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Contribution of Latin–American scientists to the study of the magnetosphere of the Earth. A review

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Abstract

Since the very beginning of the space era, Latin–American scientists have been contributing to the understanding of the magnetosphere of the Earth. This review summarizes some significant contributions in this field with emphasis on results obtained during the last decade. Special attention is paid to most important topics of the magnetosphere of the Earth such as geomagnetic storms and substorms and possible relations between them, interplanetary origin of storms, role of turbulent processes in the magnetosphere dynamics, and analysis of the dynamics of the magnetosphere as a complex self-organized non-linear system.

Keywords: Magnetosphere; Latin–American contribution

1. Introduction

Since the very beginning of the space era, Latin American scientists have been contributing to space science. Associated with south America are the names of Otto Schneider, Juan Roederer, Mario Acuña, Horacio Ghielmetti, Sandro Radicella and Roberto Manzano from Argentina; Fernando de Mendonca from Brasil, Phenix Ramírez, from Chile, Ronald Woodman from Perú, and many others. The official lemma of the Latin American Association on Space Geophysics "Ciencia hay una sola y comunidad científica hay una sola" ("There is only one science, there is only one scientific community") formulated by Juan Roederer remains living in the hearts of new generations of Latin American space scientists.

The International Geophysical Year (1957–1958) initiatives undoubtedly played a most significant role in the development of space science in Latin America, particularly on ionospheric research. One of the oldest recognized institutions dedicated to space science is the Brazilian Instituto Nacional de Pesquisas Espaciais (National Institute for Space Research, INPE). Scientists working in the Space Geophysics Division have been contributing to the study of the magnetosphere of the Earth from the very beginning, concentrating their effort mainly on the study of the origin of geomagnetic storms and space weather forecast (Gonzalez, 2004). In Argentina, there are two institutions having strong traditions in the study of the magnetosphere: Universidad Nacional de Tucumán (National University of Tucuman) and Instituto de Astronomía y Física del Espacio (Institute for Research in Astronomy and Astrophysics, IAFE). The main research interests of the Argentinian scientists are magnetosphere–ionosphere interactions (Manzano, 1994), solar wind–magnetosphere interactions, and impact of geomagnetic activity to the ionosphere.

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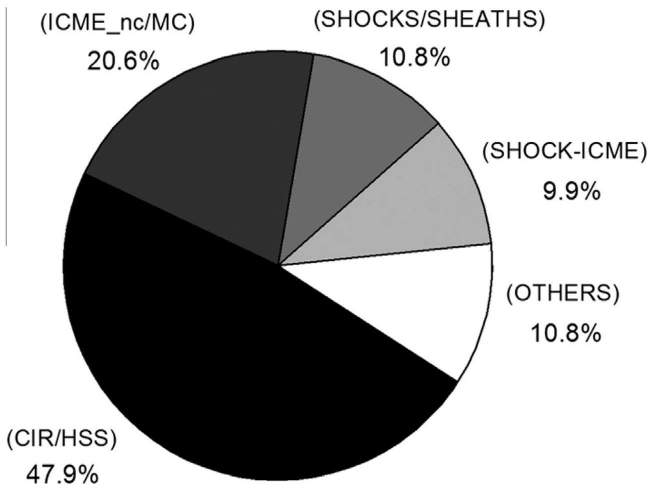

Fig. 1. Sector graph showing the percentage of moderate geomagnetic storms in solar cycle 23 caused by major interplanetary structures. From Fig. 8 of Echer et al. (2013).

In Mexico the magnetospheric studies have been developed for decades in the Instituto de Geofísica, Universidad Nacional Autóma de México (Institute of Geophysics, National Autonomous University of Mexico, UNAM). The research activities are mainly focused on shocks, waves and solar wind–magnetosphere interactions (see, for example, Rojas-Castillo et al., 2013). The establishment of a satellite tracking facility and the Jicamarca incoherent radar in the 60's started space research activities in Perú, where main efforts have been devoted to equatorial ionospheric studies and magnetosphere–ionosphere interactions. In Chile it was the installation of a coherent radar in Concepcion in 1957 and later a satellite tracking station near Santiago. Now the universities of Chile, Santiago de Chile, Concepción, La Serena and Magallanes collaborate covering a wide range of problems of the physics of the magnetosphere: geomagnetic storms and substorms, waves and turbulence, dynamics of the magnetosphere as a complex non-linear system among many others (see, for example, Gallardo-Lacourt et al., 2014b; Mac-Mahon and Gonzalez, 1997; Navarro et al., 2014; Pinto et al., 2011; Stepanova and Antonova, 2011, 2015; Valdivia et al., 2003, 2006). Lately, Costa Rica has also seen the development of space research activities. We hope that in the nearest future there will be many more strong research groups in other Latin–American countries dedicated to magnetosphere studies.

In general, during the last decades space Physics in Latin America has experienced an exponential growth in the number of researchers, number and quality of publications, training of undergraduate and graduate students, and strengthening of inter-university and international cooperation. The research activities have been focused on all main research areas of Space Geophysics, including the most pressing problems in the physics of the magnetosphere of the Earth. The magnetosphere is a cavity surrounding the planetary magnetic field, filled by plasmas and having a complex structure (Blanco-Cano et al., 2004). The Latin–American scientists have contributed to the study not only to the magnetosphere of the Earth, but also to the magnetospheres around other planets of our solar system (see, for example, Russell et al. (2006)), and even to the magnetospheres of exoplanets (see, for example, Chian et al., 2010). While preparing this review we have found that Latin–American scientists have published more than 1000 papers related to magnetospheric research, thus making it an almost impossible task to summarize all important and interesting contributions in the field.

We decided to organize this review on Latin–American research on physics of the magnetosphere following its main topics, starting from the most important phenomena, namely, geomagnetic storms and substorms, including their possible external and internal causes, to likely space weather forecast. Finally, the role of the waves and turbulence in the dynamics of the magnetosphere is considered and a global approach to the magnetosphere of the Earth as a complex non-linear self-organized system.

2. Space weather and geomagnetic storms

Some processes in the Sun and the solar wind, magnetosphere, ionosphere and thermosphere can cause the malfunction of space-borne and ground-based technological systems (Saiz et al., 2013), and even could affect human health (Azcarate et al., 2012), although this last results are a little controversial. Different physical phenomena cause different impacts. For example, solar flare radiation can directly affect the ionospheric total electron content (Meza et al., 2009) and block high-frequency radio waves used for radio communication. Solar energetic protons can penetrate satellite electronics and cause electrical failure, and also block radio communications at high latitudes.

However, in this review we will pay special attention to the effects caused by magnetospheric phenomena, especially by geomagnetic storms. They can degrade power grid operations, modify signals from radio navigation systems (GPS and GNSS), and cause damage to satellite electronics due to the surge of relativistic electrons in the inner magnetosphere.

A geomagnetic storm is characterized by a strong intensification of magnetospheric current systems, including the ring current. The disturbance storm time (D_{st}) index is widely used for storm study and classification. A typical geomagnetic storm has three phases: an initial phase also known as a storm sudden commencement, a main phase and a recovery phase (Gonzalez et al., 1994). However, not all geomagnetic storms have an initial phase and not all sudden commencements are followed by a geomagnetic storm. The main phase lasts a few hours, while the recovery phase can take several days. The geomagnetic storms are generally classified as weak (minimum D_{st} between -30 and -50 nT), moderate (D_{st} between -50 and -100 nT), intense (great) (D_{st} less than -100) (Gonzalez et al., 1994). In some works very intense storms are referred as extreme (Gonzalez et al., 2011a), superintense (Echer et al., 2008), and superstorms (Mac-Mahon and Gonzalez, 1997). Geomagnetic storms have a strong impact on the modern society. A storm with characteristics similar to the Carrington event – the most intense in recorded history storm (Tsurutani et al., 2003) – could cause a catastrophe. However, even moderate and intense storms cause negative impact on the telecommunication and navigation systems, that is why the prediction of geomagnetic storms is one of most important elements of any space weather activity, and Latin–American scientists have made a significant contribution to this field.

2.1. External sources of geomagnetic storms

The most important phenomena responsible for geomagnetic storms can be divided into two principal groups: the fast speed corotating streams originated in the coronal holes and coronal mass ejection transients (Echer et al., 2013). Corotating streams can be observed as pure high-speed streams (HSSs) or lead to the appearance of Corotating Interaction Regions (CIRs). The coronal mass ejection (CME) transients may be of two types: magnetic clouds (MC) and nonmagnetic cloud coronal mass ejections (ICMEnc) (Echer et al., 2013). Magnetic clouds (MCs) are a particular subset of CMEs, forming large-scale magnetic flux ropes. Their evolution in the solar wind is complex and mainly determined by their own magnetic forces and the interaction with the surrounding solar wind (Nakwacki et al., 2011). Compound interplanetary magnetic structures can be more geoeffective than single interplanetary magnetic structures (Echer and Gonzalez, 2004). In all cases the southward orientation of the interplanetary magnetic field (IMF) persisting during a few hours is the main cause of storms (Gonzalez et al., 1999; Echer et al., 2013). Fig. 10 summarizes the percentage of interplanetary structures involved in the geomagnetic storm development during the whole solar cycle 23. As it can be seen, corotating streams (CIR + HSS and their combinations) are the most frequent phenomena causing a moderate storm (47.9%), followed by coronal mass ejections (20.6%). The rest of the storms can be associated with shock/sheath fields and combinations of CMEs and sheath fields. About 10.8% of storms were not caused by any of aforementioned structures (Echer et al., 2013). However, this distribution changes during the solar cycle. CMEs generally take place during the rising phase and around the solar maximum, while CIR events cause geomagnetic storms during all phases of the solar cycle, but their relative contribution is higher during the declining phase and at the solar minimum.

Intense and very intense storms are mainly generated by CMEs (Gonzalez et al., 2011b). Generally, there are two structures, which may produce a strong southward IMF orientation: the sheath region just behind a fast forward interplanetary shock, and the CME ejecta itself. Behind the shock there is an increase in the ram pressure, accompanied by a sudden pulse at the Earth. Very intense storms often but not necessary always, take place when the orientation of the IMF in the sheath region and magnetic cloud are oriented mainly southward. As shown by Gonzalez at al (2002), in this case two-step main phase storms can result and the storm intensity can be very high (see Fig. 1).

Intense geomagnetic storms can also be caused by the resultant structure of the interaction between MCs. Fig. 2 illustrates a development of storm caused by two MCs, that interacted during their travel from the Sun to 1 astronomic unit (AU). This storm took place on 15 May 2005 reaching the minimum value of $D_{st} = -263$ nT at 08:00 UT. It has been studied in detail by Dasso et al. (2009) and Szajko et al. (2013). Two MCs are generated due to two consecutive eruptions of two portions of the active region filament. The time between the first and second vertical dashed-dotted lines corresponds to the sheath. After the sheath, a first cloud is observed between 15 May 05:42 UT and 14:10 UT. This MC is identified by observing the large coherent rotation of B_z that goes from South to North. After this period there is a change in the rotation and discontinuity in the magnetic field. A rear part of the structure is observed between 10:20 UT and 14:10 UT. Later, between 15 May 14:10 UT and 16 May 04:10 UT there is a second very extended MC, characterized by a coherent rotation of the magnetic field, low proton plasma β and a low proton temperature. However, only the first MC leads to the storm development due to the strong southward orientation of the IMF.

Propagation of a CME can generate multiple shocks, discontinuities, waves, and pressure pulses that complicates the analysis (Tsurutani et al., 2008; Echer et al., 2010). MCs also have different magnetic field polarities that may strongly affect their geoeffectiveness and change the scenario of their interaction with the magnetosphere. A prolonged southward orientation of the magnetic field is one of the main causes of geomagnetic storms (Vieira et al., 2001). In general, it is expected that fast and intense southward oriented MCs are more geoeffective, although the effectiveness of slow MCs could also be very high (Tsurutani et al., 2004). Rodriguez et al. (2009) also found that non-radial direction of eruption, passage of the Earth through a leg of an interplanetary flux rope, and strong compression at the eastern flank of a propagating interplanetary CME during its interaction with the ambient solar wind are important factors that have a direct influence on the resulting north–south IMF component and thus on the CME geoeffectiveness.

Generally, the intensity of the magnetic field inside a magnetic cloud increases with the cloud velocity, which could be related to the mechanisms in the Sun leading to the cloud release and acceleration (Gonzalez et al., 1998). The geoeffectiveness of magnetic clouds also depends on the compression due to the follow-up presence of a higher speed stream which leads to a stronger magnetic field strength at the back region of the cloud (Dal Lago et al., 2001).

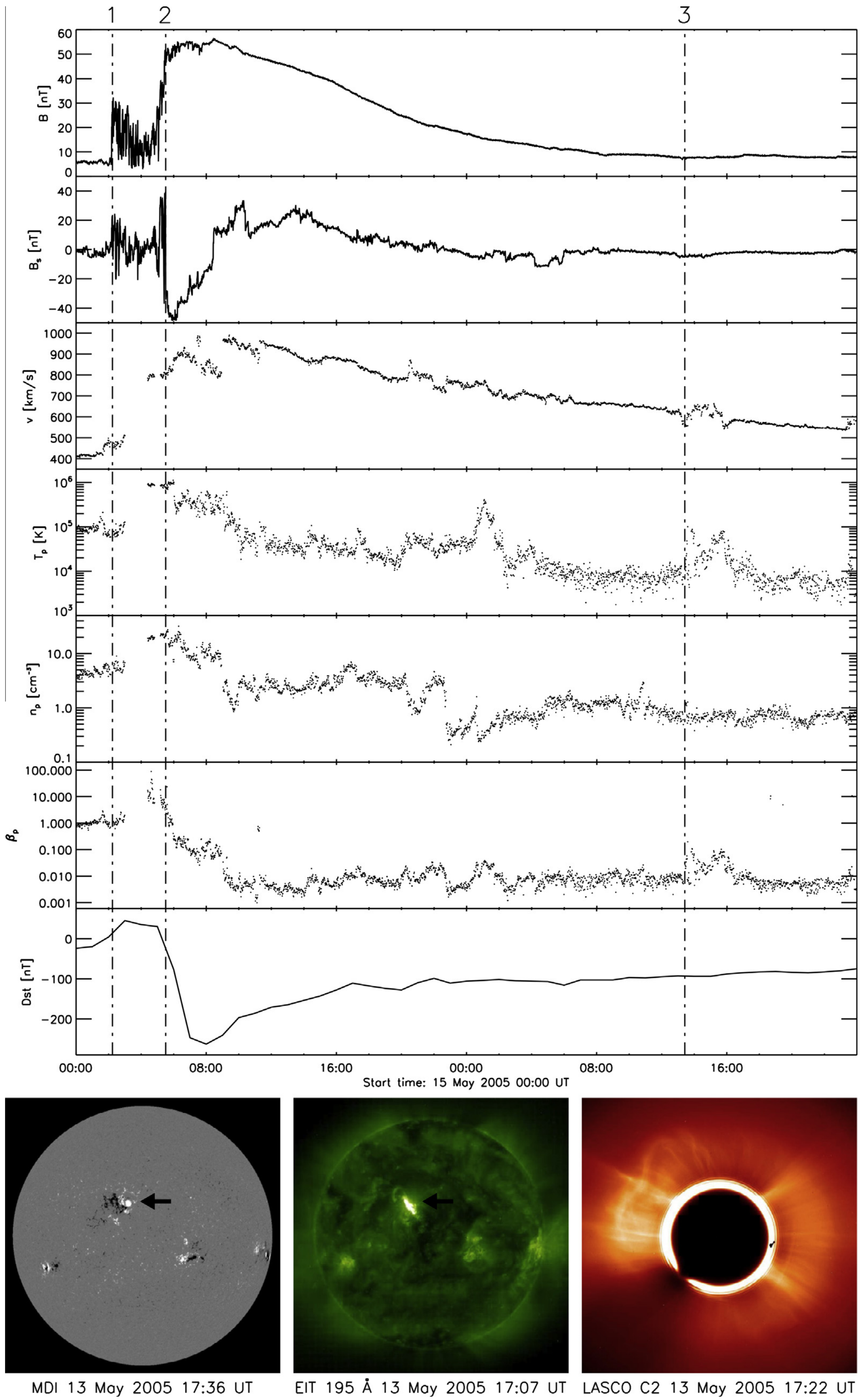

Fig. 2. From top to bottom: the interplanetary magnetic field intensity, the southward component of the IMF in GSM coordinates, the solar wind radial velocity, the proton temperature and density, the proton plasma β parameter, and the geomagnetic field profile. The vertical lines indicate the time intervals of arrival of two MCs, that interacted during their travel from the Sun to 1 AU. The three images at the bottom illustrate the location of the source active region (pointed with an arrow) in an MDI magnetogram, extreme ultra violet flare in extreme ultraviolet imaging telescope (EIT) (pointed with an arrow), and the LASCO C2 field of view at 17:22 UT for 15 May 2005 geomagnetic storm. From Fig. 4 of Szajko et al. (2013).

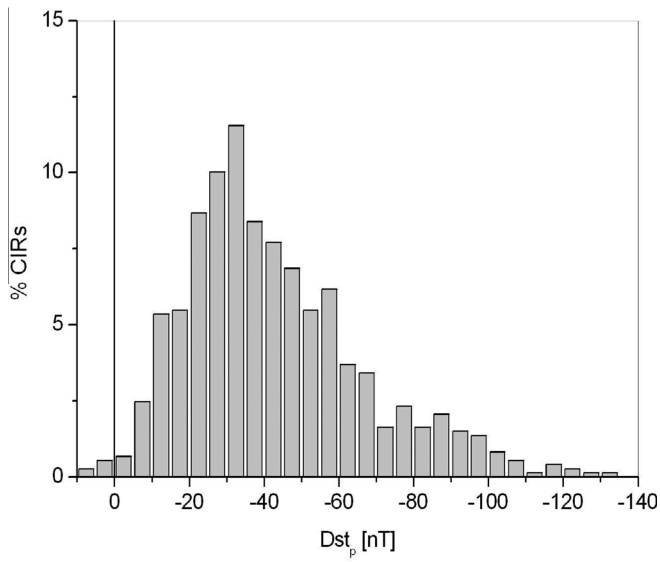

Fig. 3. Distribution of percentage of CIRs against the minimum values of D_{st}. From Fig. 6 of Alves et al. (2006).

Generally, the CMEs have an origin in the active regions with high magnetic complexity (Szajko et al., 2013) (see Fig. 2). Although the most geoeffective events correspond to locations close to the solar central meridian, Cid et al. (2012) found that CME events originated at the west limb can also be geoeffective. One of important properties of a MC is its magnetic helicity, which quantifies several aspects of a given magnetic structure, such as the twist, kink, number of knots between magnetic field lines, linking between magnetic flux tubes, etc. The helicity is approximately conserved in the solar atmosphere and the heliosphere, and it is very useful to link solar phenomena with their interplanetary counterparts (Dasso et al., 2005).

CIRs are another source of geomagnetic storms (Tsurutani et al., 2006). They are formed as a consequence of the compression of the solar wind at the interface between fast solar wind streams emanating from the coronal holes and adjacent slow streams mainly associated with the heliospheric current sheet. The CIR storms are recurrent and in general their geoeffectiveness is low. As it can be seen Fig. 3, the most probable value of Dst caused by CIRs is > -40 nT (Alves et al., 2006).

Corotating high speed streams often produce the high-intensity long-duration continuous AE activity (HILDCAA) events during the recovery phase of CIR geomagnetic storms (Guarnieri et al., 2006).

2.2. Internal causes of geomagnetic storms, role of substorms, and ring current dynamics

Geomagnetic storms are not fully determined by the solar wind conditions. More intense solar events do not necessarily result in more intense storms. The internal magnetospheric conditions like plasma sheet density and ion composition, magnetosphere–ionosphere coupling including the substorm development and the outflow of ionospheric-origin O^+ ions play very important role in the storm development (Daglis et al., 2007).

2.3. Geomagnetic substorms

According to the classic definition of substorm given by Akasofu (1964), a substorm represents “the sequence of auroral events over the entire polar region during the passage from auroral quiet through the various active phases to subsequent calm”. It has a life time of a few hours and consists of “expansive” (now “expansion”) and “recovery” phases. An isolated substorm generally starts with a sudden brightening of the most equatorial auroral arc. In most cases, during the expansion phase this brightening is followed by a rapid polarward motion of the auroral arcs and formation of an expansive bulge near to the midnight meridian. The formation of the bulge is followed by a subsequent westward traveling surge. During the recovery phase the aurora moves mainly equatorward and the auroral activity gradually fades.

The nature of geomagnetic substorms has been an important subject of scientific discussions during the last decades. Despite a significant effort of many researchers, including the contribution of Latin–American scientists, there are no conclusive answers to the majority of key questions about the physical processes leading to the substorm development.

2.3.1. Location of the substorm expansion phase onset and possible causes of substorms

The identification of a possible instability responsible for the substorm expansion phase onset is strongly related to the correct identification of the onset location. The majority of existent substorm theories can be associated with the inside-out or outside-in scenarios of substorm development. The first scenario assumes the existence of an instability in the inner magnetosphere that subsequently propagates tailward. The second scenario considers that an instability responsible for the substorm triggering is located in the tail and propagates earthward.

In Latin America (Stepanova et al., 2002, 2004b, 2006a, 2008a and Antonova et al., 2009c) provided important observational evidences in favor of the inside-out paradigm. From analyses of auroral electron precipitations they were able to show that the substorm onset is located at the equatorial boundary of the auroral oval where the magneto sphere–ionosphere decoupling is maximum (see the maximum in the differential ion precipitating flux in Fig. 4, left panel). Furthermore, an analysis of both ion and electron auroral precipitations made it possible to obtain the radial profiles of inner magnetosphere plasma pressure as a function of the volume of magnetic flux tube per unit flux (see Fig. 4, right panel). It was found that these profiles apparently are not sharp enough for the ordinary interchange instability, related to radial plasma pressure gradients, to develop, according to the Kadomtsev's

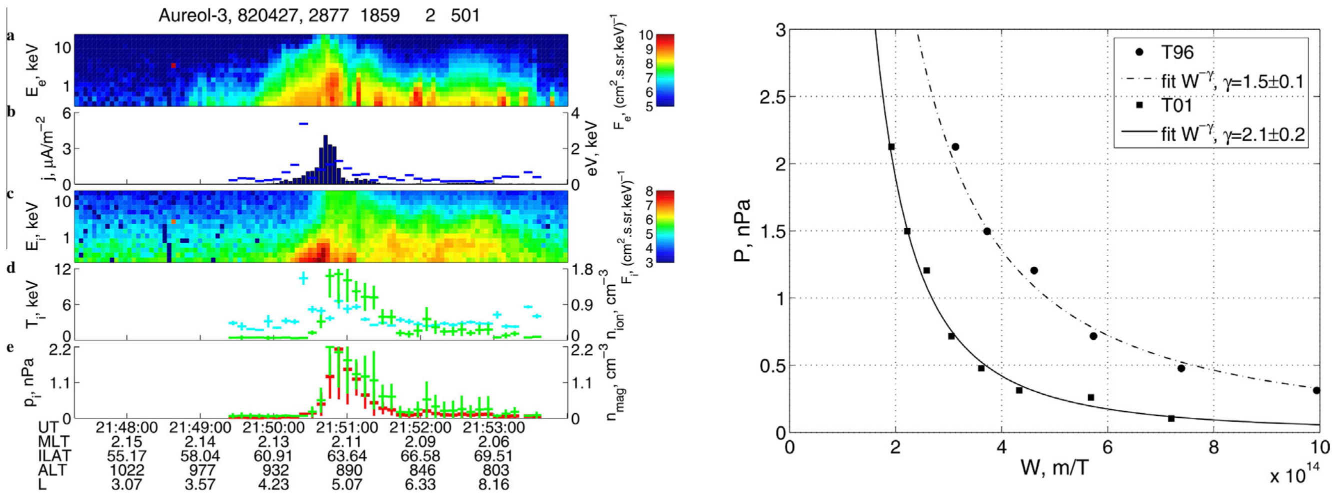

Fig. 4. Left panel, from top to bottom: differential electron precipitating flux, field-aligned current density (black bars, left axis) and field-aligned potential drop (blue lines, right axis), differential ion precipitating flux, ion temperature (cyan lines, left axis) ion number density (green lines, right axis) at the altitude of the Aureol-3 satellite, ion number density (green lines, right axis) and ion pressure (red lines, left axis) in the magnetosphere. Right panel: variation of pressure with the volume of the magnetic flux tube per unit flux calculated using the Tsyganenko 1996 and 2001 geomagnetic field models. Adapted from Figs. 1 and 4 of Stepanova et al. (2006a). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

criterion $\frac{dp^0}{dW} > \kappa \frac{p^0}{W}$, where κ is the polytropic index. They proposed the existence of a modified instability related to azimuthal plasma pressure gradients which develop when the density of the field-aligned current reaches a definite threshold. The instability develops faster in the region of upward field-aligned current, where the existing field-aligned potential drop leads to the magnetosphere–ionosphere decoupling.

At the substorm auroral onset, the initial brightening along a preexisting or a newly formed arc is often observed in the form of a wavy auroral pattern, which is referred to as auroral beads. Taking advantage of the high temporal resolution data provided by THEMIS All-Sky-Imagers and the Super Dual Auroral Radar Network, Gallardo-Lacourt et al. (2014a) identified the flow of extremely fast (1000 m/s) structures, showing a strong temporal and spatial correlations between the beading and the alternation of fast equatorward and polarward flows. This study suggests that the substorm onset process involves the formation of fast earthward/tailward flow structures. This result is consistent with particle-in-cell (PIC) simulations performed by Pritchett and Coroniti (2010) to study the structures and consequences of the kinetic ballooning/interchange instability (BICI) modes in the plasma sheet. A direct association between the bursts of earthward flows in the plasma sheet and auroral streamers was recently showed by Gallardo-Lacourt et al. (2014b) using the data from the THEMIS ASIs and SuperDARN radars (see Fig. 5).

The aforementioned studies indicate that the substorm onset is probably located near the midnight meridian at geocentric distances 7–10 Earth's Radii (R_E). Fig. 6 shows the averaged distribution of the plasma pressure and magnetic field lines at the equatorial plane, and the value of plasma β parameter considering the location of the minimum value of the geomagnetic field outside the equatorial plane (Antonova et al., 2014) in the dayside. The majority of researchers considers the night-side portion of this region as a near-Earth portion of the plasma sheet. However, Antonova et al. (2009a, 2013, 2014) showed that the corresponding night-side transverse currents, generated by plasma pressure gradients, are closed inside the magnetosphere.

This current system, named the Cut-Ring-Current, was first introduced by Antonova (2004). This name reflects the topology of the day-side geomagnetic field: for these geocentric distances the minimums of the geomagnetic field are located outside of the equatorial plane leading to the splitting of the transverse currents into two branches (see Fig. 7). According to this paradigm, the field-aligned currents are generated by the azimuthal plasma pressure gradients (Stepanova et al., 2004a; Antonova et al., 2006), and the formation of the large-scale auroral structures can be attributed to the stratification of field-aligned currents (Antonova et al., 1998; Luízar et al., 2000; Ermakova et al., 2006). Together with the ordinary ring current, the Cut-Ring-Current contributes to the D_{st} variation.

2.3.2. Possible external triggering of substorms

An important question for understanding substorms is whether substorm onset is the result of a change in the external conditions or the result of an instability that is purely internal to the magnetosphere. There has been a long debate on the extent to which substorms are externally triggered by IMF changes. Recently, Gallardo-Lacourt et al. (2012) examined the substorm triggering hypothesis by applying the three different triggering criteria used in earlier studies (Lyons et al., 1997). They have found that

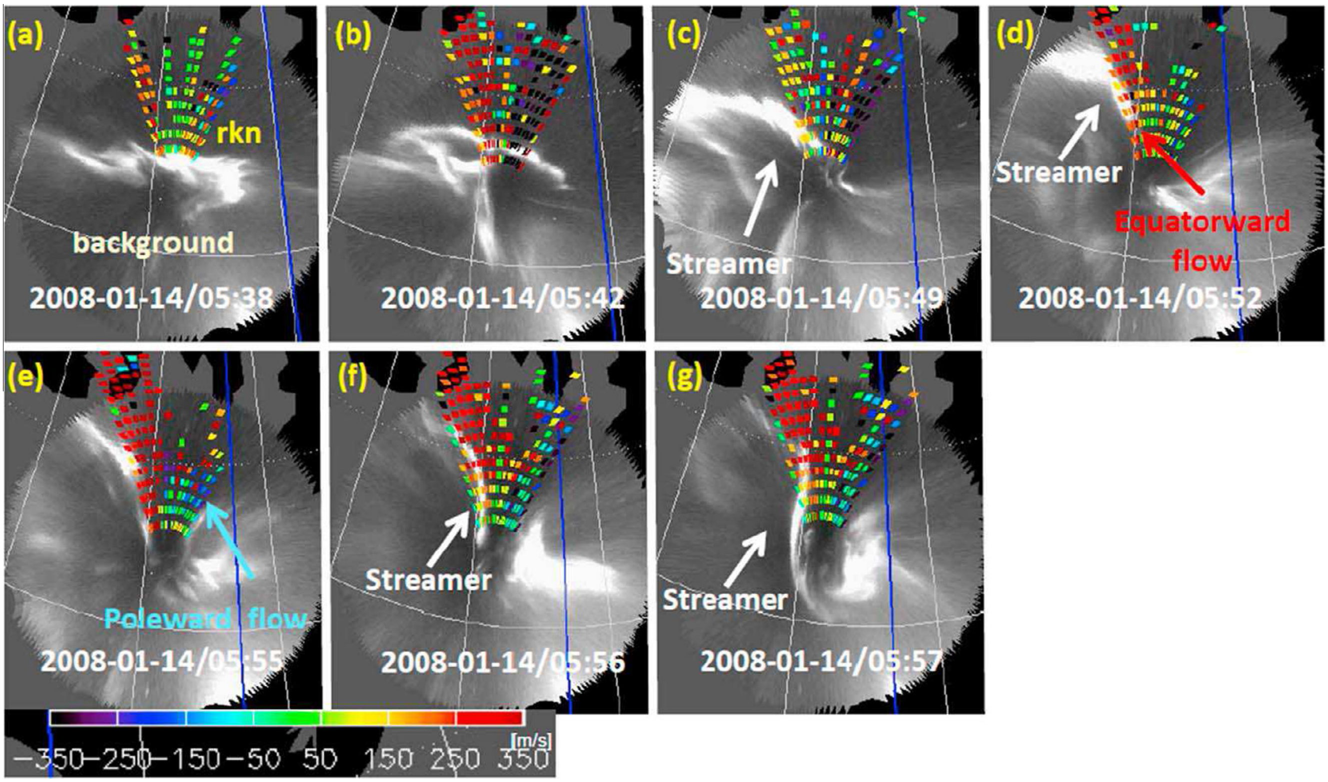

Fig. 5. Equatorward motion of the auroral streamer and the ionospheric flow channel obtained using the THEMIS ASI and Rankin Inlet SuperDARN radar on 14 January 2008. (a) Background flows before the auroral streamer propagated into the radar FOV. (b–g) The sequence of flow and auroral streamers. The solid blue line indicates magnetic midnight. The white lines correspond to 75 and 70 MLAT contours, respectively. From Fig. 2 of Gallardo-Lacourt et al. (2014b).

triggering percentage is significantly higher when applying relaxed criteria and including IMF B_y triggering. This suggests that the external triggering could be common even when the (Lyons et al., 1997) criteria give a low percentage of triggered events.

Strong increase in the solar wind dynamic pressure could also act as a substorm trigger. Tsurutani et al. (2015) analysed the extremely intense substorms and found that these events are apparently triggered by small regions of very high density ($\sim$30–50 cm^{-3}) solar wind plasma parcels (see Fig. 8).

2.4. Ring current dynamics

The dynamics of geomagnetic storms is mainly related to the intensification and decay of the ring current (Gonzalez et al., 1994), which induces a magnetic field, opposite to the geomagnetic field at the Earth surface. There is a direct relation between the D_{st} index and the energy stored in the ring current. The most popular relation is the Dessler–Parker–Scopke relation (Dessler and Parker, 1959; Sckopke, 1966), however this does not take into account that the value of the magnetic pressure in the external border of the magnetic trap is of the order of the plasma pressure. A relation proposed by Carovillano and Maguire (1968) considers the distortion of the geomagnetic field related to the particle motion, and makes it possible to obtain the variation of D_{st} using the radial plasma pressure profiles by consecutive iterations (see Antonova et al. (2013) and references therein).

At the beginning of space era (Akasofu and Chapman, 1961) considered substorms as the key elements of a geomagnetic storm. The discussion about the role of substorms in the storm dynamics has not faded yet (Daglis et al., 2003). For example, Tsurutani and Gonzalez (2006) argue that substorms may be a separate entity from storms, HILDCAA and convection events. However, many scientists believe that substorms are very important for the ring current development, being a source of particle injection and a source of O^+ of ionospheric origin (Daglis et al., 2007). Changes in the O^+ density can significantly affect the storm development (Kozyra et al., 2002).

Knowledge of plasma pressure distribution in the inner magnetosphere is very important for understanding the main magnetospheric processes including geomagnetic storms and substorms (Stepanova et al., 2008c). The use of low-orbiting satellites makes it possible to obtain a radial profile of plasma pressure within a few minutes (Stepanova et al., 2002, 2004b). In quiet geomagnetic conditions, the obtained profiles coincide with the profiles obtained before from high-altitude measurements. During a geomagnetic storm the plasma pressure increases, its profile becomes sharper, and the location of pressure maximum shifts towards the Earth. There is then a possibility

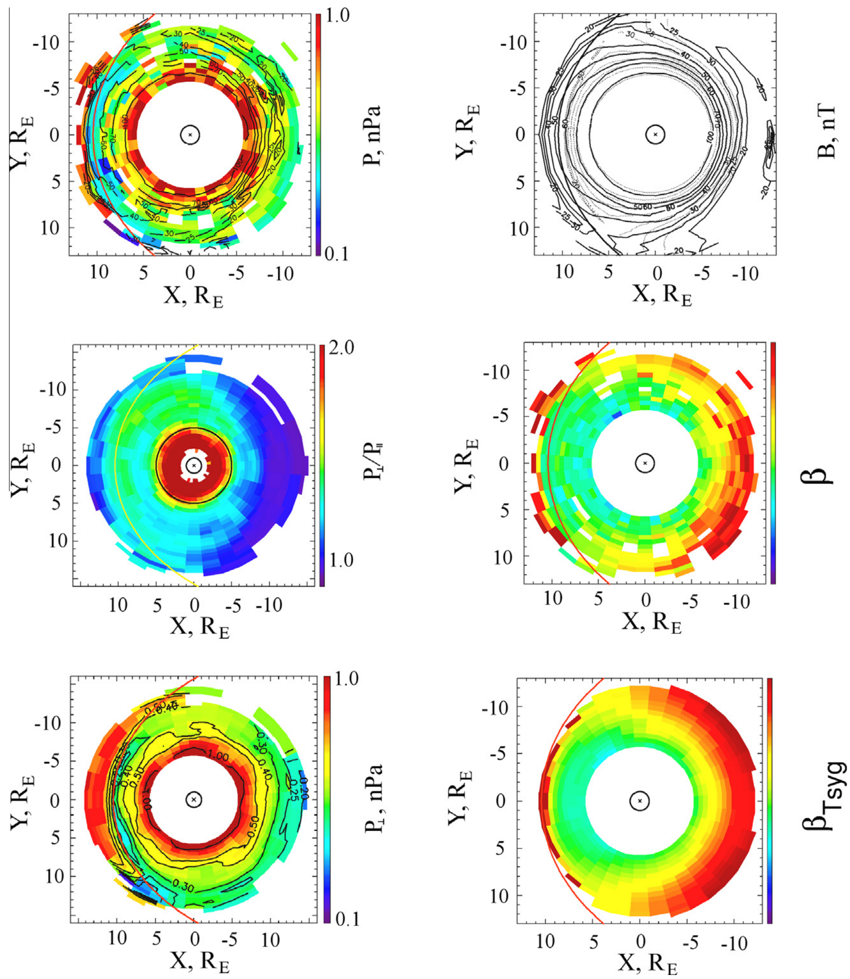

Fig. 6. From top to bottom left side: The averaged distribution of the plasma pressure and magnetic field (black lines) at the equatorial plane; pressure anisotropy; smoothed on the nearby bins distribution of plasma pressure and contours P = const (black lines) at the equatorial plane. From top to bottom right side: Comparison of the distribution of the magnetic field at the equatorial plane shown by solid lines with minimal values of the magnetic field at the field-line B_{min} (dashed lines) calculated using Tsyganenko-2001 model; plasma beta parameter at the equatorial plane; results of β calculation at the B_{min} surface using measured pressure and Tsyganenko-2001 magnetic field model. Adapted from Figs. 1 and 3 of Antonova et al. (2014).

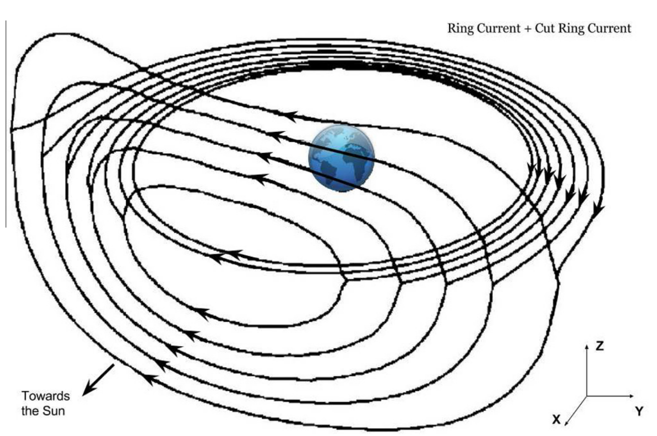

Fig. 7. Schematic illustrating the structure of transverse currents closed inside the magnetosphere (ordinary ring current and cut-ring current). Arrows show the current directions. Adapted from Fig. 1 of Antonova et al. (2013).

to consider the interchange instability as one of the important factors for the development of the main phase of geomagnetic storm.

After reaching the minimum of D_{st}, the ring current starts to decay. Dasso et al. (2002) analyzed the behavior of the D_{st} index during the recovery phase for more than 300 intense geomagnetic storms and found that it fits a negative exponential law very well. For intense storms with minimum of D_{st} less than -250 nT, the decay time increases linearly with the D_{st} minimum value (see Fig. 9). This should be related to the nonlinear τ suggested by Valdivia et al. (1996).

One of the main endeavors of the Space Weather program on storm dynamics is the prediction of the surge of very large fluxes of relativistic electrons with energies more than 1 MeV, because they represent a serious potential hazard for satellite missions. Large fluxes of relativistic electrons are formed in the outer radiation belt during the

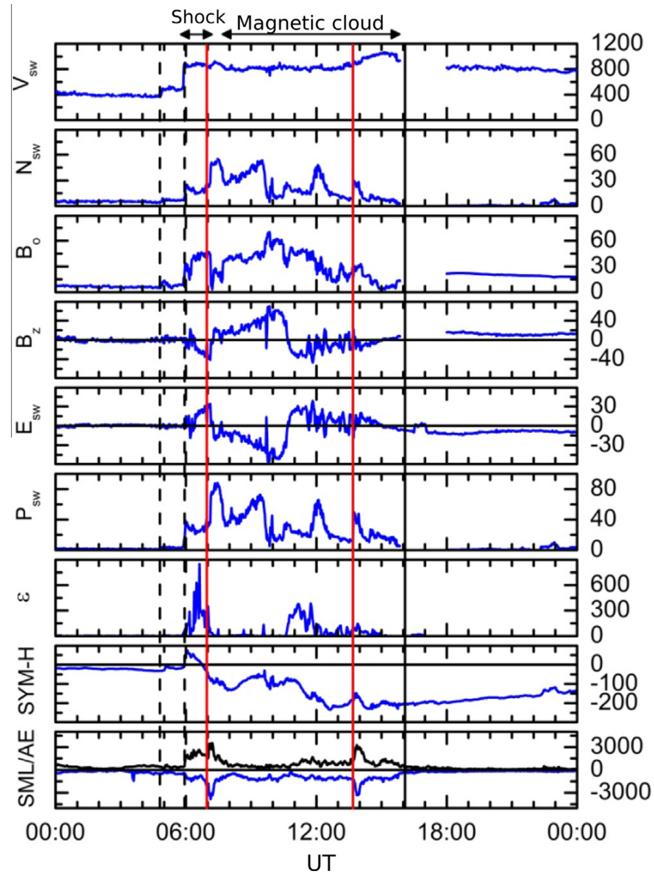

Fig. 8. Interplanetary parameters during two super substorm events (SSSs) occurring on 24 November 2001. From top to bottom, the panels are the solar wind speed V_{sw} in km/s, the density N_{sw} in cm^3, the interplanetary magnetic field (IMF) magnitude (B_0 in nT), the north–south component of the IMF (B_z in nT), the interplanetary electric field (E_{sw} in mV/m), the plasma ram pressure (P_{sw} in nPa), and the interplanetary epsilon parameter (ϵ in 10^{11} W). The next to the bottom panel contains the SYM-H (nT) indices. The bottom panel contains the ground SML (nT) indices (blue) and the AE indices (black). Onsets of two SSSs are indicated by vertical red lines during the complex magnetic storm on 24 November 2001. Interplanetary shocks are denoted by the dashed vertical black lines. A magnetic cloud is present and is shown bounded by solid vertical black lines. The MC lasted from ~07:50 to ~16:00 UT. It is identified by the northward-then -southward rotation of the IMF B_z component. Adapted from Fig. 2 of Tsurutani et al. (2015). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

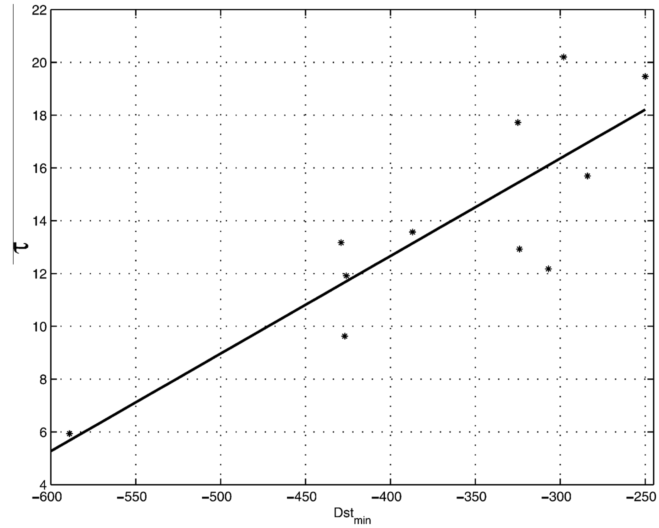

Fig. 9. Decay time as a function of the intensity of the storm for cross correlation $r < -0.97$ and for very intense storms (minimum value of $D_{st} < 250$ nT). Adapted from Fig. 5 of Dasso et al. (2002).

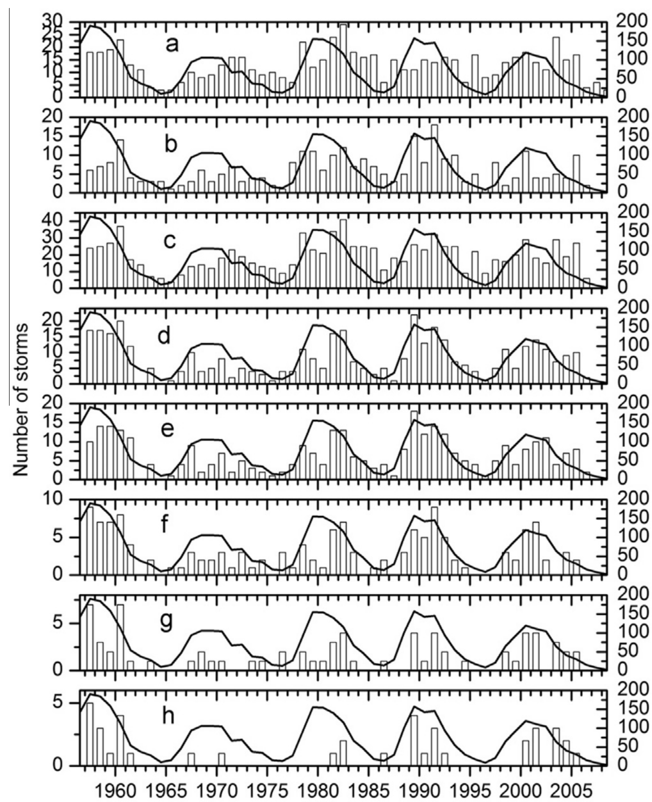

Fig. 10. The number of storms per year and sunspot number for different levels of storm strength according to the minimum (peak) value of the D_{st} variation: (a) between −75 and −50 nT, (b) between −100 and −75 nT, (c) between −100 and −50 nT, (d) less than −100 nT, (e) between −200 and −100 nT, (f) less than −150 nT, (g) less than −200 nT, (h) less than −250 nT. From Fig. 4 of Echer et al. (2011).

recovery phase of some storms. A two-step acceleration process is usually considered. A seed population with energies of hundreds of keV is first generated during the expansion phase of the geomagnetic substorm. This is additionally accelerated to relativistic energies by some other process. Antonova et al. (2009b) proposed that changes in the topology of the high latitude magnetosphere during large geomagnetic storms connected to asymmetric and symmetric ring current development could be an important factor determining the acceleration of relativistic electrons. Hajra et al. (2013, 2014, 2015) showed that the HILDCAA intervals are well correlated with an enhancement of magnetospheric relativistic electron fluxes observed at geosynchronous orbit with a delay of 1–1.5 days from the onset of the HILDCAAs. The electron flux enhancements are stronger for the long-duration

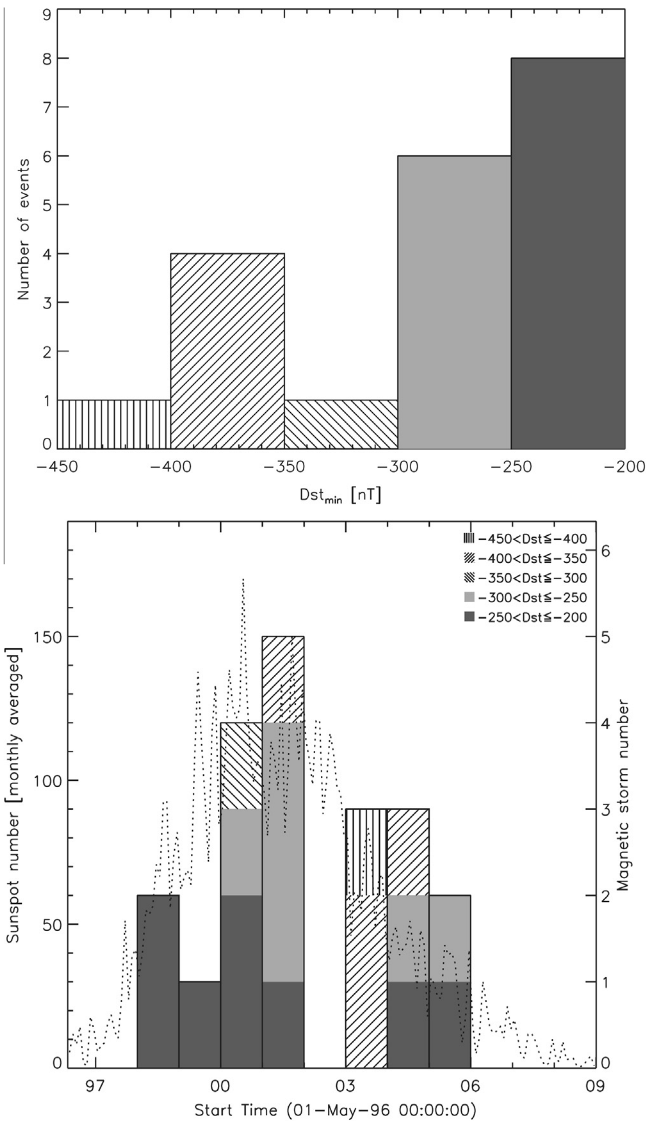

Fig. 11. Top: histogram showing the distribution of minimum values of the D_{st} variation for very intense geomagnetic storms. Bottom: storm occurrence rate per year (vertical left-hand axis). The overlaid dotted line shows the monthly averaged sunspot numbers (vertical right-hand axis). From Fig. 1 of Szajko et al. (2013).

HILDCAA events. Another possibility of generation of relativistic electrons is related to the local particle traps at the boundary of the outer radiation belt (Antonova et al., 2011).

2.5. Periodicity in the geomagnetic storm occurrence

The occurrence of geomagnetic storms correlates with the solar cycle (see Fig. 10). However, for some cycles it displays a two-peak distribution, with one peak close to solar maximum and the other a few years later in the beginning of the declining phase (Echer et al., 2011). However, this distribution depends of the storm strength. For example, Szajko et al. (2013) analyzed distribution of intense storms along Solar Cycle 23 and found that 15% had occurred during the rising phase of the cycle, 45% during both cycle maxima, and, surprisingly, 40% during the cycle descending phase. This latter set includes half of the superstorms and the single observed extreme event (see Fig. 11).

The occurrence of moderate and fairly intense geomagnetic storms also has a pronounced annual variation with maximums around the equinoxes and minimums near the solstices. Nevertheless, the occurrence of more intense storms deviates from this behavior, having a peak near July (Clua de Gonzalez et al., 2001).

2.6. Prediction of geomagnetic storms

Considering that a CME/MC propagates from the Sun to the Earth during a few days, the prediction of geomagnetic storms based on halo CME-expansion speed observation near the Sun is very promising (Gonzalez et al., 2004). Rigozo et al. (2011) developed a technique for the determination of CME speeds using coronograph image processing. Ojeda González et al. (2014) used conjugate fluctuation analysis for automatic identification of MCs in the solar wind, although it is not enough to have a MC to drive a geomagnetic storm. This analysis allows to calculate “the memory of persistence”, i.e. to detect how structured is a time series, and by selecting a threshold value to identify the presence of a cloud with a probability of 80%.

However, the major effort is devoted to the prediction of geomagnetic indexes, especially the D_{st} variation, starting from the empirical model proposed by the Burton et al. (1975). Valdivia et al. (1996) developed a non-linear model of D_{st} prediction from the IMF data, considering a nonlinear decay time that depends on D_{st}. After that Valdivia et al. (1999a) used a similar approach to model and predict the spatiotemporal activity of magnetic storms as measured at a number of stations distributed in local time. Vassiliadis et al. (1999, 2000) developed a non-lineal autoregressive moving average model to adjust the variation of the D_{st} index considering the storm magnitude and phase, the solar wind electric-field input VB_s, the solar wind ram pressure, and the substorm intensification (AL index).

Stepanova et al. (2005b,e) used the feed-forward neural network to forecast the D_{st} variation solely from Polar Cap (PC) index. From the 15 moderate and strong geomagnetic storms observed during 1997, nine were successfully forecast. In three cases the observed minimum D_{st} value was less than predicted, and only in three cases the neural network was not able to reproduce the features of the geomagnetic storm.

Stepanova et al. (2008b) compared the efficiency of the neural networks for D_{st} index forecast using separately the following input parameters: PC index, AL index, solar wind VB_z. It was found that in all three cases the storm-time intervals were predicted much more precisely than the quite-time intervals. The majority of cross-correlation coefficients between predicted and observed D_{st} for strong geomagnetic storms are between 0.8 and 0.9. Changes in the neural network architecture, including the number of nodes in the input and hidden layers and the transfer functions between them lead to an improvement of a network performance up to 10%.

3. Turbulent processes in the magnetospheric plasmas

It is commonly found in space plasmas that the dynamical variables describing the system; such as electromagnetic fields, density, pressure, etc. vary widely in time and space, covering a large range of temporal and spatial scales. When these variations are self-similar in time (or space), with a power spectrum characterized by a power law over many decades in frequency (or wavenumber), the system is usually denoted as turbulent. It should be noted that in general, in turbulence, the fluctuations cascade up to larger scales or down to smaller ones due to nonlinear processes, moving energy to scales where it can be dissipated more efficiently (Kolmogorov, 1941, 1991; Frisch, 1998; Horton, 2012).

Turbulence plays a significant role in the dynamics of the different regions of the Earth's magnetosphere and in the solar wind–magnetosphere coupling (Borovsky et al., 1997, 2003). However, the nature of the magnetospheric plasma turbulence is still not understood. Probably, there exist a number of physical processes contributing to the generation of turbulence at different scales. Latin–American scientists have been actively contributing in the study of different aspects of turbulence.

3.1. Possible sources of magnetospheric turbulence and its main features

The nature of turbulence in the magnetosphere of the Earth can be seen from several points of view. For example, Antonova et al. (1998) suggested that plasma pressure gradients are the most probable candidates for the generation of large- and medium-scale harmonics of magnetospheric turbulence. This approach considers the predominance of a direct turbulent cascade.

At the same time, there are evidences that electromagnetic fluctuations can be generated by fluctuation–dissipation processes occurring in any plasma in a quasi-equilibrium state (Navarro et al., 2014), including the Earth's magnetosphere (Viñas et al., 2015). It was found that plasmas composed of anisotropic thermal (Maxwellian) and non-thermal (Tsallis-kappa-like) electron distributions provides a source for spontaneous emissions of electromagnetic fluctuations, which could lead to an inverse turbulent cascade (see Fig. 12). The presence of fluctuating electric fields may lead to the unmagnetized stochastic motion of the plasma sheet electrons (Antonova et al., 1999).

A number of works indicate that the magnetospheric turbulence has an intermittent character. For example, Stepanova et al. (2003, 2005a) studied fluctuations of the PC index and found that the probability distribution functions (PDFs) of the index increments display a strong non-Gaussian shape and exhibit intermittency. The parameters are close to those reported before for solar wind magnetic field PDFs. This indicates that the PC index adequately reflects the effects of the turbulent solar wind on the high-latitude magnetosphere.

Similar studies of the riometer auroral absorption observed at South Pole showed that the PDFs for the pre-midnight sector clearly exhibit the typical shape associated with intermittency, and that the intermittency is strongly magnetic local time (MLT) dependent with the maximum between 20 and 24 h. It was also found that auroral absorption is more intermittent in small scales. These results indicated that the acceleration of precipitating particles is intermittent as well, especially near the substorm eye, where the level of turbulence is increased (Stepanova et al., 2005d, 2006b).

3.2. Properties of the turbulent plasma sheet

One of the most dynamic and turbulent regions of the magnetosphere is the plasma sheet. The existence of the turbulent plasma sheet is quite natural considering that the flow of the solar wind around the Earth is characterized by high fluid and magnetic Reynolds numbers. In such a case a turbulent wake is expected to form. In pure hydrodynamics, the size of a wake is similar to the size of the obstacle. However, the geomagnetic tail segregates into the turbulent plasma sheet and the non-turbulent tail lobes.

Starting with the work of Borovsky et al. (1997) there are a number of studies dedicated to different properties of the turbulence in the plasma sheet. Some interesting works were done in Latin America. For example, Stepanova et al. (2005c, 2009, 2011) and Pinto et al. (2011) have studied the turbulent eddy diffusion in the plasma sheet and found that the eddy diffusion increases during substorms, especially during the expansion phase. The values of eddy diffusion coefficient increase tailward. A transition region between turbulent and laminar plasma is located approximately between 5 and 12 R_E (see Fig. 13).

Antonova and Ovchinnikov (1999) developed a model of a stable and compact plasma sheet under the assumption that the regular plasma transport, which is transverse to the plasma sheet and related to the dawn–dusk electric field, is compensated by the eddy-diffusion turbulent transport. This model has been successfully substantiated by Stepanova and Antonova (2011) through direct verification of a balance between the regular and turbulent transport in the plasma sheet.

Eddy turbulent transport may also be very important for the net plasma transport toward the tail, and there is a balance between the average regular bulk transport toward the Earth and the turbulent transport by eddies in the tailward direction (Stepanova and Antonova, 2015).

Weygand et al. (2007, 2009, 2010) studied the magnetic field fluctuations in the plasma sheet and compared them with the fluctuations measured in the solar wind.

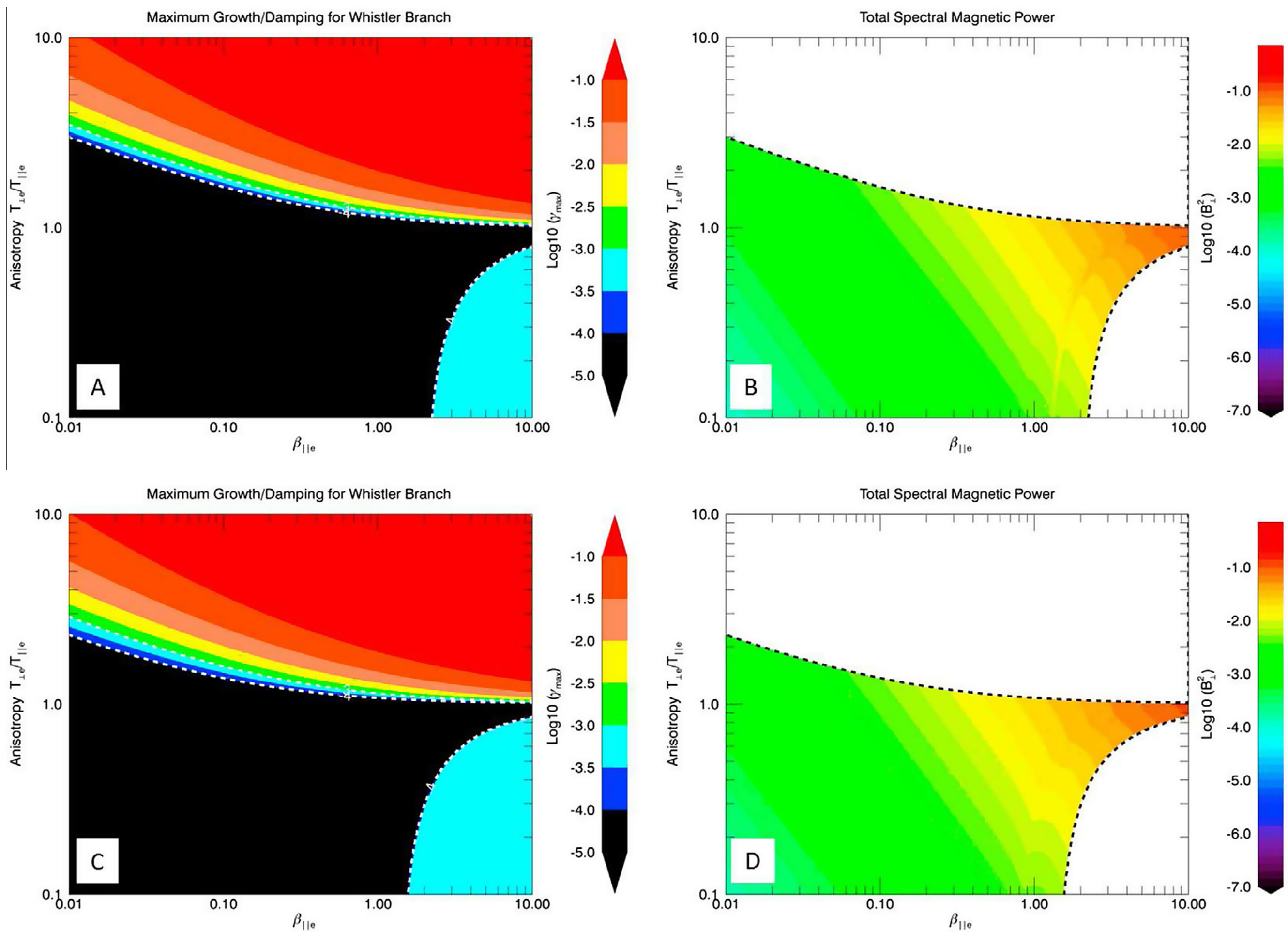

Fig. 12. Maximum growth and total spectral power of magnetic fluctuations for a bi-Maxwellian and anisotropic Tsallis-kappa-like distributions for the case of $\omega_{pe}/|\Omega_e| = 5$ (magnetospheric parameters). (a) Maximum growth rate and (b) magnetic fluctuation power for a bi-Maxwellian. (c) Maximum growth rate and (d) magnetic fluctuation power for a Tsallis-kappa-like. From Fig. 3 of Viñas et al. (2015).

They calculated the Taylor scale as the square root of the ratio of the mean square magnetic field fluctuations to the mean square spatial derivatives of their fluctuations, the correlation scale, and corresponding effective magnetic Reynolds numbers. It was found that the correlation scale is anisotropic with respect to the magnetic field and varies with auroral electrojet activity, decreasing along the mean magnetic field, and increasing perpendicular to it. The Taylor scale does not show any clear variation with geomagnetic activity, being longer parallel to the magnetic field. Nevertheless, the effective magnetic Reynolds numbers were found to be approximately independent of the angle relative to the mean magnetic field.

4. Magnetosphere as a complex non-linear system

Beyond turbulence, there is mounting evidence that space plasmas can display very complex behavior. During the last decades, Latin–American scientists have contributed to the study of the magnetosphere of the Earth as a nonlinear system (Vassiliadis et al., 1999, 2000) that displays multi-scale dynamics (Valdivia et al., 1999a; Uritsky et al., 2001), emergence and self-organization (Klimas et al., 2000; Valdivia et al., 2003, 2005, 2006, 2013; Takalo et al., 1999a,b, 2001), phase transitions (Sitnov et al., 2000), turbulence (Pinto et al., 2011; Stepanova and Antonova, 2011; Stepanova et al., 2011), spatio-temporal chaos (Valdivia et al., 2003), etc.

The proposal of a multi-scale self-organized spatio-temporal complex dynamical magnetosphere was formulated to resolve two seemingly contradicting observations: (a) the magnetotail plasma sheet appears to be a dynamic and self-similar turbulent region (Borovsky et al., 1997; Stepanova et al., 2011; Pinto et al., 2011; Stepanova and Antonova, 2011), and (b) the substorm cycle seems coherent and repeatable with identifiable distinct phases (Baker et al., 1999) and predictable geomagnetic indices (Valdivia et al., 1996, 1999b,a). The suggestion is that these seemingly contradicting statements may be reconciled by proposing that the plasma sheet is driven into a non-equilibrium self-organized "global" state (Chang, 1999), as suggested initially by Chang (1992), that is characterized by critical behavior (Uritsky et al., 2001, 2003) with scale invariant events, self-similar spatial structure

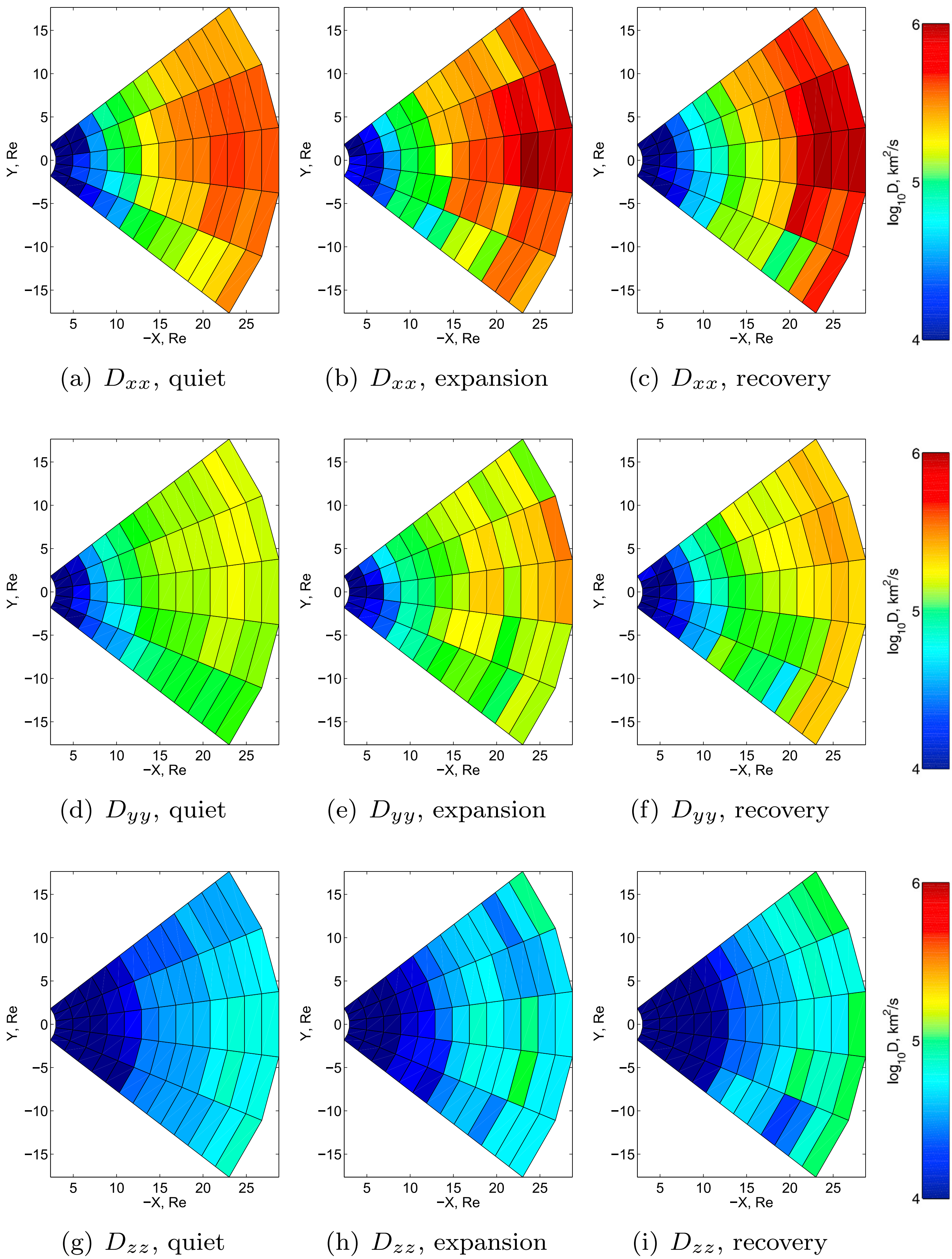

Fig. 13. Estimations of the spatial profile of diagonal terms of the eddy diffusion coefficients (a–c) Dxx, (d–f) Dyy, and (g–i) Dzz during the three different phases of isolated substorms considered in the analysis: (left) quiet phase, (middle) expansion phase, and (right) recovery phase. Adapted from Fig. 3 of Stepanova et al. (2011).

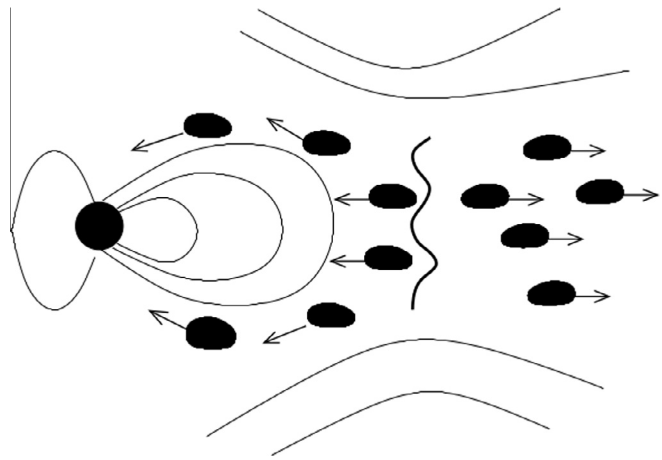

Fig. 14. Conceptual view of the complex magnetosphere. Adapted from Fig. 1 of Valdivia et al. (2003).

(Valdivia et al., 2003), multifractal topology (Valdivia et al., 2006, 2013), with behavior that resembles phase transitions (Sitnov et al., 2000). Such states, were initially seen to emerge naturally in discrete sandpile type models (Takalo et al., 1999a,b, 2001) that intended to reproduce the power law distribution of events observed in the magnetosphere, as characterized by many researchers (Consolini, 1997; Valdivia et al., 2005). Afterwards, it was observed that similar behavior was possible by constructing plasma physics models that display sporadic intermittent dissipation in a natural manner, through spatio-temporal chaos (Klimas et al., 2000; Valdivia et al., 2005, 2006). In fact, it was possible to reconstruct bifurcation diagrams from these models that present the type of driven behavior expected in the magnetosphere. This paradigm is in sharp contrast to the standard picture of plasma sheet transport with laminar earthward flow in a well ordered magnetic field. Instead they are more consistent with the presence of elementary transport events, probably bur bulk flows (Baumjohann et al., 1990; Angelopoulos et al., 1992), that are accelerated in local reconnection regions (Klimas et al., 2004) (see schematic diagram in Fig. 14). The multi-scale behavior present in these models seem to occur naturally in complex systems, and is of particular relevance for the existence of an out-of-equilibrium globally stable state with underlying multifractal turbulent behavior. The dissipation and transport events seem to follow scaling laws that are similar to the intermittent properties of the waiting time distribution of the bursty bulk flows (BBFs) (Angelopoulos et al., 1999) and the power law behavior of the ionospheric spatial energy dissipation from Polar UVI images (Lui et al., 2000; Uritsky et al., 2003).

We know that the magnetosphere, and in general turbulence (Terry, 2000), could be represented by a complex set of very nontrivial equations, however, many approaches take the complementary route and focus on the self-similarity associated with this behavior to illustrate the basic nature of the dynamics (Chang, 1999; Frisch, 1998). The multifractal dissipation observed in the magnetospheric dynamics is a robust characteristic and fundamental to the understanding and modeling of its evolution (Valdivia et al., 2013). In turn, this behavior can be used to discriminate the models that can be used to describe its evolution (Boffetta et al., 1999). Hence, self organization, in a consistent manner with the multifractal behavior, is the key to understand the substorm evolution. Even though the self-organized state is a dynamical state in nature with a superimposed multifractal and unpredictable behavior, its "global" structure is inevitable and repeatable (this is true of sandpile systems as well (Bak et al., 1987)). Thus, we are led to conceptualize the substorm phenomena as an ensemble of multiscale dissipation and flow burst events in the turbulent plasma sheet under the assumption that it can reach a global state.

5. Conclusions

In our opinion, Latin American scientists have significantly contributed to the development of the physics of the magnetosphere, often in cooperation with the scientists from other regions. Latin American scientists contributed high-quality results to all main topics presented in this review: geomagnetic storms and substorms, turbulent processes in the magnetosphere and magnetospheric dynamics. These topics provide a global and self-consistent view of the magnetosphere.

Although it is very difficult to identify results that can be solely attributed to the Latin American scientists, their principal contributions were made in the areas of interplanetary origin of geomagnetic storms, inner magnetosphere causes of geomagnetic substorms, turbulence in the plasma sheet, and study of the magnetosphere as a complex nonlinear system.

There are many other researchers at a number of universities and institutions that have contributed significantly to the magnetospheric research in Latin America. For example, we can mention the interesting research conducted at Jicamarca Ionospheric observatory in Peru, or INPE in Brasil, among many others. Of special relevance are studies related to Sun–magnetosphere–ionosphere interactions, generating very important results about the physics of the solar corona, solar wind, reconnection, ionosphere, etc. topics that are covered in complementary reviews, published in this Special Issue.

In parallel with the research that we have mention in this manuscript, many universities and institutions in Latin America are becoming involved in the design and construction of scientific satellites, particularly, with nano-satellites, that are quite versatile at a reduced cost. We expect to see in the short the conclusion of a number of these projects (see, for example, Diaz et al., 2016).

In summary, currently the Latin American counties show an explosive growth of Space Science and Technology being a relevant actor of space research community.

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