14.6.2 Magnetic Storms

Magnetospheric storms are large, prolonged disturbances of the magnetosphere caused by variations in the solar wind. Many magnetic storms follow solar flares or coronal mass ejections, which produce large nonrecurring interplanetary disturbances that interact with the magnetosphere. The impulse from the interplanetary disturbance impulsively compresses the magnetosphere. This sudden compression rapidly increases the magnetopause current, which is observed as a sudden increase in the horizontal component of the surface magnetic field. This *sudden commencement* can be seen in midlatitude magnetograms. It typically has a rise time of a few minutes. The rise time corresponds to the propagation time of MHD waves from the magnetopause to the observation point. When not followed by later storm phases, this phenomenon is called a *sudden impulse*. The initial compressive phase of the magnetic storm typically lasts two to eight hours.

Most magnetic storms are related to long periods (several hours) when the interplanetary magnetic field has a significant southward component. This is the most favorable configuration for magnetic reconnection at the dayside magnetopause. In contrast, purely northward IMF only allows minimal dayside reconnection, and, consequently, it minimizes the transfer of magnetic flux into the geomagnetic tail. Extended periods (several hours) of southward IMF lead to the *main phase* of magnetic storms.

The increased dayside reconnection increases the penetration of the solar wind motional electric field into the magnetosphere, and, consequently, it increases magnetospheric convection. The enhanced duskward electric field increases the number of particles injected into the ring current. Stronger electric fields not only lead to more energetic ring current ions but also result in an earthward expansion of the ring current region. Heavy ionospheric particles are also accelerated outward and a part of this population is eventually accommodated into the ring current.

It was discussed earlier in this chapter that the ring current causes decreases in the horizontal component of the surface magnetic field. These decreases, measured by the D_{st} index, can reach hundreds of nanotesla during strong magnetic storms. As long as the injection of new particles continues, the ring current will grow and it will asymptotically approach a saturation value, when particle sources and sinks balance each other. The time period during which the ring current increases and the horizontal magnetic component decreases is called the *main phase* of the magnetic storm. The main phase typically lasts from a few hours to about a day.

As soon as the southward component of the IMF weakens or disappears, the ring current starts to decay and the horizontal component of the surface magnetic field gradually returns to its normal value. This is the *recovery phase* of the magnetic storm. The recovery phase occurs in several steps. As the southward IMF component weakens, the reconnection rate decreases. This reduced reconnection rate results in decreasing electric fields, which in turn decrease the injection of new particles into the ring current and move the convection boundary outward. The ionosphere starts to fill the depleted flux tubes within this expanded boundary with cold ionospheric plasma.

Thus in the inner region of the expanded ring current the cold ionospheric plasma overlaps the energetic ring current ion population. The interaction between the two plasma populations increases the ring current loss rate due to growing plasma waves (which pitch-angle scatter the ring current particles) and via direct charge exchange. These processes result in a gradual decay of the ring current, which is the recovery phase of the magnetic storm. The recovery phase typically takes several days.

14.6.3 Substorms

Large-amplitude transient magnetic field fluctuations observed during the night in high-latitude regions (such as Scandinavia) have attracted the attention of scientists for most of the twentieth century. The auroral signatures of these transient magnetic perturbations were termed *auroral substorms* by Akasofu,[10] and the magnetic signatures themselves became known as *polar magnetic substorms*. The complete phenomenon, which includes magnetospheric, auroral, and ionospheric disturbances, became known as a *magnetospheric substorm*.

A *magnetospheric substorm* is a time period of enhanced energy input into the magnetosphere from the solar wind and its subsequent dissipation in the magnetosphere–ionosphere system. It is termed substorm because the main phase of large magnetic storms often appear to be the superposition of many smaller storms, each of which contributes to the growth of the ring current. The intermittent and impulsive nature of substorms account for the noisy nature of the main phase of magnetic storms.

Isolated substorms are generated by relatively brief (about one hour) periods of southward IMF. Many of the details of the complicated plasmaphysical processes leading to the development and evolution of magnetospheric substorms are still hotly debated (for a summary of the present models, we refer to a set of review articles recently published in the *Journal of Geophysical Research*.[11])

Individual substorms usually follow periods of northward IMF configuration. During such periods there is very little magnetic reconnection going on near the dayside magnetopause. When the IMF turns negative, the reconnection rate increases considerably at the front of the magnetopause. This leads to a subsequent increase in the magnetic flux transferred to the geomagnetic tail. The increased reconnection also increases the magnetic energy converted to plasma kinetic energy, and the plasma flow in the magnetospheric boundary layer also increases. This process of energy storage in the tail is referred to as the *growth phase* of the magnetospheric substorm. The growth phase usually lasts for about an hour. After that time period too much magnetic flux and thus magnetic energy has been accumulated in the tail. The tail becomes unstable and releases its surplus energy. This is the time of *substorm onset* and marks the beginning of the *substorm expansion phase*.

The substorm expansion phase typically lasts about thirty to sixty minutes. During this period of time, auroral activity in the auroral ovals is greatly enhanced. During

[10] Akasofu, S.-I., "The development of the auroral substorm," *Planet. Space Sci.*, **12**, 273, 1964.
[11] *J. Geophys. Res.*, **101**, A6, 12,937–13,113, June 1996.

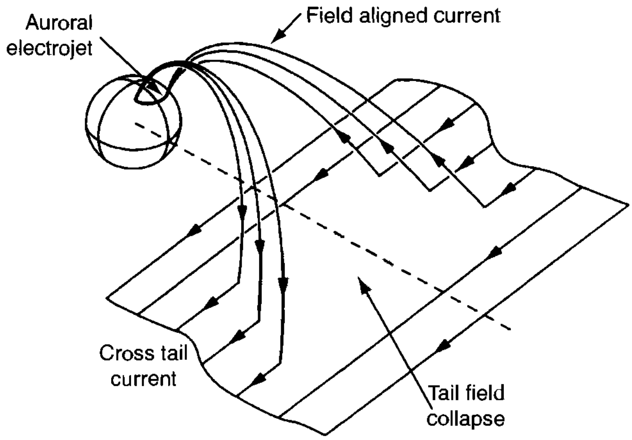

Figure 14.19 Schematic representation of the generation of the substorm electrojet by near-Earth current disruption. (From *McPherron et al.*[12])

the growth phase, auroral arcs can be observed in this region. At substorm onset these arcs suddenly brighten, and they may even fill the whole sky. The dramatic increase in auroral brightness is usually accompanied by large-amplitude magnetic disturbances in the auroral oval.

In addition to the increased auroral activity the ionospheric current flow is also greatly enhanced during the substorm expansion phase. The current increases in two ways. First, because of enhanced convection the *auroral electrojet* increases. This current starts to increase during the growth phase of the substorm. The second way the current flow increases is through the *substorm electrojet* or *substorm current wedge*, which is related to the unloading of magnetic energy in the tail. The current in the substorm electrojet flows westward in the midnight sector. This current is coupled to the cross-tail currents via field-aligned currents, and it is closely associated with the reconfiguration of the magnetotail.

The formation of the substorm current wedge is a consequence of the reconnection process taking place in the near-Earth magnetotail. During the growth phase, the magnetic flux in the tail lobes increases and the cross-tail current sheet (which separates the two lobes) becomes thinner and thinner due to the increased pressure from the lobes. When some portion of the current sheet reaches an appropriate threshold, reconnection begins spontaneously near the center of the current sheet. This reconnection disrupts the cross-tail current and part of the current is diverted toward the ionosphere along magnetic field lines connecting the reconnection region to the polar region of Earth. The closure of disrupted current in the ionosphere is the substorm current wedge. This process is shown in Figure 14.19.

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[12] McPherron, R. L., Russell, C. T., and Aubry, M., "Satellite studies of magnetospheric substorms on August 15, 1968, 9. Phenomenological model for substorms," *J. Geophys. Res.*, **78**, 3131, 1973.

About an hour after the substorm onset, the ionospheric current flow and the bright aurora start to decrease and the *substorm recovery phase* begins. This phase lasts a couple of hours and ends when the magnetosphere returns to a "quiet" state. However, during extended periods of significant southward IMF, the recovery of one substorm may overlap with the growth phase of the next substorm.

14.6.4 Geomagnetic Activity Indices

Magnetic indices are widely used to characterize the dynamic state of various aspects of the magnetosphere–ionosphere system. Here we briefly describe some of the most commonly used magnetic indices.

Geomagnetic indices are based on ground magnetograms that record the magnetic field vector as a function of time. The magnetic field vector is fully determined by three components, but different observatories measure somewhat different independent quantities to characterize the magnetic field vector. In standard terminology the magnitude of the geomagnetic field vector is called *total intensity* and it is denoted by F; the magnitude H of the horizontal component of the magnetic field vector is called *horizontal intensity*; and the vertical magnetic field component, Z, is called *vertical intensity*. The northward and eastward components of the horizontal field are denoted by X and Y, respectively. X, Y, and Z comprise the Cartesian components of the magnetic field vector (we note that the Z component points downward). The angle, D, between north and the horizontal magnetic field component is called *declination*, while the angle, I, between the horizontal component and the total magnetic field vector is called *inclination*. The quantities F, H, X, Y, Z, D, and I are called *magnetic elements*.

General Activity Indices The range, R, of a magnetic quantity for a given time interval is defined as the difference between the highest and lowest values after subtracting the regular daily variation.

The *K index* is a measure of the irregular short-term variations of standard magnetograms and characterizes the general level of disturbance at a given observatory. The K index is defined for each 3-hour interval on the basis of the largest value of the 3-hour ranges in X, Y, D, or H. The K value for a given value of R is found from a lookup table in which the location of the station is taken into account. Because the K index reflects primarily auroral zone activity, stations nearer to the auroral zone have higher sensitivity. K values are integers ranging from 0 through 9 with a roughly logarithmic scaling.

The *K_p index* (the subscript p stands for planetary) is probably the most widely used geomagnetic index. Originally it was intended to characterize the worldwide geomagnetic activity level; however, it is most sensitive to auroral zone activity and quite insensitive to some other types of disturbance. The K_p index is based on K indices from about a dozen stations. The individual station indices are first standardized through tables that translate the integer (0–9) K value into a fractional value with quantized units of 1/3 (28 possible values, 0, 1/3, 2/3, . . . , 9). The K_p index is then defined as the arithmetic average of these fractional values.

Auroral Electrojet Indices The auroral electrojet indices were defined to obtain a measure of the strength of the auroral electrojet that is relatively uncontaminated by ring current effects. These indices are calculated from corrected H component plots measured by a worldwide chain of auroral zone magnetometers. Monthly mean values are first subtracted from each station's H-component time series, and the resulting curves are plotted in a single plot. In the next step an upper and a lower envelope are determined that represent the highest and lowest corrected H values measured by any of the participating observatories. At any instant the *AU index* (auroral upper index) is defined as the maximum positive disturbance recorded by any station in the chain. Similarly, the *AL index* (auroral lower index) is defined as the lowest negative disturbance recorded by the magnetometer chain. The *AE index* and the *AO index* are now defined as $AE = AU - AL$ and $AO = (AU + AL)/2$.

Ring Current Index The hourly *D_{st} index* is a measure of the strength of the current. It is the average around the world of the adjusted residuals of the H components measured by low magnetic latitude observatories. Adjustment is made for the quiet day levels and for the station's magnetic latitude. In the manner in which it is derived, the D_{st} index is similar to the auroral AE index.

14.7 Problems

Problem 14.1 A magnetic field line crosses the magnetic equator at 4 R_e. Assuming that the Earth's field is dipolar, where does this magnetic field line intersect the surface of the Earth?

Problem 14.2 The polar cap of Jupiter can be approximated by a circular cap of extent 10° from the dipole axis.

1. Calculate the magnetic flux content of the Jovian tail.
2. Calculate the cross-sectional radius of the tail assuming that the magnetic field strength in the tail is 10^{-9} T.

Problem 14.3 The total magnetic energy contained in volume V is given by

$$E_V = \int_V dV \frac{B^2}{2\mu_0}. \tag{14.75}$$

1. Calculate the magnetic energy of Earth's dipole field contained outside the surface of Earth.
2. Calculate the the total magnetic energy for a magnetosphere including both the IMF and the dipole field. What is the energy difference between the southward and northward IMF configurations?