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Introduction to planetary electrodynamics: A view of electric fields, currents and related magnetic fields

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Abstract

The environment surrounding a planet is composed of plasma, ionized gases and a neutral atmosphere that are continuously under the influence of solar effects. The complex dynamical interactions among these media and the generated electric fields create complicated interrelated current systems in the magnetosphere, ionosphere and atmosphere of the planets. Electric fields, currents and the related magnetic disturbances constitute the planetary electrodynamics scenario that will be considered in this tutorial. Beside providing a comprehensive and integrated view of the planetary electrodynamics, this tutorial intends to introduce the necessary theoretical background to understand the physical processes involved and particularly, to discuss some topics in which the authors are currently focussing their interests: Sun–Earth electrodynamical coupling, numerical simulations, plasmaspheric electron content variability, atmospheric electrical discharges, and the effects of intense magnetic storms at the Earth's surface and in the magnetic anomaly region. New results on these subjects are also presented. A deeper and broader comprehension of this complex scenario involving multidisciplinary investigations will certainly bring several implications in the observational, theoretical, computational and technological developments, with repercussions in biological and medical sciences.

Keywords: Planetary electrodynamics; Sun–Earth coupling; Earth's magnetosphere; Atmospheric discharges; Geomagnetic storms; South Atlantic Magnetic Anomaly

1. Introduction

The increasing number of satellites exploring the Sun and interplanetary space surrounding the planets (see, for instance, Hofer et al. (2003); Little et al. (1999); Feldman et al. (1995)) has revealed an enormous range and variety of physical processes occurring in association with the Sun–planet coupling. This whole physical environment defines an area of investigation known as the *Space Environment* (Chian, 2003). In this context, the *planetary electrodynamics* is becoming a more and more relevant research area, because of the electrodynamical effects produced in planetary atmospheres (Cravens et al., 2003; Little et al., 1999). In the specific case of the Earth, these effects impose serious implications to the adequate performance of sophisticated technological services currently available, such as telecommunication systems, information systems, power transmission networks, manned space missions, transcontinental flights, as well as on the health of the living beings (Campbell, 2003; Shepherd and Shubitidze, 2003; Stozhkov, 2003).

As the planetary electrodynamics issues are related to natural processes which are in general intrinsically complex (Sharma, 1995; Ott, 1994), the investigation of such phenomena requires intensive and multidisciplinary discussions, involving global and sophisticated data acquisition systems. Currently, in space environment studies, different features of electrical phenomena must be

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explored regarding their potential implications and applications, such as electric fields, currents, and the associated magnetic disturbances (Brautigam, 2002; Roederer, 1995; Vladimirskii et al., 1995).

Since the properties of Earth's space environment are typical of the entire solar system, the discussions of the general aspects of planetary electrodynamics will be based on the characteristics of our own planet. To allow for a deeper and wider scientific investigation, this huge region of the space environment is generally studied according to the peculiar physical processes that occur in each region. Therefore, different topics such as neutral atmosphere, ionosphere, magnetosphere and solar wind, are usually identified (Kivelson and Russell, 1995; Hargreaves, 1992; Bertotti and Farinella, 1990).

The electrodynamical discussions on the space environment presented here will concentrate on the main subjects that are being investigated by the authors: Sun–Earth electrodynamical coupling, atmospheric electrical discharges and magnetic disturbances. A better understanding of these topics will surely improve multidisciplinary approaches in theoretical, observational, computational and technological developments, with consequences even to biological and medical sciences.

In the second section, the characteristics of the electrodynamical environment involving the solar wind, the interplanetary magnetic field, the Sun–planetary coupling and magnetosphere are described. The third section deals with the planetary electric fields, currents and the related magnetic fields. Some applied results, in which the authors are interested, are summarized in section four and section five is devoted to the final comments.

2. The electrodynamical environment

In recent years, some spacecraft have been conducting an extensive study of the Sun, the solar wind and the interplanetary medium (Hofer et al., 2003; Feldman et al., 1995). Instruments onboard these spacecraft are continuously measuring the composition and physical properties of the surrounding hot plasma. Undoubtedly, the Sun is the ultimate cause of the natural processes occurring in the Earth's environment, as well as in the Earth's surface, where life blossoms (Crooker et al., 1997).

2.1. Solar wind and the interplanetary magnetic field

The Sun is a star like many others that populate the many galaxies of the Universe. It is formed by gaseous material which rotates faster at the equator than at the poles, with an average rotation period of 27 terrestrial days. About 70% of the solar mass is made of hydrogen, a small percentage of helium and minor parts of almost all chemical elements. Nuclear reactions are continuously occurring in the interior of the Sun, maintaining a temperature of 10^7 K in its center. The pressure reaches values as high as 10^{11} times that at the center of the Earth. The Sun can be observed from two different standpoints: the *quiet Sun model* which considers the Sun as a steady and symmetrical sphere of hot gas and the *active Sun model* which takes into account the transients (or time dependent) processes occurring in its surface (Usoskin and Mursula, 2003; Kivelson and Russell, 1995).

In the quiet Sun model, the Sun can be viewed as a series of concentric shells where the physical properties can vary radially from its center, but remain unchanged over any of the shells. In the inner part of the Sun ($\lessapprox 0.2$ Solar Radius (SR)), the solar particles are highly compressed by the Sun's gravity, producing densities and temperatures sufficiently high to enable the gas molecules to undergo nuclear reactions. These reactions are the source of the energy that is continuously being radiated to the surrounding space. In the intermediate region (from 0.2 to 0.8 SR), the energy is released by radiative and diffusive processes. The convective turbulent processes dominate in the convective region (from 0.8 to 1.0 SR). The major part of the solar energy is emitted as visible radiation by the photosphere (1.0 SR), which is known as the visible disk of the Sun. This region is constituted by magnetic structures which produce a background of low polarization degree. These structures allow the quiet Sun magnetic fields to carry most of the magnetic flux and energy present in the photosphere. In the upper subsequent region, the chromosphere, the absorption and reemission of electromagnetic radiation in H_α is the most relevant radiation process. The solar corona, the outermost region of the Sun, spreads out to the interplanetary medium and can reach a distance larger than 2×10^6 km. The solar corona is so hot (10^6 K) that even the extremely strong gravity of the Sun is unable to inhibit the ionized particles from scaping. For this reason, part of the solar corona is always evaporating as a steady-state flux, known as the *solar wind* (Parker, 2001; Bertotti and Farinella, 1990). The solar wind is an ionized gas, a plasma, formed primarily by hot electrons and protons with a minor fraction of He^{2+} ions and some other heavier highly ionized ions (Russell, 2001).

In the active Sun model, the large scale magnetic field of the Sun and its differential rotation are responsible for the solar activity, i.e., the local perturbations which allow the magnetic energy to be partially released as kinetic energy. The overall heliomagnetic field results from the contribution of a huge amount of fields produced in the uppermost layers of the Sun. When the stored energy extracted from the magnetic field is suddenly released, accelerating electrons and ions to higher energies, we observe bursts, eruptive prominences, or coronal mass ejections (Parker, 2001; Russell, 2001).

The solar plasma expands out from the Sun driven by thermo-electrodynamical processes. The solar magnetic field propagates *frozen in* in the solar wind in a spiral-like configuration, due to the Sun's rotation, and penetrates the interplanetary medium. This magnetic field lines are orientated towards the Sun in one hemisphere and outwards from the Sun in the opposite hemisphere (Jones and Balogh, 2003). As time goes by, they undergo an inversion of polarity characterizing the 22-*year solar cycle*. The strength and orientation of the interplanetary magnetic field, and the density, composition and velocity of the solar plasma depend on the phenomena occurring in the Sun and on the electrodynamical features present in the interplanetary medium (Lyatsky et al., 2003; Hargreaves, 1992; Tsurutani et al., 1997a). Some relevant features of these kinds of phenomena have been highlighted by Tsurutani and Gonzalez (1997). Current Sheet Sectors are regions defined by an electric current sheet that appears in the discontinuity region of opposite interplanetary magnetic field lines, undulating the surrounding space in 2, 4 or 5 main sectors. Interplanetary Shocks can be produced by several structures evolving through the interplanetary medium, for instance, plasma streams that move supersonically. Interaction Region of Interplanetary Streams are an interface region that appears because of the different velocities of the solar wind originated at coronal helmet streamers (slower) and at coronal holes (faster). Noncompressive Plasma Density Enhancement region is characterized by an enhancement in the solar plasma density without compression in the interplanetary medium. Alfvenic Waves Fluctuations ares perturbations of the interplanetary medium characterized by correlated fluctuations between the solar plasma parameters and the interplanetary magnetic field components. Besides the emission of electromagnetic radiation, simultaneously with the modulated solar wind, under certain conditions coronal mass ejections can intercept planetary orbits, and in particular, that of the Earth (Tsurutani et al., 2003; Crooker et al., 1997; Mendes, 1992).

2.2. Sun–planetary coupling and magnetospheres

In the specific case of the Earth, the planet behaves like a huge magnet. In a first approximation the magnetic field generated by this magnet is a dipole that is tilted by about 11° with respect to the spin axis. The Earth is made of a solid and fluid inner core, of about half of Earth's radius, probably composed by a mixture of molten iron, nickel and sulfur at temperatures of the order of 6000 K. Surrounding this core there is the mantle and the crust. The origin of the Earth's magnetic field is generally attributed to the movements of the conducting fluid core and the circulating flows that dissipate the internal heat. These motions create a system of electric currents, that are curled in the core, because it spins faster than the outer regions. This current system behaves somewhat like a Faraday's disk dynamo (Bertotti and Farinella, 1990; Golovkov et al., 2004). The resultant magnetic configuration affects the Earth's outer space that is replenished with a low density and magnetized plasma.

Near the Earth, the typical velocities and densities of the solar wind are respectively of about 400 km/s, and 10 particles/cm^3. The incoming magnetized solar wind interacts with this Earth's plasma creating an electrodynamical region surrounding our planet – *the magnetosphere* (Hargreaves, 1992). In this region the physical processes are driven by the geomagnetic field providing the energy and particles deposition in the atmosphere (Cowley and Bunce, 2003). All the interplanetary data obtained from planets and comets have shown evidences of the existence of a magnetosphere around them. The presence of a magnetosphere does not depend on whether the planet or comet has an intrinsic magnetic field or not. In the planets that do not have an internal magnetic dynamo, the solar wind gives rise to a magnetosphere according to the interactions with their upper atmosphere and ionosphere. The nature of these interactions defines the shape of the magnetosphere (Hargreaves, 1992).

Shock waves develop in the sunlit face of the magnetosphere because of the supersonic nature of the solar wind. Part of the solar wind is channeled to the planets' magnetosphere, ionosphere and atmosphere, causing convection and energizing the plasma trapped in the planets' magnetic field lines; creating the magnetic activity; heating the polar upper atmosphere; and producing large neutral atmospheric winds (Kivelson and Russell, 1995).

Experimental and theoretical results have shown that the coupling between the solar wind and the magnetosphere is basically maintained via a magnetic reconnection process which merges the interplanetary magnetic field with the Earth's magnetic field (Ukhorskiy et al., 2003; Kivelson and Russell, 1995). The energy transfer involved in this process is more efficient when these fields are oppositely orientated (Tsurutani and Gonzalez, 1995, 1997). The magnetospheric cavity facing the Sun is compressed by the solar wind creating a sharp boundary at an average distance of about 10.5 Earth radii (RE), although interplanetary phenomena could push it to distances of about 6 RE or even less. On the nightside, the Earth's magnetic field lines are stretched creating two lobes that are connected to the polar caps. These lobes that extend to a distance of 200 RE away from Earth is called the *magnetotail*. The energy stored in the tail is lately channeled in a continuous and/or turbulent regime towards the Earth, and part of this energy is channeled, in the form of plasma bubbles (*plasmoids*), towards the outer space.

The outer boundary of the magnetosphere is called the *magnetopause*. The bow shock is a standing wave in front of the magnetosphere at which the supersonic solar wind is slowed down, heated up, and deflected around the planet. The strength of this shock depends on the velocity of the solar wind in relation to the velocity of the compressional waves in the plasma (Hargreaves, 1992). This latter velocity decreases with increasing distance from the Sun, while the former remains quite constant. As a result, the strength or the Mach number of the bow shock increases remarkably from the inner to the outer planets of the solar system. In Mercury, the Mach number of the bow shock is about 4 and in Neptune it is about 20. At lower Mach numbers the shock is smoothly varying or has a laminar shape, but at higher Mach numbers the shock becomes particularly turbulent. The reconnection seems to be influenced by the Mach number. Under solar wind conditions typical of the inner planets of the solar system, this process is mainly controlled by the orientation of the solar wind magnetic field in relation to the planetary magnetic field. However, when the solar wind conditions change to those typical of the outer planets of the solar system, reconnection seems to disappear. At a Mach number close to 7, the reconnection rate goes to zero. Thus, reconnection is expected to be more effective in the inner planets of the solar system where the Mach number is typically less than or equal to 7, than in the outer planets, where the Mach number is often greater than or equal to 10.

3. Planetary electric fields and currents

3.1. Electric fields

Before the space era, experiments setup in balloons revealed the presence of an "atmospheric capacitor" made up by the electrosphere (70–150 km altitude), the conducting surface of the Earth and the air (*the dielectric*) between these "surfaces" (Viemeister, 1972). Currently, it is understood that a more complex system is formed by planetary electric fields in a low frequency regime. In a weakly conducting atmosphere, an electric field can be maintained if non-electric forces (convective motions, drag forces, diffusive motions and so on) are provided (Volland, 1984). The basic interaction mechanisms that maintain these conditions are the solar wind–magnetosphere coupling, the tidal winds-ionospheric plasma interactions in the ionospheric dynamo region and the thunderstorms in the lower part of the atmosphere. The importance of the electrical scenario that involves the Earth is that the electric fields can energize particles and allow them to be trapped or removed from a given magnetic field line in a certain region, above about 100 km (Rakov and Uman, 2003a).

The solar wind gives rise to the interplanetary electric field. An observer in motion relative to the solar plasma will detect an electric field, $\vec{E}$, given by

$$\vec{E} = \vec{V} \otimes \vec{B}_{\mathrm{h}}, \tag{1}$$

in which $\vec{V}$ is the relative velocity between the observer and the plasma, and $\vec{B}_{\mathrm{h}}$ is the heliospheric magnetic induction field.

The convection electric field in the terrestrial magnetosphere is a large scale quasi-static electric field that can be produced by two mechanisms: (a) a viscous magnetospheric plasma, dragged by the solar wind, creates a plasma flux in the magnetotail, that gives rise to an electric field:

$$\vec{E}_{\mathrm{cv}} = -\vec{V}_{\mathrm{cv}} \otimes \vec{B}_{\mathrm{i}}; \tag{2}$$

or (b) a magnetospheric reconnection process appears, allowing the interplanetary electric field to reach the interior of the magnetosphere:

$$\vec{E}_{\mathrm{i}} = -\vec{V}_{\mathrm{s}} \otimes \vec{B}_{\mathrm{i}}, \tag{3}$$

in which V_{cv} is the plasma motion towards the Earth in the magnetotail, V_{s} is the solar wind velocity and $\vec{B}_{\mathrm{i}}$ the interplanetary magnetic induction field.

These mechanisms bring the plasma contained in the magnetotail closer to the Earth. When this occurs, the energy of the plasma increases with the increasing of magnetic field strength. The drift produced by the gradient and the curvature in the Earth's magnetic field plays an important role in the plasma movement, causing the separation of the proton and electron trajectories. This charge separation produces an *Alfvén layer*, that behaves like a polarization electric field. These electric fields are produced in the dusk–dawn direction to shield the plasmasphere (a region of ionized material that corotates with the Earth) from the convection electric field. The Alfvén layer depends on the conductivity of the ionosphere and on the energy of the particles coming from the tail. In the lower atmosphere, the presence of a transient electric field due to the unbalance between the convection and the polarization electric fields can emerge (Kivelson and Russell, 1995).

The electromagnetic radiation and cosmic rays incident in the Earth's atmosphere create an intense ionized region that dominates in the altitude range from 70 to 1000 km, known as the *Ionosphere*. Considering that the ionosphere is a highly conducting plasma completely merged in the atmosphere, the global configuration of the geomagnetic field, B, will tend to rotate with the Earth. This mechanism establishes an electric field E, in a reference frame that is moving in relation to the magnetized environment:

$$\vec{E}^{\star} = \vec{E} + \vec{V} \otimes \vec{B}, \tag{4}$$

$$\vec{B}^{\star} = \vec{B}, \tag{5}$$

The symbol ★ refers to the moving system. The zonal velocity is given by

$$V_{\lambda} = \omega_t R \cos(\lambda), \tag{6}$$

where λ is the latitude, ω_t is the angular velocity of rotation, and R is the radial distance to the center of the Earth. Under these conditions, a co-rotating electric field is generated

$$\vec{E}_c = -\omega_t R B \cos(\lambda)\hat{R}. \tag{7}$$

This electric field establishes the dominant mechanism that controls the plasmasphere.

The combined effects of the Sun's and Moon's gravities and the Sun's heating produce oscillatory forces in the atmosphere that give rise to neutral air movements (tidal winds), mostly in the horizontal direction. The displacement of the air-dragged electric particles through the lines of the Earth's magnetic field generates electromotive forces, known as the electric field of the ionospheric dynamo, that produce electric currents at altitudes where the electrical conductivity is considerably high (above 10^{-6} S/m). The conductivity is actually a tensor because the magnetic field makes the medium anisotropic in its response to an applied electric field (Kivelson and Russell, 1995). As the conductivity changes vertically and horizontally, the currents cannot flow freely in all directions, and then, polarization patterns are produced and a vertical electric field is created. The altitudes where the dynamo occurs range from 90 to 150 km. The electric field strength is of the order of 1 mV/m. The relative values of the electric field resulting from the lunar effect is approximately 5% of the that resulting from the Sun. During magnetically disturbed periods the ionospheric dynamo current system is disturbed by the thermospheric winds produced by auroral heating (Ratcliffe, 1972).

Yet in the lower atmosphere, at altitudes <70 km, another electric field appears. It is the fair weather electric field that predominates in regions of fair weather. It is a quasi-stationary, vertical downward electric field. The electrical potential difference between the *electrosphere* ($\leqslant$150 km) and the Earth's surface is of about 250 kV. The magnitude of the electric field measured on the ground is about 100 V/m. The atmospheric gases (a homogeneous mixture of nitrogen and oxygen) present in this region cannot be considered as a perfect electric insulator, but only as a partial insulator, due to ionization produced by natural nuclear radiation on the ground and cosmic rays. Hence these gases allow an electric current density of about 2×10^{-12} A/m^2 to flow downwards. Integrated over the surface of the Earth, this current is of approximately 1 kA. The fair weather electric current would dissipate the electric potential difference between the ground and the ionosphere in a period of about 10 min, but this does not occur because of the continuous action of electrified convection. The maintenance of this potential difference is ordinarily attributed to the Cumulonimbus clouds (WMO, 1956) that occur in several regions of the Earth's troposphere. This type of cloud can be interpreted as a battery driving a current of the order of 1 A, from the Earth and into the upper atmosphere (Rakov and Uman, 2003a).

The electric structure of the Cumulonimbus clouds can be roughly characterized by a vertical electric dipole with two main centers of charges: one positive above and one negative below. There are evidences that a secondary center of positive charge can develop below the main center of negative charges (Williams, 1989a,b; MacGorman and Rust, 1998). Two hypothesis can be evoked to elucidate the creation and maintenance of these electrical centers. The precipitation hypothesis asserts that negative electric charges are produced by the descending movement of hydrometeors in relation to smaller and lighter particles positively charged. In this hypothesis two microscopic loading mechanisms need to be explored: (a) charge transport by electric induction and (b) charge transfer by collisions between graupel particles and ice crystals, for instance. The convection hypothesis refers to the transfer and selective storage of electric charges in specific regions of the cloud. The electric charges should originate in the convective movement of space charges due to the corona effect (charges released at the tip of an object) and/or by the space charges associated with different electric conductivities, creating a shielding layer – space charge accumulated near the cloud boundary.

This low-atmosphere scenario leads to the proposition of a global electrical atmospheric circuit (Rakov and Uman, 2003a). In such context, the Cumulonimbus clouds act as an electric battery, supplying charges to the atmosphere. Horizontal transient electric fields observed below these clouds are attributed to positive charges deposited during precipitation caused by lightning. Although lightning flashes to ground are interpreted as a discharging process of the thundercloud, they can also be considered as charging the global electric circuit (MacGorman and Rust, 1998).

3.2. Electric currents and particle precipitation

In this planetary environment, complex dynamical interactions are accomplished between energy and electrodynamics by the generation of complicated interrelated current systems such as magnetosphere current, tail current, ring current, field-aligned currents, ionospheric currents and a lower electric circuit with atmospheric discharges. In Fig. 1 the geomagnetic topology, regions of plasmas and some current systems of the Earth's magnetosphere are presented. Kivelson and Russell (1995) and Volland (1984) give some insights on how these currents are decoupled from one another based on the mechanisms involved and resulting effects.

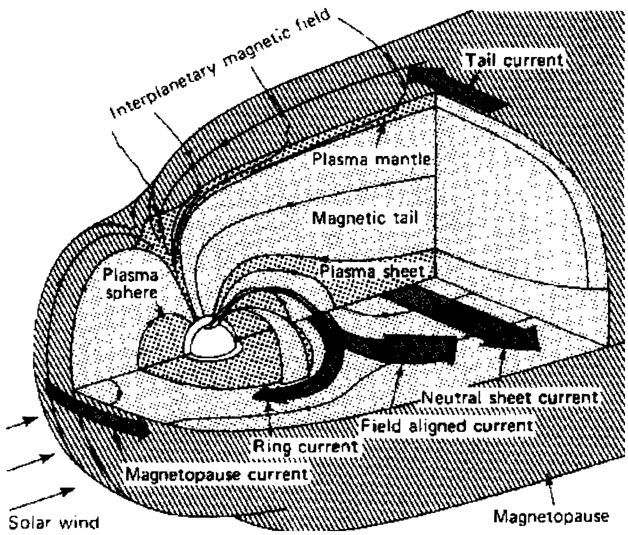

Fig. 1. Geomagnetic topology, regions of plasmas and some current systems of the magnetosphere. Source: Potemra (1983).

A current appears and flows in all the extension of the magnetopause producing a magnetic field that cancels out the Earth's magnetic field outside the magnetopause and enhances it inside this boundary. It is known as *the magnetopause current*.

In the upper lobe of the magnetotail, the magnetic field points towards the Earth, and in the lower lobe, it points in the opposite direction. In between these lobes a *neutral sheet current* and a *plasma sheet* are formed. The neutral sheet current is related to the magnetopause current vortex, a current flowing across the plasma sheet from the dusk to the dawn side forming a double solenoid (Hargreaves, 1992). The plasma sheet is characterized by a plasma with higher temperature and density than the surrounding region. It can be considered as the upper extension of the auroral ionosphere and acts as the main source of auroral electrons. On the other hand, the closed lines of the Earth's dipolar magnetic field provide the mirroring conditions for the trapped particles (ions and electrons) to drift slowly through adjacent field lines back and forth. These particles, gradually circling around the globe clockwise (positive ions) and counterclockwise (electrons), obey a convective-driven motion towards Earth. They are submitted to space variations of the geomagnetic field, that causes the opposite movements. In a simplified fashion, these moving charges generate a worldwide equatorial electric current, *the ring current*, which induces mid- to low-latitude magnetic disturbances at the Earth's surface, known as *geomagnetic storms*. Under these conditions, the global geomagnetic field becomes weaker by about 0.5–1% (Gonzalez et al., 1994; Tsurutani et al., 1997a; Tsurutani and Gonzalez, 1997; Clua de Gonzalez and Gonzalez, 1998).

In the Earth's magnetic environment there is a permanent structure formed by trapped particles distributed in a toroidal shape that circles the Earth above the equator, known as the *Van Allen radiation belts*. The inner radiation belt is a quite stable trapping region observed from 0.1 to 3 RE, mostly populated by protons produced by galactic cosmic radiation. Energetic particles, although dense enough to cause radiation damage, are unable to carry a current. The outer radiation belt, 2–8 RE, contains a higher concentration of protons and electrons of moderate energies.

While the ring current develops particularly in the external part of the outer radiation belt, in the inner part of the magnetosphere is located the plasmasphere where the magnetic flux tube is filled with the cold plasma from the ionosphere below.

The Earth's plasmasphere is a region of cold (about 1 eV), dense (tens to thousands of particles per cubic centimeter) plasma that is roughly coincident with the inner magnetosphere, where the ring current and radiation belts develop. It is populated by the outflow of ionospheric plasma along mid- and low-latitude magnetic field lines (i.e., those that map to magnetic latitudes of about 60° and less). H^+ is the principal plasmaspheric ion, with singly ionized helium accounting for about 20% of the plasmaspheric plasma.

Unlike the plasma of the central plasma sheet, which in general flows in the dawn-to-dusk direction (dayside magnetopause), the plasmaspheric plasma is captured by Earth's magnetic field lines that co-rotate with it. It is the competitive interplay between these two flow regimes – one convecting sunward, the other co-rotating – that, together with the outflow of plasma from the ionosphere, determines the size, shape, and dynamics of the plasmasphere, that varies strongly according to the level of magnetospheric activity (Carpenter et al., 1993).

During periods of low magnetic activity, when corotation dominates the near-Earth plasma flow, the plasmasphere becomes "saturated" with the up flowing ionospheric plasma and extends to about 6 RE or beyond. Its density decreases steadily with increasing distance from the Earth. When the magnetosphere is disturbed by a magnetic storm, enhanced convection "erodes" the outer plasmasphere, capturing plasma in the afternoon–dusk sector and transferring it outwards and sunwards to the magnetopause. Some of the eroded plasma convected to the magnetopause may escape into the solar wind, while some is thought to be transferred to the magnetotail, and eventually to the plasma sheet. When the magnetosphere is getting quiet, with the weakening of convection, as much as 10–30% of the eroded plasma appears to become trapped between the plasmasphere and the magnetopause and remains for several days in the afternoon–dusk sector of the outer magnetosphere. Finally, some of the eroded plasmaspheric material, in the form of extended plasma streamers or tails attached to the main body of the plasmasphere, may begin to rotate with the Earth as convection weakens and eventually may wrap around the plasmasphere, contributing to its post-disturbance recovery.

Following erosion, that can last from a few hours to tens of hours, plasma flowing upward along magnetic field lines from conjugate ionospheric points begins to "refill" the depleted plasma of the plasmasphere. Conjugate points are those where a given field line enters the ionosphere in both hemispheres. Refilling of the plasmasphere typically requires several days. The upper part of the plasmasphere is limited by the lines of the geomagnetic field, corresponding to approximately 6 RE. These lines intercept the Earth's surface at latitudes of about 66°. At higher latitudes, the plasmasphere almost disappears.

The bright visible arcs of the auroras are associated with strong electric currents that flow along the magnetic field lines which guide the charged particles, mainly electrons (Sandholt et al., 2004; Sergeev et al., 2004). Such currents, unlike the ring current, are driven by a potential difference. *Field-aligned currents* (or Birkeland currents) are crucial in the solar–magnetosphere–ionosphere system coupling (Nakano and Iyemori, 2003). Near the Earth, the loop is completed by the high conductivity of the ionospheric E-layer that appears at an altitude of about 110 km. These currents do not reach the ground, because the air is a good electric insulator. The charges are then pilled up creating a large horizontal current system flowing in the D and E regions of the auroral ionosphere, that is called *the Auroral Electrojet* (Gjerloev et al., 2003). During magnetically quiet periods, the electrojet is generally confined to the auroral oval, however during disturbed periods, these currents are intensified and their limits can extend beyond the auroral regions. This expansion is mostly caused by enhanced particle precipitation and enhanced ionospheric electric fields. These currents are related to auroral geomagnetic disturbances, called geomagnetic substorms. There is some controversy over the application of the term "substorm" to the signatures of the energy injection seen during storms. A substorm is generally thought of as being, at least in some regards, a global and coherent process with a growth phase, dipolarization and energization particles. During storms the changes in the magnetic field and injection of particles are so rapid that it becomes difficult, if not impossible, to identify individual substorms (Kamide et al., 1998; McPherron, 1997; Wu et al., 2004).

Electric forces parallel to the magnetic field lines are able to speed up auroral electrons downwards and positive oxygen ions (O^+) upwards. The positive ions are pulled away from the ionosphere and accelerated equatorwards, where they contribute to enhance the ring current.

In addition to the auroral current system, at altitudes of the ionospheric D and E regions, another current can be observed as an enhancement of the diurnal variation in the geomagnetic field near the dip equator: the *Equatorial Electrojet – EEJ* (Ritter et al., 2004; Doumouya et al., 2003; Jadhav et al., 2002). The dip equator is the trace along the Earth's surface for which the dipole inclination is equal to zero. The largest amplitude and the maximum width of the EEJ is found in the American sector where the Cowling conductivity attains its maximum value (Sizova, 2002). It has a current–density peak of about 8 A/km^2 at an altitude of 105 km at the dip equator over Brazil and a width of about 15° in latitude (Campbell, 1997; Hargreaves, 1992). The intensity of the EEJ is subject to a day-to-day variability that depends on the tidal forces and on the increase of the ionization produced by the solar radiation. The analysis of a magnetic storm signature on the auroral, mid-latitude and equatorial magnetic field measured on the ground and the ionospheric electrodynamic data have led to the identification of a sensitive response of the equatorial electrojet to large-scale auroral return current.

As a part of this electrodynamical scenario, it is necessary to mention the development of thunderstorms that occur in the lowest part of the atmosphere, the *troposphere*. During the electrical storms, atmospheric electric discharges and stratospheric transient optical phenomena are generated. These phenomena are being more and more emphasized as atmospheric tracers, since they are related to the meteorological features and the electrodynamical properties of the atmosphere as well. Moreover, their detection in a more systematic and effective way is being eagerly encouraged (Valdivia, 2003; Williams, 2001; Sentman, 1998; Williams, 1995).

Lightning as usually understood is an electrical discharge that dissipates the electric charges stored in particles clustered in the atmosphere. In the Earth, these high intensity transient currents (30 kA) are produced by the electric charges accumulated (≈10–100 C) in the Cumulonimbus clouds. Lightning can occur when the local electric field exceeds the dielectric strength of air (>400 kV/m). Lightning can be classified according to two aspects: (a) origin and development, and (b) polarity (associated with electric charge). Regarding the first aspect, they can be of several types: cloud–ground, ground–cloud, cloud–cloud, intraclouds, horizontal (laterally projected to the empty space) and towards the stratosphere (Rakov and Uman, 2003a; Bazelyan and Raizer, 2000; Uman, 1987).

A simpler classification considers only lightning flashes between clouds and ground or lightning flashes in the sky. Cloud–ground lightning, although less frequent than lightning in the sky, had received special attention by scientists in the past because of the material damage and death risks they impose. However, due to the recent technological advances, for instance the spacecraft nowadays are more susceptible to electrical or electromagnetic effects than ever, all kinds of lightning are receiving attention. Usually, cloud–ground lightning consists of a single electric discharge called a *stroke*, although they can also be formed by multiple consecutive strokes, that can take ≈10–200 μs and a time interval between consecutive strokes of about 3 to 500 ms, with a typical value around 40 ms. The polarity of the stroke is dictated by the polarity of the charge brought to Earth. If it displays both sign of charge transfer, it will be a bipolar lightning. The physical process associated with the polarity is quite subtle, because of the lack of knowledge about the details of the charge transfer.

In general, a descending lightning is characterized by a *preliminary dielectric disruption* that occurs in the lower part of the main negative charge center of the cloud; then a *stepped leader* develops (discharge that precedes and creates the lightning channel); close to the ground an ascending *connecting discharge* completes the channel; and finally the charges in the ionized channel are neutralized as the *return stroke*. Sometimes, subsequent discharges occur. Occasionally a longer direct current is maintained by the lightning ionized channel, called a *continuity current* (Uman, 1987).

Besides the effects of some waves that are generated by lightning in the magnetosphere (Valdivia, 2003), recently new evidences suggest an active coupling among the troposphere, the middle and the upper atmosphere (Su et al., 2003; São Sabbas et al., 2003; Pasko et al., 2002, 1998). Since the last decade of the 19th century, several publications have reported the occurrence *of gamma ray bursts*, *X-rays* and of a great variety of transient luminous phenomena associated with lightning and thunderstorms (Pasko, 2003; Greenfield et al., 2003; Moore et al., 2001; Lyons et al., 2000; Sentman, 1998). A sketch of the transient luminous phenomena can be found in Rakov and Uman (2003a).

In general, any observable signal from a lightning source can be used to detect and locate the lightning process that produce it. Nowadays, to collect experimental information on the electric activity of the atmosphere in order to study the worldwide phenomenum, several detection and monitoring methods have been developed (Krehbiel et al., 2000; Rakov and Uman, 2003b).

Instruments on board spacecraft monitoring transient luminosites, electromagnetic emissions, and the presence of waves that affect the behavior of electric particles moving along the magnetic field lines allow to study the possibility of occurrence of lightning in the planetary atmospheres of Venus, Jupiter and Titan, and Neptune (Gibbard et al., 1995; Gurnett et al., 2001; Desch et al., 2002). Information on the planetary environment conditions and the comparison of the behavior of the planetary electric discharges with those occurring in the Earth are very important to the knowledge of the cloud structure and the electrification processes. The proliferation of information of this kind in forthcoming years will provide new approaches to the physical models applied in the study of intense thunderstorms in the Earth's atmosphere and the importance of its relationship to other regions and processes in the magnetosphere (Rodger et al., 2003; Trakhtengerts et al., 2003).

For more information on the subjects presented in this section, consult Kivelson and Russell (1995), Hargreaves (1992), Bertotti and Farinella (1990) and Rakov and Uman (2003a).

4. Researches on planetary electrodynamics

In the previous section of this tutorial, some theoretical aspects of the electrodynamical processes occurring in the Sun–planet coupling have been described and the complex relations between the electric fields, currents, and the magnetic disturbances involved have been discussed. In this section, some applications on topics concerning atmospheric electricity and the ground-based study of geomagnetic storms will be presented.

4.1. Lightning analysis and numerical simulations

To achieve a deeper understanding of the mechanisms involved in the electrification of clouds, new findings on relevant parameters such as electric fields and charges, air displacements, atmospheric ionization processes, and lightning behavior are still needed. This knowledge depends on the analysis of macroscopic and microscopic features involved in the physical processes of the thundercloud.

In the last 30 years several models have improved the understanding of atmospheric electrodynamic behavior concerning a global atmospheric electrical circuit. Due to the complexity of this task, many proposed models are limited to specific cases.

The model developed by Anderson and Freier (1969) establishes the basic formalism necessary to study the lightning path in the atmosphere. Considering the fast changes of lightning discharges compared to the atmospheric quasi-stationary conditions, they obtained the potential distribution for a dipolar structure. They assumed a steadily conducting atmosphere and an exponentially increasing conductivity. During the increase of the positive charge the potential varies upwards from the ground and this eventually annihilates the lower dipole charge. They also presented a convective mechanism for thunderstorm regenerative charging.

Considering the positions of a vertical and a tilted dipole in the atmosphere, Takagi et al. (1986) have computed the increase in the fraction of positive ground flashes occurring at various points of lightning charges in a thundercloud. They used a stepped leader model in which a streamer, starting from an infinite cylindrical charge (to simulate cloud charge) proceeds in the direction of the maximum difference of the electric potential at the top. Takagi et al. (1986) considered a tilting in the vertical dipole axis produced by the opposite centers of charge in the thundercloud. This mechanism intends to explain the high percentage of positive lightning at middle latitudes in the North Hemisphere.

Dellera and Garbagnati (1990) provided a model for (a) the progression of the negative channel downwards to the ground, (b) the beginning of the positive channel from structures connected to the ground and (c) the connection of the ascending positive channel to the descending negative channel. They considered a lightning already in progress at about 1 km above the striking point on the ground. They also assumed a ring unipolar charge distribution for the clouds, a straight line charge path for both leaders (downward and upward), and a point or online charges for the electrodes connected in the ground from which the upward leaders are supposed to develop. Adopting a fractal technique, Kawasaki et al. (1989) improved this model by adding a certain tortuosity and branching as representative characteristics of the lightning channel. These procedures allow evaluate the vunerability of structures such as electric power towers, located in flat areas and in different orographic conditions.

A different approach to the problem of the stepped leader path calculation in the atmosphere has been presented by Takeuti et al. (1993), considering a statistical method rather than the electric nature of the phenomenum. A stepped leader reaching the ground just below the cloud could be modeled by using random simulation with values distribution obtained from photographs. They have also analyzed the role of high structures such as towers, in the shielding effect.

Ma et al. (1998) have developed a model to calculate both the transient electric fields and Maxwell currents, at altitudes from the ground (0 km) to the ionosphere (150 km), due to the charge rearrangement from cloud–ground or intracloud strokes. They used a finite difference time domain technique developed in a three-dimensional computer model. They concluded that the height of the thunderstorm above the ground, as well as the height of the ionosphere, can significantly affect the shape of the post-stroke electric field and the transient Maxwell current.

Mazur and Ruhnke (1998) have replaced, the usual spherical distribution of cloud charges by a cylindrical geometry in order to maintain a uniform probability of lightning triggering over the active area of the storm. In their electrostatical model, they assumed that the positive charge center was above the negative center, adopted the bidirectional leader concept, and considered that the cloud-to-ground leader developed vertically along the axis of symmetry. An important feature that differentiates this model from others is that the cloud-to-ground leader, as well as the intracloud leader originate in the same point inside the cloud.

Another model for the cloud charge distribution adopting a positive charge center at the top and a negative charge center at the bottom has been used by Kumar and Nagabhushana (2000). The simulations were restricted to vertically straight leader without any branches. All cloud charges were aligned one below the other along the axis of the leader. This model can be useful to refine the calculation of the attractive radius/shielding efficiency of lightning protection structures.

The authors of this tutorial have developed a simplified numerical simulation of the stepped leader just taking into account macroscopic assumptions (Mendes et al., 2003b). Usually, to get a model for the path and behavior of a lightning, it is assumed that the *stepped leader* proceeds in the direction of the existing electric field ($-\nabla\phi$, which is the gradient of the electric potential) ahead of this leader. The developed model is similar to Takagi's model (Takagi et al., 1986). According to the complexity degree and the quality of the numeric simulation, some approximations have been introduced. Assuming that the generated magnetic fields can be neglected, the electric conductivity of the atmosphere (σ) is a scalar that increases exponentially with height, the electric current follows the simplified Ohm's law, the charges are finite spheres and the lower and upper boundaries are the ground and the ionosphere respectively, the scalar potential can be represented by

$$\frac{1}{\tau_c}\nabla^2\phi - \frac{\sigma}{\varepsilon_0}\left(\nabla^2\phi + 2K\frac{\partial\phi}{\partial z}\right) = \frac{1}{\varepsilon_0}\nabla\cdot J_s, \tag{8}$$

where τ_c is the characteristic time of the process; ε_0 is the electric permissivity of free space; σ/ε_0 is the electric relaxation time of the air; K is a constant that represents the scale height of the electric conductivity; and J_s is the surface density current of the source charges. This potential allows the calculation of the electric field $\vec{E} = -\nabla\phi$. A derivation of Eq. (8) can be found in Holzer and Saxon (1952), Anderson and Freier (1969).

The lightning flashes occur in a very short characteristic time τ_c (<100 ms), then only the first term of Eq. (8) needs to be considered. In this case the solution of Eq. (8) is coulombian. When the characteristic time is longer, $\tau_c > 1$ s, the first term of Eq. (8) can be neglected. In this case the solution corresponds to the charge separation in the cloud before the electric discharge occurs. This solution is the initial condition for the numerical simulation developed by Mendes et al. (2003b). The sum of these two solutions allows to evaluate the electrodynamic conditions of the atmosphere and specially to simulate the lightning path.

This numerical simulation of the stepped leader has led to some important results: the occurrence of positive lightning to the ground depends on the conductivity model adopted in the simulation; there is an increase in the percentage of positive lightning even for vertical dipoles when the conductivity increases exponentially; the numerical results are in agreement with experimental values previously obtained in Brazil (Mendes et al., 1998; Pinto et al., 1996). This work enlarges the results of Takagi's model because it includes the southern hemisphere and sheds light on the behavior of the discharges in tropical regions. As an example, Fig. 2 shows a natural cloud-to-ground long-path lightning, obtained at Brazil Southeastern in 2001, and Fig. 3 shows the corresponding simulation of the lightning path, using a statistical function to simulate tortuosity. Another cause of the behavior observed in Fig. 2 is that low level space charge distribution would play a role, that could be included in the simulation discussed.

In all the models discussed many assumptions have been made in order to simplify the simulations. Although not realistic, they help to find some peculiarities inherent to the electrodynamical discharge process in the atmosphere and to identify the most relevant parameters involved. The theoretical and experimental results described, using different approaches, are isolated and empirical. A great effort is needed to integrate them into a comprehensive electrodynamical model for lightning paths.

Nowadays, there are many techniques available for lightning detection. Radio-frequency emissions associated with dielectric breakdown and electric discharge processes in the cloud are observed in a wide range of the electromagnetic spectrum, from a few Hz to 10 GHz. These emissions are likely produced by the speed up of charges at the top of the lightning channel; small scale branching in the development of channel structures inside and outside the Cumulonimbus; and electrical interactions among the precipitating particles inside the thundercloud. The detection of these emissions allows the identification of the regions where they take place and the investigation of the electric structures and the propagation of electric discharges associated with Cumulonimbus clouds (Rakov and Uman, 2003a).

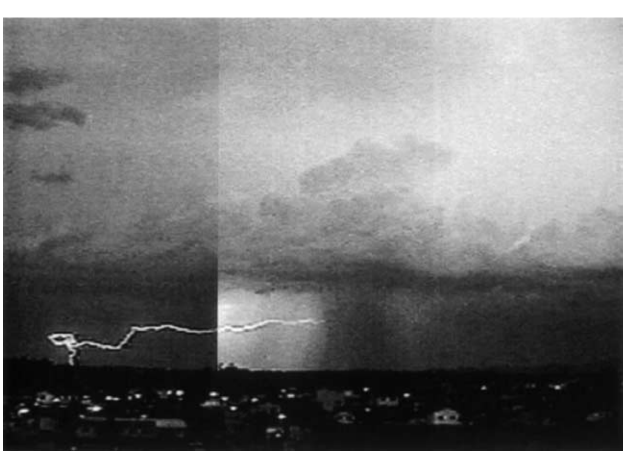

Fig. 2. A natural long horizontal lightning path. Image obtained at Brazil Southeastern in 2001.

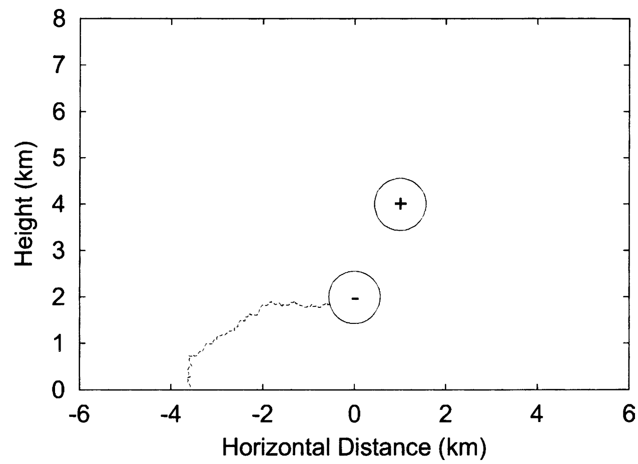

Fig. 3. Simulation of a long lightning path using a statistical function to simulate tortuosity.

On the other hand, the use of imagery techniques for the electrodynamical analysis can help in the identification of important features of lightning that can be lost during the remote electromagnetic monitoring (Mendes et al., 1999). Surely new advances in these techniques would improve the lightning detection networks and would provide subsidiary information to the weather forecasting. The results obtained from imagery analysis should also be used as parameters in numerical simulations of lightning.

In general, the investigation of objects with random and fractal features can reveal some hidden physical processes or mechanisms related to the objects (Takayasu, 1992; Stoyan and Stoyan, 1995; Vechi et al., 1994; Tsonis and Elsner, 1987). The authors of this tutorial have selected and applied some fractal techniques and geometrical statistic methods to specific features of lightning (Mendes et al., 2003a). Images taken from lightning flashes occurring under different conditions have been analyzed. The imagery devices were conventional cameras (30 frames per second) or high speed camera (500 frames per second). The proposed methodology consisted in the use of integrated information on channel characterization, imagery fractal analysis, stroke/lightning geometrical statistics and discharge characteristic time.

The parameters of interest are: (a) branching, that seems to be related to the electric breakdown, (b) tortuosity, that seems to be associated with atmospheric conductivity and space charge, (c) peak current intensity, multiplicity, time lag, and stroke/lightning clusters, that are connected to charge storage processes, atmospheric conductivity and the thermo-electrodynamics of convective cells. In order to emphasize the features of the channel, some filters were applied to the image treatment

(Russ, 1999). In principle, for a given object, the fractal dimensions are not the same using different filters, because the analyzed features are different. Due to the differences in brightness and background, it is necessary to define threshold values for each image analyzed. Regarding to space dimension, the measurement obtained from the *box counting* technique (Stoyan and Stoyan, 1995) can be used as an index for lightning branching. Actually these indices do not measure branching or tortuosity directly, although they can be quite useful.

If the index is close to one, there is no branching. Values close to 1.7 are typical for laboratory discharges that normally are very branched (Takayasu, 1992). Concerning the path changes (direction and length), the measurement obtained from the *scalar ruler* technique (Stoyan and Stoyan, 1995) can be used as an index for lightning tortuosity. These values can help in the interpretation of the physical behaviour of the lightning in the atmosphere and can be used as parameters in the simulations as well.

The results have been discussed in terms of the electrodynamics properties of the lightning or the atmosphere. Partial results have been attained regarding the channel characterization. Fig. 4 shows an example of the cloud-to-ground lightning flash with branching and tortuosity, collected in Brazil Southeastern. Figs. 5 and 6 show how the main channel of the first lightning stroke (not shown) is analyzed. Fig. 5 presents the step length, the angle with the vertical and the angle between consecutive steps in relation to the lightning position, in order to characterize some morphology features. The most important information is the fluctuation, not the absolute values. The parameters given in Fig. 5 allow to discuss the local disturbance in terms of the electrical conductivity and space charge. Fig. 6 shows the histograms for the parameters of Fig. 5. Using the box counting method for the images analyzed, the branching indice for the lightning over Brazil ranged mainly from 1.3 to 1.5. Higher values are obtained when cloud lightning flashes are also included. These studies are being developed at present.

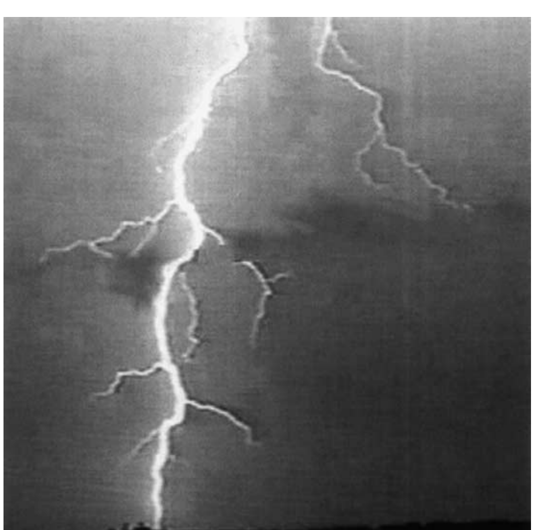

Fig. 4. A natural lightning collected in Southeastern Brazil in order to study the path morphology.

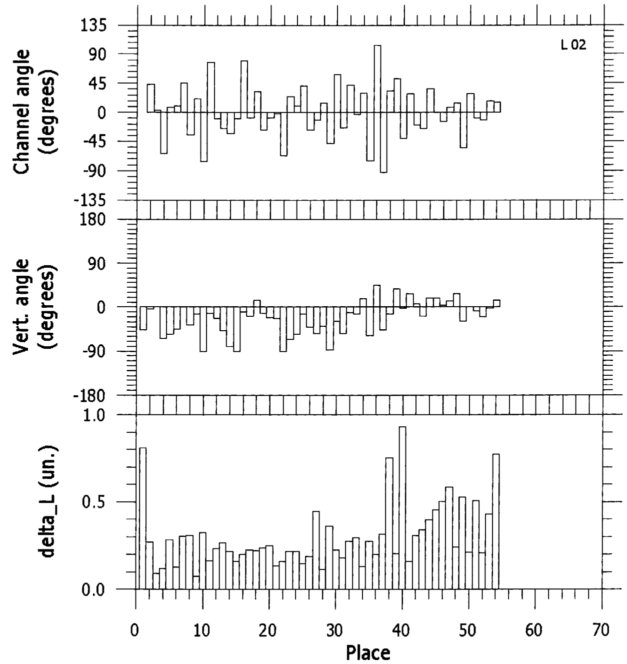

Fig. 5. The horizontal coordinate is the step (place), from the top (zero) to the bottom of the cloud. In the upper panel is represented the angle between consecutive steps. The middle panel shows the angle with the vertical and in the lower panel, the step length is presented. The corresponding lightning is not shown here.

4.2. Sun–Earth electrodynamical coupling analysis

It has been shown that the Earth's space environment can be visualized as a self-consistent electrodynamical coupling mechanism. The ionosphere and the magnetosphere are closely linked together via magnetic field lines. Magnetospheric electric fields are transferred to the ionosphere, creating, e.g., plasma convection, frictional heating and plasma instabilities. Auroral particle precipitation ionizes the high latitude atmosphere also during nighttime, and the joule heat generated can be conducted downwards from the magnetosphere to the ionosphere (Olsson and Janhunen, 2003; Vorobjev et al., 2003). On the other hand, some of the cold ionospheric electrons and ions evaporate into the plasmasphere, plasma sheet and tail lobes. These changes in the magnetospheric ion composition can produce large effects on some important magnetospheric processes. Collisions between the convecting ionospheric plasma and the neutral atmosphere lead to the generation of neutral winds and Joule heating of the neutral gas. This neutral gas can be further heated by plasma instabilities

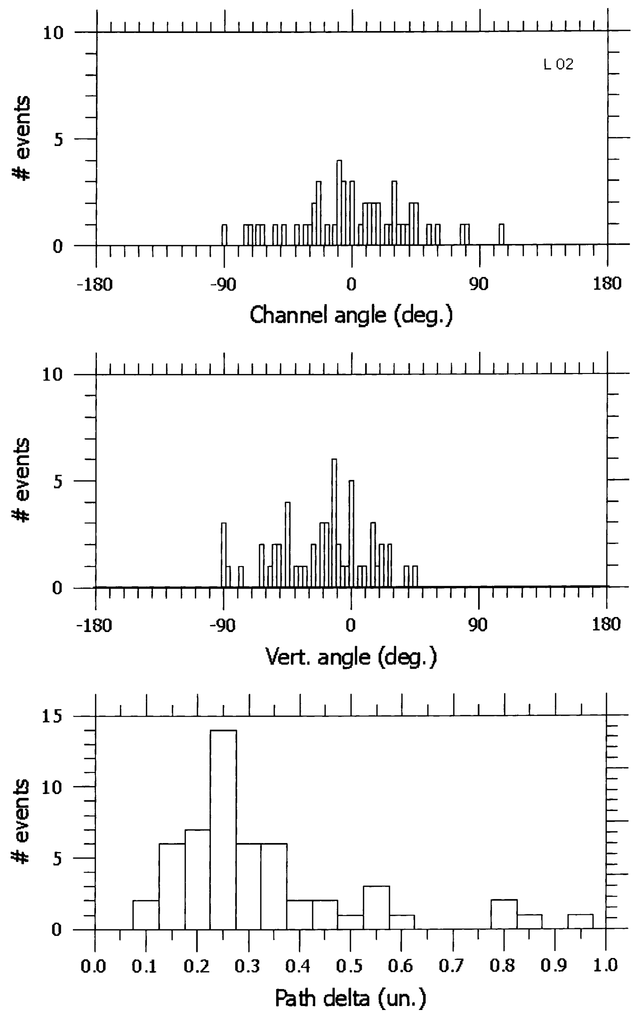

Fig. 6. From top to bottom, histograms of step length, angle with the vertical and angle between consecutive paths are presented.

induced by the ionospheric currents. Energy and particles penetrating into the magnetosphere can affect all levels of the atmosphere in different ways (Turner et al., 2001; Forster and Jakowski, 2000). All these current systems earlier described induce magnetic fields that disturb the intrinsic Earth's magnetic field, producing geomagnetic activity.

Since the ionosphere and the plasmasphere are strongly linked adjacent regions, modelling the ionospheric/plasmaspheric plasma requires the inclusion of properties of both regions.

Since the mid 1920s vertical radio soundings techniques (ionosondes) have provided much of the information about the ionized upper atmospheric layers. More recently many other ground based observations such as Faraday rotation observations of radio beacon signals from various satellites, the incoherent scatter radar technique, whistler measurements and in situ measurements by satellites have complemented our knowledge of the upper ionosphere and plasmasphere. The most complete and comprehensive data of the total columnar electron content (TEC) including the plasmaspheric electron content (PEC) and the ionospheric electron content (IEC) have been obtained from geostationary satellites since 1974 (Maynard et al., 1983). In general, the experimental results measured all over the world have revealed that the PEC can change considerably with season, latitude, longitude, solar activity but it does not seems to vary with the time of the day (Balan et al., 2002; MacPherson et al., 2000; Lunt et al., 1999; Jakowski et al., 2002).

The GPS receiver onboard the Brazilian microsatellite, Equatorial Atmosphere Research Satellite (EQUARS) that is being build at INPE[1] will provide an opportunity to investigate the increase in the ionization due to the ionospheric heating by the turbulent dissipation of the ring current energy in the plasmapause, mainly where measurements from the ground are scarce. Furthermore, it will allow a better understanding of the variability of plasmaspheric electron content associated with intense and superintense magnetic storms measured in the South Atlantic Anomaly, from satellite altitudes (about 700 km) to GPS constellation altitudes (about 20,000 km).

In order to help the monitoring and the understanding of several electrodynamical features, the authors of this tutorial have explored the remarkable ability of wavelets (Domingues et al., 2005) to highlight the singularities associated with discontinuities present in the horizontal component of the Earth's magnetic field (Mendes et al., 2005).

Magnetograms obtained at five magnetic stations (Boulder–USA, Kakioka–Japan, Hermanus–South Africa, Dumont d'Urville–Antarctica and Fort Churchill–Canada) have been studied in periods which included a moderate and a superintense magnetic storm that occurred on November 7, 1978 and on August 29, 1979, respectively. Wavelet transform decomposition levels have been applied to the horizontal component (H) of the geomagnetic field. The magnitudes of the wavelet coefficients at the three first decomposition levels have been analyzed. In both cases, the coefficients have proved to be an efficient tool in the detection of the physical discontinuities in the horizontal component of the geomagnetic field as well as in the identification of the disturbed intervals when the geomagnetic storms occurred. It was possible to identify singularity structures in the signals of all the magnetic stations considered. For instance, in Fig. 7, from top to bottom, the Dst index, the H-component of the geomagnetic field for the Boulder station and the first three levels of the wavelet coefficients from the wavelet discrete transform for the geomagnetic storm of August 29,1979 are presented.

As the highest relative amplitudes are all time coincident, the obtained structures allow the identification of

[1] http://www.laser.inpe.br/equars.

quiescent and non-quiescent periods in the *H*-component of the geomagnetic field signals independently of the signature of the magnetograms considered. Actually, this tool allows to survey the intrinsic energy transfer processes involved in a geomagnetic storm. A subsidiary result is that the non-quiescent periods are associated with the main phase of geomagnetic storms. These results suggest that the wavelet analysis can be considered as a useful technique in the study of geomagnetic storm using raw data at middle-to-low latitude magnetic stations. At present the parameters of interplanetary medium are being analyzed following the same procedure.

Apparently, at higher latitudes, the wavelet coefficients of higher amplitude are more frequent in the first two decomposition levels, while for lower latitude the most relevant decomposition levels are the second and the third levels. This fact, actually, confirms the already known concepts that at higher latitudes the penetration of charged particles and the energy injection are characterized by phenomena that involve higher frequency signals. At lower latitudes there are coupling processes that attenuate the higher frequency signals (Morioka et al., 2003). This seems to suggest that an injection process

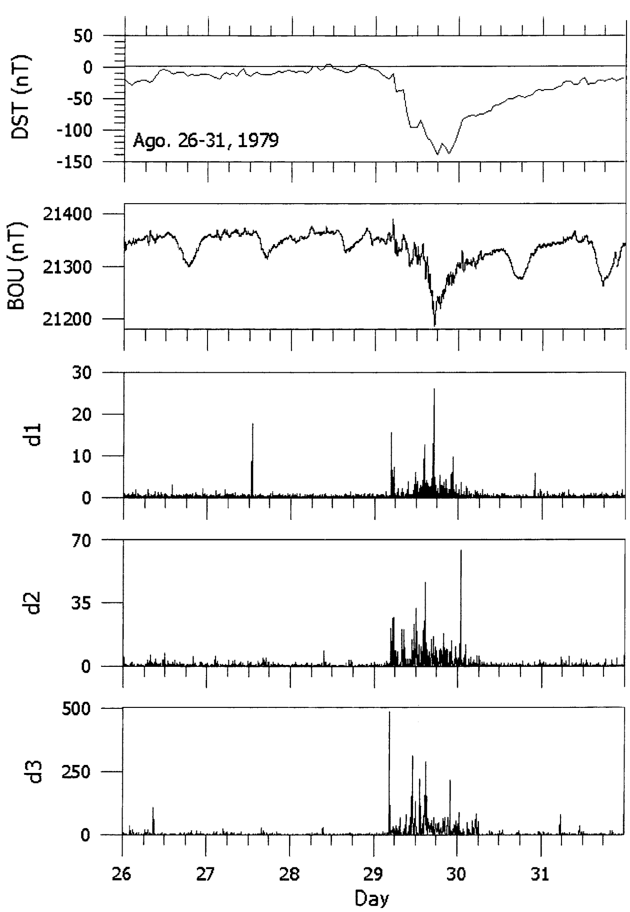

Fig. 7. Geomagnetic field data set for Boulder station and three wavelet coefficient levels for the geomagnetic storm of August 29, 1979.

in the ring current is associated with an injection process in the auroral region, but the opposite may not be true, i.e., the injection process in the auroral region is not necessarily associated with an injection in the ring current.

There is a peculiar feature in the electrodynamical scenario of the Earth's space environment: an oval-shape region characterized by a depression in the total intensity of the Earth's magnetic field is observed partially over the South Atlantic ocean and the Brazilian territory, known as the *South Atlantic Magnetic Anomaly* – SAMA (Kivelson and Russell, 1995). There is a consensus that this depression is due to the eccentricity between the geographic and magnetic dipole axis of the Earth (an offset of 527 km of the magnetic dipole center in the direction of the Pacific Northeast). This region is of remarkable importance to the Earth's electrodynamical environment, with serious atmospheric and ionospheric implications (particle precipitation into the denser atmosphere, and the increase of radiation into the lower atmosphere) that deserve investigation.

At higher latitudes, in the auroral region, electric currents generated by geomagnetic field variations can induce transient fluctuations that can cause interruptions in electric power transmission lines, saturation of transformer's cores, as well as large scale blackouts due to the overload of high voltage networks. These currents may also accelerate corrosion processes in pipelines, producing metal degradation, leakages and disruptions with severe environmental consequences. Analogously to what happens in the auroral regions, in which the energetic particles can reach altitudes as low as 100 km strongly interacting with atoms and neutral molecules of the atmosphere, at lower latitudes in the SAMA region, this behavior should also be observed although to a lesser extent, in such a way that it can be considered as a pseudo auroral-region.

Recently riometer imagery (IRIS) installed in southernmost part of Brazil has been used to investigate the precipitation of energetic particles in the SAMA. An unusual ionospheric absorption event has been observed during the geomagnetic storm of September 22–23, 1999. This event showed a west–east ionization drift in the Anomaly and, assuming electric fields in the plasmasphere of 1.8 mV/m, the energy of the precipitated electrons was estimated to be 20 keV. No evidence of ionospheric absorption has been observed by the ionosonde installed in Cachoeira Paulista (45°00′ W; 22°41′ S) at about 1000 km from the IRIS station in association with this event (Nishino et al., 2002).

The penetration of electric fields at low latitudes and an increase in the total electron content has been recorded in Fortaleza during the occurrence of the super-intense magnetic storm of July 15, 2000. An intense variation in the ion density has been observed almost at 30° S and the ROCSAT-1 satellite has measured large vertical ion drifts in the same sector. These effects are well correlated to sudden decreases in the SYM-H index (Basu et al., 2001).

Scans produced by incoherent radar at longitudes within the SAMA show evidences of strong perturbation in the magnetosphere–ionosphere coupling system in the initial phase of the magnetic storm of November 4, 1993. Ionospheric perturbations were coincident with the peaks of particle flux loss in the inner van Allen radiation belt in the SAMA region. Similar effects have been observed during the occurrence of the event of March 20, 1990 (Foster and Rich, 1998).

Some effects related to the SAMA have already been reported as damages to satellites, spacecraft, Space Shuttle and the International Space Station when moving in low Earth's orbits (Baker, 2000; Brautigam, 2002; Gubby and Evans, 2002). Over the SAMA the radiation intensity is higher than elsewhere. The charged particles populating the region can create static discharges in satellites. MODIS, NASA's premier remote sensing instrument, was made inoperative during 16 days after the July 15, 2000 geomagnetic storm. When surveying the ocean topography, the TOPEX/Poseidon satellite had problems during the years 1992–1998, due to Sudden Event Upsets, when apparently a unique particle can cause a partial misfunctioning of an instrument or devices. Many other effects have been reported in the SAMA, concerning signals losses and interference in telecommunication, radio broadcasting systems, telemetry, data transmission, global positioning systems, mostly in periods associated with intense magnetic disturbances (Campbell, 2003). In relation to radiation effects on human beings, surprisingly high radiation values have been detected by the dosimeters onboard Skylab (from December 1973 to January 1974) and MIR (March 2–11, 1995) at an altitude of approximately 400 km when the space stations were orbiting through the SAMA region (Heirtzler, 2002). Some projects also had to be redesigned to avoid the satellites passing through that region.

Some experiments carried out on animals and on cultures of mammal cells show that energetic protons and heavy ions are able to induce oncogenic mutations in cells. There are increasing evidences that variations in the geomagnetic field can strongly affect biological systems (Ritz et al., 2000; Gedney, 1984). The most studied case concerns the lack of orientation of carrier pigeons in association with geomagnetic storms (Davis, 1981). Others studies reveal that human biological systems under physical stress can respond to minimum but measurable fluctuations of magnetic fields. The number of patients hospitalized with heart diseases seems to increase during magnetically disturbed conditions (Mendonza and Diaz-Sandoval, 2004; Rodriguez Taboada et al., 2004). Another study concerning emergencies of patients suffering brain strokes and myocardiac diseases has shown a significant increase in days when a magnetic storm was under development (Otsuka et al., 2000; Halberg et al., 2001). Stimulated by these results, studies on the effects of the SAMA in living beings should be encouraged.

5. Final remarks

In this tutorial the electrodynamical processes occurring in the Sun–planet coupling have been described and the complex relations between the electric fields and currents, and the magnetic disturbances involved, have been discussed. An integrated view of this scenario is indispensable to a better understanding of the phenomena that are continuously affecting the Earth and the near space, from both theoretical and applied standpoints.

As examples of applied studies, some topics being investigated by the authors of this tutorial, regarding atmospheric electricity and the ground-based study of geomagnetic storms, have been discussed.

A simplified numerical simulation was used to analyze the development of the stepped leader in the atmosphere. The results have emphasized the relevance of the atmospheric conductivity in this development. In order to improve these simulations, fractal analysis related to the lightning morphology (tortuosity and branching) has been done. Other studies have been briefly presented in order to show the different approaches on lightning paths. It is worthwhile to mention that the models are limited, not unique, and demand further improvements.

Regarding the study of geomagnetic storm effects on the ground, it was possible to identify singularity structures associated with moderate and very intense magnetic storms. The results suggest that the wavelet coefficients are an effective tool to detect discontinuities and to discriminate between disturbed and quiescent intervals, using non-processed data such as magnetograms. This study is also being developed in the peculiar region of Earth's magnetic field known as South Atlantic Magnetic Anomaly.

Since the Space Environment is continuously affecting the Earth, the nearby space and everyday life, Planetary Electrodynamics undoubtedly plays a remarkable role in this scenario.

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