Chapter 2

Geospace storm dynamics

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Abstract Geospace storms, also known as space or magnetic storms, interconnect the Sun and interplanetary space with the terrestrial magnetosphere, ionosphere, and atmosphere – and often even the surface of the Earth – in a uniquely global and synergistic manner. Energy from the Sun drives a continuous interaction of these distinct but coupled regions. Geospace storms have traditionally been called geomagnetic storms, because of the defining feature of global geomagnetic field disturbances that they induce. However, observations over four decades of space-borne instrumentation have shown that storms involve more than just variations in the geomagnetic field: they involve acceleration of charged particles in the magnetosphere, modification of the electrodynamic properties of the ionosphere, heating of the upper atmosphere, and creation of geomagnetically induced currents on the ground. This chapter attempts a synoptic discourse of geospace magnetic storm history, the classical perception of magnetic storm dynamics, and deviations from long-time accepted paradigms. In particular, we review in some detail one of the critical issues of storm dynamics, namely the storm-substorm relationship.

Keywords Geospace storm, magnetic storm, ring current, radiation belts, geospace, magnetosphere-ionosphere coupling, particle acceleration, space-atmosphere coupling, space weather, space hazards.

1. INTRODUCTION AND HISTORICAL CONTEXT

The first priority of NASA’s Living With a Star Geospace Mission (Kintner et al., 2001) is to understand the acceleration, global distribution and variability of energetic electrons and ions in the inner magnetosphere. Given that the most distinct result of geospace storms in the near-Earth space environment is the intensification of the radiation belts and of the ring current, geospace storms are an object of special interest within the Living With a Star Program.

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The geospace storm is the most complex collective phenomenon in the near-Earth space environment. It encompasses a large number of physical processes and effects in near-Earth space environment: Acceleration of charged particles in space; intensification of electric currents in space, in the upper atmosphere and on the ground; impressive aurora displays, which expand equatorwards; global magnetic disturbances on the Earth surface, which have actually been the defining storm feature and the origin of the classical denomination "magnetic storms". Despite their complexity, geospace storms have been identified by a rather simple pattern that is imposed by their development on the time profile of the magnetic disturbances measured on the ground (see Figure 1 and discussion in section 2).

At this point I consider it noteworthy to remark on names, because I disagree with the notion "nomina nuda tenemus" (i.e., "we hold naked [empty] words", Bernard de Morlaix, in *De contemptu mundi*, 12th century). A few years ago I had suggested and had used the term "space storm" (Daglis, 1997b; 1999a; 1999b; 2001a), but I was criticized that "space storm" sounds too general and non-specific, or simply trendy. More recently I proposed in a forum article in Eos (Daglis, 2003) the expression "geospace storm" instead of "magnetic storm". Accordingly, this chapter uses the term "geospace storm".

The eminent German explorer Alexander von Humboldt was probably the first to use the expression "magnetic storms" for the definition of an intense geomagnetic phenomenon. However, von Humboldt was not the father of the magnetic storm concept; he used the term to describe time intervals of intense magnetic fluctuations rather than a prolonged worldwide weakening of the horizontal component, H, of the geomagnetic field. This is, of course, expectable, as there was no way for him to know about worldwide negative H-excursions. In his letter to Prof. Paul Erman, published in *Annalen der Physik* (von Humboldt, 1808), von Humboldt had described a night of impressive observations in Berlin during the night of December 20-21, 1806, remarking that "there was no magnetic storm", since "the (magnetic) fluctuations were not especially intense" ("Dabei fand kein magnetisches Ungewitter statt; die Schwankungen waren nicht besonders stark").

Even in the 19th and early 20th century, scientists used "magnetic storm" for periods of intense geomagnetic variations in general, and not for what we identify as magnetic storms nowadays. Birkeland (1908), for example, used the term "magnetic storm", to collectively describe five distinct types of magnetic perturbations (details by Chapman and Bartels, 1940).

The ground manifestation of geospace storms as we perceive it today emerged from a discussion of the long series of Bombay, India, magnetic data by the Indian scientist Dr. Nanabhoy Ardeshir Framji Moos, Director of the Colaba-Alibag Observatories. Although it had generally been known (e.g. Broun, 1861; Adams, 1892) that for some time after a period of great geomagnetic disturbance the *H*-component of the geomagnetic field is reduced below its mean value, this critical information became much more complete by the work of Moos, which was decisive for the identification of the now familiar storm pattern in the time variation of *H* (Moos, 1910).

Later Sydney Chapman, one of the great pioneers and founders of modern solar-terrestrial research, who led much of the early work on magnetic storms, applied Moos' methods to study the average features of moderate storms at many stations in different geographic latitudes. Chapman (1919) demonstrated the global aspect of magnetic storms and named the storm-time variation of *H* "*Dst* variation" (meaning "Disturbance Storm-Time"). The characteristic average variation of *Dst* led Chapman to regard the storm geomagnetic variations as a unity, with a beginning, middle and end. In fact, Chapman was the one who combined the method and the name in his seminal statistical work and established the present concept of magnetic storm (S.-I. Akasofu, personal communication).

The foundations of modern geospace storm research were laid by Chapman and Ferraro (1930, 1931), who proposed a transient stream of outflowing solar ions and electrons to be responsible for terrestrial magnetic storms. Chapman and Ferraro claimed that once the solar stream had reached the Earth, charged particles would leak into the magnetosphere and drift around the Earth, creating a current whose field would oppose the main geomagnetic field. This is astoundingly close to what we believe today. The only major element of Chapman's theory that has changed is the existence of a continuous - instead of transient - stream of ionised gas from the Sun. This stream was christened "solar wind" by Eugene Parker (Parker, 1958) and its existence was later confirmed by measurements performed by the Venus-heading Mariner 2 spacecraft (Neugebauer and Snyder, 1962).

The basic idea of the Chapman and Ferraro theory was that the physical reason for the magnetic perturbation on the Earth's surface is a huge "ring current" in space circling the Earth. This idea was further elaborated by Singer (1956, 1957) and was eventually confirmed by in situ spacecraft measurements. The first measurements in space were conducted by Geiger Mueller tubes of the group of James Van Allen on board the first Explorer satellites in the end of the 1950s. Van Allen interpreted those measurements as the result of intense corpuscular radiation (Van Allen et al., 1958; Van Allen, 1959).

The ability of the geomagnetic field to trap relativistic electrons was experimentally verified by the Argus experiment, which was proposed by Nicholas C. Christofilos in 1957 and carried out in 1959 (Christofilos, 1959).

Christofilos, an unconventional Greek scientist who had been working as an engineer designing elevator systems in Athens before migrating to the US in 1953, had actually communicated to the US Army in the early 1950s that many charged particles, due to the dipole magnetic field, could be trapped around the Earth. He further proposed that an artificial radiation belt, due to beta decay, could be created by exploding a nuclear bomb at high altitude. This proposal evolved into Argus - the first active experiment in space.

2. THE CLASSICAL PICTURE AND PARADIGM SHIFTS IN GEOSPACE STORM DYNAMICS

During the two decades that followed the dawn of space exploration, experimental data led to a rough morphological model of geospace storms, which was in general agreement with the theoretical postulations of Chapman and Singer.

In the past, the solar antecedents of storms were thought, and are still sometimes erroneously considered, to be strong solar flares. The obvious reason is that the observability of flares permitted their identification and connection to geomagnetic storm disturbances as early as Richard Carrington's solar flare observations during the superstorm of September 1859 (Carrington, 1863). In the 1990s however, Gosling (1993) questioned this paradigm. He argued on the basis of accumulated observational indications that the coronal mass ejection (CME) is the solar event, which is the origin of large geospace storms.

Nevertheless, not every CME leads to a storm in geospace (Tsurutani, 2001). The decisive interplanetary condition for a storm to develop is a prolonged, southward-directed IMF. Russell et al. (1974) had suggested threshold values of $B_z \leq -5$nT and $\Delta T \geq 2$ hours for the development of moderate storms with -100 nT < peak *Dst* ≤ -50nT. Gonzalez and Tsurutani (1987) have empirically found that interplenatary disturbances with $B_z \leq -10$nT and $\Delta T \geq 3$ hours lead to intense storms with peak *Dst* < -100nT.

Even impulsive solar events, like great solar flares, or large CMEs, are not geoeffective if the IMF does not turn southward near 1 AU to permit magnetic reconnection at the dayside magnetopause. A characteristic example is the superflare of November 4, 2003, which was classified as an X28 flare and became the most powerful in recorded observational history (Simpson, 2003).

The classic graphical representation of measurable geospace storm effects on the surface of Earth, is the time profile of the *Dst* index - a geomagnetic index commonly used as a measure of storm intensity (Figure 1). The index is produced from data provided by low-latitude ground magnetometers, which record the decrease of the horizontal component of the geomagnetic field due to the westward-flowing ring current (Sugiura, 1964).

In accordance with Singer's and Chapman's ideas about the reason for the magnetic perturbations on the Earth's surface, the *Dst* index was conceived as a ring current measure. The concept was based on the assumption that the global decrease of the geomagnetic *H*-component is solely due to an external westward electric current system (the ring current), which encircles the Earth symmetrically (Akasofu and Chapman, 1961). This paradigm has been questioned both by spacecraft observations and by simulations: the storm-time ring current is often highly asymmetric in the main phase and becomes symmetric only in the late recovery phase (e.g., Kozyra et al., 2002; Daglis et al., 2003).

The general morphology of a geospace storm in terms of *Dst* variations is shown in Figure 1: a relatively sharp and large decrease of *Dst* signifies the "main phase" of the storm, and the subsequent slow increase of *Dst* marks the storm recovery. Some storms, especially the largest ones, begin with a sudden impulse (positive excursion of *Dst*), which marks the arrival of an interplanetary shock.

The *Dst* index is widely used to monitor and predict magnetic storm activity and therefore attracts special attention. As mentioned, the original assumption and corresponding paradigm was that *Dst* is influenced only by the ring current fluctuations. Today this paradigm is also under question. The prevailing perception is that there are other magnetospheric currents (cross-tail current, substorm current wedge, magnetopause current, Birkeland field-aligned currents), which also fluctuate during geospace storms and influence the ground magnetic field and, consequently, the *Dst* index (Liemohn and Kozyra, 2003).

The most distinct result of geospace storms in the near-Earth space environment is the intensification of the ring current and of the radiation belts. As perceived by scientists before the space era, and confirmed by spacecraft observations afterwards, energetic charged particles can be trapped by the geomagnetic field and thereafter perform a drift motion around the Earth. The most energetic of these trapped particles comprise the Van Allen radiation belts (Figure 2), which include high-energy ions and relativistic electrons (energies above several hundred keV). Although the acceleration of ions to the moderately high ring current energies (up to a few hundred keV) is firmly associated with storm development, there are still ambiguities about how efficient storms are in terms of radiation belt intensification. For instance, Reeves et al. (2002) showed that storms can either increase or decrease the fluxes of relativistic electrons in the radiation belts.

Although the abundance of these particles is relatively low, their impacts on space technological systems are appreciable, and at times severe (Baker, 2004).

According to the classical picture, radiation belts have a fairly stable basic structure, with a well-known stationary radial profile of the flux represented by standard radiation models (e.g., Walt, 1994). However, inner magnetosphere missions in the 1990s, like SAMPEX and, in particular, CRRES, have demonstrated the highly dynamic and complex nature of the electron radiation belts (e.g., Lemaire, 2001). The shift from the classical radiation belt paradigm is discussed by Vassiliadis et al. in chapter 3 of this book.

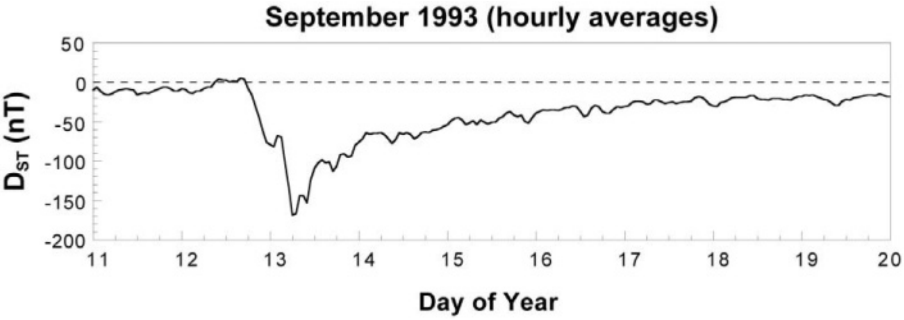

Figure 1. Typical time profile of the *Dst* index - a geomagnetic index commonly used as a measure of storm intensity (courtesy of J. K. Arballo, Jet Propulsion Laboratory). Despite their complexity, geospace storms have been identified by the rather simple pattern that is imposed by their development on the *Dst* time profile.

Ions in the medium-energy range of ~10 keV to a few hundreds of keV constitute the terrestrial ring current (see recent reviews by Daglis et al., 1999; Daglis, 2001b). Long-standing paradigms pertaining to the ring current have included its exclusively solar origin, its build-up through substorms and its decay through charge exchange ("trinity of ring current life", Daglis, 2001a). All of these paradigms have been questioned. The solar origin paradigm, for example, persisted for a couple of decades, from the dawn of the space era to the mid-1980's, when conclusive composition measurements covering the whole energy range important for the storm-time ring current, were performed by the AMPTE mission (Krimigis et al., 1985). The other two ring current paradigms are addressed in more detail in the following sections.

3. IMPORTANCE OF SUBSTORMS IN PARTICLE ACCELERATION AND STORM DEVELOPMENT

One of the oldest and rather classic storm paradigms is the role of substorms in storm development. Sydney Chapman introduced the term "substorm" to suggest that geospace storms and their ring current are the result of a series of intense substorms (Chapman, 1962; Akasofu et al., 1965). Chapman noted that the same storms, which at near-equator magnetic observatories (e.g. in Hawaii) followed simple curves of growth and decay, in Alaska seemed to consist of a number of distinct "sub-storms". We now know that substorms are independent processes and exist at other times as well. Substorms do not need much of a stimulus: during times of southward interplanetary field, the magnetotail seems to quickly reach the rim of instability, and small changes in the solar wind can then trigger a substorm.

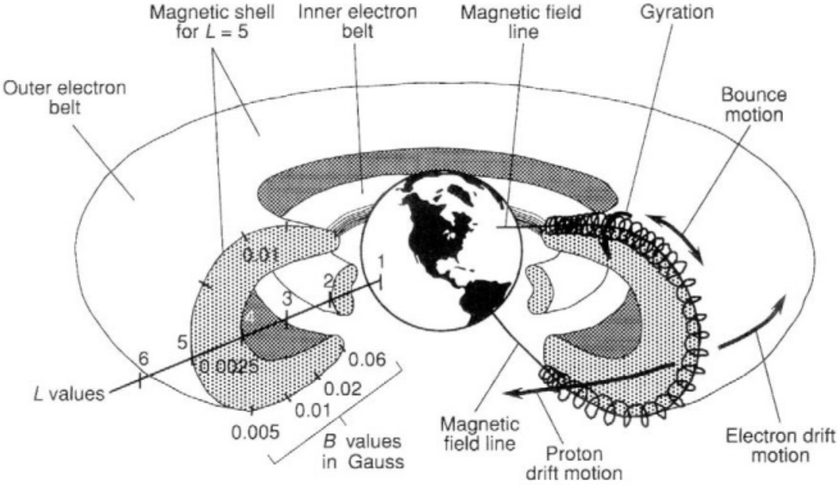

Figure 2. A three-dimensional representation of the inner and outer radiation belts around the Earth (Mitchell, 1994).

Chapman and Akasofu had postulated that the bulk acceleration of particles during storms is the additive result of “partial” acceleration during consecutive substorms (e.g., Akasofu, 1968). This paradigm has been heavily disputed during recent years. A new line of thought is that substorm acceleration may be sufficient to produce individual high-energy particles that create auroras and possibly harm spacecraft, but it cannot produce the massive acceleration that builds-up the storm-time ring current. In other words, it has been suggested that substorm occurrence during storms is incidental and does not have any causal relation to storm development (Kamide, 1992).

The storm-substorm relation paradigm according to which storms are the result of a superposition of successive “sub-storms” has been addressed by several studies recently (e.g., Kamide et al., 1998). No conclusive evidence has been obtained yet. Studies opposing the “Chapman-Akasofu paradigm” have claimed that substorm occurrence is incidental to the main phase of storms, and that ion transport into the ring current is accomplished solely by enhanced large-scale convection electric fields, with little contribution from substorms if any.

The storm-substorm dispute as appearing in published papers relates to two coupled, yet distinct, issues which are often confused: the effects of substorms on the ring current growth and the effects of substorms on *Dst* variations. The two issues are distinct because the ring current growth is how a storm materializes, while the *Dst* variations is how a storm is measured. We will here discuss only the issue of substorm influence on the bulk particle acceleration that leads to the build-up of the ring current.

Both geospace storms and magnetospheric substorms are characterized by the efficient acceleration of charged particles and their subsequent injection into the inner magnetosphere. However, non-storm substorms are of notably lesser efficiency in the extent of acceleration and inward penetration of charged particles, as compared to geospace storms.

The case against substorms as building blocks of the storm-time ring current is based on the a priori assumption that storm-time substorms do not differ from non-storm substorms, hence the “inability” of non-storm substorms to produce significant ring currents, condemns all substorms to “storm-impotence”. However, there are no sound research results that could justify this assumption and therefore it is still too premature to dismiss substorms as particle accelerating processes significant for the storm-time ring current.

The dispute actually refers to the relative efficiency of the large-scale convection electric field and of the substorm-associated impulsive electric fields in accelerating and transporting ions into the ring current. Short-lived impulsive electric fields are induced by magnetic field reconfigurations at substorm onset: i.e., “dipolarizations” from a stretched tail-like configuration to a dipole-like configuration. Wygant et al. (1998) showed that during the large March 1991 storm, the large-scale convection electric field penetrated Earthward, maximizing between L=2 and L=4 with magnitudes of 6 mV/m. Such magnitudes are 60 times larger than quiet-time values. During magnetic field dipolarizations in the inner magnetosphere (i.e., during substorm expansions or intensifications) Wygant et al. also observed strong impulsive electric fields with amplitudes of up to 20 mV/m, which is more than three times the largest convection electric field. Consequently, substorm induced electric fields can certainly compete with the convection electric field in ion acceleration during storm development. Substorm electric fields may be episodic, but they are much stronger.

In order to reach a conclusion on this issue, it is of essential importance to assess the efficiency of substorm-induced electric fields in ring current development. The problem has been addressed by a number of simulations with contrasting results. While Chen et al. (1994) and Fok et al. (1996) suggested that the substorm contribution is subtle and possibly negative to the development of a ring current, a more recent study by Fok et al. (1999) suggested that the substorm-associated induced electric fields significantly enhance the ring current by redistributing plasma pressure Earthward.

Another approach to this problem relates to the aspect of compositional changes. Massive outflow and preferential acceleration of ionospheric O^+ ions is outstanding during intense storms (Figure 3), when the oxygen to proton energy density ratio can reach values of up to 400% (Daglis, 1997a,b; Daglis et al., 1999b).

As a matter of fact, the O^+ abundance increases with the intensity of storms (Daglis, 1997a). Remarkably, this is also a feature of magnetospheric substorms, certified by relevant studies with measurements from the AMPTE and CRRES missions (Daglis et al., 1994, 1996). Consequently, the magnetosphere-ionosphere coupling may be the final tuning factor of solar wind driving of the two main dynamic magnetospheric phenomena, storms and substorms, in the sense that it regulates their eventual intensity. We shall elaborate a little bit on this suggestion.

Recent modeling of ring current dynamics, based on observational support (Daglis et al., 2003), has put constraints on our empirical recognition that the prolonged southward orientation of the interplanetary magnetic field (IMF) is the main driver of geospace storms. The simulations have shown that this driver is conditioned by internal magnetospheric conditions: the plasma sheet density is of critical importance to the eventual result of the interplanetary drivers, as measured by storm intensity (e.g., Kozyra et al., 1998). Variations in the plasma sheet density significantly modify the geoeffectiveness of southward IMF: high plasma sheet densities result in stronger ring currents. The outflow of ionospheric O^+ ions increases the plasma sheet density. In this sense, the magnetosphere-ionosphere coupling represents a tuning factor for storm development.

Obviously, one must consider and explain the efficient acceleration of relatively cold O^+ ions. The O^+ acceleration is moreover preferential with regard to H^+ and He^{++}, and therefore cannot be accounted for by simple convection. An analysis of single-particle dynamics in simulations of magnetic field dipolarizations (Delcourt, 2002) revealed prominent short-

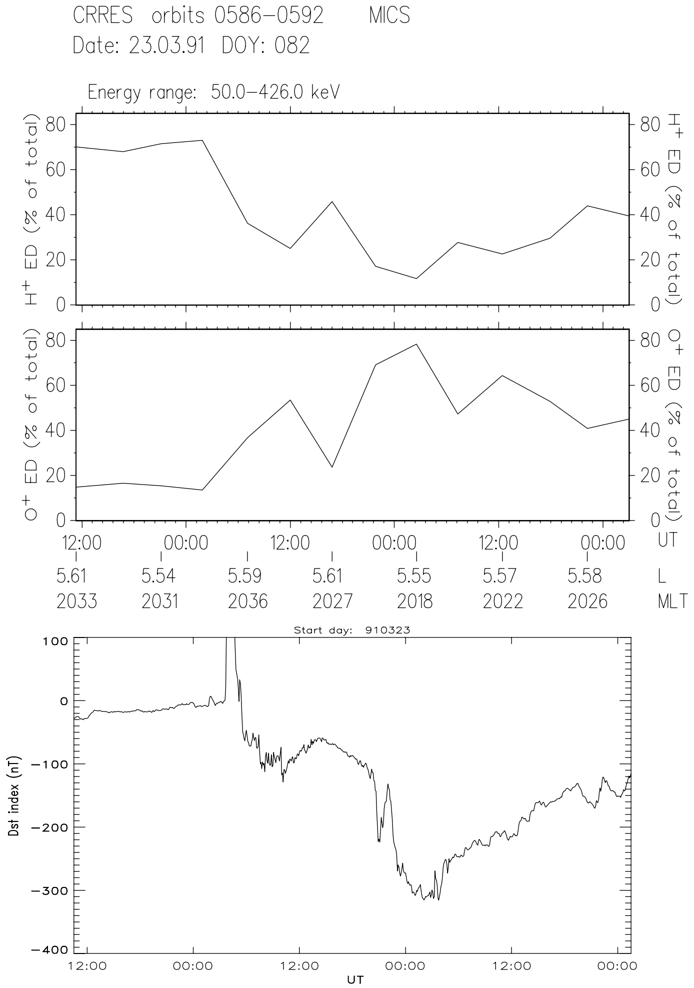

Figure ıner magnetosphere during the main phase of intense storms. During the March 23-25, 1991 storm, O^+ ions contributed nearly 80% of the ring current energy density at storm maximum. This figure shows the time profile of the H^+ (top panel) and O^+ (middle panel) contribution to the total ion energy density in the *L*-range 5-6. The bottom panel shows the time profile of the 5-min resolution *Dst* index. It is remarkable that the *Dst* minima are concurrent with O^+ maxima, implying that the ring current intensifications are due to the acceleration and transport of new ionospheric ions into the inner magnetosphere (adopted from Daglis et al., 1999b).

lived acceleration of plasma sheet ions during the expansion phase of substorms.

Under the effect of the transient impulsive electric fields induced by relaxation of the magnetic field lines, ions with gyro-periods comparable to the field variation time scale can experience dramatic non-adiabatic heating. For example, when considering a 1-min magnetic reconfiguration, low-energy O^+ ions originating from the terrestrial ionosphere are found to be accelerated up to a few hundreds of keV during Earthward injection. These ions evidently can provide a significant or even major part of the ring current. This tells us that, in principle, inductive electric fields, and therefore substorms, are of considerable importance for the storm-time particle acceleration and ring current dynamics.

O^+ is interesting and important not only because of its role in increasing the plasma sheet density or the ring current density itself, but also because of its role in a storm-substorm relationship scenario, which we will outline here. Observations and simulations have indicated a feedback between O^+ injections and substorm breakups moving progressively duskward and Earthward (Baker et al., 1982, 1985; Rothwell et al., 1988). Such a feedback will substantially contribute to a rapid enhancement of the ring current. This feature is also consistent with a relatively old storm study (Konradi et al., 1976), which had shown that the substorm injection boundary was displaced Earthward with each successive substorm during the storm.

Combining model predictions with observations, and considering the fact that O^+ abundance increases with storm size (Daglis, 1997a), we suggest a scenario of a feedback between enhanced (in quantity and spatial extension) O^+-feeding of the plasma sheet and/or the inner magnetosphere and series of intense substorms occurring at progressively lower L-shells. Such a combination of successive substorms and continuous O^+ supply can facilitate successive inward penetration of substorm ion injections, consistent with the model of Rothwell et al. (1988) and with the observations reported by Daglis (1997a) and Konradi et al. (1976). The result of successive inward penetration of substorm injections would be the transport of increasingly more energetic ions into the inner magnetosphere, resulting in the intensification of the storm-time ring current. This scenario can explain why some substorms seem to influence the storm time ring current growth, while others don't: substorms resulting in weak inward penetration of injections will not contribute much to the ring current growth. An experimental verification will be possible through detailed global imaging of storms with sufficient composition information.

4. STORM RECOVERY AND RING CURRENT DECAY

According to the traditional *Dst*-profile storm representation, storm recovery manifests itself as the increase of *Dst* from its low, negative values reached during the storm main phase, to its pre-storm level around zero. As already mentioned, Sugiura (1964) designed *Dst* as a ring current measure, according to the original storm - ring current paradigm of Chapman and Singer. Therefore, storm recovery as seen in the *Dst* profile has been traditionally linked to ring current decay. Nevertheless, we now know that *Dst* change does not necessarily reflect changes in ring current intensity, but may signify changes in the intensity of other magnetospheric currents (e.g., Ohtani et al., 2001). This is another important paradigm shift in geospace storm dynamics.

Here we will briefly discuss ring current decay and storm recovery, and we will also refer to some recent results that further modify the classical picture. The loss mechanisms of ring current ions include charge exchange, convective drift losses through the dayside magnetopause, Coulomb collisions with thermal plasma, and wave-particle interactions that cause pitch angle scattering into the atmospheric loss cone. The main mechanism of ring current decay is generally believed to be the charge exchange of ring current ions with cold hydrogen atoms of the geocorona. The geocorona is an exospheric extension of relatively cold (~1000 K) neutral atoms, which resonantly scatter solar Lyman-α radiation, thus optically resembling the solar corona.

All ring current ions are subject to charge-exchange decay, although the decay rate depends on the ion mass and energy. While the O^+-H charge exchange cross section hardly depends on ion energy, the H^+-H charge exchange cross section is dramatically reduced with increasing energy, resulting in much longer charge-exchange lifetimes for higher energy H^+. While at 50 keV H^+ and O^+ lifetimes are comparable, at 100 keV they already differ by an order of magnitude (Smith and Bewtra, 1978). Furthermore, the charge exchange decay rate grows with exospheric hydrogen density, i.e. at lower altitudes. Therefore, ions with mirror points at lower altitudes (i.e., ions with smaller equatorial pitch angles) will charge-exchange easier.

Accordingly, high-energy O^+ will be lost much faster than H^+, and field-aligned pitch-angle distributions will experience larger losses than pancake pitch-angle distributions. It is noteworthy that storm-time O^+ distributions tend to be more field-aligned than H^+ ones (Daglis et al., 1993). Consequently, the storm-time O^+ population will additionally experience faster charge-exchange decay because of their smaller pitch angles.

Therefore, the ring current composition plays a significant role in storm evolution (Daglis, 1997a; Daglis et al., 2003).

Nevertheless, a paradigm shift regarding the extent of charge exchange losses has been introduced during the last few years. Simulation studies have pointed out that convective drift losses through the dayside magnetopause can be the dominant loss process during the storm main phase (e.g., Liemohn et al., 1999; Kozyra et al., 2002). Accordingly, it has been suggested that convective drift loss out the dayside magnetopause has been suggested as the dominant (and fast) process in removing particles from the inner magnetosphere during the main phase and the initial recovery phase of storms. Furthermore it has been suggested that a combination of convective drift loss with a sharp drop in plasma sheet density at the end of the storm main phase, results in a rapid initial *Dst* recovery, as seen during many intense storms that exhibit a two-step recovery (Kamide et al., 1998).

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