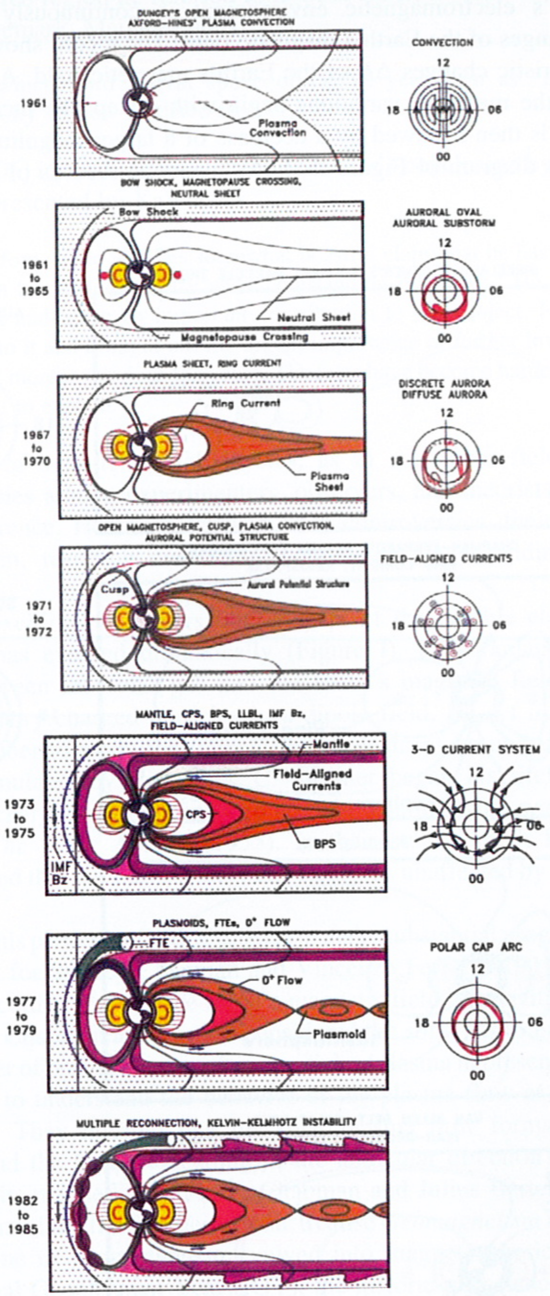


FIGURE I. (*Continued*) Schematic presentation of the development of the concept of the magnetosphere.

Source: Akasofu, S.-I., *Magnetospheric Substorms*, ed. by J.R. Kan, et al., AGU Monograph, 64, p. 3, Washington D.C., 1991

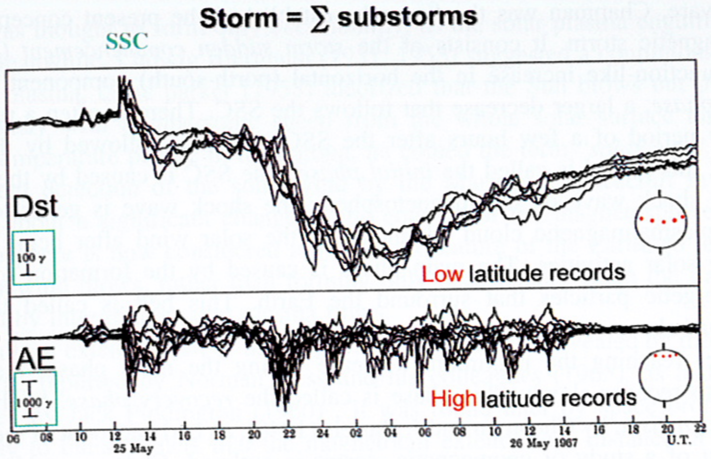


FIGURE II. Upper – Superimposed magnetic records (the north-south component) on May 25–26, 1967, from six low-latitude observatories separated widely in longitude. Lower – Superimposed magnetic records on the same dates from nine high-latitude observatories separated widely in longitude. Note the difference of the scale between the upper and lower diagrams.

Source: Akasofu, S.-I. and S. Chapman, *Solar-Terrestrial Physics*, p. 542, Oxford University Press, Oxford, 1972

component from several low-latitude stations widely separated in longitude; northward changes are recorded as positive changes, while southward changes are recorded as negative changes. The first increase and the subsequent larger decrease are observed at all stations, indicating that those changes occurred on a global scale. This phenomenon is called the *geomagnetic storm*. The development of the study of geomagnetic storms is one of the important subjects of this book. It may be noted that the term magnetic storm was coined by A. Von Humboldt in his treatise *Cosmos* (1871).

The geomagnetic storm field $\Delta \boldsymbol{B}$ is produced by various electric current systems that develop around the Earth when solar disturbances reach the Earth. The field $\Delta \boldsymbol{B}$ is thus superposed on the Earth's main field $\boldsymbol{B}_o$, which does not change in days or months.

During a geomagnetism storm, at high-latitude observatories, fluctuations of a much greater magnitude than those seen in low latitudes, consisting of a number of simultaneous impulsive changes, can be observed. In the lower diagram of Figure II, magnetic records from a number of high-latitude stations are shown; note the difference of the scale for the low- and high-latitude records. Those impulsive changes are magnetic manifestations of what we now know as *magnetospheric substorms*. During a geomagnetic storm, a number of such intense impulsive disturbances occur.

Birkeland classified fluctuations of the Earth's magnetic field in terms of equatorial positive/negative and polar positive/negative changes. As far as I discovered by Scott Forbush and is called the *Forbush effect*. It is likely that the so-called "11-year cycle variations" of cosmic ray intensity result from an accumulated effect of the shock waves. Chapter 9 describes the magnetic field structure of the heliosphere and how it is disturbed by solar activities.

It is hoped that the readers of this book will find a number of long-standing unsolved problems in the four disciplines and that my non-traditional ideas stimulate better ideas than mine. I believe that many of the difficulties the present generation is facing are not due to the lack of basic knowledge and technical problems (for example, the capability of a supercomputer), but to our inability to recognize fundamental flaws in the presently prevailing concepts, namely paradigms. The Epilogue is devoted to discussing this issue. The new generation of scientists are encouraged to challenge the present paradigms and advance our understanding of electromagnetic phenomena around the Earth, in interplanetary space, and the heliosphere.

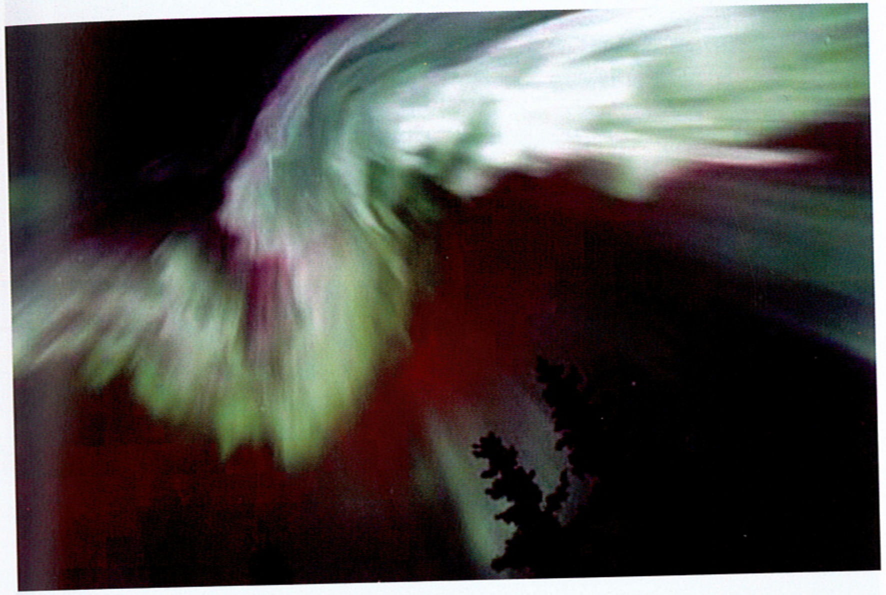


PLATE 1. An active auroral curtain near the zenith. This form is sometimes referred to as the corona-type display. Photographed by Jan Curtis.

Source: Photographed by Jan Curtis

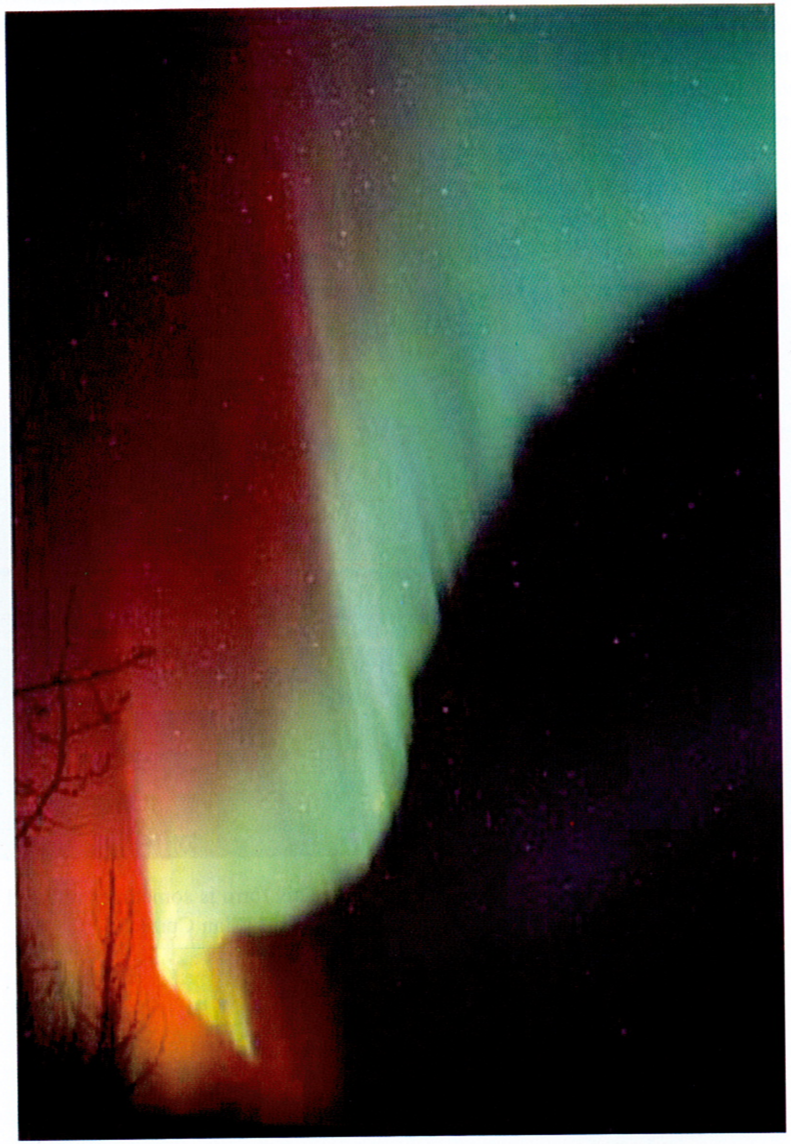


PLATE 2. The curtain-like form of the aurora. The upper part of the curtain is rich in the dark red emissions from atomic oxygen. Photographed by Jan Curtis.

Source: Photographed by Jan Curtis

PLATE 3. An active auroral display called the westward traveling surge. The upper part of this particular aurora shows the dark red emission (660 mm) from atomic oxygen. Photographed by Jan Curtis.

Source: Photographed by Jan Curtis

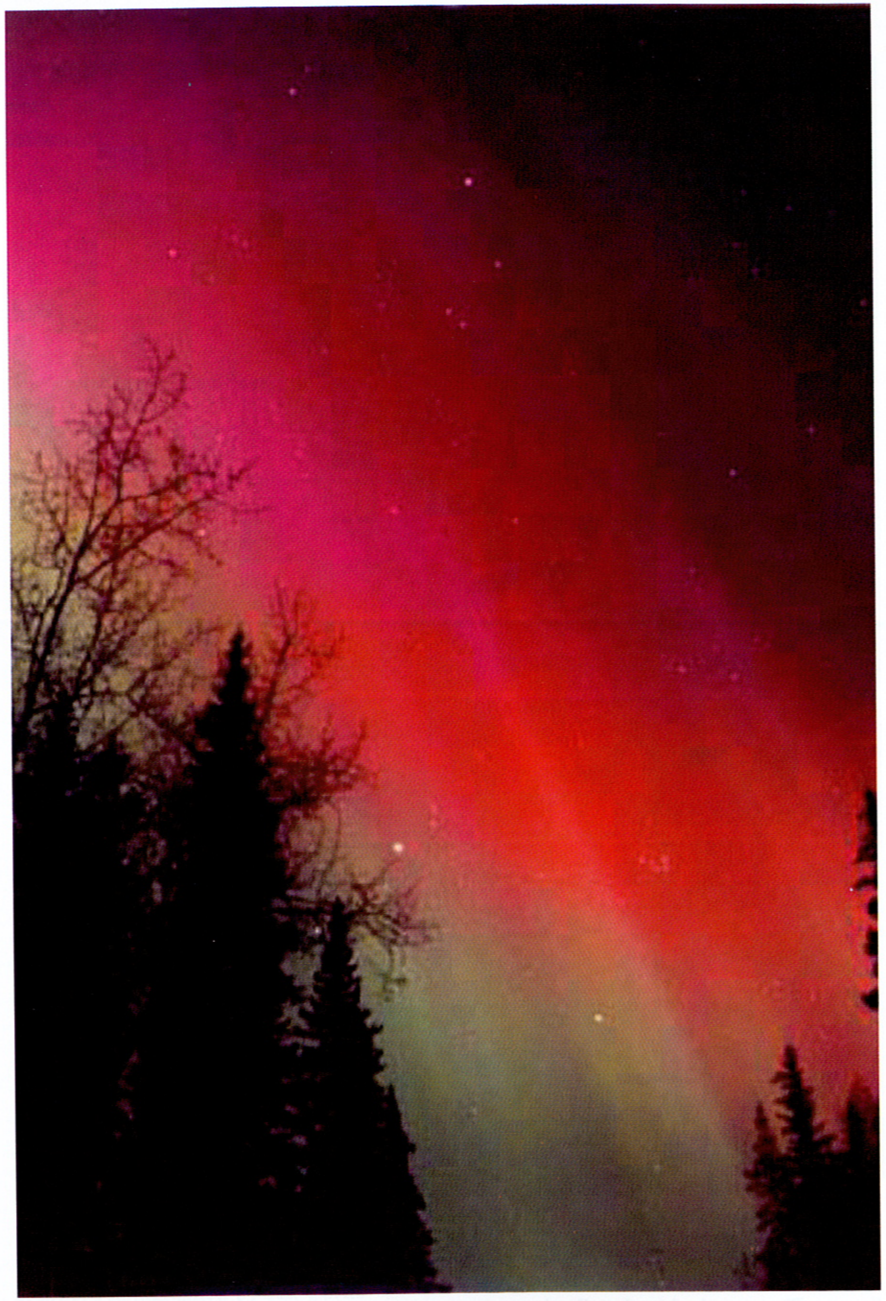


PLATE 4. A typical red aurora. Photographed by Jan Curtis.
Source: Photographed by Jan Curtis

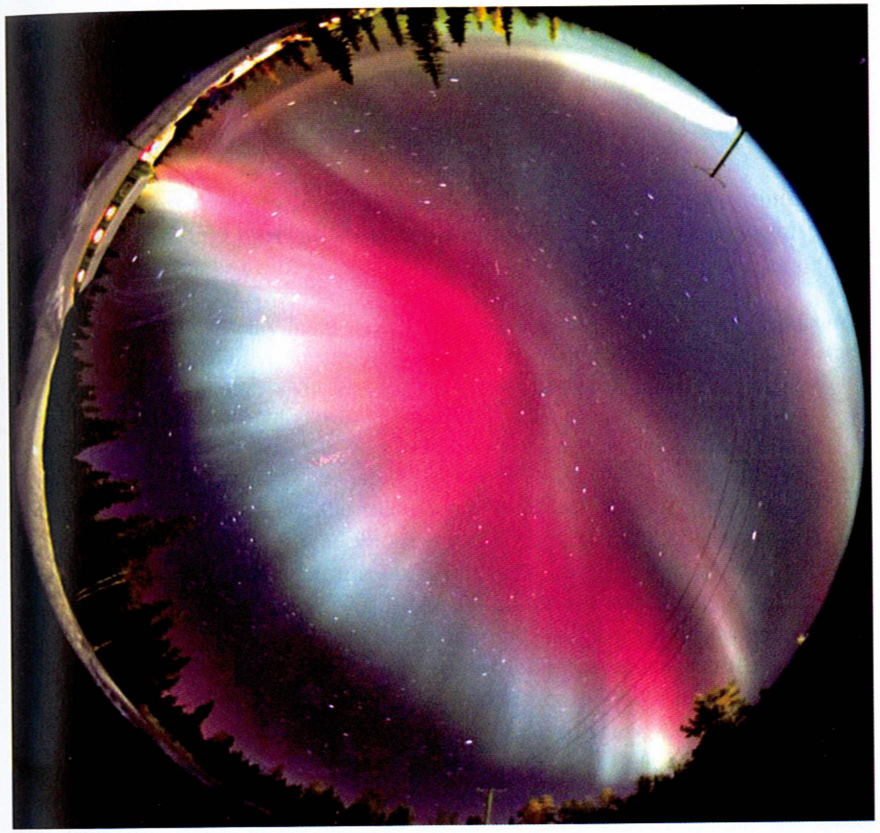


PLATE 5. An all-sky photograph of the aurora: photographed by J. Yokota.
Source: Photographed by J. Yokota

cause delicate movements of the spot. It was during this time, my student days, when I associated the memory of my mother's song with what I was learning.

However, as mentioned in Chapter 1, it was Chapman–Ferraro's paper that brought me to Alaska.

2.2. The Auroral Zone to the Auroral Oval

E. Loomis (1860) was the first to assemble the first extensive collection of auroral appearances over the Earth and found that the aurora tends to appear most frequently along a fairly narrow belt centered around a point at the northwestern tip of Greenland, not at the geographic pole (Figures 2.1 and 2.2). H. Fritz (1873), using much more data covering the period from 503 B.C. to A.D. 1872, confirmed Loomis' findings and constructed his well-known map of isochasms the lines of equal average annual frequency of auroral visibility expressed by "M" nights per year. The maximum frequency of auroral visibility thus defined was found to lie approximately along Loomis' belt. This auroral belt has been called the auroral *zone*. The centerline of the aurora zone coincides well with a geomagnetic latitude (gm lat.) of 67°. The width of the auroral zone is about 5°–6° of latitude. Thus, on a geomagnetic longitude–latitude map centered around the geomagnetic pole (located near the northwestern tip of Greenland), the auroral zone is a circumpolar belt (Figure 2.3). Harry Vestine (1944) refined Fritz's isochasm map with the aid of additional data covering more than a century, including the two International Polar Years.

FIGURE 2.1. E. Loomis (1811–1889).
Source: Courtesy of Yale University

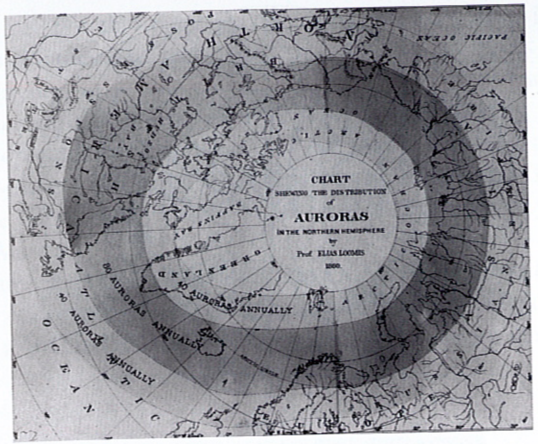


FIGURE 2.2. The auroral zone determined by Loomis.
Source: Loomis, E., *Amer. J. Sci. and Arts*, **30**, 89, 1860

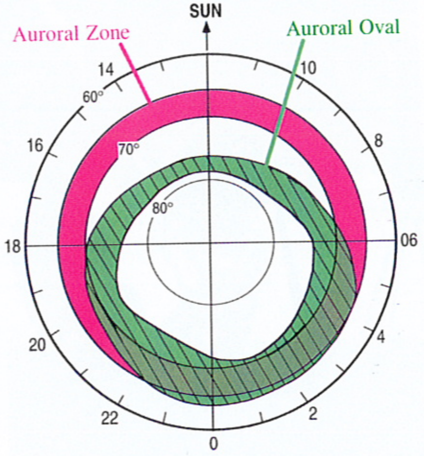


FIGURE 2.3. The auroral zone (red), the auroral oval (green) on the geomagnetic latitude-magnetic local time coordinate system.
Source: Akasofu, S.-I., *Aurora and Airglow*, ed. by B.M. McCormack, p. 267, Reinhold Pub. Co., New York, 1967

Figure 2.4 shows an auroral sketch made by N. Carlheim-Gyllensköld at Cape Thordsen in Svalbard during the First Polar Year (1882). This was one of the first scientific recordings of the aurora. A photographic method was introduced in auroral physics at the beginning of the twentieth century (Figure 2.5). A number of auroral expedition parties were dispatched to Greenland, Siberia, Canada, and many other countries during the Second Polar Year (1932). The isochasm map

Parks, R. Pellat, Risto Pellinen, Mikhail Pudovkin, Pat Reiff, Gordon Rostoker, Chris Russell, V.A. Sergeev, George Siscoe, Dan Swift, O.A. Troshichev, N.A. Tsyganenko, Vytenis Vasyliunas, Jack Winckler, and Dave Winningham. Later, waves of the new generation joined in our effort, particularly during the International Conference on Substorms (ICS). My former students Ching Meng, Koji Kawasaki, Lee Snyder, Fumi Yasuhara, Paul Perreault, Tom Berkey, and my associates Yosuke Kamide, Joe Kan, Lou Lee, and Tony Lui worked very closely with me on substorm research.

Finally, long-awaited images from the Dynamic Explorer satellite began to arrive (John Craven and Lou Frank, 1983). I visited my colleagues at the University of Iowa to witness this event. I thanked Lou Frank and congratulated him on this great success. It was the ultimate test of the concept of the auroral substorm because the auroral substorm must be the same seen from below and above, see Figures 2.22a and 2.22b. Auroral morphology was further advanced by the Canadian group (Elphinstone et al., 1996).

It is important to learn that it takes much more time than one thinks to convince colleagues if one's finding is radically different from what has been believed for years. Figure 2.23 shows schematically the auroral features at about the maximum epoch of a typical substorm. The visible feature consists of three parts, as shown on the left-hand side, the dayside part, the nightside part, and the diffuse aurora, which is located equatorward of the first two arc structures. Note the diffuse aurora evolves into many arcs that develop further complex folds.

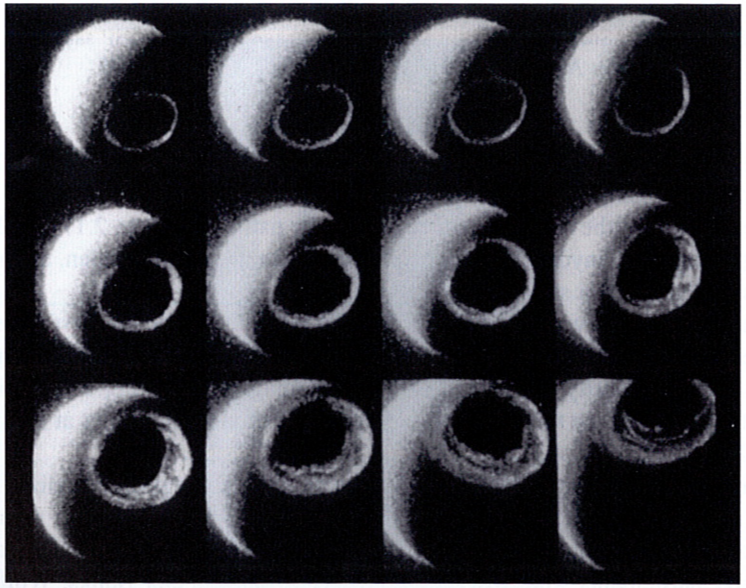


FIGURE 2.22a. Auroral images taken from the DE satellite that depict the development of an auroral substorm.
Source: Craven, J.D., Y. Kamide, L.A. Frank, S.-I. Akasofu, and M. Sugiura, Magnetospheric Currents, ed. by T.A. Potemra, *Geophysical Monograph*, 28, AGU, Washington D.C., 1983

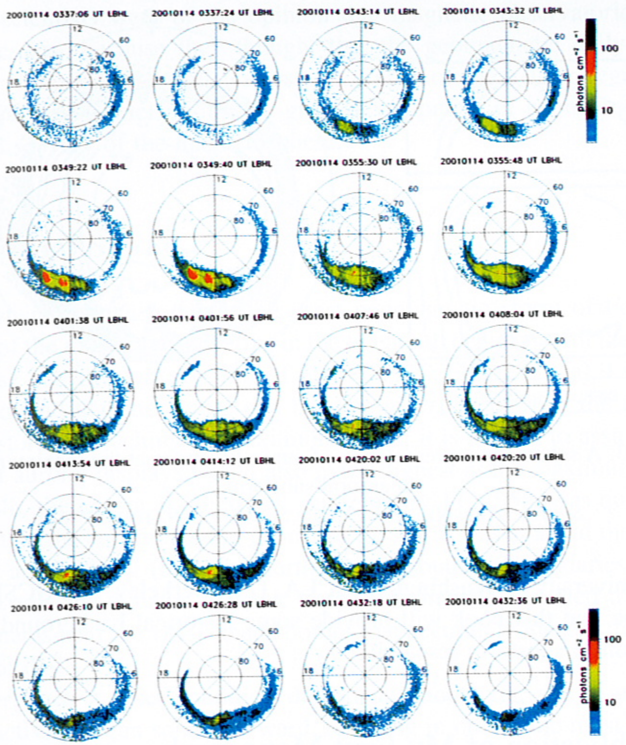


FIGURE 2.22b. A typical substorm depicted by the POLAR satellite.
Source: Courtesy of G. Parks

As the study of substorms had progressed by the work of a large number of researchers in the 1980s, we thought that an organized effort was needed to advance it further. Joe Kan was instrumental in establishing the ICS. The first conference was held in 1992 under the leadership of Bengt Hultqvist at the Swedish Institute of Space Physics, in Kiruna, Sweden. The second conference was held in 1994 at the University of Alaska Fairbanks, commemorating the publication of my 1964 paper on auroral substorms. The conference was blessed by active auroral displays over Fairbanks. The ICS brought many younger researchers who have considerably advanced the study of magnetospheric substorms. I also wish to express great appreciation for the close interaction with the following groups: the Swedish group in Stockholm, headed by Carl-Gunne Fälthammer; the Norwegian group in Oslo, headed by Alv Egeland; the Danish group, headed by Knud Lassen; the Canadian group headed by Cliff Anger; the Russian groups at Apatity, Moscow, Irkutsk, and Petersburg; and many U.S. groups, including Aerospace Corporation, Boston University, Johns Hopkins University, University of New Hampshire, Rice University, Southwest Research

FIGURE 2.29. The aurora on Earth, Jupiter, and Saturn, NASA Hubble Space Telescope Project.
Source: Bhardwaj, A. and G.R. Gladstone, *Rev. Geophys*. **38**, 295, 2000, Hubble Space Telescope Project

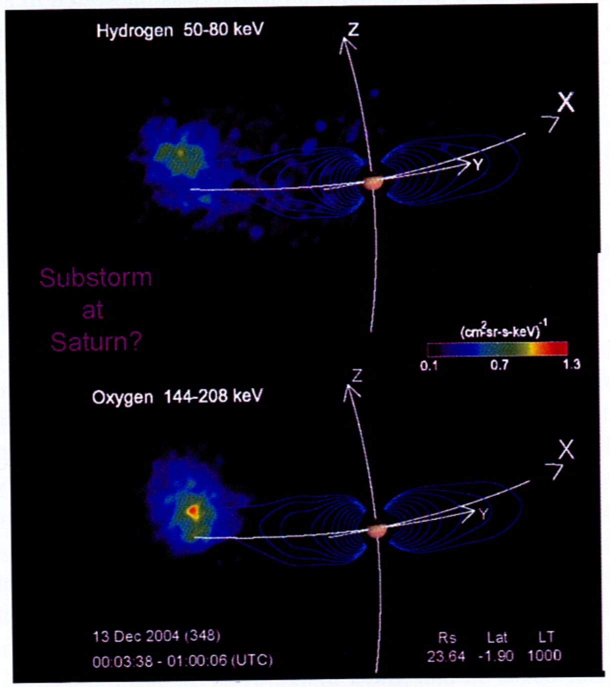


FIGURE 2.30. Energetic neutral atom (ENA) imaging of substorm-like activities in the magnetosphere of Saturn.
Source: Courtesy of D. Mitchell, Earth-Sun System Exploration: Energy Transfer, January 16–20, 2006, Kona, Hawaii

The solar wind causes both the aurora and the comet's tail.
Source: Geophysical Institute, University of Alaska Fairbanks

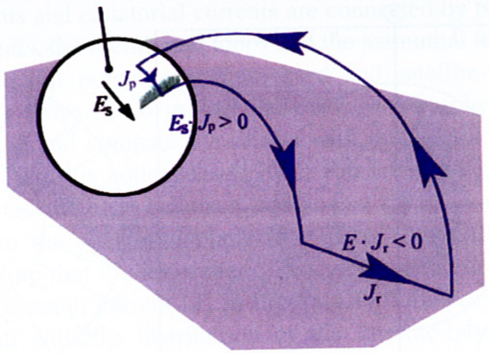


FIGURE 4.3. The Pedersen current circuit. Because $\boldsymbol{E} \bullet \boldsymbol{J}_p > 0$, the dynamo must be found in the equatorial plane $\boldsymbol{E} \bullet \boldsymbol{J}_r < 0$. The auroral arc is formed at the feet of the upward field-aligned current.
Source: Akasofu, S.-I.

in the equatorial plane using the AMPTE satellite data set that is shown on the right hand side of Figure 4.2.

The fact that the distributions on the left and right sides in Figure 4.2 are strikingly similar suggests that the Pedersen current is connected to the radial current $\boldsymbol{J}_r$ where the electromotive forces $\boldsymbol{E}$ and $\boldsymbol{J}_r$ must be related by $\boldsymbol{E} \bullet \boldsymbol{J}_r < 0$ in order to drive the meridional current system, including the Pedersen current and the upward and downward field-aligned currents (Figure 4.3). The fact that the Pedersen current is connected to the field-aligned currents, as shown in the insert of the right-hand side of Figure 4.2, is demonstrated by the distribution of the field-aligned currents in Figure 4.4a. The field-aligned current associated with meridional currents is a *sheet* current. The upward sheet current, which is carried by downward flowing electrons, must be associated with an auroral arc.

Thus, the ionospheric and equatorial observations are combined to indicate that the current element in Figure 4.3 constitutes a sheet current circuit in Figure 4.4b, and that there must be a process within a distance of 10 Earth radii to drive J_r (Figure 4.3). Further, the upward field-aligned current in a sheet form, carried by the downward streaming electrons, causes the curtain form of an auroral arc.

4.1.3. *The Westward Electrojet is the Hall Current*

It has long been known that the westward electrojet is the Hall current, which is driven by a southward oriented electric field (Akasofu, 1960).

In 1971, at the occasion of the International Symposium on Solar-Terrestrial Physics, held in St. Petersburg, Russia, May 12–19, I presented an idea that both the poleward expansion of the bulge and the poleward shift of the westward electrojet were associated with the disruption/diversion of the cross-tail current and its tailward expansion. My Figure 12 is reproduced here as Figure 4.5. Its popularized version was later promoted by a UCLA group (McPherron

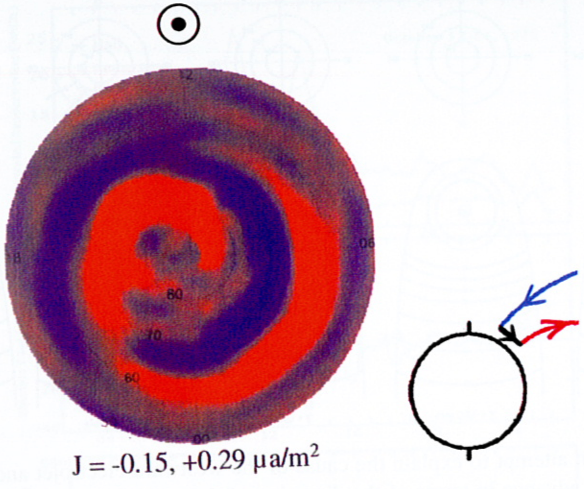


FIGURE 4.4a. The distribution of field-aligned currents determined by the Iridium satellite.
Source: Waters, C.L., B.J. Anderson, and K. Liou, *Geophys. Res. Lett.*, **28**, 2165, 2001

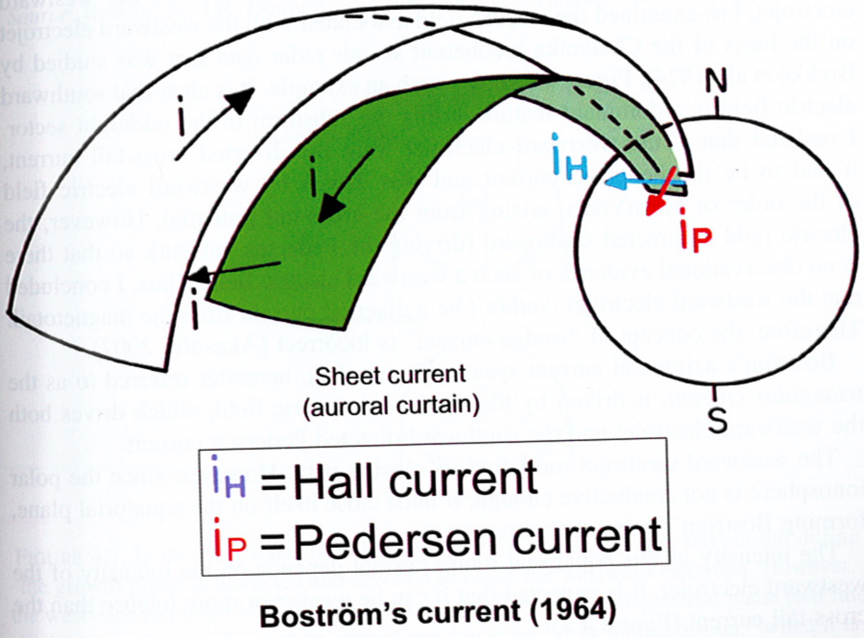
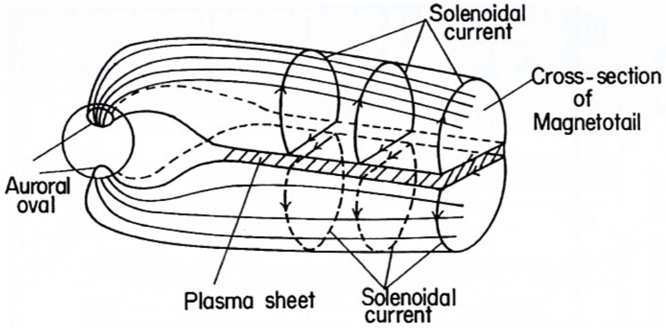


FIGURE 4.4b. The upward sheet current must be related to an auroral arc.
Source: Akasofu, S.-I.



$$\varepsilon = VB^2 \sin^4(\theta/2)\, l_o^2$$

θ 0° → 180° ε ↑ solenoidal current ↑ tail flux ↑

θ 180° → 0° ε ↓ solenoidal current ↓ tail flux ↓

FIGURE 4.15. The solar wind-magnetosphere dynamo produces the power given by ε. It generates two solenoidal currents, one in each hemisphere of the magnetotail. The intensity of the solenoidal current varies with ε.
Source: Akasofu, S.-I.

Based on the above observation, instead of the idea of transferring magnetic flux from the dayside of the magnetosphere to the tail lobe during the growth phase and transferring back from the tail lobe to the dayside after substorm onset, it is possible to interpret the magnetic field observations in the magnetotail without contradictions in terms of increase and decrease of the solenoidal current and the cross-tail current as ε increases and decreases. A complicated MHD simulation is not needed to understand changes of the lobe field intensity.

4.4. Substorm Onset

4.4.1. *An Example of Integration/Synthesis*

In the earlier sections of this chapter, the essential ingredients for considering processes associated with substorms are assembled. When theoretical progress stagnates, it is best to go back to the fundamental observed facts. There are three distinct and well-established phenomena at substorm onset, as well as an enhanced convective flow after the so-called southward turning of the IMF or an enhancement of the solar wind-magnetosphere dynamo power ε:

1. A sudden brightening of an auroral arc over a distance of 1000 km at the poleward boundary of the diffuse aurora in the late evening or the midnight sector; the arc is located just the poleward side (~gm lat. 65°) of the diffuse aurora (caused by energetic electrons from the outer radiation belt), Figure 4.16.

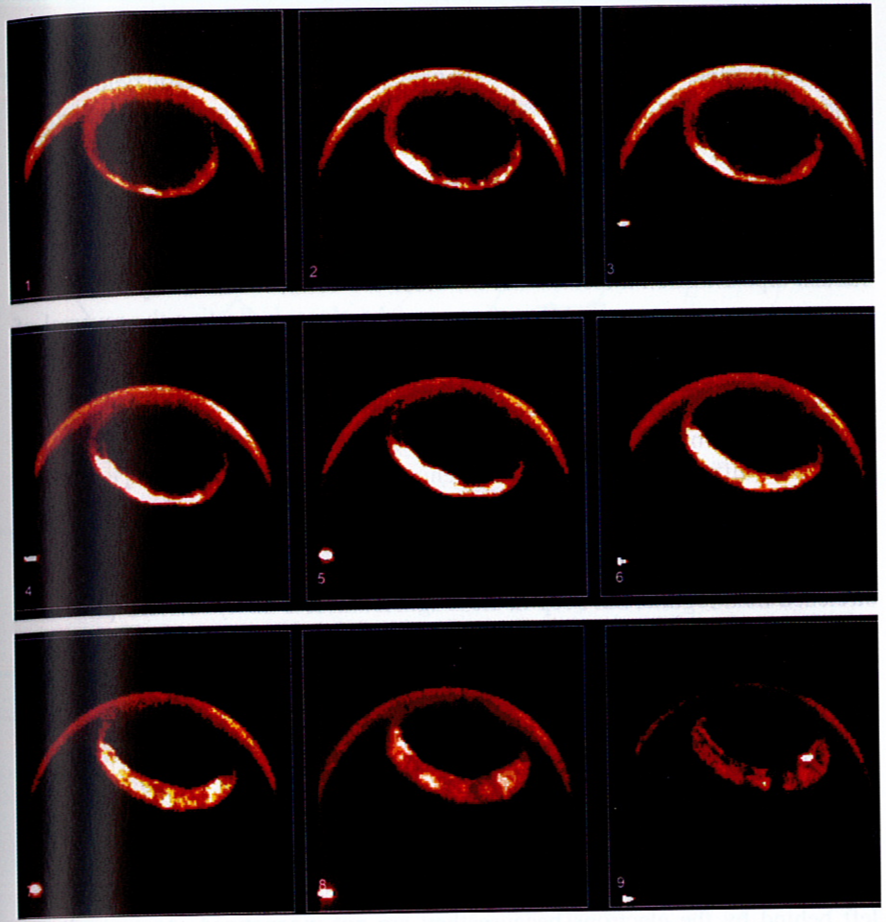


FIGURE 4.16. An example of substorm onset.
Source: Courtesy of L. Frank

2. The westward electrojet develops suddenly along the brightening arc.
3. The magnetic field structure changes suddenly from a tail-like configuration to the dipolar structure in the magnetotail. This phenomenon is often referred to as dipolarization and is known to propagate outward.

The three phenomena have the following physical meanings:

Sudden Brightening:

This phenomenon must be associated with an increase of the energetic electron flux into the existing arc, carrying the upward field-aligned current over an east–west extent of the order of 1000 km within the narrow width of an auroral arc (see Figure 4.4b).

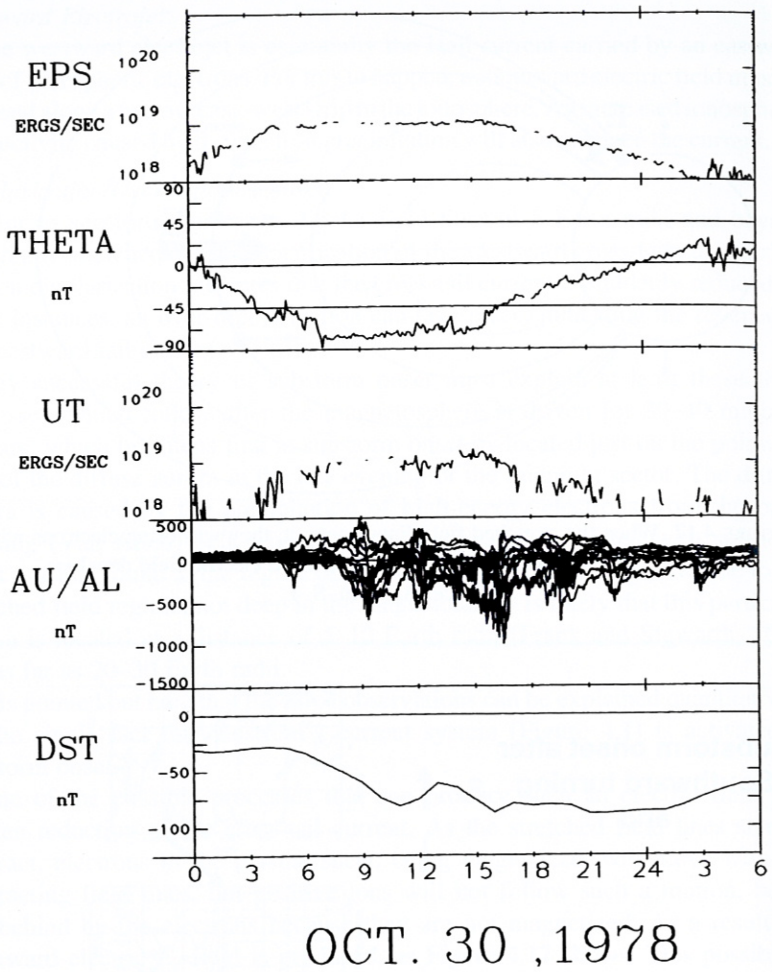


FIGURE 4.19. An example of the occurrence of substorms when the IMF *Bz* component does not show a northward turning, but when the magnetosphere is continuously driven. *Source*: Akasofu, S.-I., *Space Sci. Rev.*, **113**, 1, 2004

cause substorms when the magnetosphere is continuously driven (Figure 4.19). Figure 4.20 summarizes schematically the sequence of the events, which are also shown in a block diagram in Figure 4.21.

The three phenomena that are associated with substorm onset are likely to be directly related to each other and to occur simultaneously:

(a) After an enhancement of the cross-tail current during the growth phase, some plasma instability suddenly reduces the cross-tail current, causing the contraction of the magnetotail field, the "dipolarization."

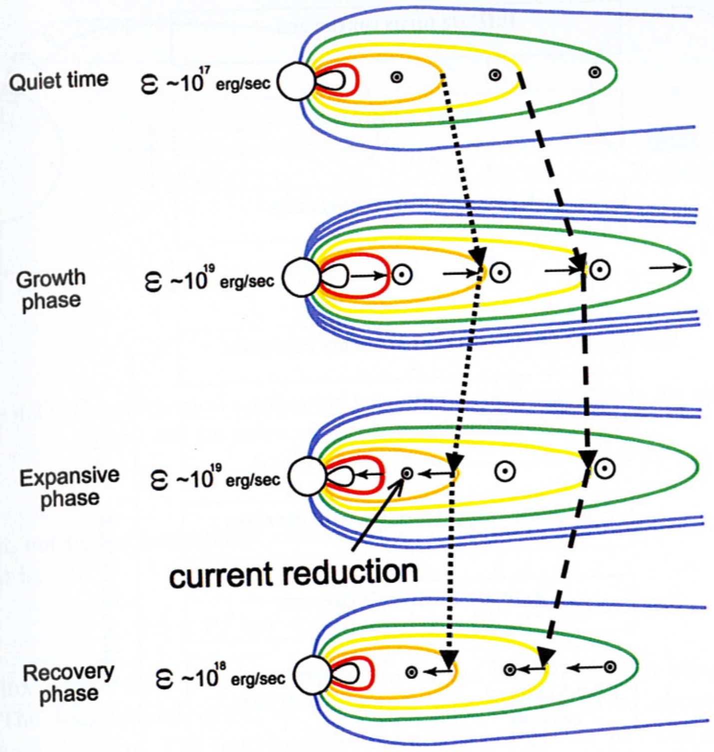


FIGURE 4.20. The summary of one possible sequence of the events from the quiet time to the recovery phase. It shows changes of the intensity of the cross-tail current and the magnetic field configuration. *Source*: Akasofu, S.-I.

(b) Processes associated with the "dipolarization" result in a sudden activation of Boström's current system at a distance of 5–10 RE, causing the meridional currents. The upward portion of the sheet current will brighten the aurora.

(c) The same process will bring the equatorward electric field in the ionosphere, driving the westward-directed Hall current, the westward electrojet.

(d) The westward electrojet must close its circuit on the equatorial plane, disrupting the cross-tail current. This process further causes the "dipolarization." This is a positive feedback process that is needed for the sudden growth of substorms. In some cases, the eastward current becomes stronger than the cross-tail current, causing over-dipolarization.

4.4.2. The Poleward Expansion

The most prominent feature of auroral substorms is the poleward expansion of the auroral system in the midnight sector (Chapter 2). In the past, this feature has been explained by piling up of the reconnecting closed field lines. However, magnetic