

# A BRIEF HISTORY OF MAGNETOSPHERIC PHYSICS DURING THE SPACE AGE

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**Abstract.** After 1958, when scientific satellites began exploring the Earth magnetic environment, many puzzling phenomena could be directly examined, especially the polar aurora and disturbances of the Earth's magnetic field [see *Stern*, 1989a]. The notion of the solar wind, also introduced in 1958, helped clarify the role of the Sun in driving such phenomena. The large-scale structure of the magnetosphere, the space region dominated by the Earth's magnetic field, was gradually revealed within the next decade: its trapped particles, its boundary, and its long magnetic tail on the nightside.

Inevitably, however, at a more fundamental level, the new discoveries led to new questions about the transfer of energy, the flow patterns of plasmas and electric currents, the acceleration of the aurora, and transient events such as magnetic substorms and storms, which energized ions and electrons. Though significant progress has occurred in some of these areas, many unresolved issues still remain. This review outlines the history of magnetospheric research, draws some general conclusions, and provides an extensive bibliography.

## 1. INTRODUCTION

This is the second part of a concise history of observations of the Earth's magnetosphere and of their interpretation. It and the first part [*Stern*, 1989a, hereinafter referred to as BH-1] are meant to help trace the development of magnetospheric physics in a unified context and to outline its framework of observations and ideas. The early years, around 1957–1964, are covered chronologically, after which the coverage is arranged by topics: convection, reconnection, aurora, Birkeland currents, and substorms. At the end some overall trends are assessed, as well as the current state of the discipline. Readers who find this article too technical are referred to an exposition on the World Wide Web by Stern and Peredo (The exploration of the magnetosphere, <http://www-spof.gsfc.nasa.gov/Education/Intro.html>)

This brief account is based primarily on work published in English, which covers U.S. efforts fairly completely but is unfortunately far less detailed on space research in the former Soviet Union and elsewhere. BH-1 covered earthbound studies of the magnetosphere before artificial satellites were available, and here the rest of the story is presented. The concluding section contains an assessment of overall trends as well as of the current state of the discipline.

This account is mainly based on published sources, rather than on personal papers or interviews. It must therefore be viewed as a mere framework, in which many details remain to be filled.

## 2. DISCOVERY OF THE RADIATION BELTS

Early U.S. magnetospheric research was focused mainly on the Earth's radiation belts, discovered by J. Van Allen and his colleagues in the spring 1958. It drew from four sources. The first source was laboratory plasma physics, aimed at achieving nuclear fusion. Its early focus was in Princeton, where a number of "stellarator" confinement machines were built [*Bishop*, 1958], and it is interesting to note that Van Allen, too, worked at the Princeton Plasma Lab in 1953–1954 [*Van Allen*, 1983a, 1990]. Early plasma research provided an understanding of particle confinement in magnetic fields and of adiabatic invariants [*Spitzer*, 1956; *Rosenbluth and Longmire*, 1957; *Northrop and Teller*, 1960], essential to the theory of the radiation belts.

The second source was high-altitude research on radiation in space, mainly cosmic rays, using balloons and rockets [*Friedman*, 1994]. Balloon studies of the primary cosmic radiation started shortly after World War II (WWII) [*Simpson*, 1994]; among other things, they led to the discovery of the pion (pi-meson), and they were greatly expanded toward the International Geophysical Year (IGY) [*Van Allen*, 1983b; *Odishaw and Ruttenberg*, 1958]. Rocket-borne studies began shortly after the end of WWII, when captured German V-2 rockets were brought to the United States and were used for high-altitude research [*DeVorkin*, 1992]. These studies continued with vehicles specifically designed for science, in particular the Aerobee [*Newell*, 1959]. Rocket instru-

ments of the University of Iowa were launched in 1954 toward the aurora, and their particle counters registered the presence of radiation [Meredith *et al.*, 1955], later credited to X rays produced by the electrons in the rocket shell or the atmosphere [e.g., Van Allen, 1995]. On the first day of the IGY, balloon-borne instruments of the University of Minnesota also observed X rays produced by auroral electrons, which penetrated deeper into the atmosphere than the electrons themselves [Winckler *et al.*, 1957, 1958].

The third source was interest in high-energy particles originating at the Sun. This interest was given a great boost by the large solar particle event of February 23, 1956, which registered on cosmic ray detectors around the world. Solar particle research was also one of the active foci of the IGY (July 1, 1957 to December 13, 1958), which coincided with a peak in the sunspot cycle. It was believed at the time that such particles were energized in solar flares by processes involving magnetic fields [Giovanelli, 1947; Hones, 1984b], and this stimulated the developments of theories of particle acceleration. Many of the results developed in this context, especially those of “reconnection theory” (see below), were later applied to the magnetosphere.

A fourth source was the study from the ground of the aurora and of magnetic variations. Its community included S. Chapman, J. Heppner, E. Vestine, and N. Davis and was initially rather loosely coupled with the space observations. Soon, however, it contributed in major ways to their interpretation.

Sputnik 1 was launched October 4, 1957, followed on November 3 by Sputnik 2; Explorer 1, the first successful U.S. spacecraft, was launched January 31, 1958; and Explorer 3, by which the radiation belt was discovered, was orbited March 26.

Sputnik 1 carried no radiation detector, but Sputnik 2 did so, rising to an altitude of 1680 km. S. N. Vernov actually reported a significant (though not overwhelming) increase of the radiation rate between 500 and 700 km, and in hindsight, this apparently marked the fringes of the radiation belt; however, he did not realize the implications [Singer, 1962, pp. 249–258]. The apogee of Sputnik 2 was above Australia; the Australians who tracked it there asked the former Soviet Union for the key to its signals but were refused, and hence the data were not analyzed at that time [Hess, 1968, p. 11; Dessler, 1984].

The mission of Explorer 1 was assembled in a hurry. The United States was trailing the former Soviet Union in space exploration, and the first attempted launch of its official entry, the Vanguard, ended in flames on the launching pad. A launch vehicle was therefore improvised from available components, a backup plan devised earlier by Von Braun [1964] [also Pickering, 1963]. The resulting orbit was rather noncircular and rose to an apogee of 2500 km, deep inside the radiation belt. Explorer 1 carried a radiation detector, a Geiger counter provided by Van Allen's team at the University of Iowa

(Figure 1), which also included Carl McIlwain, Ernest Ray, and George Ludwig [Van Allen, 1981, 1983a]. The counter was meant to measure the overall cosmic ray intensity, which by Stoermer's theory (see BH-1) was expected to increase with magnetic latitude, and its predicted counting rate was about 30 counts per second. The experimental package was a modified version of one designed for a later launch in the Vanguard series and included a tape recorder designed to store the data for retransmission when the spacecraft passed over tracking stations. However, it was decided to provide this feature only on later missions and to omit it from Explorer 1, so that stations were only able to collect a few minutes' worth of data whenever Explorer 1 passed within range.

On passes below 600 km the counting rate was nominal. Near apogee, however, no counts at all were detected, and on one pass, with the spacecraft around 1200 km and rising, counts were received but suddenly stopped [Van Allen, 1981, Figure 8]. Actually, much of this was only noted later: what was mainly observed was that sometimes the counter on the spacecraft operated normally, and at other times it seemed dead. McIlwain showed experimentally that very high particle fluxes would overwhelm the counter and produce zero counts, and there is little doubt that further analysis of Explorer 1 data would probably have led to the discovery of the radiation belt. Before that could happen, however, much less ambiguous data were obtained from another experiment.

Explorer 2 failed to orbit, but Explorer 3 was successful. Unlike Explorer 1, it carried a tape recorder, and its continuous record of data (Figure 2) made clear what was happening. At low altitudes, only cosmic rays were detected; then as the satellite rose, the recorded counting rate increased up to the highest it could record, and it stayed pegged there for a while. At a still higher altitude it abruptly fell to zero, and during descent the same transitions occurred in reverse order. The periods of zero counts near apogee clearly marked not the absence of radiation but a very high radiation flux: the Geiger counter was discharged so frequently that it did not recover between pulses and its output signals decreased until they no longer triggered the counting circuit.

That was how the radiation belt was discovered [Van Allen *et al.*, 1958; Van Allen, 1981]. Ray's comment was: “My God, space is radioactive!” [Hess, 1968]. The identity of the particles was quite uncertain. Auroral electrons had been observed in near-Earth space, but they lacked the energy to penetrate the counter walls. They could trigger a count by means of secondary X rays, with a probability of the order of  $10^{-5}$  [Frank, 1962], an explanation which had been previously used to explain rocket observations in the auroral zone [Van Allen, 1995]. Such an interpretation would have implied a huge flux of electrons, of order  $10^8 \text{ cm}^{-2} \text{ s}^{-1}$ , a figure that proponents of manned space flight viewed with justified alarm. Sputnik 3, launched May 12 to an apogee of 1880

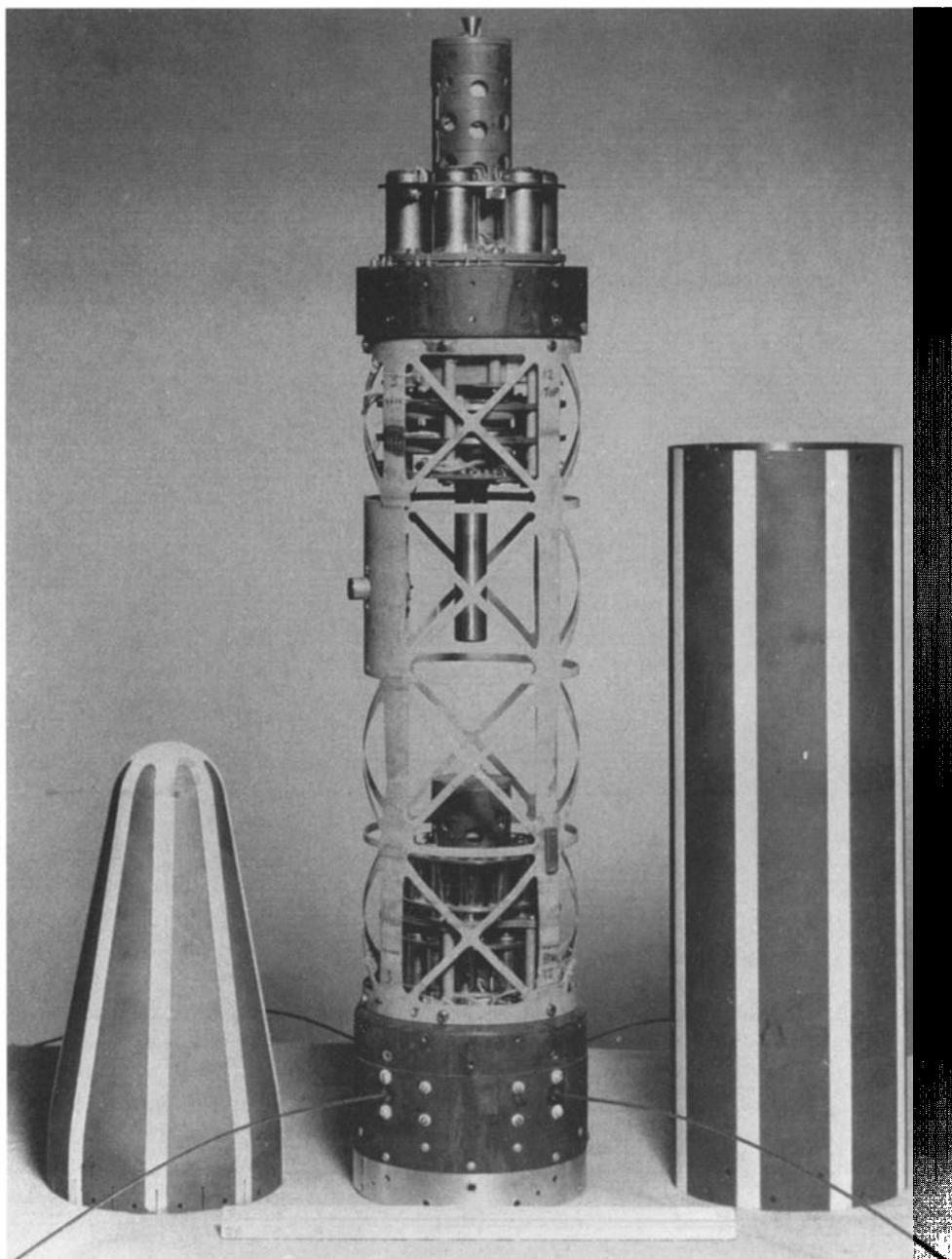


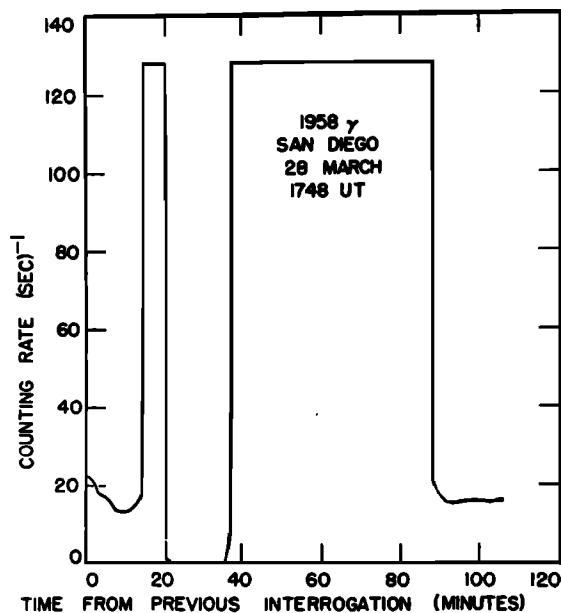
Figure 1. Explorer 1.

km, carried scintillation detectors and confirmed the existence of Van Allen's belt, but it did not resolve the identity of the particles and neither did Explorer 4, discussed in the next section [Van Allen *et al.*, 1959]. As noted further below, the particles of the intense innermost part of the belt were soon accounted for. It was later pointed out by Dessler [1960] [also Dessler and Vestine, 1960] that the extremely high fluxes, implied by the X ray interpretation, would have modified the Earth's field above and beyond the changes actually observed. However, the uncertainty about the outer belt persisted until the work of Davis and Williamson [1963, 1966] and Frank's [1967] electron measurements with OGO 3.

In conclusion, it should be stressed here that the above is a very abbreviated summary of a complex period of discovery, and a much more detailed picture is available from Van Allen [1983a].

### 3. ARTIFICIAL BELTS AND EARLY STUDIES

Explorer 4 was built in a record 77 days from initiation to its launch on July 26, 1958, and it had two goals: (1) to study the new radiation belt in greater detail and (2) to observe an artificial radiation belt produced by high-altitude nuclear bombs, a project of the U.S. Air Force code-named Argus. The idea originated with



**Figure 2.** Counting rate of Explorer 3 during a pass through the radiation belt. The highest rate was encountered during the segment of zero counts.

Nicholas C. Christofilos, a Greek engineer who on his own had studied the motion of charged particles in magnetic fields [Foster et al., 1973]. Before the principle of strong focusing was incorporated in high-energy accelerators, Christofilos proposed it independently but was ignored. He came to the United States in 1953, started working at the Lawrence Livermore Laboratory in 1956, and there he proposed the Argus experiment, designed among other things to test on a large scale the confinement of charged particles in magnetic fields.

Three small bombs, carried by rockets launched from U.S. Navy ships [Christofilos, 1960] were detonated 100–500 km above the South Atlantic on 8.27, 8.30, and 9.6.58. Because of the remoteness of the site, the project remained a secret until its results were released the following year. Scientifically, it was a great success. Artificial aurora was observed at the other end of the field line (near the Azores) and Explorer 4 recorded artificial belts of high-energy electrons which decayed within a few weeks [Van Allen and Frank, 1959; Hess, 1968].

Up to this time, all explanations of the radiation belt linked it to the aurora, but in the second half of 1958 at least three investigators independently conceived a different explanation, related to cosmic rays: Singer [1958], Kellogg [1959], and Vernov [1959]. Cosmic rays are rapidly moving atomic nuclei (mostly protons) whose energies start in the GeV range and extend in diminishing numbers much higher. They arrive at the solar system from distant space, and when they collide with nuclei of the atmosphere, they produce a spray of secondary fragments.

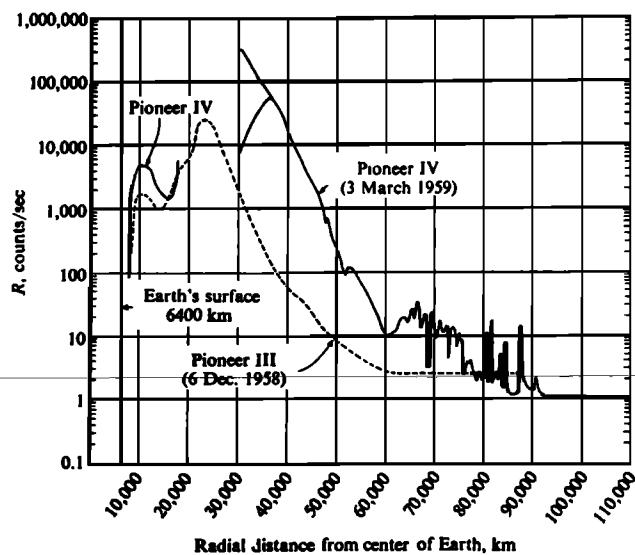
Most secondary particles from such collisions move earthward and are lost, but a small fraction ("albedo") is

splashed away from the Earth. If an electrically charged albedo particle has high energy, it either escapes or else is guided by magnetic field lines to the opposite hemisphere, where it is usually absorbed by the atmosphere. An albedo neutron, however, moves unimpeded until it decays into an electron, a neutrino, and a proton, with the latter receiving almost all the kinetic energy.

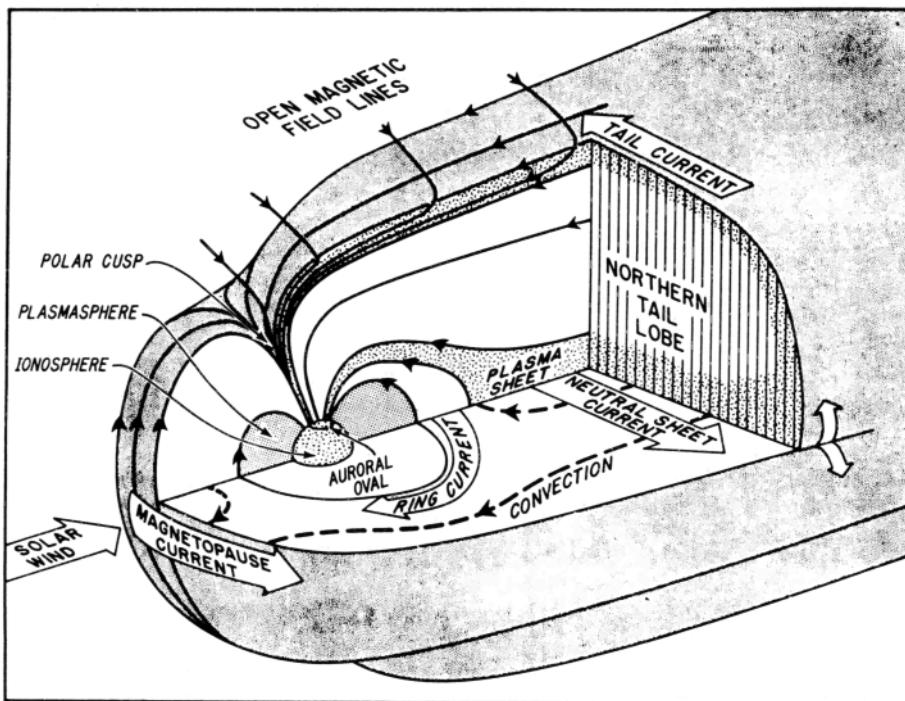
The mean decay time of a free neutron is about 10 min, but actual times for individual neutrons are distributed statistically and for a typical fragment energy of 20–50 MeV, a few neutrons may already decay within the first few hundredths of a second. The decay protons may then materialize deep enough in the magnetic field to remain trapped there, and their lifetime in such trapped orbits is long enough to allow an appreciable density of energetic protons to accumulate. This was what Singer, Kellogg, and Vernov proposed, and the existence of such protons was confirmed in 1959 by nuclear emulsions flown aboard rockets into the near-Earth radiation belt and later recovered [Freden and White, 1959; Hess, 1962; White, 1966, 1973].

In hindsight, it was realized much later that powerful shocks, created inside the magnetosphere by interplanetary shocks of solar origin, could on rare occasions accelerate protons near Earth to energies of many MeV. Thus the event of March 24, 1991, was observed to create a belt of 20-MeV protons just outside the inner belt of comparable intensity [Blake et al., 1992]. It is possible that a similar event produced the double-peaked structure of the inner belt observed by Explorer 15 [McIlwain, 1963].

Trapped radiation was, however, observed at much greater distances than albedo theory could explain. After the December 1958 flight of Pioneer 3, Van Allen and Frank [1959] concluded that there existed not one belt but two (Figure 3): an "inner belt" created by albedo



**Figure 3.** Counting rates of Pioneers 3 and 4, during traversals of the outer radiation belt [Van Allen and Frank, 1959].



**Figure 4.** Regions and currents of the Earth's magnetosphere, representing the state of our knowledge around 1970 [Lopez and Baker, 1994]. A small normal field component on the magnetopause allows some interplanetary field lines to link up with the Earth's field.

neutrons and an “outer belt” then believed to consist of energetic electrons from some other source, extending to distances of  $6\text{--}8 R_E$  (Earth radii) [Farley, 1963; O'Brien, 1963]. The outer belt was studied by Explorer 6, launched August 7, 1959 [Naugle, 1965]. Yet another particle population was added on July 9, 1962, when the Defense Atomic Support Agency (DASA) and the Atomic Energy Commission (AEC) exploded a hydrogen bomb (a project code-named Starfish) in the inner belt region. The bomb created an intense belt of MeV electrons [Brown *et al.*, 1963], which among other things damaged the solar arrays of satellites and caused three of them to fail soon afterward. Some Starfish electrons persisted for 5 years [Hess, 1968], underscoring the long lifetime of particles in the inner belt. NASA was caught by surprise: it retrieved an engineering model of Explorer 12 from one of its museum displays, hurriedly turned it into a regular satellite and launched it as Explorer 15, all within 91 days [Corliss, 1967, p. 728]. The Department of Defense reacted even more quickly, launching Starad (1962βκ; see Corliss [1967, p. 790]) within 60 days of the decision to launch the mission (M. Walt, personal communication, 1995). Before the international test ban took place, the former Soviet Union also exploded three large bombs, but these tests occurred on more distended field lines, and their radiation belts only lasted a number of weeks [White, 1966].

At first it was held that the aurora was simply the overflow of the outer belt [Van Allen *et al.*, 1959]:

... we propose that the radiation belt is the reservoir whose leakage of particles is the direct cause of visible aurora. It is further

suggested that solar plasma replenishes the reservoir from time to time, working its way into the outer reaches of the Earth's magnetic field when its density is sufficiently great, then being trapped in the field.

This was known as the “leaky bucket” theory, the bucket being the belt and the leak the aurora [O'Brien, 1967; Kennel, 1969, Figure 15]. Later it was pointed out [Dessler, 1960] that the high electron fluxes attributed to the outer belt should have significantly deformed the magnetic field. An experiment aboard Explorer 12, designed to resolve the problem, showed a large flux of positive ions, presumably protons [Davis and Williamson, 1963, 1966], energetic enough to penetrate the counters; this component later turned out to contain most of the energy. The outer belt also contained energetic electrons, but their intensity fell far short of the level needed to produce the aurora [O'Brien, 1962, 1964]. Opinion then shifted to the alternative “splash catcher theory” by which some outside mechanism was producing auroral electrons and the outer belt was merely a by-product, incidental splash captured from the main torrent.

#### 4. LARGE-SCALE STRUCTURE

The picture became much clearer during 1962–1965 [LeGalley, 1963], when the large-scale structure of the Earth's magnetic environment (named “magnetosphere” by Gold [1959]) was established (Figure 4). This phase followed the observational confirmation of the existence of the solar wind, predicted by Parker (see

BH-1). In 1962, Explorer 12 on the sunward side of the Earth repeatedly crossed a sharp boundary between the magnetosphere and the solar wind, named the “magnetopause” [Cahill and Amazeen, 1963; Cahill, 1995; Hines, 1963; Hess et al., 1965; Dungey, 1978] and resembling in many ways the boundary predicted (for storm times) by Chapman and Ferraro (see BH-1).

The following year Explorer 18 (or IMP 1, for Interplanetary Monitoring Platform) observed a collision-free bow shock ahead of the magnetopause [Ness et al., 1964], predicted by Axford [1962] and Kellogg [1962], and also established the properties of the long geomagnetic tail [Ness, 1965, 1987], briefly glimpsed in 1961 during the 52-hour mission of Explorer 10 [Heppner et al., 1963]. Those observations and others by Explorer 14 and the Vela satellites led to two predictions of a “tail” of the magnetosphere [Ness, 1969, p. 100]. Dessler and Juday [1965] predicted two bundles of magnetic flux trailing behind the Earth’s poles, twisted by the Earth’s rotation, with a current profile resembling the Greek letter  $\theta$ . Axford et al. [1965] predicted similar “tail lobes” but also suggested a layer of plasma in the equatorial region between them, carrying a cross-tail current which then closed around the tail magnetopause, also with a  $\theta$  profile. They furthermore suggested that the distant neutral line predicted by Dungey [1991] (section 7, below) was embedded in that plasma sheet. I. Axford (personal communication, 1992) has claimed that this work predated the disclosure of IMP 1 results.

IMP 1 and later IMPs confirmed Axford’s plasma sheet, finding it typically  $2\text{--}8 R_E$  thick, with a dawn-to-dusk electric current of order  $200,000 \text{ A}/R_E$ , and a plasma of  $\approx 0.5 \text{ ions cm}^{-3}$  of ions of 1–5 keV and electrons around 1 keV. The plasma of the tail lobes was very rarefied, typically  $0.01 \text{ ion cm}^{-3}$ .

The tail contained two low-density “tail lobes,” bundles of roughly parallel field lines directed sunward in the northern lobe and antisunward in the southern lobe, as required for field lines connected to the appropriate polar caps of the Earth (compare Dessler and Juday [1965]). Sandwiched between the lobes was a near-equatorial “plasma sheet.” The fact that the sheet was bounded by oppositely directed magnetic fields showed that it carried a dawn-to-dusk electric current of the order of  $200,000 \text{ A}/R_E$ , and this current closed around the magnetopause, giving the entire flow pattern the profile of the Greek letter  $\theta$  [Axford et al., 1965; Axford, 1994].

The earthward edge of the plasma sheet contained ions of about 20 keV, and these blended continuously with the ions of the ring current [Frank, 1971]; on the other hand, the energetic electron population of the sheet [Vasyliunas, 1968] displayed an asymmetrical inner edge. (Because of the presence of low-energy electrons, this does not contradict the plasma’s electrical neutrality.) The inner edge was originally credited to electrons precipitated into the atmosphere by plasma instabilities [Kennel and Petschek, 1966], but in hindsight it might

also be related to region 2 Birkeland currents (below), carried almost entirely by electrons.

The existence of a “ring current” circling the Earth during magnetic storms was inferred long before the spaceflight era, from the magnetic signatures of such storms, and was the subject of extensive speculation [Smith, 1963]. Observations in space indicated that it was carried by trapped particles of relatively low energy, as had been suggested by Singer [1957] and that it was not a transient effect of storms but a permanent feature. It was studied (launch dates given in parentheses) by the Orbiting Geophysical Observatories [Ludwig, 1963; Jackson and Vette, 1975] OGO 1 (September 5, 1964), OGO 3 (June 7, 1966), and OGO 5 (March 4, 1968), later by Explorer 45 (“Small Scientific Satellite” or S<sup>3</sup> (November 15, 1971)) [Longanecker and Hoffman, 1973] and by the European GEOS 1 (April 20, 1977) and GEOS 2 (June 14, 1978). Its energy is mainly carried by ions with energies around 100 keV [Frank, 1967], but its exact composition and energy (median value  $\approx 85 \text{ keV}$ ) were only mapped by the Charge Composition Explorer (CCE) of the AMPTE mission, launched in 1984 [Williams, 1987; Lui and Hamilton, 1992].

The ring current grows stronger during magnetic storms, and it was shown theoretically that the intensity of the magnetic disturbance observed at Earth is then very nearly proportional to its total energy [Dessler and Parker, 1959; Sckopke, 1966; Carovillano and Siscoe, 1973]. Between such injections the ring current slowly decays, mostly by charge exchange collisions [Liemohn, 1961; Smith et al., 1976] with atoms of the hydrogen cloud (“geocorona”) surrounding the Earth [Hunten and Donahue, 1976; Carruthers et al., 1976]. Each collision produces a slow proton and a fast neutral atom; such high-energy atoms are able to trigger particle counters, and since they are (like albedo neutrons) unaffected by the Earth’s magnetic field, it has been proposed to use them for remote sensing of the ring current [Williams et al., 1992]. In 1971 it was also observed that a sizable portion ( $\approx 15\%$ ) of the particles added to the ring current during a magnetic storm were O<sup>+</sup> ions of atmospheric origin, evidence of a near-Earth acceleration process [Shelley et al., 1972].

A special region is the polar cusp, the region inside the high-latitude dayside magnetopause which separates field lines that close near the “nose” of the magnetosphere from those swept into the tail. The cusp was first explored in 1969–1972 by the European spacecraft HEOS 1 and HEOS 2 (and later by Iowa’s Hawkeye 1), which found a region of disordered weak magnetic fields [Mencke-Hansen, 1976]. Such fields are unable to exclude the solar wind, or more accurately, the magnetosheath plasma, a name given by Dessler and Fejer [1963, Figure 1] to the solar wind plasma slowed and heated by passage through the Earth’s bow shock. It is therefore filled with magnetosheath plasma, which spills into a funnel-shaped region reaching all the way to the

atmosphere and produces a characteristic auroral glow [Shepherd, 1979].

The HEOS satellites also discovered a variety of boundary layers just inside the magnetopause, with a thickness of the order  $0.3\text{--}1 R_E$ , typical density  $1\text{--}3 \text{ cm}^{-3}$  and typical tailward velocity of  $100\text{--}150 \text{ km s}^{-1}$ . A narrow “low-latitude boundary layer” was found on the dayside [Paschmann *et al.*, 1976] and may be the result of reconnection processes (below) near the nose of the magnetosphere, though other origins are also possible. The much thicker “plasma mantle” found at high latitudes tailward of the cusp [Rosenbauer *et al.*, 1975] may be formed by sheath plasma crossing an Alfvénic transition extending from the site of magnetic reconnection, discussed further below [Levy *et al.*, 1964], and it gradually widens with increasing distance from Earth [Hardy *et al.*, 1975, 1979].

In what follows, coordinates in the magnetosphere will be given in the so-called geocentric solar magnetospheric coordinate system (GSM), described by Russell [1971] [also Hapgood, 1992]. In these coordinates, the  $x$  direction points to the Sun, the  $x$ - $z$  plane contains the Earth’s dipole axis and north is on the positive side of the plane  $z = 0$ . The  $x$  direction is also assumed to be the one from which the solar wind is blowing, although in very accurate work the small aberration angle ( $\approx 4^\circ$ ) due to the Earth’s orbital motion is also taken into account. The actual observed direction of the solar wind may differ from this by a few degrees (in both elevation and azimuth) as a result of effects occurring closer to the Sun.

## 5. CONVECTION

The processes producing the complex features of the magnetosphere must meet two requirements: sufficient energy must be available, and particles must somehow be accelerated to observed energies. As for the supply of energy, it was estimated [Axford, 1964; Stern, 1984] that about 1–2% of the solar wind energy impinging on the magnetopause cross section is tapped by internal processes of the magnetosphere.

In the neutral atmosphere of the Earth, energy is usually transmitted by two mechanisms: (1) by large-scale circulating flows which convect heat from the ground upwards and (2) by radiation which takes a more direct path. The magnetosphere, too, may transmit energy both by convective flows and by a more direct route, involving field-aligned currents.

In an ideal magnetized plasma, a steady bulk flow with velocity  $\mathbf{v}$  requires the existence of an electric field  $\mathbf{E}$ , satisfying the “ideal magnetohydrodynamic (MHD) condition” [e.g., Walén, 1946; Alfvén, 1950]

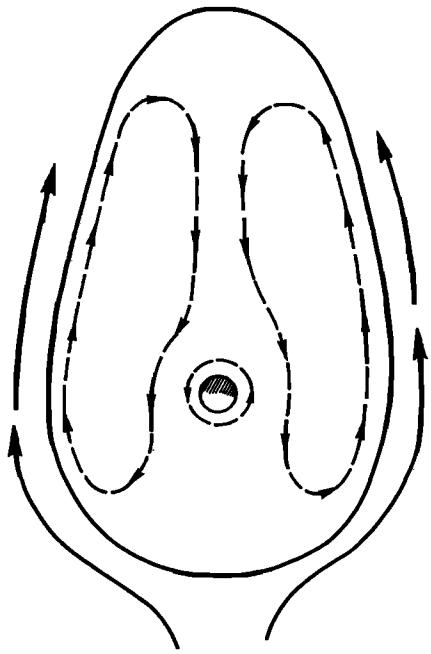
$$\mathbf{E} = -\mathbf{v} \times \mathbf{B} \quad (1)$$

Conversely, an electric field  $\mathbf{E}$  impressed on a magnetospheric plasma produces a bulk flow satisfying (1). It is a property of (1) that “particles move with field lines,” that is, any group of ions or electrons sharing a field line at one time continues doing so ever after, and a “moving field line” in what follows will mean a moving string of plasma particles, threaded by a common field line. If  $\partial\mathbf{B}/\partial t = 0$ , the magnetic configuration is fixed and on any “moving” line, the plasma population along its entire length migrates to an adjoining line: thus field lines can (for instance) transmit bulk motions from distant regions to their ionospheric ends. In inductive electric fields with  $\partial\mathbf{B}/\partial t \neq 0$ , field line sharing also holds [Newcomb, 1958; Stern, 1966], but bulk motion is not necessarily transmitted along field lines [Stern, 1990, Figure 7].

The existence of the Chapman-Ferraro cavity (see BH-1) and hence of the magnetopause may be viewed as another consequence of field line sharing: as long as such sharing is rigorously enforced, there exists no way for interplanetary plasma, threaded (presumably) by fields of solar origin, to mix with plasmas of the Earth’s field. For related reasons, as long as all terrestrial field lines are confined to the cavity’s interior (“closed magnetosphere”), it is also difficult for energy, momentum, and electric currents to enter the cavity from the outside. In the early days many scientists in fact believed that magnetospheric field lines were in this way completely confined inside the cavity. The alternative view of an “open” magnetosphere developed gradually and is discussed in sections 7 and 8.

Gold [1959, p. 1220] noted that the large-scale flow of magnetospheric plasma (a type of which he was studying) “is quite analogous to thermal convection” and that led to the term “convection” used by Axford and Hines [1961] to describe large-scale circulation inside the magnetosphere, caused by the solar wind. The theory of Alfvén [1939] (see BH-1, also Cowling [1942] and Stern [1977]), although not consistently formulated, may also be viewed as a theory of magnetospheric convection. Contemporary theories began with Axford and Hines [1961] [also Hines, 1974, p. 3, 933; Axford, 1962, 1964, 1994; Hines, 1964, 1986] and with the work of Dungey [1961] described further below. Axford and Hines proposed a convective circulation to explain an observed pattern of auroral motions [Davis, 1962, 1971] in which plasma seemed to circulate in the polar cap.

Axford and Hines visualized a magnetosphere whose field filled a cavity in the solar wind, elongated on its nightside into a tail, as previously suggested by Johnson [1960], so that all field lines emanating near the magnetic pole extended into the tail. Their proposed convective flow pattern (Figure 5a) carried plasma tailward along the flanks and returned it by means of a sunward flow near the  $x$  axis, skirting around the region closest to Earth. They furthermore suggested that such a flow could be caused by a viscous-like momentum transfer from the solar wind to adjacent regions of the tail,



**Figure 5a.** Schematic view of the convection pattern produced in a closed magnetosphere by viscous-like forces, as envisioned by Axford and Hines.

although they admitted that other processes could produce similar flows in the polar cap, including Dungey's reconnection scenario (further below).

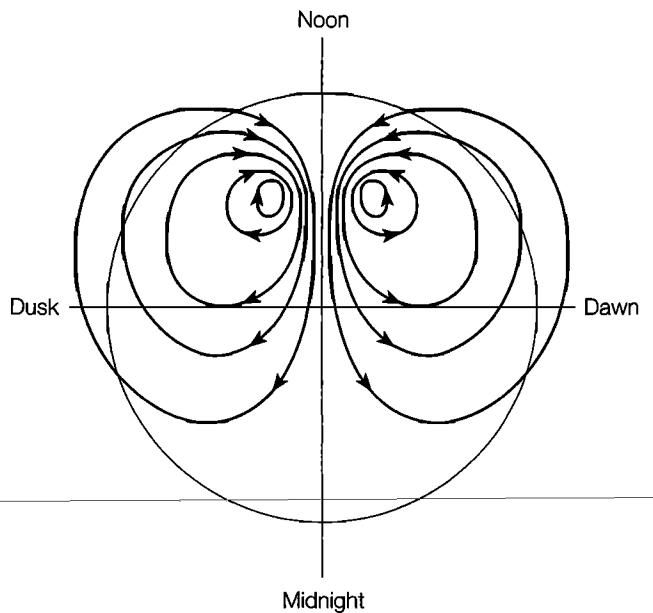
When the flow pattern of Figure 5a is mapped along field lines to the polar ionosphere, it produces a two-cell flow pattern, with plasma streaming nightward across the pole and returning to the dayside at lower latitudes, with flow lines similar to the contours in Figure 5b. By (1), if  $\mathbf{E} = -\nabla\Phi$ , it follows that  $\mathbf{v} \cdot \nabla\Phi = 0$  and therefore the plasma flow lines in Figure 5b are also lines of constant electric potential  $\Phi$ , suggesting a dawn-to-dusk electric field across the polar caps. Satellites in a low-altitude polar orbit can observe such a field directly, by measuring the small voltage difference between the tips of a long antenna [Aggson, 1968; Cauffman and Gurnett, 1972]. The first satellites to successfully conduct such observations were Iowa's Injun 5 [Cauffman and Gurnett, 1971] and the OGO 6 observatory [Heppner, 1972a, 1977]; some later missions, for example, Atmosphere Explorer 1 and Dynamics Explorer 2, measured  $\mathbf{E}$  indirectly using "drift meters" which observed  $\mathbf{v}$  through the anisotropy of particle fluxes caused by the plasma's bulk motion [Hanson and Heelis, 1975; Heelis et al., 1981].

The observations confirmed the two-cell pattern and obtained typical voltage drops of 40–70 kV; this agreed with a prediction of the reconnection model by Levy et al. [1964, section VI]. Much depends upon the state of the interplanetary magnetic field (IMF). The two-cell pattern is most stable when the IMF has a southward slant ( $B_z < 0$ , see below), and it contains asymmetries correlated with the dawn-dusk  $B_y$  component of the IMF [Heppner, 1972c; Heppner and Maynard, 1987]. The

cross-polar voltage drop  $\Delta\Phi$  on the average grows with southward  $B_z$ , though individual observations fluctuate greatly. With northward  $B_z$  the average  $\Delta\Phi$  sometimes decreases to less than 20 kV, and it has been suggested that at such times it may "bottom out" at a low level contributed by a viscous-like interaction at the flanks [Reiff et al., 1981; Wygant et al., 1983].

When the IMF has a northward slant, the two-cell pattern becomes distorted and  $\mathbf{E}$  is often irregular. At times, nonstandard patterns may develop, such as the four-cell pattern deduced by Burke [1979]. More complex patterns have also been claimed [Reiff and Burch, 1985], but they are hard to confirm without simultaneous passes by a fairly large number of satellites.

In the innermost magnetosphere the plasma density  $n$  is dominated by the thermal ionospheric plasma which tends to corotate with Earth; this is another consequence of field line sharing [Ferraro, 1937] and is enforced by a corotation electric field  $\mathbf{E}_{CR}$ , which near Earth is much larger than the convection field  $\mathbf{E}$ . It was found from whistler wave observations [Carpenter, 1963; Carpenter and Park, 1973] and later by in situ observations that  $n$  often dropped precipitously from  $\approx 20$ – $100$  ions  $\text{cm}^{-3}$  to  $\approx 5$  ions  $\text{cm}^{-3}$  at a "plasmapause" boundary on field lines that extended to  $4$ – $5 R_E$ . Brice [1967] [also Kennel, 1985] and Nishida [1966] proposed that this was essentially the boundary of the region where low energy plasma shared the rotation of the Earth; beyond it the convection electric field  $\mathbf{E}$  overpowered  $\mathbf{E}_{CR}$ . This view is now widely accepted, although the suggestion was also made [Lemaire, 1975] that the plasmapause was the limit beyond which low-energy plasma was easily lost



**Figure 5b.** Schematic view of the convection in Figure 5a when mapped along field lines to the polar cap. Ideally, the contours are also equipotentials of the electric field, which near the center of the pattern is directed from dawn to dusk.

through the interchange instability, an approach first explored by N. M. Brice (*Differential drift of plasma clouds in the magnetosphere*, unpublished manuscript, 1973).

## 6. RECONNECTION

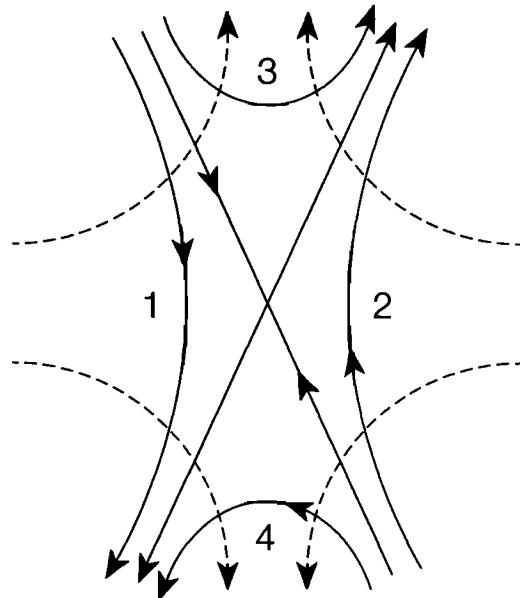
As early as 1942, cosmic ray detectors observed the arrival of high-energy ions associated with solar activity, reaching at times up to  $\approx 10$  GeV [Forbush, 1946; Pomerantz, 1984; Van Allen, 1993]. For many years such events were credited to solar flares, although recent evidence points to a much better correlation with coronal mass ejections [Gosling, 1993]; their most plausible energy source, then as now, seems to be the intense magnetic field of sunspots. It was speculated that somehow part of that field was “annihilated” by a rapid process and its energy used to accelerate ions and electrons, the latter revealed indirectly by intense bursts of radio noise, and more recently, by X rays.

The process most favored for such energy release was magnetic merging or magnetic reconnection (synonymous terms). It may be loosely defined as a flow of plasma in which some of the field lines threading the plasma pass through a neutral point or neutral line at which the magnetic field vanishes. The idea originated with Giovanelli [1947] [also Hones, 1984b] and was then developed by Sweet [1958] and especially by Dungey [1953, 1963, 1994, 1995] [also Stern, 1986].

The starting point is the observation that the field line sharing property associated with (1) can be violated if plasma flows through a neutral point (Figure 6) where  $B = 0$  and where the field's direction is undetermined. In the X-type neutral point drawn here (actually a neutral line if this configuration extends unchanged into the third dimension) field lines cross in the pattern of the letter X and plasma arriving on field lines of the regions 1 and 2 depart on differently connected lines in regions 3 and 4. Dungey, Sweet, and others proposed that this process might somehow modify the large-scale magnetic configuration and thereby release magnetic energy. Particles would be accelerated by the electric field associated with the motion, producing fast jets of plasma flowing away from the neutral line as the plasma exits on lines in regions 3 and 4, and shocks which heat the plasma [Levy *et al.*, 1964].

Additional effects must be invoked, for by (1), if  $E$  is finite and  $B \rightarrow 0$ , the velocity  $v$  which particles need to keep up their field line sharing property becomes infinite. Sweet [1950] showed that in conducting fluids with finite resistivity the plasma's motion lags behind that of field lines, and therefore reconnection theories have often assumed a finite (but small) resistivity in the region near  $B = 0$ . Other processes which preclude an infinite  $v$  may also play a role, for example, ion or electron inertia [Vasyliunas, 1975, Table 2].

A somewhat different type of process (“group 2 merg-

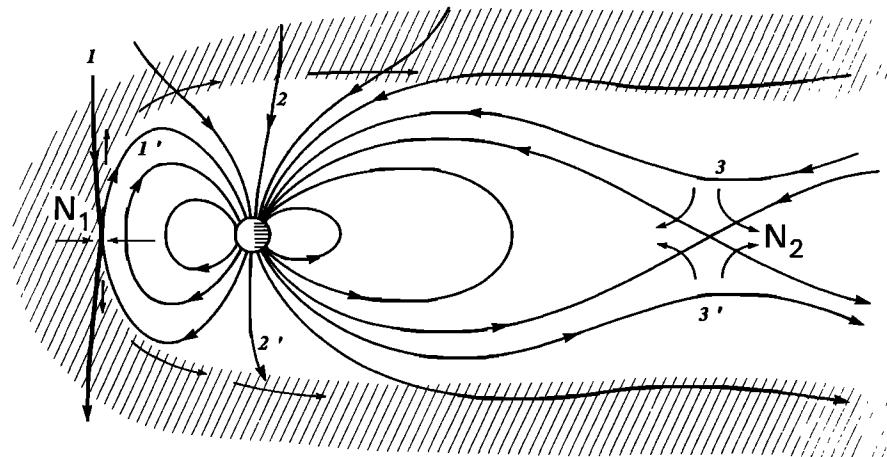


**Figure 6.** Magnetic merging at an X-type neutral line. Solid lines are magnetic field lines, dashed lines flow lines of the plasma.

ing” of Vasyliunas [1975, p. 307]) is illustrated by the collision of two bodies of plasma permeated by magnetic fields of equal intensity but opposing directions, separated by a “neutral sheet” of zero field intensity. The plasma may emerge as a narrow stream along the sheet, perpendicular to field lines, its magnetic field “annihilated,” and its particles accelerated by the attendant  $E$ , though its electric neutrality may pose problems [Stern, 1990].

Magnetic reconnection is relevant to magnetospheric physics in two distinct ways: it makes possible a realignment of field line connections, for example, the establishment of a linkage between the Earth's field and the IMF, and it may also release magnetic energy and accelerate particles. The first aspect is important to the concept of the open magnetosphere, the second to substorms, two items discussed separately further below.

As noted earlier, many researchers arrived at magnetospheric physics from the study of solar energetic particles, and they brought with them an interest in reconnection [Parker, 1963]. That led to a 1963 symposium at Goddard Space Flight Center [Hess, 1964] where, among other things, the theory of Petschek [1964, 1995] was presented, giving a more detailed scenario of the reconnection process. Important references to later work may be found in a comprehensive review by Vasyliunas [1975], in the proceedings of a 1984 conference at Los Alamos [Hones, 1984a] and in reviews by Sonnerup [1979] and by Forbes and Priest [1987]. Avenues explored nowadays include the relation to tearing instabilities in plasmas [Schindler and Birn, 1978], reconnection at multiple points [Lee and Fu, 1985], and relations to chaotic field line topology [Hesse and Schindler, 1988]. A grow-



**Figure 7.** Schematic view of Dungey's original view of the open magnetosphere, for a purely southward interplanetary magnetic field (IMF).

ing number of studies simulate reconnection by means of fast computers.

There exists some evidence for reconnection from direct observations at the dayside magnetopause [e.g., Paschmann *et al.*, 1979; Sonnerup *et al.*, 1981], but it is difficult to verify details of the mechanism. In regions where reconnection seems likely to occur, magnetic fields are quite variable, and with isolated spacecraft it is almost impossible to extract their structure. The existence of a rarefied “depletion layer” outside the magnetopause, seen only when the directions of  $\mathbf{B}$  inside and outside are similar, is taken as evidence for reconnection. Claims have also been made that characteristic oscillations of the magnetic field observed near the dayside magnetopause, associated with southward interplanetary magnetic field (IMF) and termed “flux transfer events” [Russell and Elphic, 1978, 1979; Elphic, 1994], are local signatures of “patchy reconnection,” but in spite of extensive studies, such events remain poorly understood.

## 7. THE OPEN MAGNETOSPHERE

Reconnection was first applied to magnetospheric physics by Dungey [1961], as the key ingredient of his alternative theory of convection. Dungey proposed that an X-type neutral point (or line) at the front of the magnetosphere enabled terrestrial field lines to link up with interplanetary ones and produce “open” field lines, with one end on Earth and the other in distant space.

Figure 7 gives Dungey's original scenario, which assumed a purely southward directed interplanetary magnetic field (IMF). Lines 1 and 1' merge at a sunward X-type point (denoted by  $N_1$ ) to produce open lines 2 and 2', carried tailward by the solar wind in which they are embedded, to positions such as 3 and 3'. Ultimately, these field lines reconnect at a distant neutral point  $N_2$  in

the tail, to produce an interplanetary field line which is carried away by the solar wind, and a “closed” line attached to Earth at both ends. The newly closed field line then flows sunward in the third dimension until it becomes the closed field line 1' which reconnects with 1. It is often held that these points are broadened to neutral lines of finite length in the direction perpendicular to the drawing, to accommodate the finite rate of flux reconnection.

The polar convection pattern and the polar electric field resulting from this motion qualitatively resemble those expected from the viscous-like drag proposed by Axford and Hines. The magnetopause now is no longer a surface containing field lines but instead is often identified with an observed sharp discontinuity in the magnetic field, interpreted theoretically as a shock transition related to magnetic reconnection. It will have a normal magnetic component  $B_n$  which, by all predictions, is quite small ( $\approx 0.5\text{--}1\text{ nT}$ ), making it difficult to confirm or refute this scenario by *in situ* magnetic observations.

Reconnection at  $N_1$  probably imparts little energy to the plasma. Its real significance is the creation of “open” field lines such as 2 and 2', linked to both the solar wind and the ionosphere. Because electric currents in a plasma flow easily along field lines, such lines can form a dynamo circuit, a closed circuit part of which traverses a medium moving relative to the rest. A circuit of this kind (ABCD in Figure 8) can drive an electric current and produce an electric field in the polar ionosphere: its energy is obtained by slowing down the moving solar wind or mantle plasma threaded by it, and much of that energy is then deposited as ohmic heat in the ionospheric part of the circuit. Note that the currents in this circuit (in both polar caps) flow earthward on the morningside of the pole (AB) and away from Earth on the eveningside (CD), which is also the pattern of region 1 Birkeland currents (below). If the tail current follows the “θ pattern” of Axford *et al.* [1965] [also Dessler and Juday,

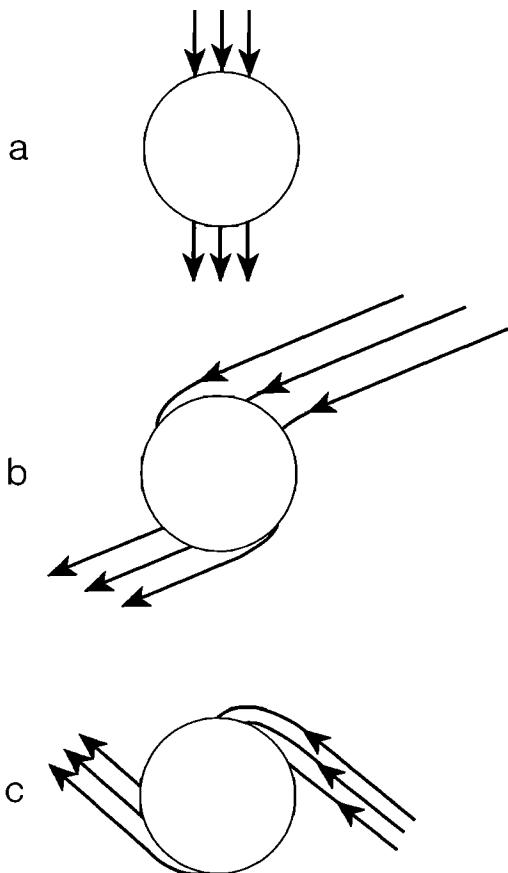
1965], the circuit EFGH may also be viewed as a dynamo, supplying energy that heats the plasma sheet.

## 8. OBSERVATIONAL TESTS

Dungey's process is expected to operate best if the IMF is purely southward, for then the IMF direction matches that of the Earth's polar field lines which link up with it (Figure 9a). If the  $B_z$  component of the IMF is southward (negative) but additional components also exist, the situation is known as "southward IMF": the linkage is still relatively easy, but interplanetary field lines must bend somewhat to make the connection (Figure 9b). The bending becomes severe if  $B_z > 0$  ("northward IMF"), because interplanetary field lines then start out headed for the "wrong" pole (Figure 9c).

A major boost for Dungey's ideas was the discovery [Fairfield, 1966, 1967] that the level of magnetospheric "storminess" and of energy transfer from the solar wind to the magnetosphere depended strongly on IMF  $B_z$ . During southward IMF substorms are more frequent, the polar caps (assumed to contain open field lines) are fairly large and display a well-defined two-cell convection pattern, and auroral ("Birkeland") currents (further below) are steady and strong. At times of northward IMF the magnetosphere is much quieter, the polar caps shrink and their E weakens. The effect is asymmetrical: when  $B_z$  is southward, increases in its magnitudes are correlated with increased activity, but the magnitude of a northward  $B_z$  seems to matter little [Burton *et al.*, 1975]. A strong dependence of magnetospheric behavior on IMF  $B_z$  was later demonstrated by numerical simulations of the magnetosphere, conducted on fast computers and based on the MHD equations [e.g., Walker *et al.*, 1993].

The Svalgaard effect [Svalgaard, 1968, 1972, 1973; Mansurov, 1969; Wilcox, 1972] is another interesting

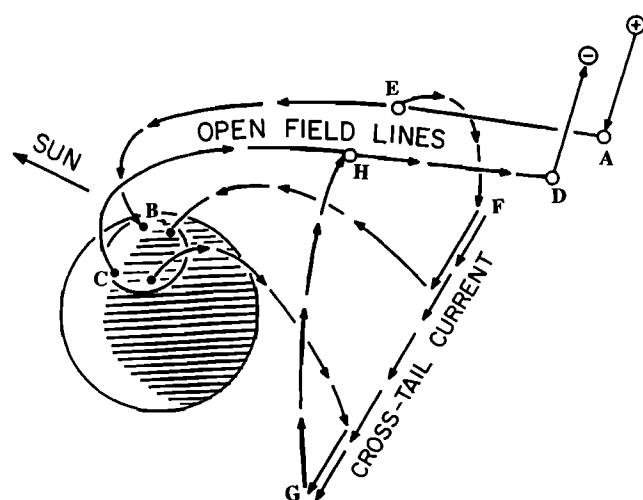


**Figure 9.** Cartoon of the connection of the IMF to the magnetosphere, for various IMF orientations: (a) purely southward IMF; (b) southward slanting IMF; (c) northward slanting IMF.

piece of evidence for a linkage between the IMF and terrestrial field lines. That is an asymmetry in the daily variation in polar regions, correlated with the interplanetary  $B_y$  component.

Owing to the interplay between solar wind outflow and the Sun's rotation, IMF field lines near Earth tend to lie close to the  $(x, y)$  plane, with  $\mathbf{B}$  in the  $(x, -y)$  and  $(-x, y)$  quadrants and making an angle of about  $45^\circ$  with the  $x$  axis, as predicted by Parker. Such lines can have one of two polarities: away from the Sun or toward it, corresponding to positive or negative  $B_y$ . Wilcox and Ness [1965; Wilcox, 1972] studied the prevalence of such polarities and showed that they tended to persist over times of a week or two, suggesting that the IMF in the plane of the ecliptic formed large-scale "sectors" of outward pointing or inward pointing field lines, corotating with the Sun. Often only two sectors exist, but at times they are more numerous, depending on the distribution of magnetic field sources on the Sun.

In 1926, K. Lassen established a magnetic observatory on Greenland which among other things observed the local daily magnetic variation. Around 1968, Svalgaard noted that the variation on quiet days could be classified as belonging to one of two patterns, and Wilcox suspected these correlated with interplanetary sectors. A



**Figure 8.** Transmission of electric fields along open field lines and to the cross-tail circuit.

large “blind” test was conducted [Friis-Christensen *et al.*, 1971] and it confirmed the effect. The phenomenon might be connected with the  $B_y$ -related asymmetry in the pattern of polar E, later found by Heppner [1972b]; it would be hard to explain, if terrestrial field lines had no link to the IMF.

Another observation suggesting the existence of “open” field lines is the asymmetric access to the polar caps of the high-energy tail (“strahl”) of solar wind electrons ( $\approx 0.5$  keV), producing the “polar rain” precipitation. Depending on the IMF sector in which the Earth is immersed, that “rain” is much more intense in the polar cap whose magnetic polarity allows direct connection to the Sun [Yaeger and Frank, 1976].

Problems in observing merging near  $N_1$  were already described. The distant nightside neutral line  $N_2$  has never been clearly identified: its signature should be a reversal of  $B_z$  from northward ( $B_z > 0$ ) to southward ( $B_z < 0$ ). Around 1983, when ISEE 3 probed the distant tail, it observed that periods of  $B_z < 0$  became more frequent at distances greater than  $\approx 130 R_E$  [Slavin *et al.*, 1985], but that was only a statistical average of a rather variable quantity.

ISEE 3 has also shown [Slavin *et al.*, 1985] and Geotail has confirmed, that in the distant tail past  $\approx 100 R_E$ , plasma flowed tailward at velocities that tended to increase with distance, up to where they about matched the velocity of the solar wind. This might be due to viscous transfer of plasma and momentum but could also be the result of reconnection.

## 9. THE POLAR AURORA

Fritz [1881] [also Eather, 1980] estimated that, given clear skies, aurora could be observed about 100 nights a year in the region where it was most frequent. However, imaging cameras aboard satellites, more sensitive than the eye, observe a ring of diffuse aurora around the polar cap at most times. In magnetic coordinates ( $z$  along the dipole axis, the Sun’s direction in the  $x$ - $z$  plane) the region where aurora is likely to occur forms a fixed pattern around the magnetic pole, known as the auroral oval [Feldshtain, 1963, 1969]. That pattern is approximately circular, centered about  $5^\circ$  nightward of the magnetic pole [Meng *et al.*, 1977], and the Earth rotates beneath it. The oval also expands and contracts with magnetic activity: its typical radius equals  $17^\circ$  of latitude. The reason the aurora is a rare sight at lower latitudes is that it only appears there when the oval is grossly expanded.

For many years the identity of the primary particles producing the aurora was uncertain, although laboratory experience suggested that they behaved like cathode rays, that is, electrons. Harang [1951, p. 140] wrote

It has been commonly assumed that the electrically charged particles producing the aurorae are cathode-rays, although no definite proof of this hypothesis can be given. The possibility of positive

rays,  $\alpha$  rays or protons being the primary cause of aurorae cannot be excluded.

Harang observed that the aurora penetrated to altitudes of 95–115 km, and assuming its particles were electrons, he deduced energies of 15–30 keV. The particles were first observed directly and identified as electrons in 1954, by a Geiger counter aboard a high-altitude rocket of the University of Iowa [Meredith *et al.*, 1955]; using data from a later rocket flight, McIlwain [1960] estimated a mean auroral electron energy of 6 keV. The usual greenish-grey glow of the aurora comes from the combination of  $N_2^+$  bands and the 5577-Å line of oxygen, but other wavelengths are also emitted: some emissions are in the ultraviolet and are often used by imaging cameras aboard spacecraft, while deep red auroras at high altitudes are produced by lower-energy electrons which excite primarily the 6300-Å line of oxygen.

Global studies of auroral electrons were first conducted by an Australian associate of Van Allen, Brian O’Brien, using the University of Iowa’s “Injun 1” satellite, launched in 1961 and named for the “Injun territory” in which Iowa was formed. Later Injun 3 measured the distribution of arrival directions of auroral electrons (pitch angles) and also their total energy flux and found the latter too high to be explained by the “leaky bucket” model [O’Brien and Taylor, 1964].

Among the many satellite observations of the aurora performed since that time, the most striking ones have been produced by imaging cameras, from which a global view of the entire oval can at times be obtained. The earliest images came from the Canadian ISIS 2 spacecraft, launched April 1, 1971 [Lui and Anger, 1973], and they revealed for the first time the true dimensions and significance of the diffuse aurora (below). Scientifically useful results were also obtained from military imagers aboard spacecraft of the U.S. Air Force [Pike and Whalen, 1974], especially those of the Defense Meteorological Satellite Program (DMSP) series, which continues to this day; later DMSPs also carried a variety of scientific sensors. The Dynamics Explorer satellite DE 1, launched August 3, 1981 [Hoffman, 1988], carried a particularly successful imager [Frank and Craven, 1988], and more recently, several other satellites employed imagers, in particular the two Swedish spacecrafts Viking [Viking Science Team, 1986; Hultqvist, 1987] and Freja, and also the Japanese Akebono [Tsuruda and Oya, 1991].

Different types of aurora may be distinguished. The brightest auroras are discrete arcs and bands. Their structure may include multiple parallel curtains, folds (“striations”), and swirls of various sizes [Hallinan, 1976]. A typical electron energy spectrum in the discrete aurora [Boyd, 1975], observed above the atmosphere (Figure 10), has a peak around 5 keV and falls off steeply around 10–15 keV, while below 1 keV a large population of secondary electrons seems to exist. During substorms (sections 12–14) the aurora greatly intensifies, and the region of such arcs expands equatorward and

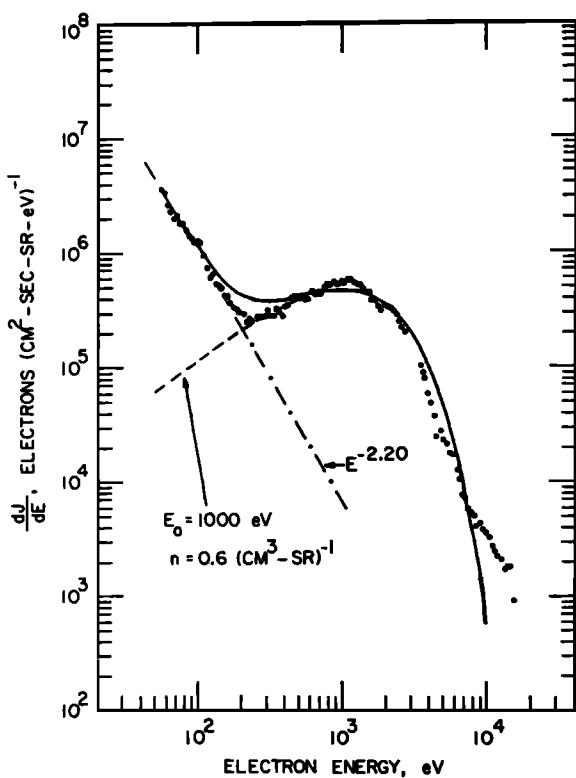


Figure 10. An example of the auroral energy spectrum, from Frank and Ackerson [1971].

intermittently poleward. The poleward expansions are highly dependent on local time and on the phase of the substorm.

The diffuse aurora is fainter (detectable on the ground by photometers but not usually by the eye), and it tends to extend around the entire auroral oval; its significance was only realized after its global configuration was seen by ISIS 2 [Lui and Anger, 1973]. It appears to be produced by electrons of the plasma sheet (typical energy, 1 keV) scattered into orbits that intercept the atmosphere. A midlatitude red aurora [Rees and Roble, 1975], produced by low-energy electrons from the ring current, is usually subvisual and was discovered by Barbier [1958]. A red aurora also appears in the regions linked to the polar cusps [Shepherd, 1979], caused by magnetosheath electrons that reach the ionosphere.

“Sun-aligned arcs” appear during northward IMF and extend from the auroral oval into the polar cap, pointing roughly sunward. They were observed by Gustafsson [1967], who felt that they were part of the regular pattern at high latitudes, rather than a separate branch; later they were studied by the ISIS 2 imager [Ismail et al., 1977] and were found to be associated with low activity and northward IMF [Burch et al., 1979]. Sometimes they stretch completely across the polar cap, forming a “theta aurora” [Frank, 1986], so called because the combined pattern of the auroral oval and the arc across its middle resembles the letter theta. No generally accepted explanation of these phenomena ex-

ists, and in general, the behavior of the magnetosphere during prolonged northward IMF is still poorly understood, although some interesting convection patterns in the distant tail, during such times, were recently noted by Nishida et al. [1995].

## 10. FIELD-ALIGNED VOLTAGE DROPS

Before the spaceflight era it was often held that auroral particles came from the Sun (see BH-1). Satellite observations suggested that the acceleration process took place in the magnetosphere, but until 1974–1977 it was widely believed that for electrons of auroral arcs, the most conspicuous and energetic type, this happened far from Earth, probably in the plasma sheet. Then Evans [1974, 1976a, b] proposed that the electrons that produced auroral arcs received much of their energy from field-aligned voltage drops within 1–2  $R_E$  of Earth. Evidence from the S3-3 satellite (below) soon convinced the community that this indeed was the case.

Previously, many theorists believed that field-aligned voltage drops (a “parallel electric field”  $E_{||}$ ) were unimportant in magnetospheric physics, because electrons and ions moving along field lines would immediately cancel any electric charges that produced such drops. In many plasma situations, this indeed holds true. However, Alfvén [1963] and his student Persson [1963, 1966] argued that  $E_{||}$  could exist if it was balanced by the “mirror force” opposing the entry of charged particles into regions of converging field lines. Such a possibility was also known in laboratory plasma physics [Grad, 1966] and is behind the operation of plasma containment machines of the tandem mirror type.

The Alfvén-Persson solution will not persist in the magnetosphere under static conditions, without a constant input of energy. However, observations indicate a strong correlation between discrete arcs, where acceleration often occurs, and field-aligned Birkeland currents (section 11). On a distended field line the bundle of orbits that reaches the ionosphere (“loss cone”) may be too small to carry the line’s share of the Birkeland current, and under such conditions, the existence of  $E_{||}$  widens the loss cone and increases the line’s capacity to carry current [Knight, 1973; Chiu and Schulz, 1978]. It is thought that such lines appropriate part of the voltage of the Birkeland circuit to provide them with the necessary  $E_{||}$ .

An important feature of the Alfvén-Persson theory is that the field-aligned potential  $\Phi$  is proportional to the intensity  $B$  of the magnetic field. A dipole field weakens with distance like  $r^{-3}$ , hence  $B$  drops by 7/8 of its value within 1  $R_E$  of the Earth’s surface, and the theory therefore predicts that the main drop of  $\Phi$  should also occur close to Earth. As will be seen, the appearance of  $E_{||}$  seems to be associated with field-aligned currents (further below). Some theorists have also suggested that  $E_{||}$  may arise from an “anomalous resistivity” along mag-

netic field lines, produced by plasma wave instabilities affecting field-aligned currents [Papadopoulos, 1977]; such processes, too, favor low altitudes where such currents have their highest density. Plasma wave instabilities are probably the source of the intense auroral kilometric radiation (AKR), discovered by Gurnett [1974]. AKR was detected before that by the first Radio Astronomy Explorer RAE 1 [Stone, 1969], but its nature and source were not recognized, and the only consequence was a decision to place the follow-up satellite RAE-2 in an orbit around the moon, away from the interfering noise.

Evans [1974] proposed that many of the low-energy electrons in discrete arcs were secondaries from collisions, temporarily trapped, unable to reach the dense atmosphere below because of a magnetic mirror and unable to escape along field lines because of  $E_{\parallel}$ . Very clear evidence came from the S3-3 spacecraft of the U.S. Air Force, supported by the Office of Naval Research (ONR), which detected beams of O<sup>+</sup> ions (the dominant positive ion in the ionosphere) rising upward, apparently impelled by the same  $E_{\parallel}$  which accelerated electrons downward [Shelley et al., 1976; Johnson, 1979; Mizera et al., 1981]. In addition to the O<sup>+</sup> beams, “ion conics” were found; these were events in which the O<sup>+</sup> flux peaked at some intermediate angle to the magnetic field direction, suggesting that plasma wave phenomena at some lower altitude had preferentially accelerated the velocity component  $v_{\perp}$  perpendicular to the magnetic field [Sharp et al., 1977]. The observation of beams and conics solved the riddle of O<sup>+</sup> ions in the ring current, first detected by Shelley et al. [1972] [also Sharp et al., 1974].

An alternative acceleration process, promoted by Alfvén [Brush, 1990] and by Block [1972, 1978] [also Goertz, 1979], centered on the existence of a “double layer,” an abrupt field-aligned voltage jump of appreciable intensity. Large impulsive electric fields were observed by electric field probes aboard S3-3 [Mozer et al., 1977], and the suggestion was made that they might be the signature of double layers. However, other possible explanations also exist, and no compelling evidence for the existence of such layers in space has surfaced since then.

## 11. BIRKELAND CURRENTS

Magnetic variations observed on the ground in the auroral zone are much larger than those at middle and low latitudes: swings of 500–1000 nT at auroral latitudes (out of about 60,000 nT) are much more common than 100-nT disturbances at the equator, which would be classified as fair-sized magnetic storms [Rufenach et al., 1992, Figures 12 and 13]. The strong polar disturbances are localized, suggesting that the currents producing them flow nearby, probably in the ionosphere.

Birkeland [1908, 1913] [also Boström, 1968; Stern,

1977; see also BH-1] noted that the direction of the disturbance field in the auroral zone tended to be perpendicular to auroral arcs. He concluded that large electric currents flowed lengthwise along the arcs and speculated that those currents arrived along magnetic field lines at one end of the arc and returned to space by a similar route at the other end. An overall pattern inferred in this way was later mapped, especially by Silsbee and Vestine [1942], and its currents were named auroral electrojets; they seemed to originate on the dayside and to flow toward midnight along both sides of the auroral oval. Sugiura and Davis [1966] combined the readings of about a dozen magnetic observatories around the auroral zone and extracted an “AE (auroral electrojet) index,” which gauged the strength of the electrojets. Values of this index are now regularly compiled and often serve as indicators of substorms and of the level of magnetospheric agitation [Rostoker, 1972b; Mayaud, 1980].

Because the ionosphere conducts electricity, the existence of a dawn-to-dusk polar electric field (Figure 5b, contours viewed as electric equipotentials) suggests that an electric current flows across the polar cap; the current might enter on the morningside of the polar cap and exit in symmetric fashion on the eveningside, like the current in Figure 8. The pattern of E, however, also has fringe fields that extend equatorward of the oval, to field lines that are shorter and therefore thread parts of the magnetosphere closer to Earth. In a static electric field  $\mathbf{E} = -\nabla\Phi$ , if  $E_{\parallel}$  is negligible, it follows from (1) that  $\mathbf{B} \cdot \nabla\Phi = 0$  and hence that the electric potential  $\Phi$  is constant along field lines. The fringe pattern then maps  $\Phi$  and  $\mathbf{E}$  to the near-Earth magnetosphere.

Schield et al. [1969] deduced from this an important new effect. The earthward flow in the tail predicted by both convection theories (Axford-Hines and Dungey) is associated (by (1)) with a dawn-to-dusk electric field E across the tail, which then maps along field lines to the polar cap, and the polar fringe pattern extends this E to nightside equatorial regions closer to the Earth. When convecting ions and electrons arrive near Earth, appreciable guiding center drifts caused by the dipole-like internal field are added to their convective flow. These deflect the flow around the inner part of the magnetosphere, as was assumed by Axford and Hines [1961] and as was claimed even earlier by Alfvén [1939] (see also BH-1).

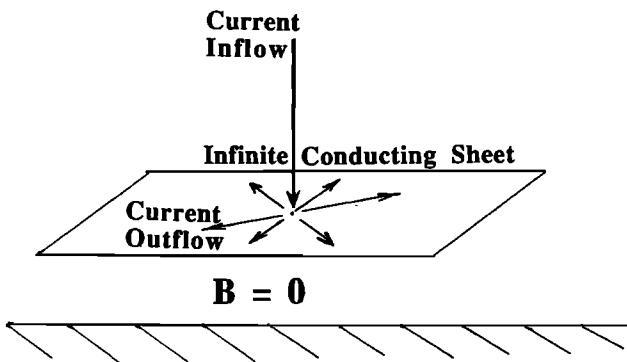
However, the magnetic drifts move positive ions and electrons in opposite directions. Schield et al. [1969] showed that as a result, if such drifts are added to the convective flow, the plasma no longer stays electrically neutral. This cannot be allowed to happen, because even a relatively tiny deviation from strict neutrality produces huge electric fields. The process may be halted in one of two ways: either E is modified in a way that keeps the plasma flow out of the region of strong magnetic drifts or electric currents arise along magnetic field lines (the

easy flow direction in a plasma) and drain away the excess of electric charge. Both processes seem to occur.

The modification of  $E$  takes the form of “shielding” of an exclusion of  $E$  from the vicinity of the Earth, making the fringe pattern in Figure 5b narrower than what a calculation based solely on ionospheric conductivity would give. This was first calculated by *Vasyliunas* [1970] and also by *Jaggi and Wolf* [1973], who devised a way of simulating the process on a computer. The method was later expanded by Wolf and his group at Rice University, Houston, Texas, with the Rice Convection Model which simulates both the shielding and the neutralizing currents [*Spiro and Wolf*, 1984].

The existence of neutralizing field-aligned currents was predicted by *Schield et al.* [1969]. Because of Birkeland’s early ideas on field-aligned currents flowing in and out of the ionosphere, they named all such currents (including the primary ones) “Birkeland currents.” The neutralizing currents flow in the opposite direction from the primary currents: out of the ionosphere on the morningside and into it on the eveningside, and they were expected to intersect the ionosphere somewhat equatorward of the primary currents (Figure 11). This qualitative theory was given a mathematical expression by *Vasyliunas* [1972].

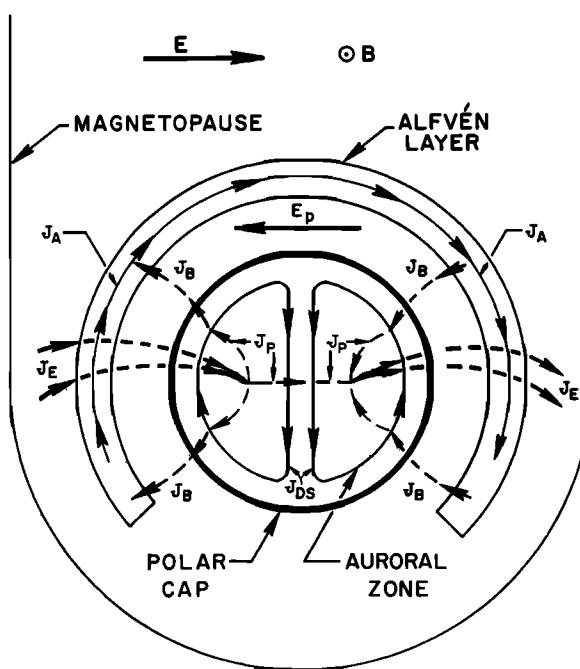
Current patterns like those predicted by *Schield et al.* [1969] were ultimately discovered by *Zmuda and Armstrong* [1974], using a magnetometer aboard a low-altitude satellite in polar orbit, and this, rather than flow



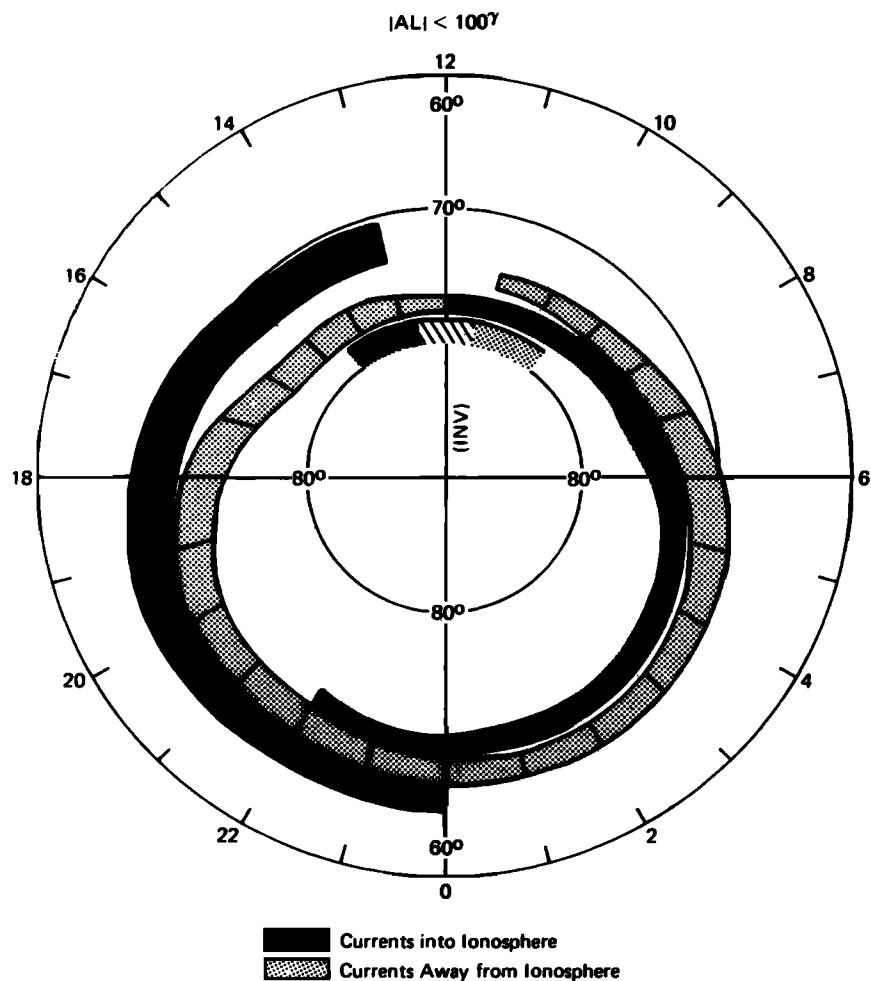
**Figure 12.** A straight current impinging on a uniformly conducting infinite flat sheet creates zero magnetic field underneath. By superposing two such patterns, with opposing straight currents, the property is extended to a current flowing into the (flat) ionosphere and out again.

across the pole, turned out to be the main mode by which the currents closed. Two factors delayed that discovery. The OGO 2, OGO 4, and OGO 6 missions, launched in 1965, 1967, and 1969, respectively, followed low-altitude polar orbits and carried precise magnetometers, but these instruments were intended for a survey of the Earth’s internal field [e.g., *Langel*, 1974], and they only returned the intensity  $|B|$ , much easier to obtain accurately than the direction of  $B$ . Unfortunately, the signature of Birkeland currents is a rotation of the observed vector of  $B$  when the satellite crosses the current sheet, accompanied by practically no change in intensity. Thus the polar OGOs (“POGOs”) failed to detect any field-aligned currents; later *Sugiura* [1975] deduced the currents’ existence by observing  $B$  on near-Earth passes of OGO 5, but his work appeared after the article of *Zmuda and Armstrong*. Some earlier observations [e.g., *Zmuda et al.*, 1966] were also tentatively identified as signatures of field-aligned currents [*Cummings and Dessler*, 1967], but no global pattern was deduced.

Another delaying factor was the fact that the current flows expected from the convection pattern of Figure 5b were quite different from the auroral electrojets inferred from ground data. One reason for the discrepancy was found by *Fukushima* [1969], who pointed out that when a current (Figure 12) flowed into an infinite plane conducting sheet through a perpendicular straight wire and flowed out again by a similar wire at another point, no magnetic effect existed on the other side of the sheet. The result was later extended to a spherical geometry [*Fukushima*, 1976], and while the actual structure of the Earth’s magnetosphere differs from these ideal cases, these results strongly suggested that Birkeland currents flowing into the ionosphere from space, across it, and then out again produced only small magnetic effects on the ground and were virtually invisible from there. The disturbance on the ground is almost entirely due to the auroral electrojets (further below).



**Figure 11.** The proposed circuit of Birkeland currents, according to *Schield et al.* [1969]:  $J_E$  are region 1 currents connected to the interplanetary field,  $J_P$  are currents in the polar ionosphere,  $J_B$  are region 2 currents, and  $J_A$  are currents of the partial ring current that close the circuit across midnight (the terms region 1 and region 2 were only introduced in 1976).



**Figure 13.** A map of the polar ionosphere, showing the average configuration of Birkeland (field-aligned) currents there. Regions where the current enters the ionosphere have dark shading, regions where it flows away from Earth and into space have light shading. From *Iijima and Potemra*, [1976b]; the origin is at the magnetic pole and the Sun's direction is on top.

The magnetometer used by A. Zmuda and J. Armstrong of the Johns Hopkins University Applied Physics Laboratory was a relatively crude instrument (resolution 12 nT) flown as an additional “piggyback” payload aboard the Navy’s navigational satellite Triad. The magnetometer had no boom to keep it away from interference, and it used no tape recorder, while the satellite itself (a long structure, three parts linked by long booms) swung back and forth like a pendulum. Yet Triad observed very clearly the predicted rotations of B. Zmuda and Armstrong found two parallel current sheets following the morningside auroral oval for almost its full length, with the polar sheet flowing into the ionosphere and the equatorial one out of it; two similar sheets, but with opposite flow directions, were found along the eveningside oval. At the suggestion of M. Sugiura, *Iijima and Potemra* [1976a, b] later named the polar sheets “region 1” and the equatorward ones “region 2” (Figure 13). Tragically, by the time their work was published [Zmuda and Armstrong, 1974], both authors had died:

Zmuda of an untimely heart attack, Armstrong by suicide.

About 75% (the proportion varies) of the current reaching Earth in region 1 leaves again as region 2, while the rest closes across the polar cap or around the auroral oval. The flow through the ionosphere encounters an anisotropic conductivity [Cowling, 1945; Dungey, 1958; Boström, 1964; see also Kelley, 1989]: in addition to a “Pedersen” current density  $j_P = \sigma_p E$ , there also exists a “Hall” current density  $j_H = \sigma_H (B/B) \times E$  at right angles, of comparable or larger magnitude. The concentrated electrojet is largely the Hall current associated with the linkage between the systems of regions 1 and 2 across the ionospheric gap between them, although it may also include Pedersen currents, guided along the auroral oval by a channel of higher conductivity due to precipitation of auroral electrons. As for the portion of the current flowing across the polar cap, it may be unevenly divided between the two hemispheres, especially near solstice when the sunlit summer ionosphere conducts far better

than the dark winter ionosphere, leading to a seasonal effect discovered by *Fujii et al.* [1981].

The pattern of Figure 13 was derived from Triad observations by *Iijima and Potemra* [1976a, b] and is marked by lines of magnetic local time (MLT), measured around the magnetic pole with noon in the Sun's direction. Note that the transition between the ingoing and outgoing portions of the pattern is centered not at midnight but around 2200 MLT: a similar rotation of the electric field pattern should be added in Figure 5b and could be due to the Hall conductivity [*Vasyliunas*, 1970]. The crossing over beginning near 2200 MLT coincides with the region of changes in auroral and magnetic activity known as the Harang discontinuity *Heppner* [1972b] [also *Fukushima*, 1994, Appendix D]. Overlaps exist at midnight and additional currents are observed near noon, possibly associated with the cusps; some have named them "region zero."

It should be stressed that Figure 13 is a statistical average and that actual sheets are much more fragmented and irregular [e.g., *Bythrow et al.*, 1984, Plate 2]. The greatest intensity of region 1 currents occurs on the dayside, in agreement with the observation [*Heelis et al.*, 1976] that E, too, is strongest in a "throat region" near noon. During substorms, region 1 is reinforced by a "wedge current" diverting part of the cross-tail current earthward [*McPherron et al.*, 1973]; during northward IMF  $B_z$ , the system may weaken and almost disappear [*Rich and Gussenhoven*, 1987], but characteristic "NBZ currents" may then be observed on the dayside, strongly dependent on IMF  $B_y$  and possibly related to the Svalgaard effect.

The flow of region 1 currents far from Earth is still being debated. While some currents near noon may flow down directly along open field lines in the manner of circuit ABCD in Figure 8, the tracing of polar field lines using data-based models of the magnetic field suggests that most of them flow on closed field lines [*Stern*, 1992] and may therefore be connected to the cross-tail current and to its sunward extensions [*Atkinson*, 1978, Figure 3]. Most recently, *Tsyganenko et al.* [1993] found in situ statistical evidence suggesting that a significant part of the nightside region 1 flow, on the nightside, originates in the plasma sheet, at distances of  $10\text{--}30 R_E$ , with very little coming from greater distances.

## 12. SUBSTORMS: EARLY OBSERVATIONS

Following a great auroral display in Connecticut, on July 1, 1837, E. C. Herrick [1838] wrote (italics in the original):

It is worthy of notice that on this occasion there were two well marked and distinct *seasons of greatest brilliance* or *fits of maximum intensity*, at intervals of about four hours. It will be found on examination of former accounts, that this is a common feature of Auroral exhibitions of unusual brilliance.

*Birkeland* [1908, 1913] [also *Boström*, 1968] observed conspicuous magnetic signatures of such "fits of maximum intensity" and proposed that here was a new type of magnetic activity, a "polar elementary magnetic storm" with a typical timescale of half an hour. More about Birkeland's pioneering work is given in BH-1 and its references and also in the work of *Stern* [1991], from which parts of this section are taken.

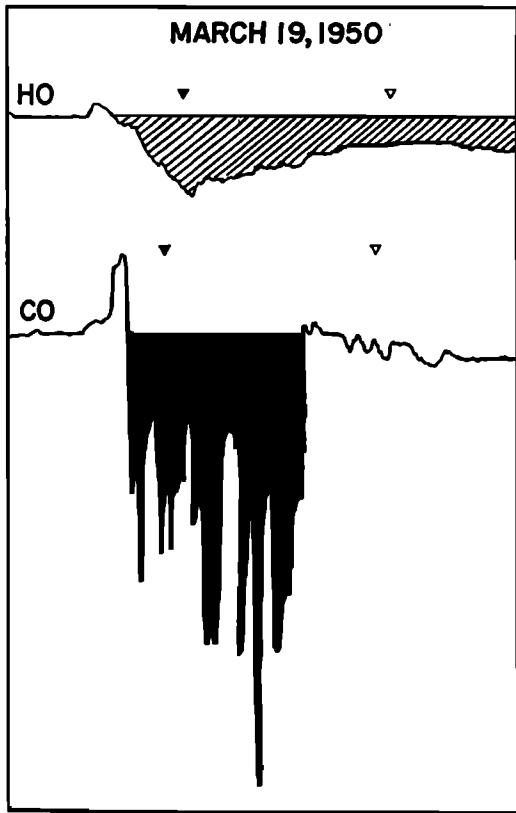
Birkeland's polar storms are now known as (magnetic or magnetospheric) substorms. These violent twitches of the Earth's magnetic tail energize ions and electrons, inject some of them into the ring current, and greatly increase the rate at which energy is released in the magnetosphere. Indeed, many parallels exist between substorms and impulsive particle acceleration events on the Sun, and both are believed to be powered by the conversion of magnetic field energy. For all these reasons the substorm may be the most interesting problem in magnetospheric physics and a great challenge to both observer and theorist.

As noted in BH-1, Birkeland's ideas were opposed by Chapman [*Chapman and Bartels*, 1940; *Fukushima*, 1994, section 6]. Chapman contrasted the short timescale of polar disturbances with the much longer one of global magnetic storms and proposed that "polar storms" were merely phases of the global storm. Around the middle of the century such events were called "magnetic bays" because on a magnetogram (the plotted output of a magnetic observatory) they resembled bays on a coastline (according to *Chapman and Bartels* [1940], this term is due to *Chree* [1912, also *Encyclopedia Britannica*, 11th ed., vol. 17, pp. 353–385, 1911]). A study of bays was conducted by *Silsbee and Vestine* [1942] [also *Stern*, 1977, Figure 2], who deduced a two-cell pattern with strong electrojets near the boundary of the polar cap.

While Birkeland believed that auroral currents originated in distant space, the consensus in midcentury was that they resembled the well-known diurnal magnetic variation whose currents were attributed to tidal dynamo effects in the ionosphere and that they were completely contained inside the ionosphere [*Vestine and Chapman*, 1938]. It was thought that the large polar magnetic variations arose by a similar process but were much more intense because ionospheric conductivity was enhanced in regions bombarded by the aurora. Thus *Harang* [1951, p. 94] after explaining the tidal dynamo, wrote

The intrusion of electrically charged particles which produce the aurorae, strongly increases the ionisation and thus the conductivity of the ionised layers. Besides this, one must also assume secondary effects, such as expansion or heating of the upper atmosphere, which may increase the movements of the layers along the auroral zone. The polar storms are therefore, according to these views, due to an increase in the conductivity and velocity of movements of the upper layers.

Chapman became more involved with the aurora after 1951, when he accepted a visiting professorship at the University of Alaska Fairbanks, and after he retired



**Figure 14.** Plot by *Akasofu and Chapman* [1963] of the magnetic disturbance associated with a magnetic storm, as observed near the equator (Honolulu) and in the auroral zone (College, in Fairbanks, Alaska). The latter is punctuated by many “substorms.”

from Oxford in 1953 he used to stay in Fairbanks several months each year [*Akasofu*, 1970]. In 1958 he was joined there by Syun-Ichi Akasofu, a young Japanese who became his main associate.

The word “substorm” first appeared in Chapman’s writings in 1961 [*Akasofu and Chapman*, 1961, p. 1339], referring to a bay-like disturbance assumed to be a phase of the global magnetic storm. Two years later, *Akasofu and Chapman* [1963] compared the signatures of magnetic storms near the equator and in the auroral zone (Figure 14). Near the equator the magnetic field variation was simple and familiar, a gradual weakening of the field on a typical timescale of 6 hours, followed by a slow recovery. In the auroral zone, on the other hand, the magnetic record was punctuated by many short but intense magnetic bays, which the authors again named substorms.

### 13. SUBSTORMS: THE SATELLITE ERA

The IGY 1957–1958 (actually extended to a year and a half) brought not only the first scientific satellites but also a great expansion in auroral observations and widespread use of “all-sky cameras” [see *Eather*, 1980], which

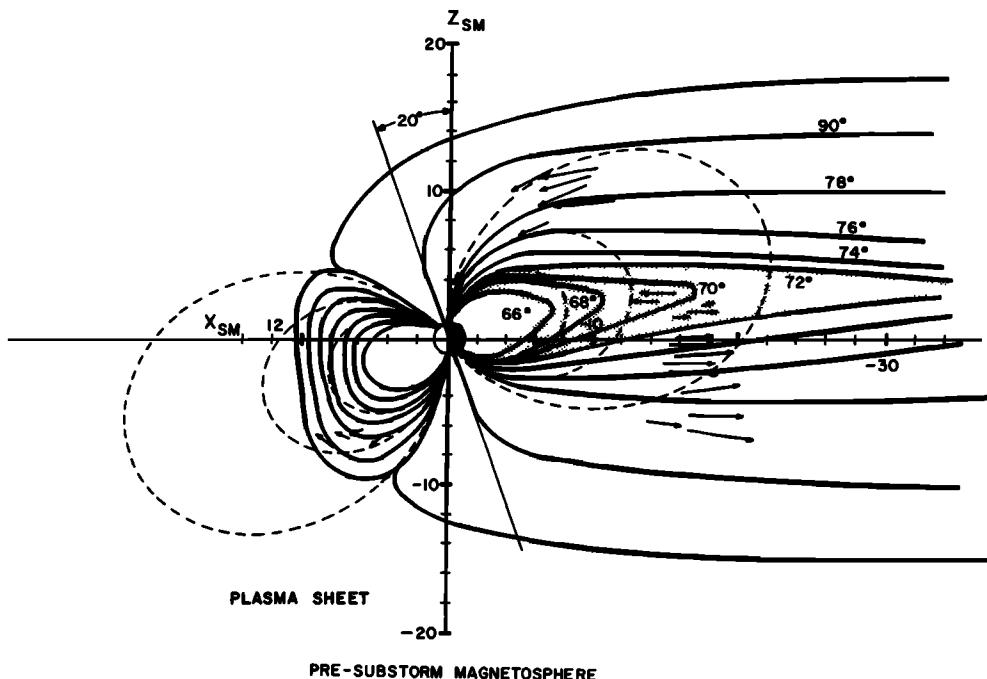
photographed the entire sky as reflected in a convex mirror. Using such records, *Akasofu* [1964] noted that magnetic bays, which also occurred widely outside magnetic storms, were associated with a distinct pattern of auroral intensification and expansion and proposed to name the phenomenon “auroral activation” [*Akasofu*, 1970]. Chapman, however, insisted on “auroral substorm” and that was the name used in the article’s title [*Akasofu*, 1964]. Later, *Akasofu* favored “magnetospheric substorm” [*Akasofu*, 1977; *Siscoe*, 1980], while *Rostoker* [1972a] has used “polar magnetic substorm”; the commonly used term nowadays is “magnetic substorm” or simply “substorm.” Today’s view is that the substorms which Chapman identified inside magnetic storms are of a similar nature, except perhaps bigger and more frequent, capable of injecting appreciable numbers of ions and electrons into long-lived orbits of the ring current region [*Lui et al.*, 1987].

During 1964–1966, *Akasofu* and his group studied the morphology of substorms in great detail [*Akasofu et al.*, 1964, 1965a, b, c; 1966a, b, c, d; *Akasofu*, 1966]. Their “classical” substorm phases (individual storms may vary) are still accepted: an initial brightening of a quiet arc, the expansion of the aurora poleward (either by the motion of existing arcs or by formation of new ones), a westward surge along the auroral oval, gradual breaking up of arcs, and final recovery.

A deeper understanding was gained after about 1965, when satellites began observing the great changes accompanying substorms in the Earth’s magnetic tail. They observed magnetic field lines becoming stretched prior to substorm onset (Figure 15, from *Fairfield and Ness* [1970]) and then rebounding to more dipole-like shapes (“dipolarizing”). This was also noted by *Heppner* [1967, p. 184] who wrote that “The view that is favored is that the tail field is partially collapsing back towards a less stressed condition during a negative bay.”

The preliminary stretching may be observed as close as synchronous orbit, at  $6.6 R_E$  [e.g., *Baker et al.*, 1981] and may begin as long as 1 hour before substorm onset: the prevalent idea (originally widely debated) is that this is the “growth phase” during which magnetic energy is stored [*McPherron*, 1970, 1972], and often an analogy is drawn between the stretching of field lines in this phase and the stretching of a slingshot. When the field lines rebound, the stored energy goes to accelerate particles and to drive currents. A large increase in the flux of ions and electrons is then observed at the nightside near the inner edge of the cross-tail current, for example, in the synchronous orbit at  $6.6 R_E$  [*DeForest and McIlwain*, 1971], but what exactly goes on is still not understood [*Mauk and Meng*, 1987]. Typical injected energies are 1–10 keV, but particles up to 100 keV and more have also been observed [*Nagai et al.*, 1983].

Satellites in the plasma sheet may observe disappearances (“drop outs”) of the plasma at the time of onset, and after onset a satellite which had been outside the plasma sheet may be suddenly engulfed by it. Early



**Figure 15.** The stretching of the Earth's magnetic tail during the "growth phase" which precedes a substorm, from *Fairfield and Ness* [1970].

observations of such changes [Hones *et al.*, 1967, 1970; Hones, 1979] were complicated by the fact that they were performed by "piggyback" instruments aboard the VELA satellites which carried no magnetometers, since their primary mission was to detect violations of the ban on nuclear tests in space. The ultimate explanation was that the plasma disappeared when the plasma sheet was severely stretched and became extremely thin, while the sudden appearances of plasma were associated with di-polarization, when plasma energized by the substorm rebounded earthward, swelled field lines of the near-Earth tail, and extended the plasma sheet past the satellite.

The deep magnetic bays accompanying the substorm arise from greatly enhanced electrojets, and the *AE* index [Sugiura and Davis, 1966] is often taken as a gauge of the level of substorm activity. Observations have suggested [McPherron *et al.*, 1973, Figures 7 and 8] that during substorms, Birkeland currents are reinforced on the nightside by a system with region 1 polarity, arising from a diversion of part of the cross-tail current through the ionosphere. Because the shape of the diversion circuit tapers toward the Earth, this is known as the "substorm wedge current." In the ionosphere the wedge current follows the auroral oval, whose conductivity is greatly increased by the aurora, and thus reinforces the westward electrojet around midnight. The wedge current may be intense enough for its magnetic effects to be observed at middle latitudes [Clauer and McPherron, 1974a, b] as well as in synchronous orbit [McPherron and Barfield, 1980].

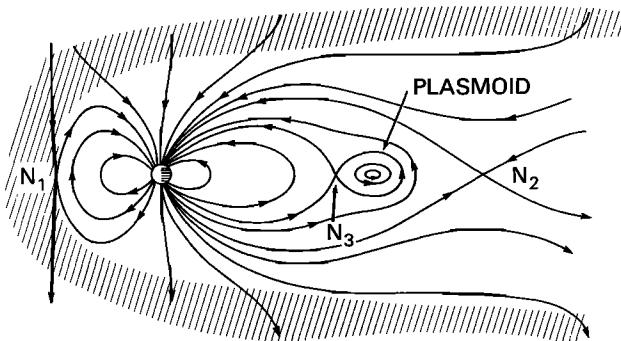
By 1972 most observational features of the substorm

had been identified, and they were reviewed by Rostoker [1972a, p. 163, 200], who also summed up the history of substorms, and by Aubry [1972]. A conference on substorms was held in October 1972 [Vasyliunas and Wolf, 1973], and an initial coordinated study of the substorms of August 15, 1973, was undertaken. The results of that study appeared in nine consecutive articles (*J. Geophys. Res.*, 78, 3044–3149, 1973); the last of which [McPherron *et al.*, 1973] presented an interpretation which included the "wedge circuit."

#### 14. SUBSTORMS: THEORY

As the features of substorms became known, attempts were made to explain them. One important feature was the strong correlation between substorms and "southward IMF." If the magnetosphere was quiet during a spell of northward IMF  $B_z$  and suddenly  $B_z$  turned southward and stayed that way, it was found that a high probability existed for a substorm to erupt within an hour or so.

A further link was provided by Aubry *et al.* [1970] [also Aubry and McPherron, 1971], who found evidence that, other things being equal, the "nose" of the magnetosphere was pushed in closer to Earth at times of southward IMF  $B_z$ , a phenomenon qualitatively evaluated by Holzer and Slavin [1978] and by Sibeck *et al.* [1991] [also Roelof and Sibeck, 1993]. Aubry termed this phenomenon "erosion" of the magnetopause and claimed it occurred because closed field lines were being reconnected to interplanetary ones near  $N_1$  (Figure 7) faster than



**Figure 16.** Schematic view of the formation of a near-Earth neutral line (NENL) and a plasmoid, as proposed by the NENL scenario of substorms.

closed lines were arriving from the tail to take their place.

*Coroniti and Kennel* [1972] explored later developments of this scenario. If magnetic flux is removed from  $N_1$  faster than the sunward flow initiated near  $N_2$  brings it back, additional flux will pile up in the tail lobes. The lobes then swell and present a larger obstacle to the solar wind, which therefore compresses the lobes more, increasing the lobe field  $B_L$ : they identified this process with the growth phase of substorms, noting that the magnetic energy in the tail, whose density is  $B_L^2/2\mu_0$ , would increase.

Ultimately, in this scenario the increased southward IMF reaches  $N_2$  and increases the rate of reconnection there, and after a while the supply of returning magnetic flux reaching  $N_1$  again matches the demand. However, in the mean time, other processes may intervene. The increased pressure on the lobe may squeeze the plasma sheet, causing reconnection at an internal neutral line  $N_3$  (Figure 16), so that the flux returning sunward is now supplied by reconnection at  $N_3$ . Tailward of  $N_3$  an isolated magnetic bubble will be created, named “plasmoid” by *Hones* [1976, p. 567], a term previously applied by *Bostick* [1956, 1957, 1986] to a type of transient plasma bubble observed in the laboratory. *Hones* [1979, p. 393] described it as “...a blob of magnetospheric plasma ... detached from the magnetotail plasma ....” The reconnection process at  $N_3$  was assumed to provide the substorm’s energy and to accelerate particles; observations of impulsively accelerated particles in the tail [e.g., *Keath et al.*, 1976; *Roelof et al.*, 1976] were believed to indicate proximity to  $N_3$ .

The preceding scenario, with various modifications, has dominated the community’s view of substorms in the last 20 years. In particular, *Hones* [1979] has collected evidence in its favor and has argued that once a new neutral line  $N_3$  was formed, the tailward motion of the plasmoid would stretch it into a neutral sheet, explaining the formation of a very thin section of the plasma sheet (“thinning”) inferred from the observed disappearance of plasma. This was disputed by *Frank et al.* [1976], who

claimed substorms originated in “fireballs,” possibly associated with boundary layers. The controversy persisted for a while [*Hones*, 1977, 1978a, b, c; *Frank and Ackerson*, 1977; *Frank et al.*, 1978a, b], with *Hones* claiming that Frank’s examples were in fact ordinary reconnection events, but it ultimately died down when no alternative scenario based on fireballs emerged.

Since that time several alternative theories of the substorm have been proposed [Kan, 1990]. Most interpretations place  $N_3$  fairly close to Earth ( $\approx 15 R_E$ ), but some views [*Rostoker and Eastman*, 1987] argued that substorms may reflect enhanced reconnection (and other processes?) at  $N_2$ . Alternative theories have invoked a “thermal catastrophe” [*Goertz and Smith*, 1989], Alfvén waves bouncing between the ionosphere and the tail [Kan *et al.*, 1988], and disruption of the cross-tail current, which was advocated by *Lui* [1991]. The proliferation of models has led to some skepticism [Stern, 1989b], and a meeting was held in Victoria, British Columbia, to seek some general agreement [*Rostoker et al.*, 1980], but it did not clarify much.

One approach to studying substorms is to try to correlate their variations with interplanetary stimuli and thus seek to identify their causes or “triggers.” Part of the problem here is the gauging of a substorm’s intensity, and many studies have used the auroral *AE* index, or the related *AU* and *AL* indices, for this. These reflect the strength of the auroral electrojets and therefore of the Birkeland current system, and they are known to become very high during large substorms.

*Coroniti and Kennel* [1972], *Hones* [1979], and most other researchers argued that the substorm obtained its energy from magnetic energy stored in the tail lobes, accumulated during a “growth phase” preceding substorm onset, during which the tail’s magnetic flux increased [*Caan et al.*, 1975]. *Perreault and Akasofu* [1978], however, found good correlation of *AE* with an “ $\epsilon$  parameter,” constructed from solar wind characteristics and very sensitive to IMF  $B_z$ . They therefore proposed that substorms represented periods of stronger coupling between the solar wind and the magnetosphere, enabling the latter to extract more energy, and were thus “driven” by interplanetary conditions rather than representing the “unloading” of stored energy [Akasofu, 1980]. Some physicists now claim that both unloading and driven processes are involved. Predictive linear filters have also been used to study the way the solar wind input relates to *AE* [*Iyemori et al.*, 1979; *Clauer et al.*, 1981].

Theorists who support the “near-Earth neutral line” (NENL) scenario have sought the “trigger” mechanism which initiates the onset of substorms, possibly some plasma instability. Computer simulations based on idealized MHD equations and assuming (purely) southward IMF [e.g., *Walker et al.*, 1993] have supported the NENL scenario, yielding (with southward IMF) even more pronounced reconnection than seems to be observed.

## 15. CONVECTION IN THE GEOTAIL

An interesting idea about the origin of substorms was proposed by *Erickson and Wolf* [1980] [also *Hau et al.*, 1989; *Erickson*, 1984, 1992]. In the ideal MHD approximation, in the absence of rapid accelerations, it is expected that the magnetosphere is always close to force balance, mainly between pressure gradients and the magnetic force:

$$\nabla p = \mathbf{j} \times \mathbf{B} \quad (2)$$

Properly,  $p$  is a tensor, but in the plasma sheet the observed distribution of ions is close to isotropic and hence a scalar  $p$  is often used there. Solutions of (2) appropriate to a realistic three-dimensional magnetosphere are not known, but two-dimensional solutions for a scalar  $p$ , assuming a linear dipole that extends indefinitely in the  $y$  direction, can be obtained (at least numerically) from the Grad-Shafranov equation [e.g., *Voigt and Wolf*, 1988].

*Erickson and Wolf* [1980] noted that the existence of a convective plasma flow in the tail imposes additional restrictions. If the tail's field lines move with the flowing plasma, either the magnetic pattern is static and satisfies (2), and then the convection is such that each field line of the pattern is carried into another one; or the pattern evolves, in which case (2) must hold at each intermediate stage. *Erickson and Wolf* showed that observed patterns of  $\mathbf{B}$  and expected patterns of  $\mathbf{E}$  were not compatible with a static scenario.

*Erickson* [1992] later simulated the field's evolution on a computer, satisfying (2) at all times; his calculation was two-dimensional, but flux arriving near Earth was allowed to "escape sideways" rather than piling up. This process led to a very weak  $\mathbf{B}$  near the earthward edge of the plasma sheet ( $x \approx -12 R_E$ ), suggesting in almost all cases the imminent formation of a near-Earth neutral line (the simulation could not go far enough to confirm it). By this scenario, substorm-type events may be an inevitable outcome of convection in the tail.

Attempts to actually observe this convection raise new problems. The double-probe method for observing  $\mathbf{E}$  in low Earth orbit fails in the rarefied plasma of the tail, but the plasma's bulk flow can be inferred by measuring ion flux anisotropies. The first attempt [*Frank and Ackerson*, 1979] suggested a great deal of back-and-forth sloshing of plasma but no underlying persistent earthward motion. A later study by *Huang and Frank* [1986] filtered out plasma sheet boundary layer observations, which contained field-aligned flows, and obtained an average earthward flow in the plasma sheet ( $r < 22 R_E$ ) of  $\approx 20 \text{ km s}^{-1}$ , much below the expected rate. Recent studies by *Angelopoulos et al.* [1992] suggest that high-speed earthward plasma flows do exist (at  $\approx 150 \text{ km s}^{-1}$ ) but only  $\approx 7\%$  of the time. The problem is thus still unsolved.

## 16. PLANETARY MAGNETOSPHERES

Space missions to the planets of the solar system have shown that most of them are magnetized. In particular, the giant planets are magnetized much more strongly than Earth [Baggenal, 1992], and their magnetospheres are all much larger than ours, in part because of the stronger dipole moments and in part because the solar wind becomes increasingly rarefied far from the Sun. Tiny Mercury has a magnetic moment only about 1/2000 that of Earth and a very small magnetosphere, Venus seems nonmagnetic, and Mars may or may not have a weak field. The magnitudes of the dipole moments of Mercury, Earth, Jupiter, Saturn, Uranus, and Neptune, in units of  $10^{25} \text{ G cm}^3$ , are  $\sim 0.004$ ,  $7.9$ ,  $150,000$ ,  $4300$ ,  $420$ , and  $200$ , respectively [Lepping, 1995].

The most striking thing about these magnetospheres is their great diversity, and this brief overview cannot possibly do justice to the extensive research done on them. Good accounts of the initial observations and of many associated discoveries can be found in special sections of the journal *Science* [1974, 1975a, 1975b, 1979a, 1979b, 1980, 1981, 1982, 1986, 1989, 1992], published soon after the planetary encounters by Pioneer 10 (Jupiter), Mariner 10 (Mercury), Pioneer 11 and Voyager 1 (Jupiter and Saturn), Voyager 2 (Jupiter, Saturn, Uranus, and Neptune), and Ulysses (Jupiter). The Galileo spacecraft reached Jupiter in December 1995 and entered an orbit around the planet after successfully launching a probe into Jupiter's atmosphere.

The strongest magnetic field and the most intense trapped radiation are found in the magnetosphere of Jupiter, which is also the largest [Dessler, 1983]. This was furthermore the first planetary magnetosphere to be discovered: in 1955, strange radio noise was traced by Burke and Franklin to the planet Jupiter [Franklin, 1959, 1985], although it was only attributed to magnetically trapped plasma after the discovery of the Earth's radiation belt [Drake, 1985].

Jupiter's magnetosphere is loaded with ions of sulfur and also of sodium, ejected from "volcanoes" on the satellite Io. Io also has an ionosphere with an interesting dynamo interaction with Jupiter [Ness et al., 1979]. Jupiter's trapped plasma carries a dense ring current and seems to corotate with the planet, perhaps up to the magnetopause. Its density profile contains dips due to absorption by Jupiter's moons and by the planet's thin ring, which resembles Saturn's ring but is much narrower; the existence of that ring was first suggested by an absorption feature in the belt [Acuna and Ness, 1976]. Jupiter also has an aurora, observable from Earth, and radio emissions with complicated patterns, some of them correlated with the position of Io.

Saturn's magnetosphere similarly tends to rotate with the planet and contains absorption features. The planet seems to have an inner belt like the Earth's, believed to arise from albedo neutrons knocked out of the planet's rings by cosmic rays [Cooper and Simpson, 1980].

The Earth's magnetic axis is very close to its rotation axis. Similar proximity between the two axes was found for Jupiter, Saturn, and Mercury (for Saturn the axes coincided within observational error), and this was therefore widely held to be a general feature of planetary magnetic fields. At the time of the encounter between Voyager 2 and Uranus, on January 24, 1986, the planet's axis pointed within a few degrees of the Sun. It was therefore expected that here was a "pole-on" magnetosphere, a previously unstudied configuration in which the axis of the planetary magnet pointed approximately into the solar wind. However, it was not to be. The magnetic axis of Uranus, and later also that of Neptune, was found to make an angle of about 60° with the planetary rotation axis, causing the field to swing widely with each rotation of the planet. As Uranus orbits the Sun, there will arise occasions when a pole-on magnetosphere is (briefly) realized, but it did not happen during the Voyager 2 encounter.

Finally, Mercury's magnetosphere [Ness, 1979] seems to be too small for energetic particles to become trapped in it. However, as Mariner 10 went past the planet's nightside, it encountered a burst of energetic particles, which could be the result of a substorm-type event in Mercury's magnetic tail.

Interesting magnetic cavities are also formed around Venus, the Moon, and comets (and probably, Mars), but if the obstacle is not a planetary magnetic field, the cavity produced is quite different from the ones described above. All this suggests a rather rich field for future research, involving configurations unlike the Earth's, on which many additional observations still remain to be made.

## 17. OTHER AREAS

A brief overview like this one must by necessity omit many important topics, such as the following:

1. Instrumentation, for example, magnetometers [Heppner, 1963; Ness, 1970], electric field probes [Fahleson, 1967; Cauffman and Gurnett, 1972], charged particle detectors, and mass spectrometers. A sampling of articles or collection of articles (only first paper cited) on specific spacecraft and their instruments includes Injun 3 [O'Brien et al., 1964], the OGO series [Ludwig, 1963; Bostrom and Ludwig, 1966], Atmosphere Explorer 1 [Dalgarno et al., 1973], S<sup>3</sup> or Explorer 45 [Longanecker and Hoffman, 1973], International Sun-Earth Explorer (ISEE) 1 and 2 [Ogilvie et al., 1978], Active Magnetospheric Particle Tracer Experiment (AMPTE) [Acuna et al., 1985], and Dynamics Explorer (DE) 1 and 2 [Hoffman et al., 1981].

2. Wave phenomena in the magnetosphere [Shawhan, 1979], including whistlers [Helliwell, 1965; Alpert, 1980; see also BH-1], auroral kilometric radiation [Gurnett, 1974], micropulsations [Hughes, 1983; Lanze-

*rotti and Southwood, 1979], 3/2 cyclotron frequency emissions, auroral hiss, and other modes.*

3. The bow shock of the Earth [Dobrowolny and Formisano, 1973; Greenstadt and Fredricks, 1979; Kennel et al., 1985, Kennel, 1987].

It is hoped that scientists and historians familiar with those areas will add their histories to the record.

## 18. ASSESSMENT

The preceding brief history only covers scientific aspects of magnetospheric physics. In addition, magnetospheric physics also has institutional, personal, and social aspects.

An institutional history traces the evolution of the field and its accomplishments in the framework of the organizations which led it, of institutions, committees, executive decisions, and the individuals involved in them [e.g., Ezell, 1988]. An instructive example is the work by Newell [1980], an account of NASA's effort in space science 1958–1975 by a former NASA Associate Administrator who led those efforts for many years. It covers all fields, not just magnetospheric physics, but where its subject overlaps this narrative, it often paints a strikingly different picture.

Personal histories are first-hand accounts by participants. At best they give an unequalled intimate view of the discovery process. At worst they are carefully filtered, and their writers also do not always have the necessary discrimination and writing skill. Such deficiencies would matter less if such accounts were plentiful enough to allow comparison and cross-checking: sadly, only very few exist, which makes them particularly valuable, and their coverage of the field is rather patchy [Van Allen, 1983a, 1990; Eather, 1980, chap. 19; Frank, 1990; Gombosi et al., 1994].

The community of magnetospheric physics has never been properly studied. It is relatively small: the membership of AGU's Space Physics and Aeronomy Section stands around 3000 (1980, 1604; 1985, 1922; 1990, ~2600). This also includes scientists whose main interests are the upper atmosphere, interplanetary space, and the Sun but may miss many workers outside the United States. As noted, this discipline arose from three main sources: (1) plasma physics, (2) work with rockets, balloons, and ground instruments, and (3) the study of cosmic rays. It began assuming its separate identity in 1959, when (led by Van Allen) it chose the American Geophysical Union (AGU) as its home organization and the *Journal of Geophysics Research* (JGR) as its main means of communication.

Today that community is in a serious crisis, made evident, for instance, by a frustrating slow down in the rate of discovery during the last decade 1984–1994. It may be instructive to speculate about the causes of this slow down and its implications to the community's future.

One can roughly divide the record of magnetospheric physics in the space age into three periods: (1) the era of discovery, 1958–1965; (2) the expansion stage, 1965–1977; and (3) the era of stagnation, setting in gradually after 1977.

In the first period the large-scale morphology was surveyed: particle populations, the main regions, and the boundaries. In addition, this was the beginning of our ideas on convection and reconnection.

In the expansion stage, details were filled in: correlations with the IMF, substorm morphology, Birkeland currents,  $E_{\parallel}$ , auroral kilometric radiation,  $O^+$  ions in the ring current, ion beams, and conics, injections at synchronous orbits, etc. Additional theoretical ideas were also introduced: the NENL theory of substorms, the Brice-Nishida theory, the Coroniti-Kennel theory, theories on the consequences of convection by Schield et al. and by Vasylunas, and others not touched on here.

Since 1977 some observational details were added, for example, about the magnetosphere with  $IMF B_z > 0$ , about the distant tail (by ISEE 3 and Geotail), the ring current (by AMPTE-CCE) and the plasma sheet (by ISEE 1–2 and AMPTE-IRM). Theories, too, have improved, but the main problems continue to elude us: the nature of substorms, structure of the open magnetopause, specifics of reconnection, convection in the tail, global structure during northward IMF, and similar questions.

Why this apparent pause? Three possible reasons will be noted here: the nature of discovery, the choice of mission strategy, and a missed transition in the evolution of magnetospheric physics.

1. There exist two kinds of discovery in this field: (1) discovery of new problems and (2) discovery of solutions. The heady early period seemed packed with discoveries, but most of them belonged to the first kind. It was inevitable that satellites passing for the first time through the radiation belt, the magnetopause, cusp, bow shock, or plasma sheet would make an important discovery; however, while new phenomena accumulated, explanations of their features lagged, and they still do. In laboratory physics, when a new phenomenon is discovered, one can design experiments to focus on it; however, magnetospheric physics, in common with the rest of geophysics, offers few controlled experiments and depends primarily on observations. Thus progress toward explanations is slow and uncertain.

2. The cost of spacecraft is high, both in funds and efforts. All early space missions therefore involved isolated spacecraft, but it seems that the amount of information available from this mode is just about exhausted. Magnetospheric physics is synergistic: to understand global behavior, a coordinated network of satellites is needed. After 1977 the field was ripe for such a network, but unfortunately the use of isolated spacecraft is still the norm. The Russian Interball mission (two spacecraft in 1995) and the European Cluster (due in 1996) are each meant to contain four coordinated spacecraft and

promise to give valuable results, in particular in conjunction with the Wind and Polar spacecraft of the United States. But a meaningful coverage demands a much larger number of platforms, as was made clear by Coordinated Data Analysis Workshops (CDAWs) [e.g., Manka et al., 1982], which tried to analyze specific events and generally found that even with all available data, important questions could not be resolved.

3. As noted, the magnetospheric community first assumed a separate identity around 1960. Independent space physics departments were established at selected universities (Iowa; University of California, Los Angeles; Rice; Alaska; then more) and space research groups were set up at NASA, Johns Hopkins Applied Physics Laboratory, Los Alamos, etc. As the community expanded in 1965–1977, it also began raising its first generation of internally trained scientists. However, something seemed missing. A community needs not only its institutional identity but also a core of its accumulated knowledge, set up in an orderly way that can be passed on. Research and symposia lead to review talks and papers, which in turn lead to textbooks and courses, telling “such-and-such we are pretty sure of and can teach, this-or-that is unclear or controversial, and here are the boundaries of our knowledge.”

Even now, rather little of this process of distillation has taken place, especially in observations: in substorm morphology, for instance, there is surprisingly little that can be regarded as well-established. Possible reasons are too long and too controversial to list here, but the result has been a narrowness of scope and a lack of broad vision which even now hamper further progress and further planning.

This review is altogether too short to properly describe what such “core knowledge” may contain. Still, one hopes it will give its readers, especially younger members of the community, a uniform historical framework of the overall structure of their field.

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