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COMMENTARY

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Key Points:

- Recollection of a first quantitative model related with magnetospheric reconnection
- Review of some fundamental aspects associated with the interplanetary origin of geomagnetic storms
- Highlights about the origin of "High-Intensity, Long-Duration and Continuous Auroral Activity" events

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Magnetospheric Reconnection and Geomagnetic Storms: A Personal Perspective

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Abstract This commentary paper presents summaries of my research work on magnetospheric reconnection and on geomagnetic storms, to which I have devoted most of my professional career in space physics. Thus, the paper summarizes: (a) my early studies on the magnetospheric reconnection-electric field, involving observations and a model of the related polar cap-electric field during events with observed interplanetary driving parameters and (b) studies on several fundamental aspects associated with the origin of geomagnetic storms, especially leading to intense and extreme levels of activity, mostly associated with the arrival of geoeffective Coronal Mass Ejections (CMEs). The latter also involves studies on recurrent geomagnetic activity caused by interplanetary high-speed streams, among which "High-Intensity, Long-Duration and Continuous Auroral Activity (HILDCAAs for short)" events were shown to represent a special class. In the final Section, I have added some comments on recent issues dealing with fundamental concepts on reconnection at the Earth's magnetopause.

Plain Language Summary The author summarizes his research work related with: (a) early studies on the magnetospheric reconnection-electric field, involving observations and a model of the polar cap-electric field during events with observed interplanetary driving parameters; (b) studies on several fundamental aspects associated with the interplanetary origin of geomagnetic storms, especially leading to intense and extreme levels of activity. The latter also involves studies on recurrent geomagnetic activity caused by interplanetary high-speed streams, among which "High-Intensity, Long-Duration and Continuous Auroral Activity (HILDCAAs for short)" events were found to represent an especial class.

1. Introduction: From INPE-Brazil to UC-Berkeley

Motivated by the rapid advance of research in space sciences by the end of the sixties and after having obtained my BS in physics in December of 1967 from the National Engineering University of Lima-Peru, early in 1968 I entered the graduate school of the National Commission of Space Activities of Brazil, which several years later was named National Institute of Space Research (INPE), located in São José dos Campos, near São Paulo, Brazil.

At INPE I joined a research group that had started studying astrophysical X-ray sources by performing X-ray measurements with proportional counters onboard rockets in collaboration with a research group from the Space Sciences Laboratory (SSL) of the University of California at Berkeley. Thus, in June 1969 I participated in a rocket campaign of that kind at the rocket launching facility in Natal, located at the equatorial region of Brazil, with the aim of measuring X-rays from the astronomical X-ray source Scorpius X-1. The analysis of the collected observations from that campaign was the topic of my MSc thesis, which was done partly at INPE and completed at the SSL of UC-Berkeley in December of 1969. For my thesis, I benefited strongly by the advice of the SSL-research associate Michael Lampton, who about a decade later was selected as an astronaut to work on NASA missions onboard the space-shuttle carriers. The experience that I gained then by working with X-ray measurements of astrophysical sources I believe was strongly influential for my involvement in experimental research done later at INPE, to measure atmospheric X-rays due to particle precipitation of energetic particles from the inner radiation belt at the South Atlantic Magnetic Anomaly (SAMA), as discussed in Section 4 of this paper.

When I started my doctoral program at UC-Berkeley in January of 1970 I moved to the field of space physics at the SSL since at that time in-situ interplanetary and magnetospheric observations started to become available and one could work closely with measurements of space plasmas.

In the following Sections, I summarize my involvement in research activities dealing with interplanetary and magnetospheric physics, especially on the two topics to which I have devoted most of my research career, namely magnetic reconnection and geomagnetic storms. I also describe briefly my involvement in two additional related topics: (a) a research topic of local interest in Brazil dealing with the intensification of energetic particle precipitation from the inner radiation belts at the South Atlantic Magnetic Anomaly (SAMA) in association with geomagnetic storms (Section 4) and (b) studies on the annihilation of quantum magnetic fluxes and on its possible importance for the overall understanding of magnetic field reconnection (Section 6).

2. Doctoral Work at the SSL of UC-Berkeley

When I started my doctoral work at the Space Sciences Laboratory of UC-Berkeley initially I joined the research group led by John Wilcox dealing with large-scale solar and interplanetary magnetic fields (Wilcox & Gonzalez, 1971). There was a particular interest in the interplanetary magnetic-sector polarity-structure, as it was known then and later was better associated with the evolving interplanetary current-sheet structure. At that time, with the collaboration of Eigil Friis-Christensen from Denmark, we also tried to understand the apparent influence of the variable interplanetary magnetic-sector polarity on the geomagnetic field behavior at the polar caps (Friis-Christensen et al., 1971).

Since the research I was doing with John Wilcox on the polar cap-magnetic field variability was apparently related to changes in the interplanetary magnetic field (IMF) overall direction, it was important to search for physical processes that could explain that correlation. For that purpose the process of magnetic reconnection between the IMF and the geomagnetic field at the magnetopause had already appeared to be a promising one. Thus, even before moving to another research group at SSL I had started to learn about the role of magnetic reconnection in magnetospheric physics, as initially proposed in that context by Dungey (1961) and Petschek (1964). In fact, in December of 1970 I had the opportunity to visit Jim Dungey at the Imperial College of London and learned from him fundamental concepts of magnetic reconnection. During that visit I also interacted with Stan Cowley, who was also working on the topic of magnetic reconnection for his doctoral thesis under the direction of Jim Dungey.

About a year later of having worked with John Wilcox, he assumed a permanent position at the Plasma Institute of Stanford University, where he built with Phil Scherrer a Solar Magnetic Observatory, presently known as Wilcox Observatory. Thus, I had to look then for another thesis adviser in order to continue with my doctoral research work at the SSL of UC-Berkeley.

Concerning my academic experience at UC-Berkeley, besides attending a highly regarded center to learn physics, with several Nobel laureates at that time and also with several famous space scientists working at the SSL, I can say that the main knowledge that I gained there was related to the interest and effort of trying always to look into fundamental issues that lie behind any research topic in science, as well as of trying to combine both theoretical and observational aspects of research in space physics problems.

3. Magnetic Reconnection: First Quantitative Model of Reconnection at the Earth's Magnetopause

Early in 1971, at the Space Sciences Laboratory of UC-Berkeley, I joined the research group led by Professor Forrest Mozer for the continuation of my doctoral program (1970–1973). Mozer was performing ionospheric-electric field observations at the polar caps and at the auroral regions using double-probe sensors onboard balloons and rockets.

Using accumulated data on ionospheric polar cap-electric fields obtained by that research group (Mozer & Gonzalez, 1973; Mozer et al., 1974), I tried to understand the large-scale electric field variability at the polar caps as a function of interplanetary parameters that could be affecting the ionospheric and magnetospheric electric fields. In that study one could clearly see that the polar cap-electric field variability was closely associated with that of the intensity and direction of the IMF arriving at the magnetosphere, as observed by solar wind monitors near the Earth.

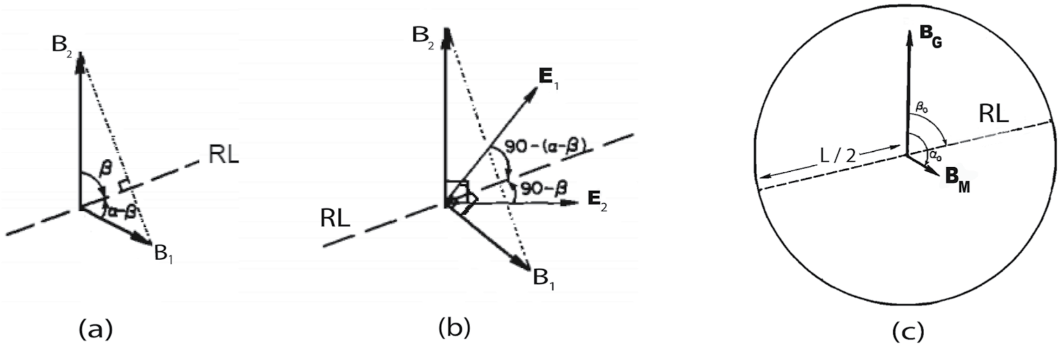

Figure 1. (a) Diagram illustrating the reconnection line (dashed line RL) assumed to lie along the direction of the current given by $\nabla \times \boldsymbol{B}$, as computed at the interface between $\boldsymbol{B}_1$ and $\boldsymbol{B}_2$, (b) Illustration of the electric fields $\boldsymbol{E}_1$ and $\boldsymbol{E}_2$ associated with $\boldsymbol{B}_1$ and $\boldsymbol{B}_2$, (c) Reconnection geometry at the nose (subscript zero) of the magnetopause. L is the length of the reconnection line (RL). $\boldsymbol{B}_G$ and $\boldsymbol{B}_M$ stand for geomagnetic and magnetosheath magnetic fields (Gonzalez and Mozer (1974), adapted from their Figures 4 and 5).

Since early studies on magnetic reconnection at the magnetopause, it was expected that the solar wind could transfer momentum and energy to the magnetosphere more efficiently when the IMF had a direction opposite to that of the geomagnetic field (Arnoldy, 1971; Fairfield & Cahill, 1966; Sonnerup, 1970). However, since the direction of the IMF was also known to be variable, as observed by solar wind monitors during the time intervals of the polar cap-electric field observations of our data set, I had the task to generalize the concept of magnetic reconnection at the magnetopause for any angle between the IMF direction and that of the geomagnetic field.

The result of that investigation was presented and discussed in my doctoral thesis, with a summary published in a paper by Gonzalez and Mozer (1974), as a first quantitative model of magnetic reconnection at the magnetopause for an arbitrary angle (*clock angle*) between the IMF and the geomagnetic field. That paper has been extensively cited until present.

The model proposed a *component reconnection* scenario as illustrated in Figure 1 (see the paper by Gonzalez and Mozer (1974) for details). Figure 1 shows: (a) a diagram with the reconnection $X-$ line (dashed line RL) assumed to lie along the direction of the current given by $\nabla \times \boldsymbol{B}$, as computed at the interface between $\boldsymbol{B}_1$ and $\boldsymbol{B}_2$, (b) the electric fields $\boldsymbol{E}_1$ and $\boldsymbol{E}_2$ associated with $\boldsymbol{B}_1$ and $\boldsymbol{B}_2$, (c) the reconnection geometry at the nose (subscript zero) of the magnetopause (Gonzalez and Mozer (1974), adapted from their Figures 4 and 5). In that model, it was assumed that only the components of the approaching magnetic fields transverse to the *reconnection X-line* would enter in reconnection in a similar way to that studied before for the simpler case of approaching fields with purely opposite directions. With that assumption, the resulting direction for the reconnection X-line also implied the existence of a uniform magnetic field component along that direction across the magnetopause (Gonzalez & Mozer, 1974). Such a field component along the reconnection line was later known as *guide field* (e.g., Paschmann et al., 1979).

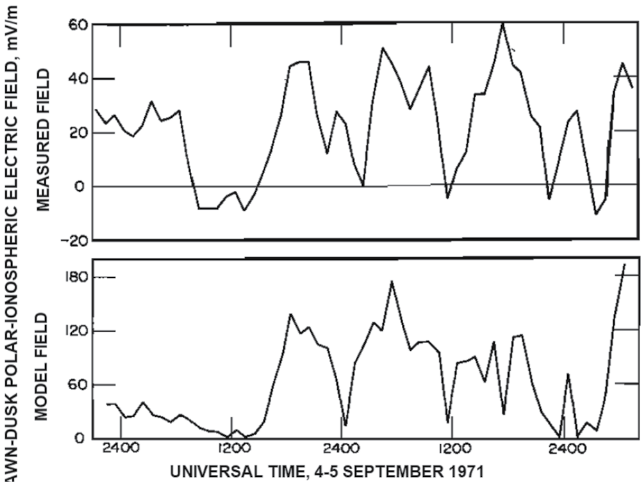

Figure 2. Hourly averages of the model electric field and of the mean dawn-dusk component of the polar cap-ionospheric electric field, measured at Resolute Bay and Thule, for the time interval of September 4–5, 1971, for which solar wind plasma and magnetic field measurements were available from a solar wind-satellite monitor (Gonzalez and Mozer (1974), their Figure 9).

The Gonzalez and Mozer (1974) reconnection model allowed a computation of the reconnection electric field, which was assumed to be transmitted to the ionospheric polar caps by the equipotential geomagnetic field and that could be compared with the measured large-scale ionospheric electric field. This implied that the reconnection process could be expected to become the main driver for *magnetospheric convection*, as suggested by previous studies (e.g., Nishida, 1968). As an example, Figure 2 (reproduced from the paper by Gonzalez and Mozer (1974)), shows hourly averages of the model electric field and of the mean dawn-dusk component of the ionospheric polar cap, as measured at Resolute Bay and Thule for the days of September 4–5, 1971, during which measurements of solar wind-plasma and magnetic field parameters near Earth were available. The model electric field was computed from the model reconnection potential over the reconnection line (RL) with extension L (as indicated in Figure 1c). Note that the vertical scale shows an amplitude for the model electric field greater than that of the measured field probably due to the several simplifications used in the model, especially for the values of the magnetosheath parameters.

Furthermore, the model also predicted that the polar-cap convection cells should become asymmetric when the B_y component of the IMF has a finite amplitude, shifting the cells toward dawn or dusk as a function of the sign of B_y, as observed by Mozer and Gonzalez (1973).

For the preparation of this magnetopause reconnection model, I benefited from discussions with Vytenis Vasyliunas during his partial sabbatical stay at UC-Berkeley in 1973, during which he was working on his highly influential review paper on magnetic reconnection (Vasyliunas, 1975).

4. South Atlantic Magnetic Anomaly

After receiving my doctoral degree from UC-Berkeley in June 1973, I returned to the Brazilian Institute of Space Research (INPE) with the main interest of trying to start there a new research group dedicated to magnetospheric physics, since by then the Institute only had research groups working with geomagnetic and ionospheric topics. Thus, during my initial years there and with the participation of some graduate students we organized a research activity related with the topic of energetic particle precipitation at the SAMA from the inner radiation belts, a topic that was (and still is) of much local interest to the space science community of Brazil.

During the interval of 1980–1984 we performed balloon campaigns at the INPE's balloon launching site in Cachoeira Paulista, near São José dos Campos- São Paulo, to measure atmospheric X-ray fluxes expected from precipitating energetic particles at the SAMA, using NaI scintillation crystals as X-ray detectors. We also used double probe-electric field detectors to measure variabilities in the large-scale atmospheric fair-weather electric field, which was expected to be influenced by the energetic particle precipitation at the SAMA.

The publications that resulted from that investigation (e.g., Gonzalez et al., 1982, 1987; Pinto & Gonzalez, 1986) described our main findings, showing that energetic electron precipitation fluxes from the inner radiation belt can become intensified during times of enhanced geomagnetic activity and also that the atmospheric fair-weather electric field can become distorted, even at balloon altitudes, by middle atmospheric ionization enhancements resulting from the enhanced energetic particle precipitation. This conclusion was later supported by computer simulations (Dutra et al., 1992).

While performing the electric field measurements with the interest of learning about ionospheric and upper-atmospheric electric fields, mapped down to balloon altitudes (Mozer & Serlin, 1969), we faced a frequent complication dealing with the local presence of thunderstorm-related electric fields, which were usually of a much larger amplitude than those originated at the upper atmosphere and ionosphere. Thus, we had to select and work with electric field measurements obtained only during flight intervals without such a thunderstorm-related “contamination.” However, since the lower atmospheric-stronger electric fields were of much interest for research in the area of atmospheric electricity, a new research group on that topic became established at INPE following our initial balloon-borne electric field measurements (e.g., Pinto et al., 1988).

5. Geomagnetic Storms

During my sabbatical year in 1985–1986, I went to work at the Jet Propulsion Laboratory in Pasadena, California, as a senior NASA research associate. Among the scientists working there in space physics I started to interact with Bruce Tsurutani in particular. This began a long-lasting research collaboration to study geomagnetic storms, especially aimed to their solar and interplanetary origin. In subsequent years that research activity also involved collaborations with several more scientists from other research institutions.

In the first year of that collaborative research activity, we started studying the behavior of interplanetary parameters that could be associated with the development of intense geomagnetic storms (defined as such when the peak value of the storm index Dst becomes <-100 nT) during the time interval of 1978–1979. For that study, we had a continuous set of solar wind-plasma and magnetic field measurements made by the interplanetary monitor ISSE-3 (located at the gravitational L_1-inner Lagrangian point of the Earth-Sun system) as well as a related list

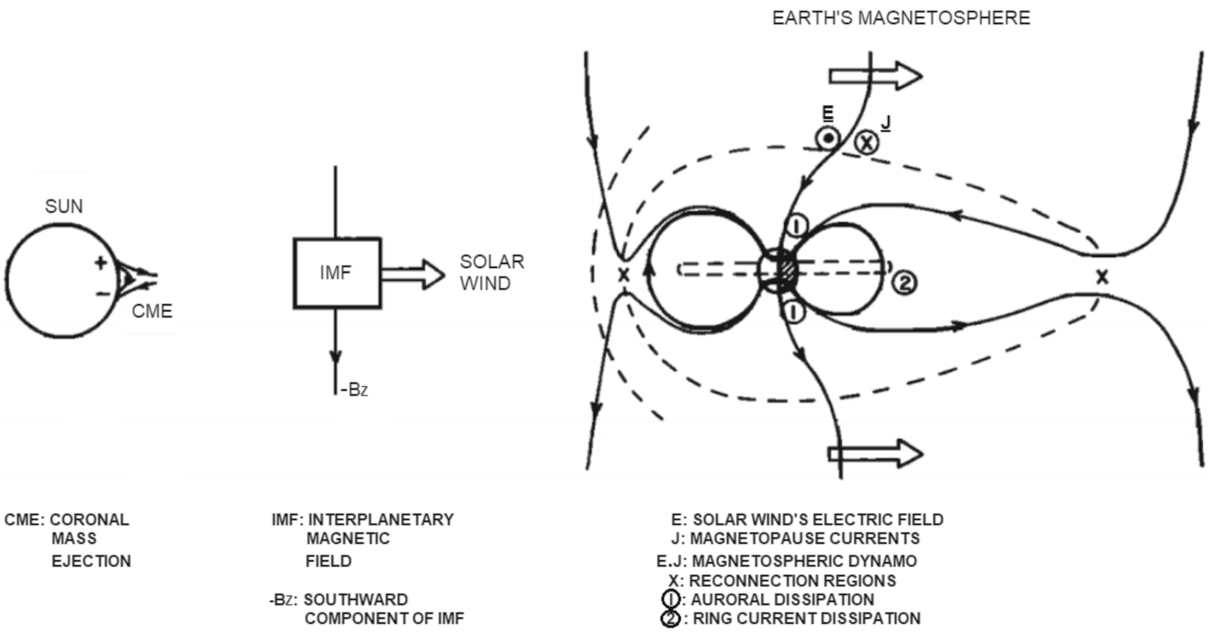

Figure 3. Schematic on the "solar-interplanetary-magnetospheric" coupling, with magnetospheric reconnection occurring due to the presence of an IMF with a negative B_z component (e.g., associated with a CME). The figure also illustrates the transfer of energy from the solar wind to the magnetosphere due to reconnection and via a dynamo process, with that energy becoming later dissipated in storm and substorm processes (Gonzalez et al. (1994), their Figure 4).

of the magnetospheric activity indices AE and Dst (provided by Syun Akasofu). In that initial study, we found the following *interplanetary criteria* for the development of intense storms: the B_z component of the IMF should have amplitudes of −10 nT, or less, during periods of 3 hr, or more; and that the interplanetary electric field associated with that IMF-B_z range should have amplitudes of 5 mV/m, or larger, during three hours, or more. We published those criteria in a paper by Gonzalez and Tsurutani (1987), which became largely cited and extended in subsequent papers (e.g., Gonzalez et al., 1989 Tsurutani et al., 1988).

Figure 3 (taken from Gonzalez et al. (1994)) shows a schematic of the "solar-interplanetary-magnetospheric" *coupling*, with magnetospheric reconnection occurring when the IMF has a substantially intense and negative B_z component (e.g., associated with a CME). This Figure shows the basics of our original study on geomagnetic storms (as presented in the review paper by Gonzalez et al. (1992)), in which the importance of the presence of a substantially intense southward B_z component of the IMF is stressed, as claimed in the Gonzalez-Tsurutani criteria for the development of intense storms (Gonzalez & Tsurutani, 1987). Figure 3 also illustrates the transfer of energy from the solar wind to the magnetosphere due to reconnection via a dynamo process at the high latitude magnetosphere. That transferred energy was claimed to become dissipated in storm and substorm processes.

While working with that intense storm project we also found, in the same initial data set, an apparently interesting association between intervals of interplanetary high-intensity Alfvén wave-trains present in High-Speed Streams (HSS) and intervals with High-Intensity, Long-Duration, and Continuous Auroral Activity, as seen in the AE index, to which we called HILDCAA events. We published that study in a paper by Tsurutani and Gonzalez (1987), which also became highly cited. From that study onward it was found that geomagnetic storms occurring during HILDCAA events had intensities mostly of a moderate level (peak Dst value between −50 nT and −100 nT) due to the fluctuating character of IMF − B_z, and therefore not reaching the criteria for the development of intense storms as claimed by Gonzalez and Tsurutani (1987). Nevertheless, since HILDCAA intervals can have a duration from several days to several weeks (typical of a HSS duration), the integrated energy deposited in the magnetosphere during such events can be substantially large involving the occurrence of frequent substorms as well (e.g., Gonzalez et al., 2006). Figure 4 (taken from Gonzalez et al. (1994)) shows an example of a HILDCAA event (29 August 1978 to 04 September 1978), indicated by a horizontal bar in the AE panel. The HILDCAA event was claimed to be associated with an interval of a large-amplitude interplanetary Alfvénic fluctuation, as seen in the IMF B_y and B_z components.

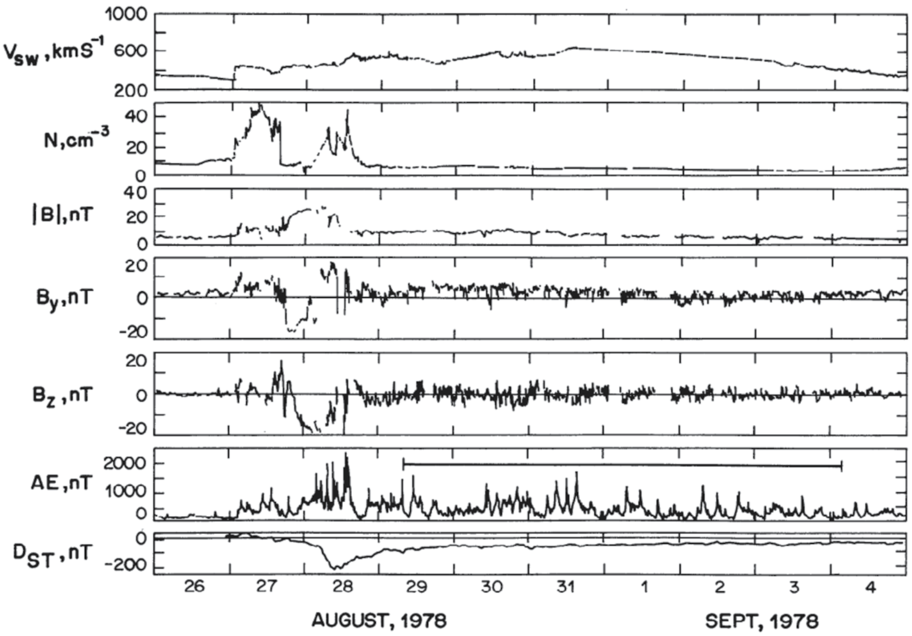

Figure 4. Example of a HILDCAA event (29 August 1978 to 04 September 1978), indicated by the horizontal bar in the AE panel. On the top five panels, some of the interplanetary parameters measured by the ISEE 3 satellite are shown. The HILDCAA event was associated with an interval of a large-amplitude interplanetary Alfvenic fluctuation, as seen in the IMF-B_y and B_z components (Gonzalez et al., 1994, their Figure 3).

In order to study several other issues related with the origin and dynamics of geomagnetic storms, we organized a series of topical workshops, with the first one carried out at INPE, Brazil in November of 1991, and with the participation of some invited scientists. The aim of that workshop was to discuss the basic concepts in magnetospheric and interplanetary physics that at that time were used to define a geomagnetic storm. For that purpose, we took advantage of the diverse and complementary knowledge in those areas of research provided by the invitees, with inputs from both the theoretical and experimental sides. As a result of that workshop, we wrote the review paper "What is a geomagnetic storm?" (Gonzalez et al., 1994), which became highly cited and influential until present times. In fact, it is still listed in JGR-Space Physics as the second most cited paper in that Journal. Later, from 1991 to 2011, as a continuation of the first workshop and with the aim of discussing topical aspects related with geomagnetic storms, we held eight more workshops in several countries and published additional review papers and AGU Monographs. Among them, the Monograph edited by Tsurutani et al. (1995) presented a collection of papers dealing with several aspects of geomagnetic storms going from solar and interplanetary issues to magnetospheric and ionospheric ones; the review paper by Kamide et al. (1998) discussed the important issue of storm-substorm relationship; the paper by Gonzalez et al. (1999) reviewed concepts and observations dealing with very intense storms; the review paper by Daglis et al. (2003) concentrated on the formation, composition, and dynamics of the ring current; the review paper by Tsurutani et al. (2006) discussed the origin and dynamics of recurrent geomagnetic storms during the descending phase the solar cycle; and the paper by Lopez et al. (2015) discussed the role and importance of the magnetospheric-tail current in the buildup of a geomagnetic storm during very intense events.

For a more theoretical understanding of the empirical results presented in our initial papers about the interplanetary origin of geomagnetic storms and trying to extend the work of Akasofu (1981), we showed (Gonzalez et al., 1989, 1994; Gonzalez, 1990) that the main interplanetary parameters responsible for the efficiency of the interaction are the amplitude and duration of a southwardly directed IMF, producing magnetic reconnection with the geomagnetic field, as suggested by the criteria of Gonzalez and Tsurutani (1987). In a paper by Gonzalez et al. (1989), several coupling functions were listed and selected from their best level of correlation with the geomagnetic activity indices AE and Dst. Most of those functions were later shown to be associated with functions dealing with momentum and energy transfer from the solar wind to the magnetosphere via magnetic reconnection (Gonzalez, 1990).

One additional aspect of later studies on the solar and interplanetary origin of intense geomagnetic storms referred to their occurrence frequency as a function of the solar cycle and of the main solar-activity structures responsible for their occurrence. It was reported that around solar maximum the most *geoeffective* solar structure is a *CME* involving the required IMF criteria mentioned above, whereas during the descending phase of the solar cycle and during solar minimum the main geoeffective structure is a HSS, also when the IMF criteria for the development of intense storms are held (e.g., Gonzalez et al., 1992, 1999; Tsurutani et al., 1995). It was additionally found that intense storms tend to have a *dual-peak* behavior within the solar cycle, one around solar maximum and the other at the descending phase of the cycle (e.g., Gonzalez et al., 1999).

Regarding CMEs as the most geoeffective structures causing intense geomagnetic storms (especially around solar maximum), it was shown since our initial studies (e.g., Gonzalez & Tsurutani, 1987; Gonzalez et al., 1994) that the CME has two distinct geoeffective substructures known as *sheath* region (right after the CME-shock) and *magnetic cloud* region (also known before as "driver gas"), with each region involving intense and negative B_z fields. Further, a combination of the intense and negative B_z fields from those two consecutive regions was shown to lead frequently to the development of a *two-step* intense geomagnetic storm (e.g., Kamide et al., 1998).

Finally, since 2003 there was a renewed interest to study the origin and magnetospheric impact of *extreme* geomagnetic storms (defined as such by Tsurutani et al. (2003) when Dst <-400 nT), especially reviewing the extreme Carrington event of 2 September 1859 and extending it to a set of *historical* extreme storms (Gonzalez et al., 2011; Lakhina & Tsurutani, 2017; Tsurutani et al., 2003). Although during the *space era* extreme geomagnetic storms had peak Dst values not smaller than about -600 nT, it was estimated that some historical extreme storms could have reached peak Dst values of around -1000 nT, or less, as during the Carrington event in which the peak Dst value seems to have reached a level of -1760 nT (Tsurutani et al., 2003).

Figure 5 shows the extreme storm of 20 November 2003, which until now is the only event of that level of intensity during the space era for which the associated interplanetary data were measured (e.g., Gonzalez et al., 2011). During this event, the interplanetary structure responsible for the development of the extreme storm was a magnetic cloud during which the negative B_z component of the IMF was very intense, with a peak value close to -50 nT. Gonzalez et al. (2011) reported that the most geoeffective structures causing very intense storms are a magnetic cloud, the sheath region of a CME, or the combination of both, each carrying intense and negative B_z fields.

It is worth mentioning the following interesting caveat regarding the definition of extreme storms (Lanzerotti, 1992). The most common definition of intense and extreme storms has been that based on intensity levels of the Dst index (e.g., Gonzalez et al., 1994, 2011; Tsurutani et al., 2003). The intensity level of Dst has been shown to be well correlated with those of the main solar wind parameters that drive energy input to the magnetosphere via magnetospheric reconnection (e.g., Gonzalez et al., 1994), and therefore, it has been successfully used as a simple index to define the level of the geomagnetic storm intensity for most of the recorded storm events during the space era. However, there have been some interesting intense and even extreme "global magnetospheric active" events, such as that of 2 August 1972, during which the main driver of magnetospheric reconnection, namely a southwardly directed B_z component of the interplanetary magnetic field, was mostly northward and yet the magnestosphere became largely active with a large compression and with a very strong substorm activity, although the intensity level of the corresponding Dst index did not correspond to the expected class of very intense storm events (Lanzerotti, 1992; Tsurutani et al., 1992). Thus, it would be very interesting to try to incorporate additional aspects of magnetospheric energization that are not necessarily related just with magnetospheric reconnection and with the intensification of the ring and tail currents, which are monitored by the Dst index, for a more general understanding of the solar wind-magnetosphere interaction during very active time intervals (Lanzerotti, 1992).

It was a very interesting experience to have participated in studies on historical extreme geomagnetic storms, even though the related geomagnetic and auroral data were very limited. Besides their academic importance, such studies gave an important input to the community dealing with space weather effects, since the occurrence of Carrington-type events in our present space and vulnerable technological era would have largely damaging consequences (e.g., Baker et al., 2009).

I would like to mention that, due to my long-term dedication to study geomagnetic storms, in June of 2013 I was happy to become elected to the Brazilian Academy of Sciences and to receive the AGU-*Space Weather* Prize in December of 2017.

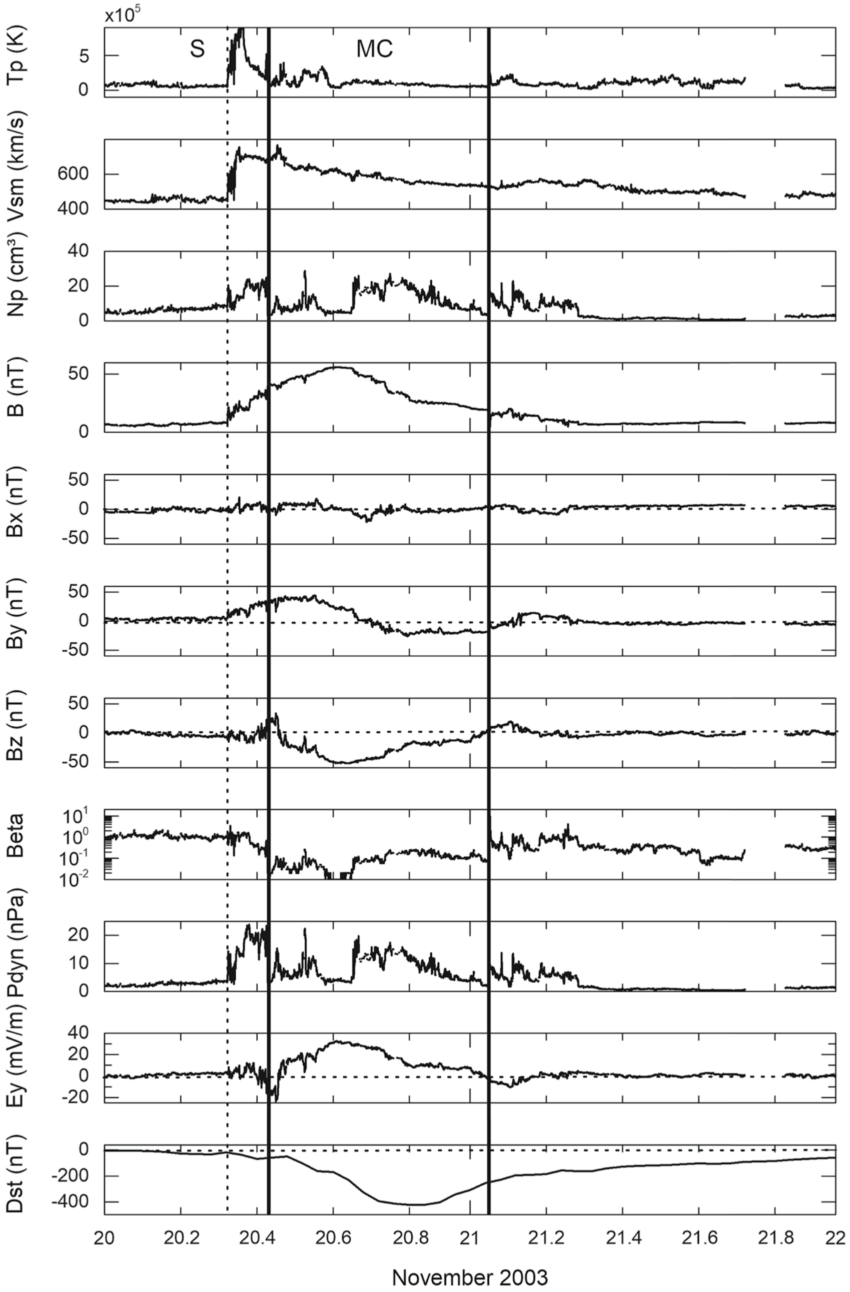

Figure 5. Extreme geomagnetic storm of 20 November 2003. The solar wind parameters measured by the ACE satellite and the Dst index are shown. The computed interplanetary plasma beta parameter, dynamic pressure, and dawn-dusk electric field are also shown. Letter "*s*" stands for shock and "MC" for magnetic cloud (indicated by the two dark vertical lines). Note that the peak intensity of the negative (IMF) B_z component was very large (close to −50 nT). (Gonzalez et al., 2011, their Figure 7).

6. Magnetic Reconnection/Annihilation and E.N. Parker

During the period of 2012–2015 I interacted with Rudolf Treumann and Eugene Parker in a study dealing with the annihilation of oppositely directed quantum magnetic fluxes (Aharonov & Bohm, 1959; Feynman et al., 1963; Gonzalez, 2016; Parker, 2007; Treumann et al., 2012). Aharonov and Bohm (1959) showed that a quantum of magnetic flux can exist in association with a phase shift in the electron wave function due to the presence of the vector potential around a localized magnetic field. Such a quantum of magnetic flux is given by $c(h/e)$, in Gaussian units, where h is the Planck constant and e is the electron charge, and is considered a constant of nature, equal to 4×10^{-7} Gauss cm^2. After the theoretical postulation of quantum magnetic fluxes by Aharonov and Bohm (1959), some laboratory experiments confirmed their existence (e.g., Chambers, 1960). Later at the Hitachi Lab in Japan (Tonomura et al., 1986), it was shown that oppositely directed quantum magnetic fluxes could become annihilated, with their associated energy possibly released in a flux of photons with energies proportional to that of the interacting magnetic fields. Since the annihilation process was shown to exist at the Lab using superconductors (e.g., Harada et al., 1996) and since the external core of some neutron stars was expected to have a superconducting behavior (Page & Cumming, 2005), involving very strong magnetic fields, it was postulated that such a process could occur at the core of neutron stars and possibly become extended via magnetic reconnection to their adjacent magnetospheres as well (e.g., Gonzalez, 2016).

As a consequence of my interaction with E.N. Parker concerning fundamental issues on magnetic field reconnection, and with the interest to celebrate the 60 years of his pioneering and highly influential professional life, we organized at the Brazilian Institute of Space Research (INPE) an international workshop on Magnetic Reconnection in March of 2014, with a participation of about 50 invited scientists from several countries. As a consequence of that workshop, we published in 2016 the Springer book "Magnetic Reconnection: Concepts and Applications" (Gonzalez & Parker, 2016).

7. Recent Research on Magnetospheric Reconnection

Due to the available in-situ plasma and magnetic field observations at the central/diffusion region of magnetospheric reconnection, obtained more recently with dedicated satellite missions (such as THEMIS and MMS), I had the opportunity to participate in some related studies (Koga et al., 2014, 2019; Lu et al., 2020; Silveira et al., 2020; Souza et al., 2017; Wang et al., 2017) and to also join (as a co-investigator) a research project of the Chinese Academy of Sciences with the aim of launching a multiscale mission to study Magnetospheric Reconnection on its micro and macro scales, using a central satellite and 12 associated cubesats (Dai et al., 2020). With such a mission one expects to observe reconnection parameters simultaneously at the central-diffusion region of reconnection as well as at several external locations of its macro domains.

Also recently, with the interest to understand more about the role of magnetopause reconnection in the global problem of solar wind-magnetosphere interaction, Lopez and Gonzalez (2017) have done an initial study on a generalized magnetopause *Chapman-Ferraro* current variability as a function of changes in the reconnection topology and efficiency as modulated by the solar wind/magnetosheath plasma and magnetic field inputs. That study showed that global plasma and magnetic field parameters at the magnetopause seem to have an important influence on the reconfiguration of the Chapman-Ferraro current system associated with magnetic reconnection at the magnetopause.

8. Comments on Fundamental Concepts Regarding Magnetopause Reconnection

One important concept related with magnetic reconnection at the magnetopause has been that associated with the reconnection *X-line direction*. The original papers dealing with that concept (Gonzalez & Mozer, 1974; Sonnerup, 1974) assumed that such a direction should be aligned with that of the magnetopause current as given by $\nabla \times \boldsymbol{B}$ of the interacting magnetosheath and geomagnetic fields. That assumption led to the concept of component reconnection, as mentioned in Section 3, also involving a guide field along the X-line direction with a uniform amplitude across the interface.

That original proposal for the direction of the X-line has been extensively confirmed by satellite observations at several magnetopause locations, using especially in situ-reconnection plasma outflow measurements, as well as related polar cap-ionospheric electric field observations (e.g., Dunlop et al., 2011; Sonnerup et al., 1981; Trenchi et al., 2008). The component reconnection model was initially based on geometric considerations of reconnection expected at the nose of the magnetosphere, assuming that the resulting X-line would extend to other latitudes and longitudes of the dayside magnetopause along a similar direction, only modified by the changing topology of the geomagnetic field at those extended locations.

As an alternative global reconnection scenario to that of component reconnection, Crooker (1979) proposed the so called *antiparallel reconnection*, assuming that reconnection at the magnetopause would occur only at regions where the magnetosheath and geomagnetic fields are antiparallel to each other, a situation expected especially at latitudes far from the magnetopause nose and when the B_y component of the IMF has a large amplitude. However, when the IMF has a negative B_z component and assuming that the geometry of reconnection X-line is initially defined at the nose (as the first region of contact) according to the component reconnection concept, one could follow its extension on the magnetopause toward larger distances both in latitude as in longitude using the same component reconnection topology concept. Then, with such a procedure, one could check that the component reconnection topology approaches that of the antiparallel reconnection concept due to the changing and more curved geomagnetic field lines at those regions. On the other hand, the antiparallel reconnection concept is poorly applicable at low latitudes and central longitudes where the component reconnection concept is best applicable. Thus, one could argue that the component reconnection model can be regarded as a more general model for magnetopause reconnection. Furthermore, efforts to understand the extension of the reconnection X-line toward the flanks of the dayside magnetopause has encountered an important question dealing with the efficiency of reconnection under a large shear-flow, with unsolved issues as yet (e.g., Cassak & Fuselier, 2016; Trattner et al., 2021).

Some other assumptions for the direction of the X-line at the magnetopause have also been proposed from studies of maximizing local reconnection parameters at the diffusion region (e.g., Hesse et al., 2013; Swisdak & Drake, 2007), although their importance for the global context of magnetopause reconnection has not been sufficiently proved. Thus, an important remaining problem to understand magnetopause reconnection refers to the role of the local physics of the diffusion region in the definition of global reconnection features. On the other hand, just looking into global processes to understand reconnection without involving inputs from important local diffusion-region processes does not seem to be a correct procedure either (e.g., Axford, 1983; Dorelli, 2019 Vasyliunas, 2016).

Finally, a recent study on magnetopause pressure balance at the magnetopause for solar wind conditions involving low solar wind-Mach number and when the IMF has a large-amplitude and negative B_z component has pointed to another important problem, namely that related with the behavior of a generalized Chapman-Ferraro current system under the presence of magnetopause reconnection (Lopez & Gonzalez, 2017).

Before closing this commentary paper, I would like to mention that during my academic life dealing with space science I obtained a great satisfaction by advising several Brazilian graduate students and by lecturing to young scientists abroad, especially in Argentina, Spain, and Italy. A particular effort was done in the organization of the Latin American Space Geophysics Association (ALAGE, in Spanish), to which I served as its first elected president from 1998 to 2002. This Association has organized periodic Conferences in Space Geophysics in several Latin-American countries since 1990 until present (with a COLAGE-acronym: Conference of ALAGE).

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Data Availability Statement

Data were not used, nor created for this research.

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Erratum

In the originally published version of this article, Acknowledgments contains this text: “the International Partnership Program of Chinese Academy of Sciences with Grant numbers”. This has been updated to “the International Partnership Program of Chinese Academy of Sciences under the China–Brazil Joint Laboratory for Space Weather and the Chinese National Space Science Center with Grant numbers”. This version may be considered the authoritative version of record.