Response of the Earth’s magnetosphere to changes in the solar wind

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Abstract

The solar wind couples to the magnetosphere via dynamic pressure and electric field. Pressure establishes the size and shape of the system, while the electric field transfers energy, mass, and momentum to the magnetosphere. When the interplanetary magnetic field (IMF) is antiparallel to the dayside magnetic field, magnetic reconnection connects the IMF to the dipole field. Solar wind transport of the newly opened field lines to the nightside creates an internal convection system. These open field lines must ultimately be closed by reconnection on the nightside. For many decades, it was thought that a magnetospheric substorm was the process for accomplishing this and that all magnetic activity was a consequence of substorms. It is now recognized that there are a variety of modes of response of the magnetosphere to the solar wind. In this paper, we briefly describe these modes and the conditions under which they occur. They include substorms, pseudo-breakups, poleward boundary intensifications (PBI), steady magnetospheric convection (SMC), sawtooth injection events, magnetic storms, high-intensity long-duration continuous AE activities (HILDCAAs), and storm-time activations. There are numerous explanations for these different phenomena, some of which do not involve magnetic reconnection. However, we speculate that it is possible to interpret each mode in terms of differences in the way magnetic reconnection occurs on the nightside.

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1. Preliminary remarks

In September 2006, the International Symposium on Recent Observations and Simulations of the Sun–Earth System (ISROSES) was held in Varna, Bulgaria. The principal author of this paper was asked to present the keynote lecture to introduce the topics of the meeting and to set its tone. In response to this invitation, he chose to describe the various ways in which the magnetosphere responds to changes in the solar wind. It is now recognized that in addition to substorms and storms there are other forms of geomagnetic activity, including pseudo-breakups, poleward boundary intensifications (PIB), steady magnetospheric convection (SMC), substorm sequences, and storm-time activations.
In this paper, we briefly describe each of the different types of geomagnetic activity using some illustrative data. As we present each phenomenon, we speculate how it might be produced by magnetic reconnection at various locations in the magnetosphere.

2. Introduction

The magnetosphere is created by the solar wind. Its size, shape, and behavior depend on the properties of the solar wind plasma and its imbedded magnetic field. The solar wind applies normal stress to the Earth’s magnetic field through dynamic, thermal, and magnetic pressure. Together, these determine the gross size and shape of the magnetosphere. Tangential stress is applied by two main processes: viscous interaction and magnetic reconnection. The viscous interaction is always present and is responsible for transporting closed magnetic flux tubes from the dayside to the nightside (Axford and Hines, 1961). Magnetic reconnection also occurs most of the time, but its effect on the magnetosphere is dramatically different when the interplanetary magnetic field (IMF) is northward, parallel to the dayside dipole field, than it is when it is southward and antiparallel (Dungey, 1961). For northward IMF magnetic reconnection connects interplanetary magnetic field lines to open field lines in the tail lobes. The consequence is a circulation of flux tubes in the lobes, but no net change in the amount of lobe flux (Crooker, 1992). The circulation drives field-aligned currents that close through the ionosphere around the magnetic poles (Iijima and Shibaji, 1987). These currents are so far from auroral zone and lower latitude magnetometers that they cause only weak perturbations. Times of northward IMF are therefore considered geomagnetically quiet.

The situation is different for southward IMF (McPherron, 1991). Interplanetary magnetic field lines connect to closed, dipole field lines near the sub-solar point of the magnetopause. These newly opened field lines are transported over the polar caps and added to open field lines already present in the tail lobes. The lobe flux increases with time squeezing the plasma sheet. The tail current moves earthward and magnetic reconnection begins in the tail returning flux to the dayside. If the IMF remains continuously southward the magnetosphere responds in a variety of different ways: pseudo-breakups; substorms; PIB; a succession of substorms; SMC; sawtooth injection events; and high-intensity long-duration continuous AE activities (HILDCAAs). Such times are considered disturbed.

A general conclusion from much of the recent work on modes of magnetospheric response is that the response of the magnetosphere depends in a nonlinear way on the level of solar wind driving (Pulkkinen et al., 2007). In addition, there is evidence that increased dynamic pressure can alter the nature of the response (Lyons et al., 2005). Finally, there continues to be support for the idea that sudden reductions in the convection electric field (northward turnings of the IMF) and dynamic pressure pulses can trigger substorm onset (Hsu and McPherron, 2002). In the following sections of this paper, we briefly discuss the various distinct modes of magnetospheric response.

3. Magnetospheric response modes

3.1. Magnetospheric substorms

There have been numerous attempts to define a magnetospheric substorm. Akasofu (1964) defined it as:

The sequence of auroral events over the entire polar region during the passage from auroral quiet through the various active phases to subsequent calm is called an auroral substorm: it coincides with a magnetic (DP) substorm, with which it has some close relationships.

An early attempt to obtain a consensus definition is reported in Rostoker et al. (1980). The authors describe some of the signatures known to be associated with substorms and argue that if these signatures are present then a substorm has occurred. Today an isolated substorm is known to consist of three phases: growth, expansion, and recovery. Features associated with the onset of the expansion phase are commonly used to establish the time line of the substorm with the hope of determining the physical processes responsible for the expansion phase. Some of the onset signatures include auroral brightening, sudden onset of a negative bay near midnight, onset of a mid-latitude positive bay, a burst of Pi 2 pulsations, sudden dipolarization of the magnetic field, and particle injection at synchronous orbit.

The behavior of the AU and AL indices as a function of time relative to auroral brightening is
The plot was constructed by superposing 303 sets of AU and AL traces corresponding to brightening events identified in Polar spacecraft UV images by Liou et al. (2000). It is obvious that the sudden development of a westward current is associated with the brightening. The majority of the events in this set are quite weak as indicated by the shaded patches bounded by the upper and lower quartiles. Less than 5% of the events in this list have a minimum AL less than $-500$ nT. The rapid change after the brightening is 10–20 min long. Recovery begins in 40–60 min.

If the IMF $B_z$ is fluctuating with durations of southward and northward field of the order of an hour, a sequence of substorms similar to an isolated substorm develops. A typical substorm is about 3 h long (McPherron, 1994), but substorm onsets can occur quasi-periodically with an average time separation of 2.75 h, or randomly with an average separation about 5.76 h (Borovsky et al., 1993). During substorm sequences, the growth phase of one substorm may begin even though signatures of recovery of the previous substorm are still in progress.

A characteristic feature of clearly defined substorms is an ordered sequence of changes in configuration of the magnetosphere. These changes can be explained as a consequence of unbalanced reconnection. In the growth phase closed magnetic flux from the dayside is opened and added to the tail lobes. Closed magnetic flux in the plasma sheet moves Sunward to replace the flux removed from the dayside. The amount of flux in the tail lobes increases, causing the diameter of the auroral oval to increase with time and the plasma sheet to thin due to compression. In the expansion phase closed field lines in the plasma sheet begin to reconnect creating shorter field lines on the earthward side of the x-line and a flux rope on the tailward side. Reconnection severs the last closed field lines at the edge of the plasma sheet releasing the flux rope that is subsequently ejected down the tail. During the expansion phase, lobe field lines reconnect adding closed field lines to the plasma sheet that subsequently move Sunward. In the recovery phase the x-line moves tailward expanding the plasma sheet but still adding closed flux to the plasma sheet. Closed magnetic flux is returned to the dayside until an equilibrium configuration is established.
3.2. Pseudo-breakups

In the original description of the auroral substorm Akasofu (1964) noted that occasionally an auroral arc would brighten and become active but within minutes would die down. He called such events “pseudo-breakups” after work originally done by Elvey (1957). Elvey described these events in the following way:

If there are several arcs in the system, one or more of the ones closer to the auroral zone may break up, with the pseudobreakup sometimes forming a rayed arc or breaking into bands and various rayed structures. These pseudo-breakups appear to coincide with the minor bays that give the irregularity to the main bay in the horizontal component of the magnetic record.

Characteristics of these events reported by McPherron et al. (1968) can be summarized in the following way. A portion of an auroral arc brightens and field-aligned rays and undulations develop overhead. Frequently, the lower border of the arc turns red. Balloon measurements of X-rays show a short-duration enhancement in electron precipitation. On the ground a burst of Pi 2 pulsations is recorded in association with a weak (~100 nT) negative bay. Within about 10 min the arc becomes quiet and the various signatures disappear. These events can occur anytime within the growth phase but with increasing probability toward the expansion onset. Nakamura et al. (1994) made a detailed study of several such events using synchronous particle and field data, finding that such signatures as tail current diversion, dipolarization, and injection are also observed. The authors concluded that the primary difference between a pseudo-breakup and a substorm expansion is that pseudo-breakups have smaller scale than expansions. Later, Nakamura et al. (2001a) examined the association of flow bursts in the tail during pseudo-breakups, demonstrating that all flow bursts studied were associated with either pseudo-breakups, small poleward expansions, or PIBs. Nakamura et al. (2001b) show that flow bursts associated with small expansions tend to occur closer to the Earth \((X > -15 \text{ Re})\) than those associated with PIBs. Kullen and Karlsson (2004) have done a statistical study and also conclude:

...These results are in agreement with the scenario that pseudo-breakups essentially are very weak substorms.

The very beautiful example of a pseudo-breakup presented in Fig. 2 was studied by Partamies (2003). The top panel of the figure shows all sky camera images of a counter-clockwise auroral spiral. The lower panel shows the spiral projected into geographic coordinates over Scandinavia. Vectors to the west and north of the spiral are the measured ionospheric flow velocity. Analysis of data from a magnetometer array indicates that the spiral is the location of the outward current from a narrow substorm current wedge. The ground magnetic perturbation from this current was only ~50 nT, but low-energy electrons were injected at a synchronous orbit nonetheless.

A possible cause of pseudo-breakups is transient, localized reconnection inside the plasma sheet. The short duration and limited extent of the event might then be a consequence of the reconnection process not proceeding to the lobes. If this is true then one might expect that such events produce a flux rope trapped in the plasma sheet. However, it is also possible that the reconnection proceeds to the lobe releasing the flux rope, but then for unknown reasons the reconnection is quenched.

3.3. Steady magnetospheric convection

SMC or convection bay are names given to a disturbed state of the auroral region characterized by the absence of the usual signatures of a substorm expansion (Pytte et al., 1975, 1978; Sergeev, 1977). SMC events can be identified by finding intervals of steady auroral zone magnetic disturbance produced by the DP-2 current system (2-celled convection) in the absence of the DP-1 system (substorm current wedge). SMC should have a steady polar cap potential, a steady polar cap (PC) magnetic index, a fixed diameter of the auroral oval, stable locations of ionospheric particle boundaries, and a constant lobe field magnitude and diameter. There should be no sudden intensifications of the westward electrojet near midnight, no mid-latitude positive bays, and no dipolarizations at synchronous orbit. An SMC event is characterized by a double auroral oval (Elphinstone et al., 1995; Pulkkinen et al., 1995) in which the diffuse equatorward border is separated from the poleward boundary by a darker region. Auroral activations frequently occur at the poleward edge of the double oval. These include brightening and decay of arcs, formation of folds and loops, equatorward drifting arcs, and
north–south-oriented streamers. These activations are now called PIBs (see below).

Many of the features seen during an SMC are similar to those seen in the recovery phase of a substorm (Sergeev et al., 1996) so it is important to distinguish between recovery phases and SMC. Usually this is done by requiring that any event identified as an SMC has a duration longer than the 90 min of a typical substorm recovery.

The average behavior of the AE index during more than 2400 SMC events has been obtained by McPherron et al. (2005) and O’Brien et al. (2002). For a sample of AE to be classified as part of an SMC these authors required that $AE > 200 \text{ nT}$, $d(AL)/dt > -25 \text{ nT/min}$, and that these two conditions are continuously true for at least 90 min. The first point of a sequence satisfying these three criteria was taken as the start of an SMC. McPherron et al. (2005) show that an SMC typically begins with a partial recovery from a preceding substorm. Most SMCs last only a few hours but occasionally they persist for as long as 10 h. The median AE during SMC was 200 nT with both AU and AL approximately equal. About half of all SMCs terminate with another substorm expansion, while the other half vanish as the IMF turns slowly.

![Diagram of auroral spiral and data points](image)

Fig. 2. All sky images of an auroral spiral at top were taken during a pseudo-breakup. A geographic projection of this spiral is plotted below on a map of Scandinavia. Arrows indicate the flow velocity of ionospheric plasma as measured by radar (from Partamies, 2003).
northward. The IMF $B_z$ during these SMCs was about $-2.5 \text{nT}$, with fluctuations about 25% smaller than those found during all activity with $\text{AE} > 200 \text{nT}$. The solar wind velocity is also low during SMCs ($< 400 \text{ km/s}$) with weaker than normal fluctuations. The longest duration SMCs occur during the lowest solar wind velocity with the smallest fluctuations (1/2 normal amplitude).

From the beginning, the lack of change in magnetospheric configuration during an SMC event has suggested that SMCs are caused by balanced reconnection much as Dungey (1961) originally suggested. Subsolar reconnection strips flux off the dayside and induces a flow of plasma and flux into the dayside merging region. Flux is added to the tail lobe, but is reconnected in the plasma sheet at the same average rate as on the dayside. Forces at the nightside x-line push plasma and flux Sunward. These flow around the Earth replacing the plasma and flux stripped from the dayside. This is more likely to work if the reconnection region on the nightside is close to the Earth and can quickly adjust to changes in the dayside reconnection rate. This also assures that the pressure inside convecting flux tubes does not build up to large values. It is also likely to work better when the solar wind conditions are steady so no adjustments are needed.

### 3.4. Magnetic storms

A magnetic storm is an interval of several days’ duration during which the magnetic field measured at low latitudes undergoes a rapid depression followed by a slow recovery. The median behavior of the Sym-H index, a 1-min proxy for Dst, is presented in Fig. 3. The three phases of a storm are well displayed in this superposed epoch analysis of storms from two solar cycles. The intense main phase is defined by the interval of rapid decrease and in typical storms is less than 12h long. For example, the median duration of all storm main phases in the space age is 11h. The average behavior plotted in the diagram hides many complex details in the variety of development of magnetic storms. Some storms have much longer main phases and these storms dominate the deciles of the cumulative distribution plotted in the figure. Some have no initial phase, some have long and others have short main phases, some have multiple minima.

![Ensemble of Sym H for 1981-2001](image)

**Fig. 3.** Average behavior of the 1-min Sym-H index over a 20-year interval. The time of minimum Sym-H was used as the reference time in a superposed epoch analysis. A storm consists of an initial phase of elevated Sym-H followed by a rapid decrease, and then a rapid recovery followed by a slow recovery. Sym-H is below $-100 \text{nT}$ in less than 20% of the storms.

There are two main types of magnetic storms. Gradual commencement magnetic storms without obvious sudden commencements or initial phases are created by corotating interaction regions (CIRs). These storms are generally weak but are often of long duration. Constant magnetic activity in the recovery phase of these storms caused by Alfvén waves (see discussion of HILDCAAs below), and equinoctial projection effects of the spiral IMF (Russell–McPherron effect) are responsible for the acceleration of relativistic electrons. These storms are most common in the declining phase of the solar cycle when recurrent high-speed streams are produced by the Sun. Sudden commencement storms are caused by the impact of an interplanetary coronal mass ejection (ICME) on the Earth. ICMEs are huge bubbles of plasma ejected from the Sun. Some of these contain magnetic clouds or flux ropes within which the magnetic field slowly and smoothly rotates from one orientation to another. ICMEs are most frequent near solar maximum. Many ICMEs travel at supersonic speeds relative to the solar wind and are preceded by interplanetary shocks. A large variety of storm signatures results from whether there is a shock, whether the compressed IMF behind the shock is southward, whether the leading edge of the flux rope is southward or northward, and so on. Storms produced by ICME are much larger that those produced by CIRs. The results plotted in Fig. 3 are averages over both types of storms.

3.5. Sawtooth injection events

Sawtooth injection events are identified by the characteristic wave form of energetic proton fluxes at synchronous orbit (Belian et al., 1995; Borovsky, 2004; Reeves et al., 2003). These events occur when the solar wind driver is moderately strong and steady (Pulkkinen et al., 2007) with \( B_z \approx -7 \) nT and \( E_y \approx 3 \) mV/m. Typical events consist of 3–8 teeth with a quasi-periodic spacing of \( \approx 2.7 \) h. The synchronous injections are associated with strong stretching and dipolarization of the synchronous magnetic field, with correlated southward turnings of the plasma sheet magnetic field in the middle tail, with auroral brightenings, with intensifications of the westward electrojet near midnight (Chao-Song et al., 2003) with mid-latitude positive bays and Pi 2 pulsations. Henderson (2004) has shown that a previously well-studied substorm interval, the CDAW-9C study, was actually a sawtooth event by today’s definition. The phenomena associated with a single tooth are identical to those seen during isolated substorms except that a double auroral oval is present as it is during SMC events (Henderson et al., 2006). Also, the morning sector is filled with eastward-drifting omega bands, and at the end of the expansion north–south streamers develop in the pre-midnight sector. During sawtooth events, there is an unusually strong current flowing around the evening–afternoon side of the Earth. Because the field is strongly stretched, protons drift very rapidly giving the appearance that they arrive simultaneously over the entire nightside (Pulkkinen et al., 2006). Nonetheless, mid-latitude magnetic perturbations suggest that the substorms span larger regions in local time than normal substorms (Clauer et al., 2006).

The result of a superposed epoch analysis of solar wind conditions associated with the onset of sawtooth injections is presented in Fig. 4. Median values of solar wind velocity, density, and dynamic pressure are typical of the normal solar wind. However, the strength of the magnetic field is nearly twice as high as normal with median \( B_z \) reaching almost 9 nT southward at onset. Because of the high magnetic field strength, the solar wind Alfvén Mach number and plasma beta are somewhat lower than normal. The results show a maximum in IMF field strength at onset and a weak tendency to turn to the north at this time. The only parameter in the plot that shows a dramatic change at sawtooth onset is the polar cap index, which exhibits a sudden increase, presumably due to substorm field-aligned currents.

Sawtooth injection events are caused by a steady solar wind driver as are SMC events. However, the driver is much stronger for sawtooth events. It is generally believed that these events are large substorms that occur quasi-periodically with a period characteristic of the state of the magnetosphere. As the driver remains constant, energy is added to the tail lobes faster than it can be removed. The configuration of the inner magnetosphere becomes distorted and a substorm expansion occurs. Since there is a steady input the distortion repeats and there is another expansion. This system is also likely to be susceptible to external triggering as conditions in the tail approach the critical threshold for a substorm expansion. This may explain the reported association between onset and dynamic pressure pulses.
3.6. Poleward boundary intensifications

PBIs often occur during and after a substorm recovery as well as in SMC and sawtooth events. A representative PBI event taken from the work of Zesta et al. (2002) is presented in Fig. 5. The PBIs are auroral intensifications that begin at the poleward edge of the aurora and then move equatorward with time. In this event, a substorm growth phase occurred in the interval 0130–0230 UT as evident in the equatorward motion of auroral arcs. The expansion phase defined by poleward expansion of the aurora occurred in two stages: the first after 0235 UT and the second after 0304 UT. This 10° expansion ended at 0320 UT with the formation of the high-latitude portion of a double oval. This bright form slowly moved equatorward for ~25 min and thereafter every 5–20 min produced equatorward-moving bright auroral forms that generally reached the bright region at the equatorward edge of the oval. A second substorm expansion occurred at 0815 UT. There were no auroral emissions poleward of the form producing the PBIs, indicating that they are formed at or close to the boundary between open and closed field lines.

This PBI event occurred during a long interval of constantly southward IMF that began around 1140 UT on December 22 and lasted until nearly 0900 UT on December 23. The minimum $B_z$ during this interval was about ~5 nT and the solar wind speed was ~380 km/s. These are conditions that one might expect, either SMC or sawtooth events, and
associated with them, PBI. Both GOES-8 and 9 magnetometers in synchronous orbit saw very strong dipolarization during the $\sim$0230 UT expansion and a weaker one after 0800 UT, but there is no indication of periodic substorms. Neither do available proton detectors at synchronous orbit suggest sawtooth events. Because the IMF is southward, but there are no substorm expansions, the interval from 0320 to 0810 UT might be classified as an SMC event although the slow changes in the location of the polar cap boundary make this identification problematic.

Previous observations of PBI reviewed by Zesta et al. (2002) suggested that PBI are caused by transient and localized reconnection at the distant x-line. They are associated with earthward-flowing bursty bulk flows (BBFs) in the tail. They primarily occur in the recovery phase of substorms, SMC, and sawtooth events. They can occur during quiet times and in the expansion phase as well, but less frequently. Using all sky camera images as well as meridian scanning photometers Zesta et al. (2002) identify at least three classes of PBI events, which may represent separate processes in the tail. These include auroral spirals on the poleward boundary of the oval, east–west arcs moving equatorward, and narrow north–south auroral forms that grow equatorward. The arcs occur closer to dusk while the north–south forms occur closer to midnight. PBI rarely occur post midnight. Spirals and arcs may be created by processes other than reconnection.

### 3.7. Storm-time activations

A long-standing argument concerns the possible difference between isolated substorms and substorms during magnetic storms. Baumjohann (1996) used AMPTE IRM data to examine the lobe field during the two types of substorms. He found that only the storm-time substorms exhibit increase and decrease of the lobe field. He speculated that only storm-time substorms are produced by a mid-tail x-line and that normal substorms are caused by some other instability closer to the Earth. However, McPherron and Hsu (2002) used the same substorm selection criteria and found that both types of substorms exhibited an increase in lobe field strength before an expansion and a decrease after. Storm-time substorms were simply larger than isolated substorms. It should be noted that it is difficult to identify and time substorm onset during the main phase of a storm and some activations of the westward electrojet may not have been identified as substorms.

A study of storm-time activations by Pulkkinen et al. (2007) tried to determine whether all activations are substorms. For a set of 150 sudden activations of the westward electrojet (AL), about half had an increase in field inclination at synchronous orbit although two-thirds showed a reduction after onset (dipolarization). About half of the events had no particle injection at synchronous orbit. These observations suggest that there are many storm-time activations that do not exhibit all the expected signatures of a substorm.

A separation of the data into high and low Mach number solar wind, keeping the median level of driving a constant, found no differences in the magnetospheric response. However, when the events are separated by interplanetary electric field or dynamic pressure, differences are seen. High electric field causes stronger activity in all indices. However, when the index is normalized by the strength of the driver $E_y$, the magnetospheric response is proportionally weaker with a stronger driver. Dynamic pressure also has a significant effect on activity with a stronger response when pressure is high. But when the data are normalized by $E_y$ there is no effect on the field inclination at synchronous orbit, but high-pressure responses are proportionally weaker than low-pressure responses.

### 3.8. HILDCAA

Many magnetic storms have a prolonged slow recovery phase. During these recoveries the auroral electrojet index $AE$ is often found to be continuously disturbed for long intervals of time. Tsurutani and Gonzalez (1987) named such intervals HILDCAA. They found that these events were associated with long trains of Alfven waves in the solar wind. Often the wave trains follow an interplanetary shock, but sometimes they are associated with high-speed streams without shocks. They postulated that these wave trains are responsible for magnetic reconnection each time they turn the IMF southward and so produce a long sequence of substorm activity. This led Tsurutani and Gonzalez (1987) to conclude

It is thus surmised that the majority of all auroral activity (is associated with Alfvenic fluctuations of this type.

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Fig. 6 demonstrates the validity of this premise for the high-speed streams following the stream interface of a CIR. The map shows the dynamic cumulative probability distribution (cdf) of total wave power calculated according to the definition used by Roberts and Goldstein (1990):

\[ E = \frac{1}{2} (\delta v^2 + \delta b^2). \]

In this formula, the magnetic field is normalized by the ratio of 3-h averages of Alfven velocity to average magnetic field so as to have the same units as velocity. Before the interface (zero epoch time) the median trace (labeled 50%) is about 50 nT. In the high-speed stream after the interface median wave power rises rapidly in less than a day, but takes many days to decay. We have also constructed cdfs of the AE index and the normalized cross helicity defined by Roberts and Goldstein (1990). The pattern for AE is virtually the same as the pattern for wave power. However, the normalized cross helicity falls to less than 0.4 before the stream interface but is about 0.9 after the interface. These results imply that strong Alfvenic fluctuations are correlated with elevated AE at least in the high-speed streams that create CIRs.

4. Discussion

In the preceding section, we have enumerated a variety of modes of response of the magnetosphere to the solar wind. These include PBI, pseudo-breakups, storm-time activations, isolated substorms, substorm sequences; SMC; magnetic storms, sawtooth injection events, and HILDCAAs. Undoubtedly these modes are frequently misidentified when only a few data types are used in a study. For example, it is difficult to determine whether a pseudo-breakup is different from a PBI. Similarly, it is difficult to rule out the possibility of small substorms during an SMC, or to distinguish an SMC from a magnetic storm when solar wind driving is strong.

Nearly all geomagnetic activity is associated with intervals of southward IMF so magnetic reconnection must be the underlying process that supplies solar wind energy to the magnetosphere. Magnetic field lines opened on the dayside and transported to the tail must eventually be returned to the dayside to maintain flux balance. Thus, reconnection must also occur in the tail rather frequently. The question is whether all of these response modes directly involve magnetic reconnection, or whether other processes use energy derived from reconnection-driven convection to cause a phenomenon.
This seems to be the position of advocates of the current disruption model for substorm onset. It is also the predominant opinion regarding the cause of magnetic storms. It is continuous global convection that delivers particles to the inner magnetosphere, not discrete substorm expansions.

It seems very likely that both the waveform of the solar wind driver and its strength determine which response mode occurs. Isolated substorms are generally produced by a slowly fluctuating IMF, which first causes dayside reconnection and later nightside reconnection. SMC is produced by moderate and steady driving with balanced reconnection on the day- and nightside. Sawtooth substorm sequences are created by strong, steady driving. HILDCAAs occur when the IMF is continuously driven by interplanetary Alfvén waves present in high-speed streams. Pseudo-breakups seem to be aborted or quenched substorms. PIBs are probably transient and localized bursts of reconnection on a more distant x-line. Storm-time activations probably include pseudo-breakups, PIBs, and weak substorms.

It is not known what effect the state of the magnetosphere has in producing a particular response mode. Mass loading of the plasma sheet by ionospheric oxygen may have a dramatic effect in the tail, and eventually on the dayside when convection transports plasma to the dayside reconnection region. Ionospheric conductivity is also extremely important. Additionally, it is not known to what extent sudden changes in the strength of convection (rotations of the IMF) or dynamic pressure pulses may trigger a change in the state of the magnetosphere. There are advocates of the position that all substorms are triggered (Lee et al., 2004; Lyons, 1995, 1996) or that no substorms are triggered (Freeman and Morley, 2005; Morley and Freeman, 2006).

Another important question concerning solar wind–magnetosphere coupling is what is the quantitative relation between the strength of the driver and the amplitude of the response. Although not reviewed here, there have been numerous suggestions that the strength of a particular interaction depends on prior activity. Thus, single-dip and double-dip storms might exhibit different degrees of coupling. Weak drivers are more efficiently coupled to the magnetosphere than strong drivers. The development of a storm depends on whether there was a long interval of northward IMF prior to the storm. The strength of coupling depends on factors other than the solar wind electric field such as the strength of turbulence or the level of dynamic pressure.

It should not be forgotten that the solar cycle and geometry of the IMF are also important and usually neglected factors in determining the strength of solar wind coupling and possibly the mode of response. The solar cycle controls the type of structures in the solar wind, the strength of the IMF, the polarity of the IMF, and the amount of ultraviolet impinging on the ionosphere (hence conductivity). Geometry of the Sun and Earth rotation and dipole axis are also very important. Magnetic activity tends to be stronger at equinox than at other times because of the Russell–McPherron effect, the Rosenberg–Coleman effect, the axial effect, and the equinoctial effect. For example, the geoeffectiveness of a CIR depends on the polarity of the IMF during the high-speed streams. If the season is near equinox and the IMF obeys the rule “spring to fall away” a HILDCAA is almost certain to occur because the IMF fluctuations due to Alfvén waves are continuously biased southward and the solar wind velocity is high.

5. Conclusion

It was once thought that substorms were the dominant mode of response of the magnetosphere and that storms were simply a superposition of substorms. Now we have identified a variety of response modes besides these two. It is apparent that the type of response depends on the waveform of the solar wind electric field and its strength. There is considerable evidence that changes in the response mode can be triggered by sudden changes in either the electric field or dynamic pressure. The particular response mode probably also depends on the internal state of the magnetosphere, which in turn depends on the recent history of the solar wind interaction as well as on many other factors. Considerable work needs to be done to further describe the characteristics of these response modes and to determine the physical processes that produce them. Quantitative relations between the solar wind variables and various measures of the internal state of the magnetosphere need to be determined as a function of the magnetospheric state. Eventually it should become possible to predict the probability of a particular type of activity and the probability that it will create a disturbance of a given size. As our physical understanding...
increases we should be able to transition from empirical models to physics-based simulations of the system (O’Brien et al., 2002).

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References

Lyons, L.R., 1996. Evidence suggests external triggering of substorms. EOS Transactions of the AGU 79 (9), 88–89.


