosphere and the altitude above the planetary surface. In all gaseous planetary atmospheres charge is generated by cosmic rays or ultraviolet radiation, but also by friction, meteoric impacts, atmospheric circulation, cloud charging, volcanism, and dust. The presence of aerosols modifies the charging process, facilitating charge transfer between ions and aerosols. In other planetary environments, dust storms or impacts are responsible for charge production. Rings around planets can become charged both actively and passively—for instance in the presence of magnetic fields and plasma—with their dynamics being at least affected, if not completely determined, by the build-up of electric fields. In one or other of these ways, charged atmospheric layers can be produced near most of the planets.

Information about planetary atmospheric electricity has been obtained by spacecraft observations, and the extraordinarily valuable measurements made *in situ* when spacecraft pass through a planetary atmosphere or even land instrumentation on the planet. On Earth, the violent discharge from large atmospheric electric fields is common and evident through lightning. On other planets, however, most discharges manifest themselves through secondary effects such as non-optical electromagnetic radiation, which can leak from their atmospheres to be detected remotely. Consequently detailed study of terrestrial lightning remains very important, and therefore many of the articles in this book are in one or the other way concerned with lightning, its causes, mechanism, effects, intracloud lightning, cloud to ground lightning, and cloud to space lightning like TLEs, as well as the generation of electromagnetic radiation from Schumann resonances through the spectrum to X-rays, and TGFs. The latter two are signatures of high-energy particles generated in the lightning discharges; they may indicate planetary atmospheric electric fields which could present hazards for missions to the planets.

In this volume (Leblanc et al. 2008), a detailed and up to date summary is given of the various problems in planetary atmospheric electricity outlined above. A feature is that it begins with an introductory overview section. These introductory overviews are intended to provide a brief, though fairly-founded, tutorial concerning the physics and chemistry of atmospheric electricity on Earth and the planets, the charging, ion production, current flow, current systems, electrical conductivities, and the observable processes involved into the quiet and the violent discharges. Based on these articles, the student and researcher of the many and various forms of atmospheric electricity should be prepared to deal with the more specialised papers that follow.

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[4] This was memorably described at the EuroPlanet-ISSI workshop in Bern as "the tail wagging the dog".

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Introductory Overviews

Investigating Earth's Atmospheric Electricity: a Role Model for Planetary Studies

K.L. Aplin · R.G. Harrison · M.J. Rycroft

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Abstract The historical development of terrestrial atmospheric electricity is described, from its beginnings with the first observations of the potential gradient to the global electric circuit model proposed by C.T.R. Wilson in the early 20th century. The properties of the terrestrial global circuit are summarised. Concepts originally needed to develop the idea of a global circuit are identified as "central tenets", for example, the importance of radio science in establishing the conducting upper layer. The central tenets are distinguished from additional findings that merely corroborate, or are explained by, the global circuit model. Using this analysis it is possible to specify which observations are preferable for detecting global circuits in extraterrestrial atmospheres. Schumann resonances, the extremely low frequency signals generated by excitation of the surface-ionosphere cavity by electrical discharges, are identified as the most useful single measurement of electrical activity in a planetary atmosphere.

Keywords Atmospheric electricity · Lightning · History of science · Comparative planetology · Planetary atmospheres

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1 Historical Introduction

The understanding of electricity is a relatively recent development in human endeavour, although lightning is known to have existed on Earth for much longer than *homo sapiens*. Lightning will almost definitely have been known to all human civilisations, some of whom recorded it in their literature, or linked the phenomena with gods unleashing thunderbolts. According to Schiffer (2003), William Gilbert (1540–1603), the physician to Queen Elizabeth I, was the first person to investigate electrical phenomena in what is now referred to as a "scientific" way. It was known amongst natural philosophers that amber and other insulators could attract straw fragments and chaff, but Gilbert was first to identify that it was only lightweight items that were subject to the mysterious attraction, and to generalise the types of material that could act as attractors.

The study of what might now be called electrostatics progressed throughout the seventeenth and eighteenth centuries (Schiffer 2003), through the development of scientific instrumentation such as the Leyden jar (Falconer 2004) and also the start of scientific academies such as the Royal Society (London) and the Académie des Sciences (Paris). Benjamin Franklin (1706–1790), the famous American polymath, is credited with suggesting that lightning was electricity, proposing an experiment later undertaken by Thomas-Francois d'Alibard (1703–1799) in 1752, who extracted sparks from a cloud. As well as making further measurements under thunderstorms, John Canton (1718–1772) observed in experiments in England that electricity was also present in cloudless air (Canton 1753). In the late eighteenth century a two-year series of quantitative atmospheric electrification measurements was made by John Read (1726–1814), who monitored, at least daily, the deflection of a pith ball electrometer connected to an insulated mast on the roof of his house in Knightsbridge, London (Read 1791). This monitoring approach was inspired by the earlier work of Giovanni Battista Beccaria (1716–1781) in Piedmont, Italy (Beccaria 1775). Beyond static electricity, the possibility of charge flow was emerging from laboratory experiments at around the same time. Charles-Augustin Coulomb (1736–1806) noticed that the charge on an object slowly decayed in air with time, and that this decay was more rapid when the air was more humid:

> *L'électricité des deux balles diminue un peu pendant le temps que dure l'experience… si l'air est humide et que l'électricité se perd rapidement…* (Coulomb 1784)

For this Coulomb is widely credited with discovering the electrical conductivity of air, though it is not clear that he realised the significance of his findings. He certainly did not have the theoretical understanding to explain the effect, as will be explained. To Coulomb, an experimentalist, the conductivity of air was just another difficulty encountered during his investigations of the inverse square law of electrostatic repulsion.

Detailed observation, but a lack of explanatory power, was a characteristic of this early work. Scientific theory did not exist to explain the electrical conductivity of gases until the discovery of the electron over a hundred years later. Similarly, the lack of an explanatory framework for an atmospheric electric potential in the absence of electrified cloud, which was well-established by the mid-nineteenth century, precluded systematic study of the phenomena. For example, early experimenters had noted that an atmospheric measuring electrode developed a positive charge during fine weather (Bennett and Harrison 2007), and that it varied considerably with the weather conditions, but Beccaria's suggestion that it might one day be possible to use atmospheric electricity for weather prediction was drawn only from experience rather than a theoretical understanding. At this stage, therefore, the theory did not exist to permit a more sophisticated approach than simple inductive empiricism.

In the nineteenth and early twentieth centuries the study of atmospheric electricity was approached more systematically. With scientific giants such as Faraday and Maxwell researching electricity and electromagnetism, a better physical context for the measurements was starting to be developed. The advent of more reliable instrumentation and, in particular, the ability to make continuous automatic measurements of the atmospheric electric field (more conventionally now known as the Potential Gradient, PG[1]), was very important during this period. Lord Kelvin[2] (1824–1907) was one of the pioneers of this autographic recording, developing an electrometer that measured the PG by letting water dribble through a pipe from an isolated tank, which, through charge exchange, caused the tank to acquire the potential of the atmosphere where the stream broke into a droplet spray. Kelvin's "water dropper" was used with photographic recording to produce continuous atmospheric electrical measurements for the first time in 1862 (Everett 1868). As a result, Kelvin concluded that electrification was a property of the fair weather atmosphere. This equipment began continuous measurements of the atmospheric PG in the UK at Kew Observatory[3] (Harrison and Aplin 2002), and at new scientific research facilities such as at the top of the Eiffel Tower in Paris (Harrison and Aplin 2003).

As well as surface measurements, new opportunities were presented by manned balloons which provided measurements of PG above the surface (Table 1). However, it was not just the PG that was measured. After the almost simultaneous discovery of the electron and ionising radiation (X-rays and radioactivity) in the last years of the nineteenth century, study of the conduction of electricity in gases progressed rapidly. Most of this work was carried out at the Cavendish Laboratory at Cambridge, first under J.J. Thomson (1856–1940), and then Lord Rutherford (1871–1937). It was during this period that many of the terms used to characterise ions in air were defined, for instance, the concept of mobility (the speed of an ion at terminal velocity in a unit electric field) (Aplin 2000). In parallel with the Cavendish laboratory studies, in Europe, Ebert, Gerdien, Elster and Geitel developed instrumentation to measure atmospheric ions *in situ* (Elster and Geitel 1900; Ebert 1901; Gerdien 1905a). Gerdien's instrumentation permitted the air conductivity to be measured on balloon ascents, providing further data on ion properties (Table 1). Wigand's ascent was one of the first to measure reliably both PG and conductivity to 9 km. This permitted determination of the conduction current, which was found to be essentially independent of height in the free troposphere (Wigand, 1914, 1921; Everling and Wigand 1921).

The beginning of the twentieth century is often considered to mark a transition between "classical" and "modern" physics. Atmospheric electricity also moved into a new phase at this time. There was new instrumentation with which to make systematic measurements of spatially varying quantities, supported by the rapid advances in contemporary physical theory. This set the scene for unification of previously disparate measurements, through the concept of the global circuit. The development of the global circuit model will be outlined in Sect. 2 followed by more detail on its properties and parameters in Sect. 3. The final Discussion section will conclude by summarising the historical development of the terrestrial global circuit and outlining its application to planetary studies.

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[1] The potential gradient (PG) and electric field have equal magnitudes, but are of opposite sign by convention. In fair weather, when the vertical electric field is negative, the PG is considered positive.

[2] Lord Kelvin was formerly W. Thomson and his papers are listed under this name.

[3] Observations at Kew continued virtually uninterrupted from 1860 until 1981, although their absolute calibration improved (Harrison 2003).

Table 1 Summary of the early European research balloon flights in atmospheric electricity listing quantities measured by different investigators (after Harrison and Bennett 2007a). (Atmospheric Electricity (AE) quantities: *PG* = Potential Gradient, surface air conductivity σ_0, positive air conductivity σ_+, negative air conductivity σ_-, air temperature T, relative humidity *RH*). Hess's 1912 ascent measured ion production, not atmospheric electrical quantities, but is significant because this flight discovered cosmic rays

Investigator	Launch date	Launch site	Max height (m)	AE quantities				Met data		Source
				PG	σ_0	σ_+	σ_-	T	*RH*	
Tuma	1892, 1894 (22nd Sep); 7 flights 1894 to 1898	Near Salzburg	3000	√				√	√	Chauveau 1925; Tuma 1899
Le Cadet	1893 (1st and 9th Aug)	Meudon-Valhermay, Paris	2520	√						Andre 1893
Börnstein	1893	Berlin		√						Chauveau 1925
Gerdien	1903 (1st July, 2nd Aug, 1st Oct, 5th Nov)	Göttingen and Berlin	7100			$\mu\pm$	$n\pm$		√	Gerdien 1903
Gerdien	1903 (14th April) 1904 (5th May), 1905 (11th May, 30th Aug)	Charlottenberg (Berlin)	6030	√		√	√		√	Gerdien 1904, 1905b, 1905c
Hess	1912 (7th Aug)	Aussig	5000	Ion production rate						Hess 1912
Wigand	1913 (12th and 27th July, 4th Aug, 9th Sep)	Bitterfeld	9005	√	√	√	√	√	√	Wigand 1914, 1921; Everling and Wigand 1921
Wigand	1919 (18th Dec)	?	2950	√		√	√			Everling and Wigand 1921
Gish Explorer 2	1935 (11th Nov)	South Dakota	22000			√		√		Gish and Sherman 1936

2 Development of the Global Circuit Concept

From the studies in the eighteenth and nineteenth centuries, basic facts of atmospheric electricity emerged. By the beginning of the twentieth century it was well-established that:

(1) a positive potential gradient was present in fair weather,
(2) ions were formed naturally in air,
(3) air had a finite electrical conductivity (known originally as the property of "dissipation").

It was known that the PG and conductivity were inversely related (Gockel 1903; Zolss 1904), and this result was extended by Simpson (1906a) to be related to "clarity" (visibility) of the air. Simpson (1906b) remarked that, from balloon ascents, the observed reduction in PG provided an inference that charge existed through the lower layers of the atmosphere. The balloon ascents of Gerdien, Wigand, and others found, from PG and conductivity measurements, that the air-Earth conduction current was constant with height. This provided evidence of current flow in an electric field between the upper atmosphere and the surface. C.T.R. Wilson (1869–1959) developed new apparatus for direct measurements of the air-Earth current, which was able to make measurements in different conditions without precipitation[4] (Wilson 1906, 1908).

The mechanism to sustain the current observed in fair weather was a matter of scientific speculation, though it was known to be generated within the atmosphere (Simpson 1906b). Wilson (1921, 1929) proposed that thunderstorms and rain clouds provided the current. It was possible to consider current flow from distant storms to fair weather regions, as the conductive properties of the upper atmosphere had then been deduced from radio wave studies. This will be discussed further in Sect 4.1.

A test for the theory that the thunderstorms, highly conductive ionosphere and surface, and partially conductive lower atmosphere together constituted a global atmospheric electrical circuit (the "Wilson circuit") came from the cruises of the geophysical research ship *Carnegie* in the 1920s. During these voyages, a characteristic daily variation (with Universal Time) of the atmospheric PG—known as the *Carnegie* curve—was found; it was noted that this was largely independent of the global position of the ship. (Oceanic air was particularly favourable for these measurements, because of its remoteness from continental aerosol pollution.) Using thunderday[5] statistics (Brooks 1925) from meteorological stations, and summing the diurnal variations in thunderstorm area for each of Africa, Australia and America, a strong positive correlation was found between the Carnegie curve and the diurnal variation in global thunderstorm area[6] (Whipple 1929; Whipple and Scrase 1936). Seasonal changes in the Carnegie curve variations are considered in Rycroft et al. (2008).

These findings confirmed one of the predictions of a global circuit hypothesis, namely that the variations in PG were linked to the electrical activity of thunderstorms elsewhere on the planet. Further evidence for the global circuit was provided when measurements of the ionospheric potential V_I were obtained in the late 1950s, by integration of the vertical PG profile using balloon or aircraft carried field sensors (Imyanitov and Chubarina 1967; Markson 2007). Soundings made by Mülheisen (Budyko 1971) from Weissenau, Germany between 1959 and 1972 included a period in March-April 1967 that showed common simultaneous variations in V_I measured over Weissenau and above the research ship *Meteor* in the Atlantic (Mülheisen 1971). The same V_I measurements made over the Atlantic have been shown to correlate closely with surface measurements of PG made at Lerwick, Shetland Islands, UK (Harrison and Bennett 2007b). Simultaneous variations of V_I at two locations coupled with synchronous changes in the PG provide important support for the global circuit concept. The existence of a Carnegie-like diurnal variation in V_I (Mülheisen 1977) provides further confirmation of the coupling and integrating properties of the global circuit.

3 Properties of the Global Electric Circuit

The Earth possesses, on average, a surface which is a good conductor of electricity. Land conductivity ranges from 10^{-8} Sm^{-1} for marble up to $\sim 10^{-2}$ Sm^{-1} for wet clay or limestone, a typical mean value being 10^{-2} Sm^{-1}(Lowrie 2007); the main mechanism of crustal

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[4] These were continued in a very similar manner by the UK Met Office between 1909 and 1979 (Harrison and Ingram 2005).

[5] A *thunderday* is a calendar day on which thunder is heard at a meteorological observing station.

[6] The original Carnegie and thunderday data is tabulated in Harrison (2003).

conduction is through impurity semi-conduction in dry silicate rocks. The ocean conductivity ranges from 3 to 4 Sm^{-1}, depending on salinity and temperature, the mean value being $\sim$3.2 Sm^{-1} (Olsen and Kuvshinov 2004). Kamra and Ravichandran (1993) point out that the Earth's surface cannot universally be considered a conductor, particularly in hot dry areas and at the poles, where the land conductivity $<10^{-9}$ Sm^{-1}. However, this is not thought to be important for the global circuit due to the specific geographical regions concerned combined with the paucity of lightning over the less conductive surface regions. At altitudes above $\sim$80 km, the ionospheric plasma produced by the action of solar extreme ultraviolet and X-radiation on the tenuous upper atmosphere is also a good conductor of electricity (Schunk and Nagy 2000). Between these two conductors lies the atmosphere, which behaves like a leaky insulator (an imperfect dielectric), as discussed by Rycroft et al. (2000), Williams (2002, 2007), Harrison (2004), Rycroft (2006) and Markson (2007). The atmospheric conductivity increases with height as the ionisation produced by cosmic rays increases, from a surface value of $\sim 10^{-14}$ Sm^{-1} (mostly from natural radioactivity emanating from the Earth) by seven orders of magnitude, to reach the large values ($\sim 10^{-7}$ Sm^{-1}) characterising the electrically conducting ionosphere.

Complex microphysical processes acting within thunderclouds generally cause the build up of reservoirs of positive electric charge at $\sim$10–16 km altitude and, in regions well below these, reservoirs of negative charge; a vertical electric dipole is thereby formed. Details of the physical mechanisms operating are given in Yair (2008) and Saunders (2008), and more complicated geometrical arrangements of charge—multipoles—often exist in a thundercloud. These thunderclouds constitute giant "batteries" which drive an upward current (i.e. positive ions moving upwards, and negative ions moving downwards) through the stratosphere and mesosphere up to the ionosphere, as was first discussed in the seminal paper by Wilson (1921). This upward thunderstorm conduction current contributes to causing the potential of the ionosphere to reach $\sim$+250 kV with respect to that of the Earth's surface. As a good electrical conductor, the ionosphere is an equipotential surface which is approximately spherically symmetric about the Earth.

Remote from thunderstorms, in the so called "fair weather" regions of the globe, an electric current flows downwards through the atmosphere to the Earth; positive ions move downwards and negative ones upwards. The value of the vertical conduction current density $J_c \sim 2\,\mathrm{pA\,m}^{-2}$ (Wilson 1906; Wahlin 1994, Rycroft et al. 2000; Markson 2007). The current flowing in this DC global circuit is closed by point discharge currents (sometimes termed coronal currents) which are created in the large electric fields existing below thunderclouds, as was first pointed out by Wilson (1921). These processes are illustrated in Fig. 1, taken from Rycroft and Füllekrug (2004). This figure was originally produced to introduce the activities of the SPECIAL (Space Processes and Electrical Charges Influencing Atmospheric Layers) Scientific Network of the European Science Foundation. The arrows show the electric currents flowing through the global atmospheric electric circuit. Further, Fig. 1 indicates that the ionosphere and atmosphere below it respond to heliospheric phenomena, such as the solar wind flowing radially away from the Sun at $\sim$400 $\mathrm{km\,s}^{-1}$, energetic charged particles precipitating from the magnetosphere, and also to cosmic rays coming from beyond the solar system.

Figure 1 also shows lightning discharges from the top and from the bottom of a thundercloud to ground; these radiate electromagnetic waves across the spectrum from Extremely Low Frequency (ELF, 3 Hz to 3 kHz), and Very Low Frequency (VLF, 3 to 30 kHz) to High Frequency (HF, 3 to 30 MHz). At Ultra Low Frequency (ULF, $<$3 Hz) lightning generates transient signals (see Fukunishi et al. 1997); pulsations at ULF are generated in the magnetosphere. Lightning acts as a source of electromagnetic radiation which excites the

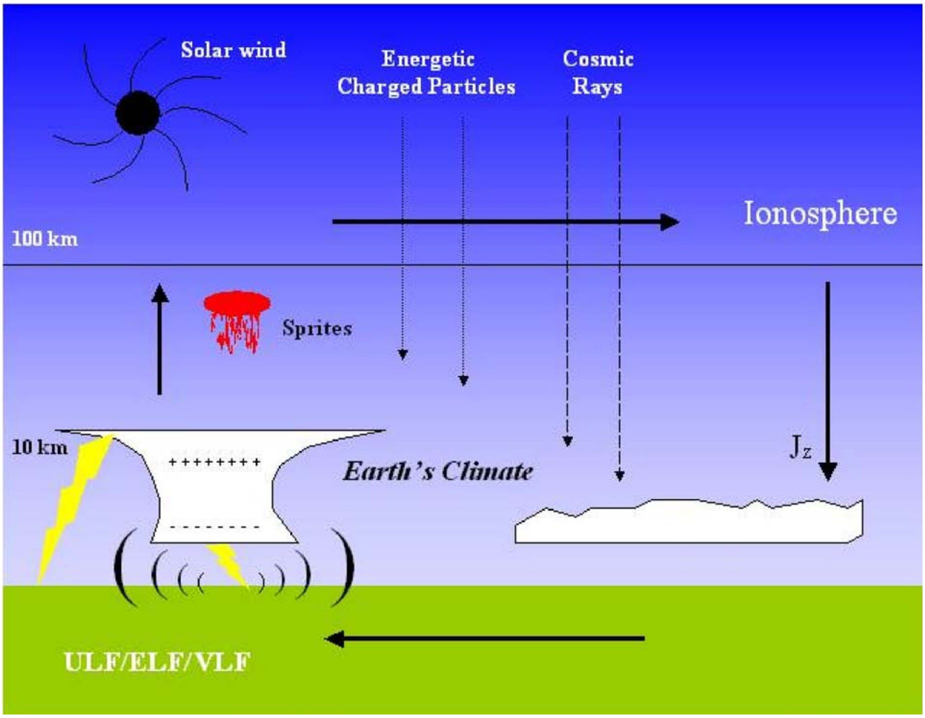

Fig. 1 Essential features of the global atmospheric electric circuit, from Rycroft and Füllekrug (2004)

AC global circuit; Schumann resonances of the Earth-ionosphere cavity exist at frequencies of 8, 14, 20, 26, … Hz (Simoes et al. 2008). Above the thundercloud is shown a sprite, a type of upward lightning discharge—for details of sprites and associated phenomena, see Füllekrug et al. (2006), Mika and Haldoupis (2008) and Mishin and Milikh (2008).

Other than thunderstorms, there are two further major mechanisms which act as drivers for current flows around the global electric circuit. Interactions between the solar wind and the Earth’s magnetic field generate additional currents (Rycroft et al. 2000), and PG modulation may arise from coupling of geomagnetically-induced changes in the magnetospheric dynamo through the global circuit. These perturbations generate polar cap potential differences, which can cause surface PG variations of ±20% (Roble and Tzur 1986). The ionospheric/magnetospheric generator is thought only to affect the global circuit appreciably at high latitudes, although weak geomagnetic influences have been detected at lower latitudes (Märcz 1976; Harrison and Märcz 2007). Another process driving current around the global circuit is precipitation (commonly called “rain”) from electrified clouds (Wilson 1921; Williams and Heckman 1993). A cloud transferring negatively charged water droplets constitutes another “battery” which causes currents to flow in the same direction as does the thundercloud mechanism already discussed. The total current flowing in the global atmospheric electric circuit $\sim$1–2 kA. Together with its physical dimensions (the Earth’s radius = 6378 km, and the base of the ionosphere at $\sim$80 km), it is the profiles of the atmospheric conductivity at all locations over the Earth which determine, via Ohm’s law, the properties (namely, the electric fields and current densities everywhere) of the global atmospheric electric circuit. An “electrical engineering” model of the circuit, originally involving only resistors, was devised by Markson

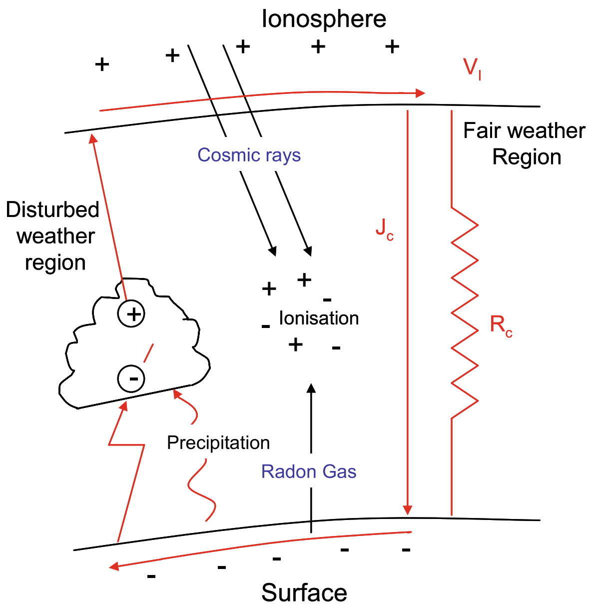

Fig. 2 Simplified "electrical engineering" model of the global circuit, illustrating charge generation in disturbed weather regions, conduction through the ionosphere (upper layer) and surface (lower layer), and discharge through the finite conductivity of fair weather regions. In fair weather regions, the ionospheric potential V_i, conduction current density J_c and unit area columnar resistance R_c are related by Ohm's Law

(1978). Some more realistic models, with capacitors as well as resistors (see Rycroft 2006; Rycroft et al. 2007), are introduced in Rycroft et al. (2008). A simplified model of the global circuit is shown in Fig. 2.

Any of the electrical processes operating in the Earth's climate system may respond to climate change (*i.e.* global warming or, specifically, increased concentrations of greenhouse gases in the atmosphere). There is also the possibility that sensitive components of the climate system can respond to atmospheric electrical changes. One sensitive aspect of the climate system is clouds.

It has been suggested that changes in the electrical properties of the atmosphere could alter the properties of clouds, resulting in a climate response. Plausible possible mechanisms have been discussed by Carslaw et al. (2002). In one scenario (the "ion-aerosol clean air mechanism"), cluster ions contribute to the formation of aerosol particles in clean air, on which cloud droplets subsequently form; in another scenario (the "ion-aerosol near cloud mechanism"), the atmospheric electrical conduction current causes particle and droplet charging which modify the cloud properties.

The clean air mechanism is illustrated in Fig. 3. In this process, condensation of vapour on freshly-formed cluster ions leads to the formation of new ultrafine particles. Laboratory and atmospheric evidence exists which demonstrates that, in the absence of other sinks of the condensable vapour, such ultrafine particle formation can occur. Ultrafine particles are not, however, able to form water clouds because of their small size. A particle needs to reach 100 nm radius to permit condensation of water in atmospheric conditions—known as a Cloud Condensation Nucleus (CCN)—but the ultrafine particles formed are about two orders of magnitude smaller. The growth stage of the ultrafine particles is therefore critical, if there is to be a later influence on the formation of cloud droplets. Modelling by Yu and Turco (2001) indicates that the growth timescale is typically 5 to 10 hours.

The near cloud mechanism results from the difference in electrical conductivity of air within and outside a cloud. In the simple case of a horizontal layer cloud, charge accumulates at the cloud boundary with clear air, as a result of the vertical current density within

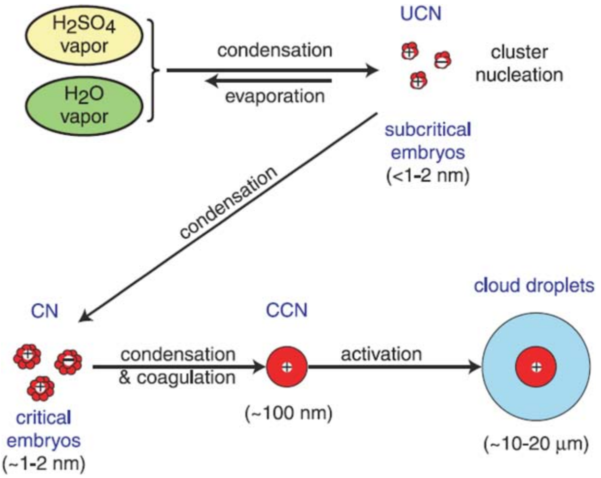

Fig. 3 Nucleation of ultrafine condensation nuclei (UCN), catalysed by ions from water or sulphuric acid vapour in the atmosphere, which could grow into cloud condensation nuclei (CCN). Reproduced with permission from AAAS from Carslaw et al. (2002)

the global circuit (Fig. 4). The effect of charge on cloud has not been investigated in detail, but, for the special case of supercooled water clouds, Tinsley and Heelis (1993) suggested that electrification might enhance the effectiveness of aerosol as ice-forming nuclei—which are relatively rare in the atmosphere—and therefore the amount of cloud ice formed. This was called *electrofreezing*. A possible mechanism for electrofreezing is the electrically-enhanced collection of charged ice nuclei by supercooled water droplets, which has been quantified through detailed modelling (Harrison 2000; Tripathi 2000; Tinsley et al. 2001; Tripathi and Harrison 2002; Tripathi et al. 2006). Such an electrically-enhanced aerosol scavenging process, known as *electroscavenging*, may lead to electrofreezing on the cloud boundary. There are laboratory observations of electroscavenging, but no direct atmospheric observations of electrofreezing. If electrofreezing does occur, there could be appreciable local latent heat release. As indicated on the right hand side of Fig. 4, the charge density on the cloud boundary is proportional to the vertical current density flowing in the global circuit. Harrison and Shine (1999) and Tinsley (2000) suggested that the global circuit may be involved in climate change via electrical effects on cloud microphysical processes in fair weather regions.

The global circuit model has recently been extended by Rycroft et al. (2007) to include the generator associated with electrified clouds; this was found to be of the same magnitude as that due to thunderstorms. Further refinements of the model could be attempted. Rycroft et al. (2007) also showed that a sprite (Füllekrug et al. 2006; Mika and Haldoupis 2008; Mishin and Milikh 2008) following a cloud to ground lightning flash which transports positive charge to ground varies the ionospheric potential in only a miniscule way. However, the effects of gigantic jets (Pasko et al. 2002; Su et al. 2003) on the ionosphere and the global atmospheric electric circuit have yet to be modelled.

4 Discussion

Based upon many observations performed and experiments conducted in the Earth's atmosphere over the last 250 years, the concept of a global atmospheric electrical circuit is one which orders the diverse measurements satisfactorily and is able to explain subsequent

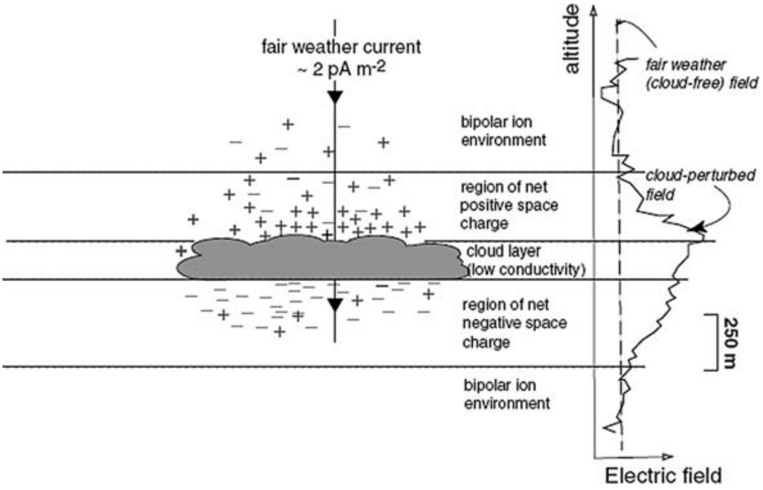

Fig. 4 Electric charge distributed around an isolated cloud in the fair weather part of the global circuit. The upward electric field is shown at the right hand side. From Harrison and Carslaw (2003)

findings adequately. Though it still has some inadequacies—notably the absence of upper atmosphere discharges and no allowance for electron density variations in the ionosphere—it still provides the best overall model available with which to unify the many disparate measurements and theoretical concepts associated with electricity in the atmosphere. Recently, other approaches to understanding the global circuit, such as simple "electrical engineering" models (e.g. Fig. 2), have provided a reasonable theoretical framework within which atmospheric electrical phenomena can be understood.

Starting from the origin of electrostatics with William Gilbert in the 16th century, the concept of a global circuit took around four hundred years to emerge in the 20th century; it is arguably still incomplete. As the word "theory" implies a still greater level of predictive power (Hesse 2000), the global circuit is referred to throughout this paper as a "model" or a "concept". In this section the development of the model is discussed so that the key concepts can be identified and used to prescribe the simplest possible measurements that could detect an extraterrestrial global circuit.

4.1 Concepts Needed in Originating the Idea of a Global Circuit

The findings leading to the development of the global circuit model were discussed in Sects. 1 and 2 above. They can be categorised into concepts that were absolutely necessary for the model to be established, and those that support or are supported by the global circuit model, but were not essential to establish it. Here the two types of finding are defined as "central tenets" and "confirming ideas", summarised in Fig. 5.

Chronologically, the first central tenet to be established was the existence of a positive potential gradient in all fair weather regions. Kelvin was probably one of the earliest to become aware of the ubiquity of the PG through his own measurements, and a compilation of the many disparate observations described in Sect. 1. For example, he described Beccaria's, "incessant observations on atmospheric electricity, night and day, sleeping in the room with his electrometer in a lofty position" (Thomson 1859; Bennett and Harrison 2007). As is also described in Sect. 1, the conductivity of the air was observed but not explained by Coulomb (1784) and attributed to the continual formation of ion pairs in air by Wilson (1897, 1899).

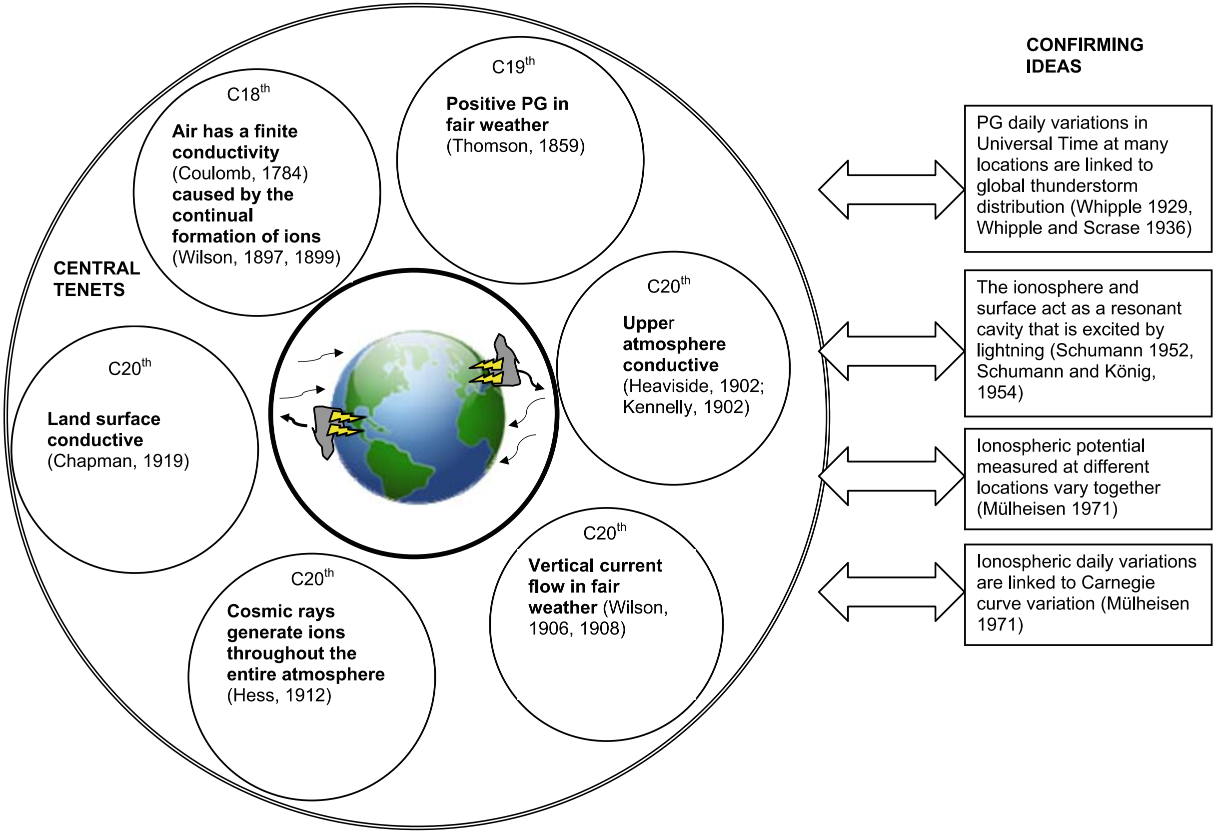

Fig. 5 Historical development of the global circuit model. Central tenets are shown on the *left*, and confirming ideas are on the *right*. The central tenets are ordered chronologically clockwise from the *top left*