RAMON E. LOPEZ

MAGNETOSPHERIC SUBSTORMS

The Earth's magnetic tail acts as a reservoir for the energy that is extracted by the interaction between the solar wind and the Earth's magnetosphere. Occasionally, a portion of that energy is released through a violent process known as a magnetospheric substorm. The substorm is one of the most important magnetospheric phenomena, and it is the subject of extensive research. Recent work utilizing data collected by the Active Magnetospheric Particle Tracer Explorers/Charge Composition Explorer satellite, built at APL, has contributed markedly to our understanding of substorms.

INTRODUCTION

A plasma is an ionized gas, and it is the most prevalent form of matter in the universe. Within our own solar system, the Sun produces a tenuous, but rapidly flowing plasma called the solar wind, which fills interplanetary space and carries the solar magnetic field imbedded into it. In the neighborhood of the Earth's orbit, the average solar wind stream has a velocity of 400 km/s, a number density of 5 cm^{-3}, a temperature of 64,000 K, and a magnetic field strength of 5 nT. Each of these quantities varies considerably over time scales ranging from minutes to years.

When the solar wind strikes a magnetized body such as the Earth, a complicated interaction occurs. Plasmas and magnetic fields exert forces on each other. Thus, on the dayside of the Earth, the progress of the solar wind is checked when the pressure exerted by the solar wind matches that exerted by the Earth's magnetic field. The solar wind flows around the dayside to the nightside, and there the Earth's magnetic field is drawn out into a long magnetic tail. This magnetotail lines up in the direction of the solar wind flow like a wind sock and extends at least 3 times the distance from the Earth to the Moon. The resulting comet-shaped magnetic cavity is known as the magnetosphere, and it is illustrated in Figure 1.

Although it is convenient to speak in terms of magnetic pressure balancing plasma pressure, in reality the distortion of the Earth's magnetic field is effected by enormous electrical currents. The interaction between the solar wind and the Earth's magnetosphere acts as a cosmic dynamo that supplies the power to drive the currents. These currents flow through space across and along lines of magnetic force. One portion of this current system flows in a sheet across the center of the magnetotail, dividing the tail into two lobes of oppositely directed magnetic field. This current is known as the cross-tail current, and, as we shall see, it plays a central role in substorms. The currents that flow along the magnetic field are known as Birkeland currents, named after the Norwegian scientist Kristian Birkeland, who first postulated their existence. They provide the crucial link between the magnetospheric dynamo and the ionosphere, where much of the power is dissipated. Thus, Birkeland currents are a fundamental element of energy transport in the magnetosphere.

The interplanetary magnetic field (IMF) carried by the solar wind also plays a crucial role in the transfer of energy to the magnetosphere. Both the magnitude and the orientation of the IMF are quite variable, and, in particular, there is no preferred z orientation of the field (where x points along the Earth–Sun line, z is positive northward, and y completes the right-handed coordinate system). The Earth's magnetic field points primarily northward, so when the IMF contains a southward component ($-B_z$), a complicated process called magnetic reconnection occurs.

Reconnection is a process by which magnetic energy is converted into plasma energy. As the name implies, reconnection (in its most commonly understood form) involves the interconnection of oppositely directed magnetic fields. This process was first postulated in the context of solar flares and was applied to the magnetosphere by Dungey.[1] An illustration of the Dungey-type, or open, magnetosphere is shown in Figure 2. When the IMF has a southward component, reconnection occurs on the dayside, and the magnetic lines of force in the solar wind become connected with the lines of force from the Earth. The place where this interconnection occurs is called an X-line because of the magnetic geometry in that region. The reconnected magnetic field lines are dragged antisunward by the solar wind flow and stretch out to form the lobes of the magnetotail. The field lines connected to the solar wind are referred to as "open." In the distant magnetotail, another X-line forms, which severs the open-lobe field lines. The reconnected field lines now have both ends attached to the Earth and are referred to as "closed." The closed lines of magnetic flux contain a relatively dense plasma that forms a sheet down the center of the magnetotail called, naturally enough, the plasma sheet. Thus, in this model, the magnetic field is visualized to undergo a grand circulation in which reconnection and the formation of X-lines play a central role. Several different processes have been shown to depend on the sign of B_z, and most scientists

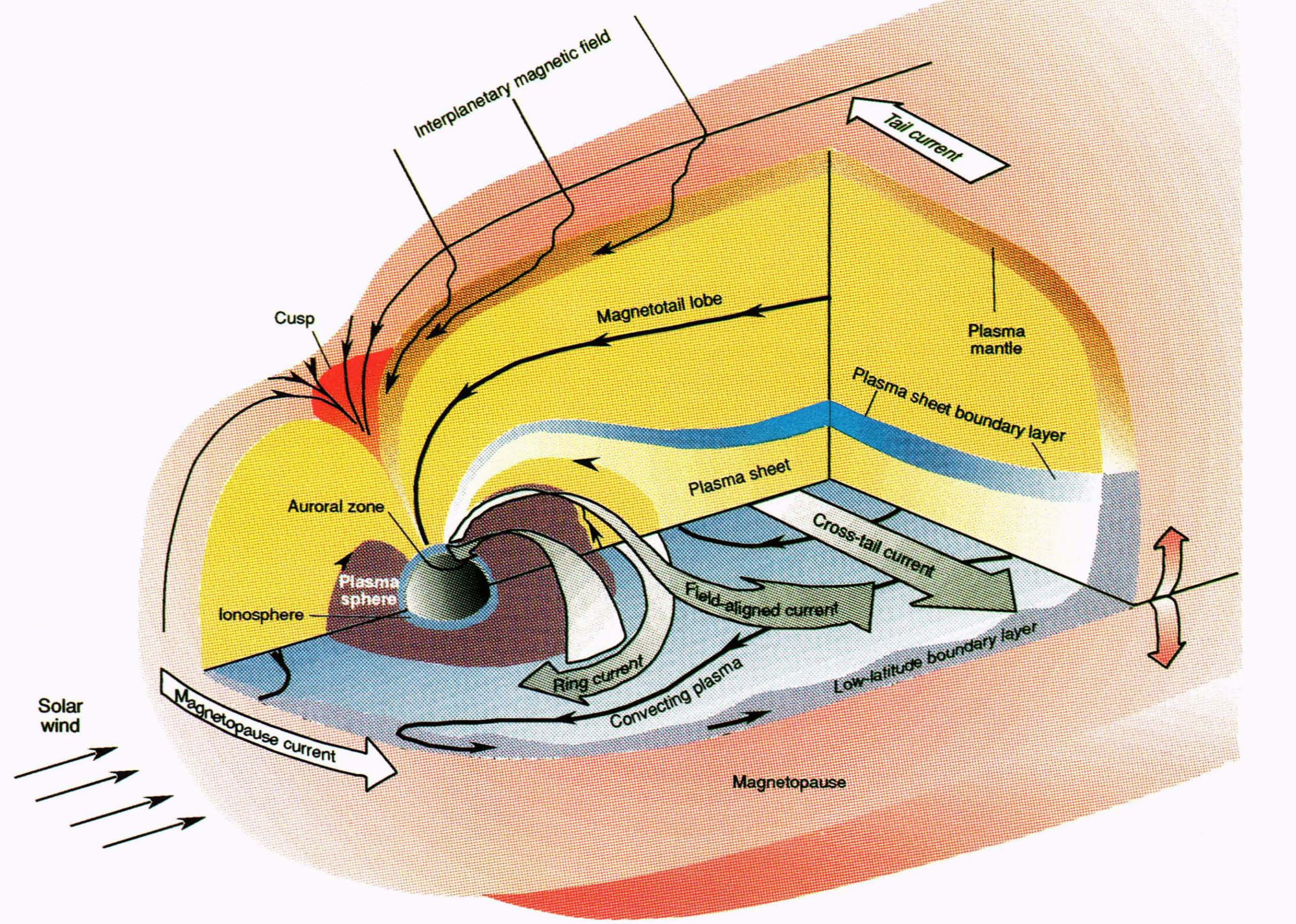


Figure 1. A cutaway view of the magnetosphere. The magnetotail is composed of two lobes (north and south) and a plasma sheet at the center of the tail. The cross-tail current runs across the center of the plasma sheet.

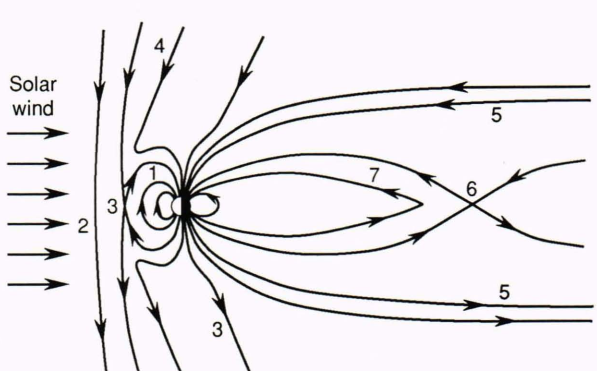


Figure 2. The Dungey-type, or open, model of the magnetosphere. Closed dayside field lines (1) reconnect with southward-pointing interplanetary field lines (2) at a reconnection region called an X-line (3). The newly reconnected field lines (4) are swept back by the solar wind to form the tail lobes (5). The open-lobe field lines reconnect at a distant X-line (6) to form closed plasma sheet field lines (7). (Adapted from Ref. 1.)

invoke reconnection with the IMF to explain such phenomena.

Reconnection transfers magnetic flux into the magnetotail, which is equivalent to storing energy in the magnetotail since the energy density (in J/m^3) of a given amount of magnetic flux density is $B^2/2\mu_0$, where B is the magnetic flux density (in Wb/m^2) and μ_0 is the permeability of free space. At some point, this energy must be released, and the process by which it is released is called a substorm. In the following sections, we will discuss the phenomenology of substorms, the history of substorm research, three of the physical models used to explain them, and the contributions made by the Active Magnetospheric Particle Tracer Explorers/Charge Composition Explorer (AMPTE/CCE) program to understanding this important phenomenon.

PHENOMENOLOGY OF SUBSTORMS

A substorm is composed of three main phases: the growth phase, the expansion phase, and the recovery phase. Before the onset of auroral activity, during the growth phase, the magnetotail stores energy it extracts from the solar wind, and as it does so, the cross-tail current intensifies. This intensification causes the magnetic field in the lobes to increase, and the magnetotail becomes more stressed as the field lines become stretched into a more tail-like configuration. The increased stress causes the near-Earth ($\lesssim 15\ R_E$, where R_E denotes Earth radii) plasma sheet to narrow in the north–south dimension; this process is referred to as plasma-sheet thinning. Since the maximum particle flux is found at the center of the plasma sheet, a satellite located in the plasma sheet will observe a decrease in the flux as the plasma sheet thins. It will also observe the increasingly tail-like configuration of the magnetic field.

The onset of the expansion phase of a substorm begins when a discrete auroral arc, generally located in the midnight sector, suddenly brightens and expands poleward.[2] In the vicinity of the brightening arc, a local intensification of the westward electrojet occurs (the westward electrojet is a current that flows in the ionosphere from east to west). This intensification produces a localized southward perturbation in the magnetic field that can be easily detected by ground magnetometers located in the auroral zone (the auroral zone consists of several degrees of magnetic latitude centered at $\approx 67°$ where auroras are most often observed). Magnetometer stations located at mid-latitudes also observe magnetic perturbations consisting of a northward and an azimuthal perturbation. The westward edge of the auroral intensification forms a feature called the westward-traveling surge. This bright convoluted structure generally, though not always, propagates from east to west, as well as poleward. The rest of the disturbed auroral features expand poleward and longitudinally to form what is known as the auroral bulge. After about one hour, on average, the activity dies down, and the auroral oval returns to its quiet state during the recovery stage. This sequence is illustrated in Figure 3, which shows a series of ultraviolet images taken of the aurora during a substorm by the polar-orbiting Dynamics Explorer 1 satellite.

In the near-Earth magnetotail at substorm onset, the magnetic field suddenly relaxes from the stressed tail-like configuration to a more dipolar configuration, as if the cross-tail current, which produces the stress, has suddenly been reduced.[3] This phenomenon is known as a dipolarization. Attending the dipolarization is an expansion of the plasma sheet, which is observed to have been heated. As the satellite enters the plasma sheet, it first encounters earthward-streaming ion beams, followed by a general increase in the flux of plasma called an injection. In contrast, in the more distant magnetotail, the plasma sheet thins at substorm onset and expands only later, during the recovery phase of the substorm. Another observed feature is an increase in the northward component of the magnetic field, which is correlated with the similar perturbation seen at mid-latitudes. Figure 4 is a schematic illustration of the magnetic field geometry and plasma observations made by a satellite in the near-Earth magnetotail during the growth and expansion phase of a substorm.

These observations have been cited as evidence for the existence of a substorm current wedge, illustrated in Figure 5, in which a portion of the cross-tail current is disrupted and diverted via Birkeland currents in the morning sector, through the ionosphere via the enhanced westward electrojet, and back out into the magnetotail. The current-wedge model is consistent with the magnetic perturbations observed on the ground and explains not only the correlation between the mid-latitude and satellite

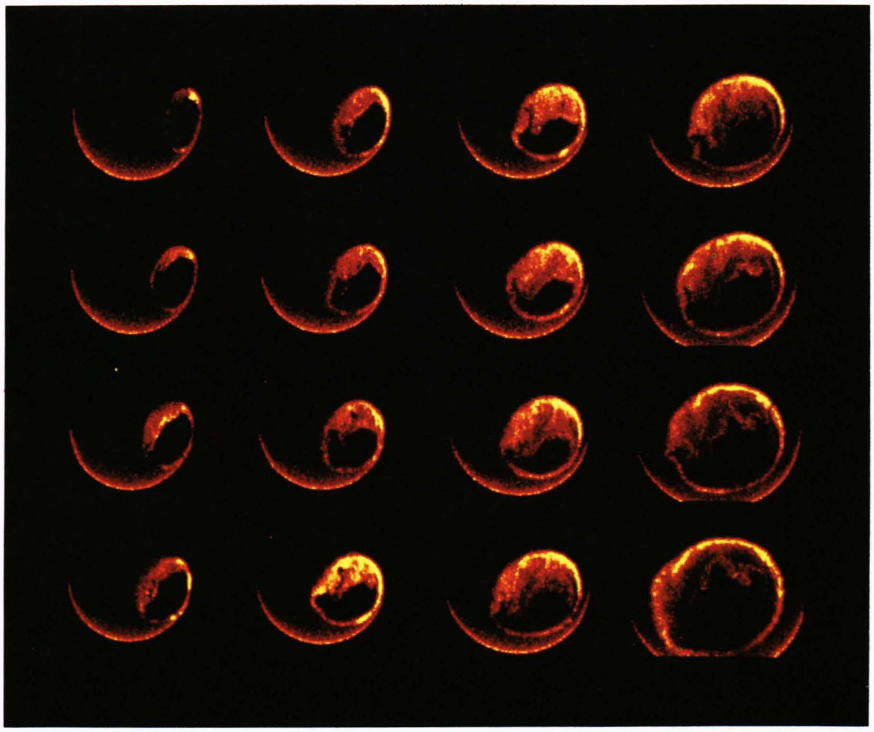


Figure 3. A sequence of images taken by Dynamics Explorer 1 from 0202 to 0517 UT on 13 June 1983 of the southern auroral zone during a major substorm. The substorm onset is observed in the first image at the upper left; time runs from top to bottom and then from left to right. The auroral brightening was initially localized and appears as a bright spot. The disturbance spread longitudinally and poleward. The last four images (the four right-most images) show the recovery phase of the event as the auroral luminosity decreased. (The photograph was supplied courtesy of Lou A. Frank and John D. Craven.)

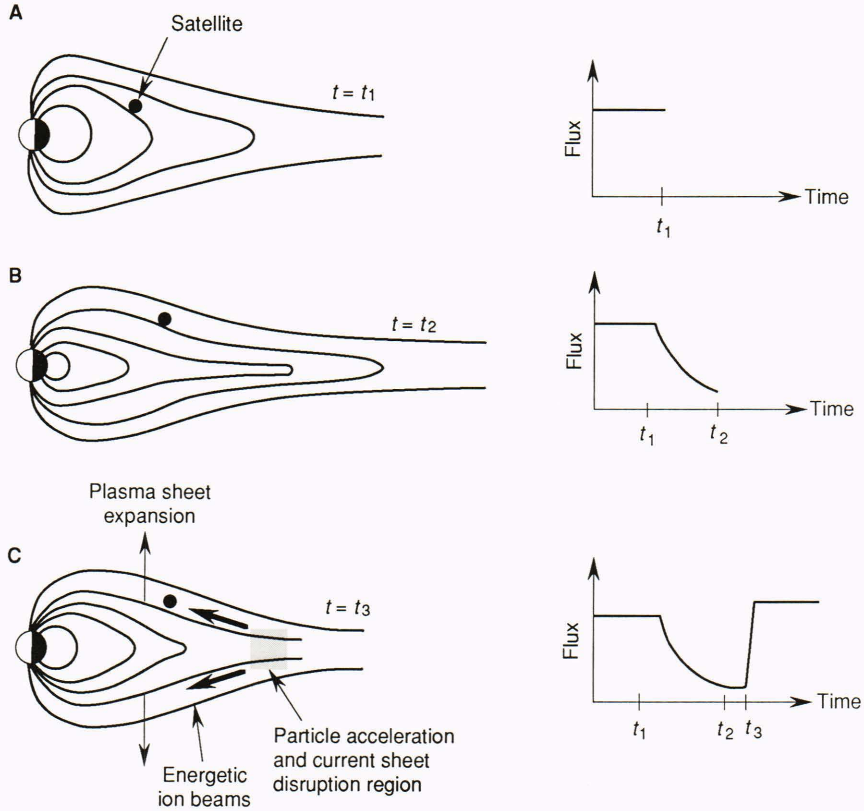


Figure 4. Energetic particle and magnetic field variations in the near-Earth magnetotail during a substorm. **A.** Quiet time. **B.** During the growth phase, the plasma sheet thins and the magnetic field becomes more tail-like. A satellite in the near-Earth magnetotail will observe a decrease in the particle flux as the plasma sheet thins. **C.** At substorm onset, the cross-tail current sheet is disrupted, plasma is energized, the plasma sheet expands, and the magnetic field relaxes to a less tail-like configuration.

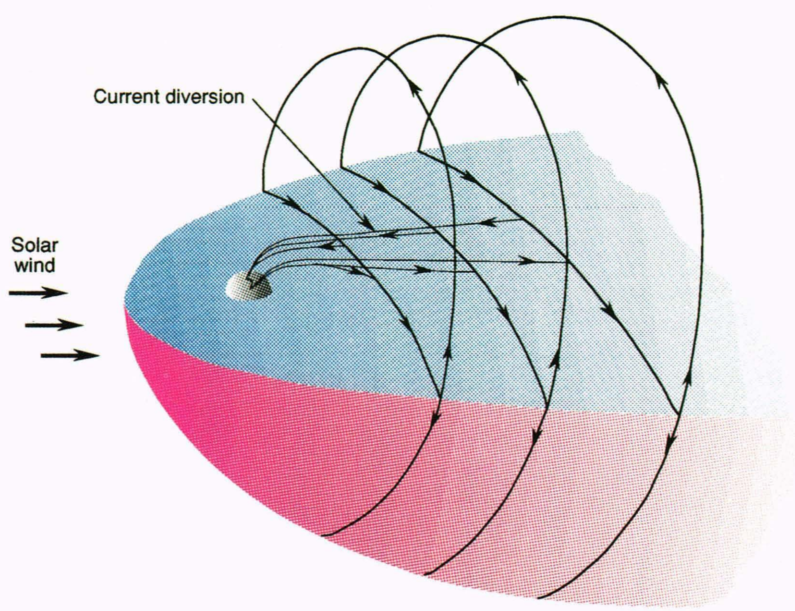


Figure 5. A schematic illustration of the substorm current wedge. Current is diverted out of the magnetotail, along the magnetic field into the ionosphere, across the ionosphere via the westward-traveling surge, and back out into the magnetotail. Satellites in the near-Earth magnetotail within the region encompassed by the current wedge observe phenomena associated with the onset of a substorm, such as plasma sheet expansion.

northward perturbations, but also the sign and the spatial extent of the azimuthal perturbations, the dipolarization of the magnetotail field, and the expansion of the plasma sheet. Moreover, the disruption of the current should energize the plasma, producing the ion beams and heating the plasma sheet. Finally, the existence of the current wedge is consistent with the structure of the westward-traveling surge. At its western edge, which is the western edge of the substorm-affected auroral zone, the current wedge consists of an intense upward Birkeland current, whereas to the east, the current is more diffuse and has a net downward polarity.

Substorm phenomena do not occur uniformly throughout the magnetotail at onset. In the ionosphere, the substorm is longitudinally limited, and the area affected increases with time. Similarly, in the near-Earth magnetotail, the current wedge is initially confined to a narrow sector, then expands longitudinally with time.[4] Outside the region encompassed by the current wedge, a satellite may continue to observe features associated with the growth phase, even though the expansion-phase onset has already occurred. Furthermore, as mentioned earlier, in the more distant magnetotail, the plasma sheet begins to thin at onset and thickens only later.

Let us summarize the basic phenomenology of a substorm, with special focus on the near-Earth magnetotail. Before a substorm, during the growth phase, the magnetotail stores energy, and the cross-tail current increases. This increased current causes the near-Earth magnetotail to become more tail-like as the plasma sheet thins, and the lobe magnetic field increases. At the onset of the expansion phase, a spatially limited region of the cross-tail current is disrupted, and a portion of that current is diverted into the ionosphere. This diverted current causes brightening of the auroral arc that is connected to the region of the magnetotail that became unstable. In short order, a westward-traveling surge is formed. The auroral brightening expands longitudinally and poleward as the current wedge in the near-Earth tail expands. Within the current wedge, a dipolarization of the magnetic field occurs, the plasma sheet is heated and expands, and an injection of plasma takes place. Further down the tail, the plasma sheet thins, and then it thickens later. Now that we have examined what happens during a substorm, let us review the history of substorm research.

A BRIEF HISTORY OF EARLY SUBSTORM RESEARCH

In 1741, it was discovered that a close relationship existed between geomagnetic disturbances in the polar region and auroral displays. Among the first to systematically study these phenomena was a Norwegian scientist named Kristian Birkeland, who established magnetic observatories in northern Scandinavia in the late nineteenth and early twentieth centuries. Birkeland proposed that the disturbances observed in the high-latitude regions, which he called polar elementary storms, were produced by electrical currents that ran along the magnetic field from space, proceeded horizontally through the ionosphere, and returned to outer space. Birkeland also conducted experiments with a terella, which is a small magnetized sphere in a vacuum chamber. Occasionally, when the terella was bombarded by electrons, phosphorescent ovals would form in the polar regions encircling the magnetic poles, mimicking what we now know to be the auroral oval.

Birkeland's career was ending at the time that Sydney Chapman began his pioneering work in the field. Chapman laid the foundation of much of modern space physics through his studies of large magnetic disturbances called magnetic storms. Chapman suggested that magnetic storms were caused by the impact of a plasma cloud ejected from the Sun upon the Earth's magnetic field. He also proposed that this interaction would produce a magnetic cavity we now call the magnetosphere. The disturbances due to a magnetic storm were quantified into three mathematical terms:[5] DCF, the perturbation due to the currents at the boundary of the magnetosphere; DRC, the perturbation due to a ring current flowing through space and encircling the Earth; and DP, the disturbance polar that Chapman associated with Birkeland's polar elementary storms. These latter disturbances could be seen to wax and wane during the course of a given magnetic storm, so Chapman referred to them as substorms.

One of Chapman's students, Syun-Ichi Akasofu, popularized the use of the term substorm and provided the first global description of auroral behavior during such events, introducing terms such as expansive phase and westward-traveling surge. Initially, many types of substorms were thought to have existed, such as auroral substorms and magnetic substorms. For example, in the classic paper, "The Development of the Auroral Substorm," Akasofu[6] wrote, "The sequence of auroral events . . . is called an auroral substorm: it coincides with a magnetic (DP) substorm, with which it has some close relationships." After more research, it became clear that substorms were associated with enhancements in a variety of auroral activity, and that they could occur independently of magnetic storms. The advent of the space age led to the space-based study of substorm effects. It soon became obvious that field-aligned, or Birkeland, currents were an essential part of substorms, and the idea of the substorm current wedge surfaced. Moreover, studies of the westward-traveling surge mapped the pattern of Birkeland currents, and satellite measurements documented such phenomena as plasma sheet thinning and expansion. All of these phenomena were seen to be different facets of a process known as a magnetospheric substorm.[2] This understanding led to the basic picture of substorm phenomenology as we know it today.

PHYSICAL MODELS FOR SUBSTORMS

Once the basic features of substorm phenomenology were established, scientists began to develop physical models that could explain the magnetospheric substorm. We will briefly examine three of the most well-known substorm models: the near-Earth neutral line model, the boundary layer model, and the magnetosphere–ionosphere coupling model. These are by no means the only substorm models, but they illustrate the broad range of approaches to the problem.

The first comprehensive model for substorms, and still the most widely accepted, is the near-Earth neutral line model.[3] This model views reconnection as the central physical process in the collection of phenomena that we call a substorm, and it has as its basis the Dungey model of the open magnetosphere. The near-Earth neutral line model starts with the supposition that a southward IMF produces reconnection on the dayside magnetosphere. The reconnected field lines are swept tailward by the solar wind flow and added to the magnetotail. This phenomenon increases the magnetic flux in the tail lobes, implying that the cross-tail current has increased. The added lobe pressure causes the plasma sheet to thin.

When the plasma sheet has thinned sufficiently, an X-type reconnection region forms in the near-Earth tail, which disrupts the cross-tail current and forms a bubble of closed magnetic field lines known as a plasmoid. To maintain continuity, the cross-tail current is diverted along the magnetic field into the ionosphere, across the ionosphere via the westward-traveling surge, and back out along the field into space, thus forming the current wedge. Earthward of the neutral line, the reconnected field lines snap back to Earth, producing an expansion of the plasma sheet, whereas tailward of the neutral line, the plasma sheet thins rapidly. Reconnection proceeds until the X-line eats its way to the lobe field lines, which are connected to the solar wind. At that point, the plasmoid is released, and it moves rapidly down the tail. The tailward-retreating near-Earth neutral line now becomes the new distant neutral line, and the plasma sheet expands behind it. This situation is illustrated in Figure 6; a more comprehensive discussion of this model can be found elsewhere.[7]

Another model for substorms is the boundary layer model.[8] This model is of more recent vintage and emphasizes the plasma sheet boundary layer, which is a region lying at the interface between the plasma sheet and the lobe. In this model, Birkeland currents flow through the plasma sheet boundary layer to a region of the distant magnetotail where a velocity shear exists. During enhanced reconnection at the distant neutral line (see Fig. 1), the velocity shear increases and may become unstable, causing the currents that flow through the plasma sheet boundary layer to bunch up. It is proposed that the bunched Birkeland currents are the westward-traveling surge. The convoluted features of the westward-traveling surge are interpreted to be the signature of these Birkeland currents wrapped up around themselves. The boundary layer model also claims that the southward B_z signatures seen in the magnetotail, and cited as evidence for the X-line geometry of reconnection, are just the fringe field effects of the bunched currents. The boundary layer model does not provide an explanation for near-Earth phenomena, however.

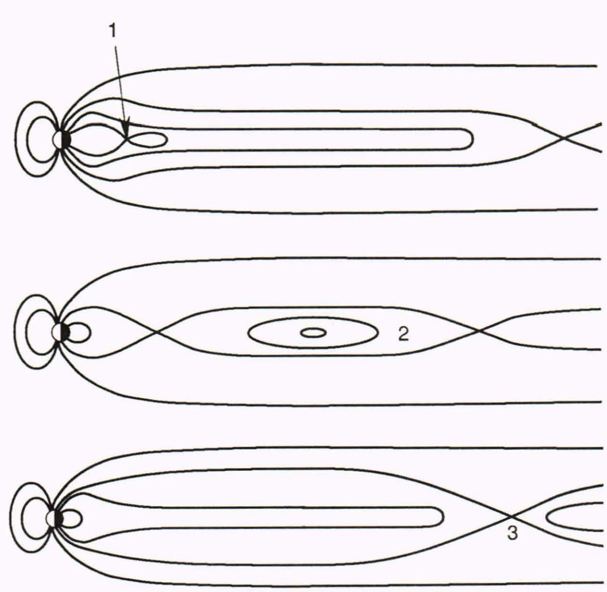


Figure 6. A schematic illustration of the near-Earth neutral line model. A substorm begins when a near-Earth reconnection region, or X-line, is formed (1), causing a disruption of the cross-tail current and an expansion of the plasma sheet earthward of the X-line. Tailward of the X-line, the plasma sheet quickly thins. When the X-line cuts through the last plasma sheet field line, a disconnected bubble called a plasmoid (2) is released and moves rapidly down the tail. The retreating near-Earth X-line becomes the new distant X-line (3), and the plasma sheet fills and expands behind it. (Adapted from Ref. 7.)

The magnetosphere–ionosphere coupling model[9] represents a third type of substorm model. This model stresses the effects of coupling of the magnetosphere and ionosphere via Birkeland currents. Given certain conditions, this coupling causes a great increase in the Birkeland current density, and the enhanced current flow produces the auroral brightening associated with the substorm expansion-phase onset. One point in favor of the magnetosphere–ionosphere coupling model is that the magnetosphere is indeed intimately linked to the ionosphere, so the ionosphere must play an important part in the process. Moreover, aspects of the magnetosphere–ionosphere model could play a role in either the near-Earth neutral line or boundary layer model, although the time scale for the magnetosphere–ionosphere coupling model is minutes (the time it takes information to propagate from the ionosphere to the magnetosphere), whereas, as we shall see, the time scales for dramatic changes in the magnetotail are on the order of seconds.

The near-Earth neutral line model is able to explain in a relatively satisfactory way the major phenomenological features of substorms. Moreover, considerable evidence supports the existence of plasmoids or similar structures passing through the distant magnetotail in association with substorms. Statistical evidence suggests, however, that neutral lines do not form inside of $\sim 20\ R_E$, yet substorms have drastic effects in the inner ($\lesssim 10\ R_E$) magnetosphere. It has been suggested that the neutral line forms outside of $20\ R_E$, but that it launches a compressional wave, or injection front, that propagates earthward into the inner magnetosphere. The boundary layer model is able to account for some auroral forms and points out the possible importance of the boundary layers in substorm dynamics. Similarly, the magnetosphere–ionosphere coupling model points out the importance of ionosphere dynamics during substorms. The questions to be examined are, "To what extent are these models correct," and "How many of their predictions can be verified by satellite observations?"

AMPTE/CCE: A UNIQUE SATELLITE FOR SUBSTORM STUDIES

The AMPTE spacecraft were launched on 16 August 1984 with an ambitious mission to study the transport processes of the magnetosphere by releasing clouds of tracer ions that could act as a dye in the cosmic plasma.[10] The actual releases were to be made by a German satellite, the Ion Release Module (IRM), which was accompanied by the United Kingdom Subsatellite. An

American satellite, the CCE, completed the trio. Its job was to monitor the inner magnetosphere for signs of the tracer ions and to study the natural magnetospheric composition, structure, and dynamics. What makes CCE such a good satellite for substorm studies is its unique orbit. The apogee of CCE is 8.8 R_E, and it has a near-equatorial inclination. Substorm studies based on geosynchronous (6.6 R_E) spacecraft have indicated that the intense cross-tail current sheet that builds up in the equatorial magnetotail during the growth phase has its inner edge at about 7 R_E, which is the exact region explored in detail by CCE.

The first CCE substorm studies were based on CCE data alone or with other data, such as ground magnetograms playing a supporting role. Figure 7 shows an example of a typical substorm event. The data are 72-s-averaged energetic particle data and 68-s-averaged magnetometer data. One can clearly see that the particle flux level decreased as the plasma sheet thinned. At the same time, the x component of the magnetic field increased and the z component decreased, which means that the field became more tail-like. At substorm onset, the particle flux increased as the plasma sheet expanded over CCE, and the field became more dipolar as the x component decreased and the z component increased. Studies of events such as the one in Figure 7 provided further information on the behavior of particles and fields during substorms and on such features as the earthward-streaming ion layer at the boundary of the heated plasma sheet. Also studied was the radial and longitudinal distribution of substorm events. Although several previous results were confirmed, such as the plasma sheet thinning model for particle flux variations, many surprises occurred as well.[11]

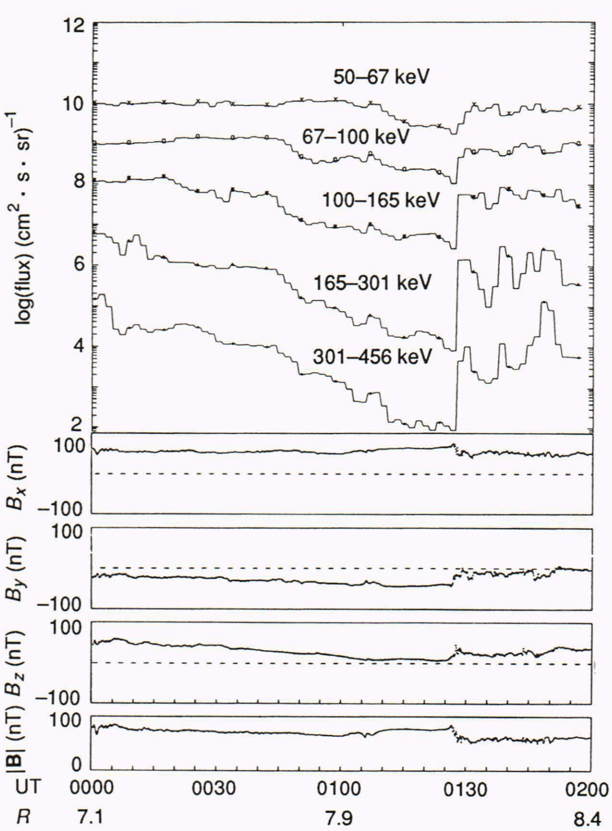


Figure 7. A typical substorm event observed on 7 July 1986 by CCE. Before the substorm, the flux decreased as the plasma sheet thinned. At substorm onset, the plasma sheet expanded, the flux increased, and the magnetic field **B** reconfigured to a less tail-like orientation. B_x, B_y, and B_z are the three components of **B**. UT = universal time, MLT = magnetic local time, and R = radial position in units of Earth radii (R_E).

Occasionally CCE would record dramatic variations of the magnetic field during these events. Such variations had been observed in the more distant magnetotail but not in the near-Earth magnetotail. It was first postulated that these violent variations of the magnetic field could be the signature of a near-Earth neutral line, but further study pointed to a turbulent disruption of the cross-tail current as the agent. These current disruption events became a major focus of CCE studies and have led to a theoretical model for the breakdown of the current sheet.

Another set of studies focused on the global development of substorms by using data from CCE in conjunction with data from other satellites and ground stations. Those studies confirmed that the inner magnetotail is a region of great importance for substorms. The available evidence also suggests that the disruption of the current sheet begins in the near-Earth region within the CCE orbit and then expands radially outward and longitudinally. Furthermore, a topological change does not appear to occur within the CCE orbit, and one would expect such a change if a reconnection region had formed. These results suggest that in the initial phases of a substorm, the current sheet is disrupted in a turbulent fashion, but that this disruption does not produce an X-line. Any such topological change must occur further down the tail.

The most dramatic of these multisatellite studies involved one of the current sheet disruption events, and data from this event are presented in Figure 8. The data shown are magnetometer measurements from CCE and IRM; the CCE data are 0.125-s samples, and the IRM data are 1-s averaged. The violent nature of the current sheet disruption is evident in the CCE data, but what is even more interesting is that IRM clearly observed the onset of activity before CCE. At the time of the event, IRM was located earthward of CCE, and the two satellites were separated only by 1.6° in longitude. Furthermore, both spacecraft were longitudinally aligned with Syowa, a Japanese Antarctic research station. An analysis of magnetic field data and all-sky camera photographs from Syowa shows that the westward-traveling surge passed directly over Syowa within 20 s of the time that the current sheet was disrupted at CCE. Furthermore, calculations using a model magnetic field indicate that the westward-traveling surge seen at Syowa mapped to the CCE location in the magnetotail. This finding suggests that substorm-associated auroras are the results of processes that occur in the near-Earth magnetotail just beyond the orbit of communication satellites.

Such results have significant implications for substorm models. Our results appear to be in serious contradiction

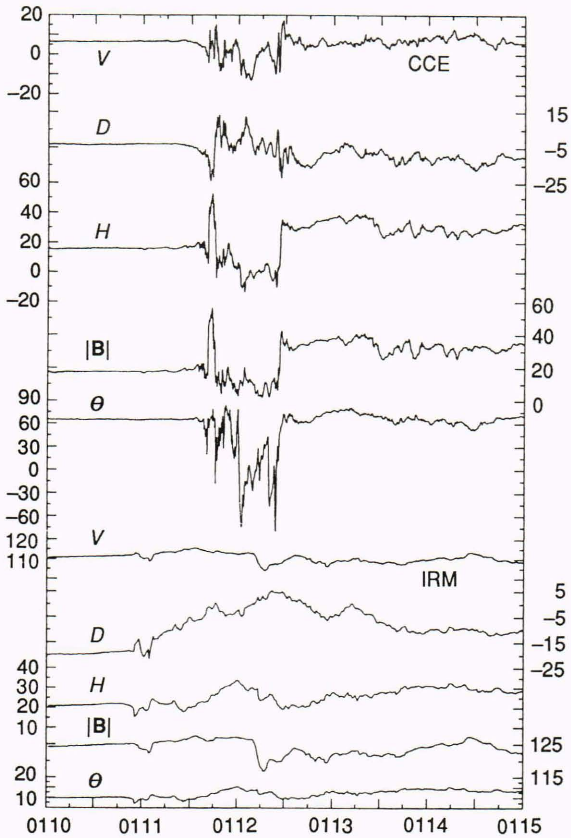


Figure 8. Magnetic field data from CCE and IRM, the German AMPTE satellite, during a substorm that occurred just after 0110 UT on 25 April 1985. The CCE was located at the center of the magnetotail within the cross-tail current, and the IRM was radially aligned with and earthward of CCE. The IRM, however, observed the onset of activity before CCE did, suggesting that the activity began earthward of CCE. Shortly after the activity began at IRM, CCE observed the violent disruption of the current sheet. This activity seems to have been connected by magnetic lines of force to an auroral display that was simultaneously observed in Antarctica. Such events were observed in the near-Earth magnetotail for the first time by CCE, and they are a major focus of study. The measurements were taken in a coordinate system where $V \approx x$, $D \approx y$, $H \approx z$, θ is the polar angle, and **B** is the magnetic field. All values along the y-axis are given in nanoteslas (nT).

with the boundary layer model. That model connects the westward-traveling surge to the distant magnetotail, whereas our study indicates that the westward-traveling surge is connected to the near-Earth region. Similarly, the coordinated observations made between CCE and the ground station Syowa indicate that the time scales for substorm phenomena are much shorter than envisaged in the magnetosphere–ionosphere coupling model, although the ionosphere probably does play a very strong regulating role in the process. What about the near-Earth neutral line model? The CCE observations seem to suggest that that model needs to be modified. One proposed modification supposes that reconnection does not begin until after the onset of the substorm. In this situation, current disruption spreads down the tail until the influence of the Earth's magnetic field is so weak that the disruption region can coalesce into a reconnection region, severing a portion of the magnetotail to form a plasmoid. This model has the advantage that not every substorm needs to develop a reconnection region. Examples are known of substorms in which dramatic effects occur close to the Earth but not further down the tail.

These issues are by no means settled, but continuing analysis of the CCE data will likely prove central in attempts to expand our understanding of substorms. Already, the results of the CCE investigations have added substantially to our knowledge and have brought to light phenomena not previously reported, such as observations of current disruption just beyond geosynchronous orbit. These results are having a significant effect on substorm theories and are causing a reassessment of long-held ideas. In this regard, CCE has been an extremely successful and important mission.

REFERENCES

[1] Dungey, J. W., "Interplanetary Magnetic Field and the Auroral Zones," *Phys. Rev. Lett.* **6**, 47 (1961).

[2] Akasofu, S.-I., "What is a Magnetospheric Substorm?," in *Dynamics of the Magnetosphere*, Akasofu, S.-I., ed., D. Reidel, Dordrecht, pp. 447–460 (1979).

[3] McPherron, R. L., Russell, C. T., and Aubry, M. P., "Satellite Studies of Magnetospheric Substorms on August 15, 1968: 9. Phenomenological Model for Substorms," *J. Geophys. Res.* **78**, 3131–3149 (1973).

[4] Nagai, T., "Observed Magnetic Substorm Signatures at Synchronous Altitude," *J. Geophys. Res.* **87**, 4406–4417 (1982).

[5] Chapman, S., *Solar Plasma Geomagetism and Aurora*, Gordon and Breach, New York (1964).

[6] Akasofu, S.-I., "The Development of the Auroral Substorm," *Planet. Space Sci.* **12**, 273–282 (1964).

[7] Hones, E. W., Jr., "The Earth's Magnetotail," *Sci. Am.* **254**, 40–47 (1986).

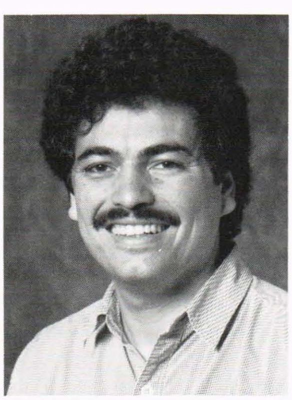
[8] Rostoker, G., and Eastman, T. E., "A Boundary Layer Model for Magnetospheric Substorms," *J. Geophys. Res.* **92**, 12,187–12,201 (1987).

[9] Kan, J. R., Zhu, L., and Akasofu, S.-I., "A Theory of Substorm Onset and Subsidence," *J. Geophys. Res.* **93**, 5624–5640 (1988).

[10] Krimigis, S. M., Harendel, G., McEntire, R. W., Paschmann, G., and Bryant, D. A., "The Active Magnetospheric Particle Tracers Explorers Program," *Eos* **63**, 843–850 (1982).

[11] Lopez, R. E., Lui, A. T. Y., Sibeck, D. G., Takahashi, K., McEntire, R. W., et al., "On the Relationship between the Energetic Particle Flux Morphology and the Change in the Magnetic Field Magnitude during Substorms," *J. Geophys. Res.* **94**, 17,105–17,120 (1989).

THE AUTHOR



RAMON E. LOPEZ is employed by Applied Research Corporation and is under contract to the Space Physics Group as part of the AMPTE/CCE science team. He received a B.S. (1980) in physics from the University of Illinois at Urbana–Champaign and a Ph.D. (1985) in space physics from Rice University. His research interests include the dynamics of the Earth's magnetotail, the aurora, and the solar wind. He also has a strong interest in education and has participated in the Mentor Program at APL.