Chapter 15

Space Weather

"Space weather" is a recent phrase and indeed a buzzword in space physics. It refers broadly to the conditions in space that may affect human activities on Earth and in space. These conditions change in response to solar activity like flares, solar wind phenomena like CMEs, CIRs and periods with southwards IMF (interplanetary magnetic field), and the associated changes in coupling between the ionosphere, magnetosphere, and solar wind. One important point is that the magnetosphere is a dynamic, time-varying entity which responds in complex, poorly understood ways to changes in the solar wind.

A very nice overview of space weather phenomena and associated physics is given in the article "Solar Storms: The Silent Menace" by Sten Odenwald in the popular magazine *Sky and Telescope*, in the March 2000 issue, starting on page 50. If possible, you should read the article. Gratifyingly, the article is quite similar to this lecture and its predecessors. Both media reports and scientific investigations can be found on the "superstorms" of 29-31 October 2003 and 20 January 2005.

This Lecture is set up as follows. The first section contains a general overview of space weather, in which the phenomena, solar-terrestrial relationships, locations, and important effects of space weather events are summarized and then explained in more detail. The second section describes some of the geomagnetic and space weather indices used to quantify these effects. The third section contains a basic physical model which integrates space weather phenomena into an understandable (but incomplete) model. The final section sets space weather in context by describing one of the most intense space weather events in recent history, that of January 1997. (The 1999 notes also describe the storm of March 13, 1989.) At the present time obtaining a detailed understanding and predictive capability for space weather is one of the main goals of the Australian space science community, as well as one of NASA's main goals in Space Physics. Perhaps some of you will be able to help to do this.

Those of you interested should look up today's space weather at

`http://www.sec.noaa.gov/today.html or http://www.ips.gov.au/Space_Weather .`

By the end of the lecture you will hopefully understand everything predicted for today and the next few days.

Aims and Expected Learning Outcomes

The **Aim** is to explore the physics and phenomena of space weather, and the reasons it is important to technological human societies. This draws heavily on magnetic reconnection, particle flows, orbit theory, and magnetic fields produced by currents, which link the solar wind to Earth's magnetosphere and ionosphere.

Expected Learning Outcomes. You should be able to

- List, describe, and explain at least 5 space weather phenomena that occur in multiple regions of the solar wind-magnetosphere-ionosphere system.
- Describe and explain qualitatively the physical links between the solar wind and the magnetopause, magnetosphere, and ionosphere of the Earth.
- Explain why magnetic reconnection is vitally important in space weather and how it leads to buildups and release of energy in the magnetosphere, particle energisation and entry into different regions of the magnetosphere and into the ionosphere and solar wind.
- Explain why many types of space weather depend sensitively on the local solar wind environment, particularly on the sense of B_z in the solar wind (northwards or southwards).
- Describe and explain qualitatively when different space weather phenomena should occur.

15.1 General Overview

Broadly speaking, terrestrial space weather events are usually due to

- changes in the ionosphere associated with auroral activity, particle precipitation, coupling to the magnetosphere, and solar radiation,
- enhanced transport of solar wind plasma, energetic particles, and reconnected magnetic field lines into the magnetosphere,
- magnetic substorms in the magnetosphere and associated changes in magnetic fields, currents, and electric fields in the magnetosphere, ionosphere, and at Earth's surface. .

Space weather can be summarized in terms of the following headings.

1. Broad phenomena:
   - increases in solar X-ray, UV and other radiation,
   - increases in the number or energy of energetic charged particles,
   - changes in currents, magnetic fields and induced electric fields,
   - auroral displays,
   - changes in the ionosphere, and
   - changes in radio reception and scattering.
2. Associations with solar and solar wind phenomena:
   - solar flares
   - CMEs, associated shocks, energetic particles, and magnetic field rotations,
   - CIRs and associated changes in magnetic field orientation, and
   - changes in the north-south component of the solar wind magnetic field.
3. Different locations for the activity, such as

- the solar wind,
- Earth's magnetosphere (magnetopause, geosynchronous orbit, plasmasheet, auroral field lines),
- Earth's ionosphere,
- Earth's upper atmosphere, and
- Earth's surface.

4. Causes for particular human concern and interest:

   - radio communication, GPS, and navigation difficulties due to ionospheric scintillations and changing ionospheric reflection conditions,
   - magnetic field changes cause induced currents and EMF's on cables that result in power blackouts and communication failures,
   - variable magnetic fields and induced currents cause difficulties with prospecting equipment and high-tech manufacturing processes,
   - radiation damage, dielectric charging and breakdown of space systems such as spacecraft and satellites,
   - increased ionospheric drag and other difficulties in controlling spacecraft, and
   - radiation damage for humans (airline crew / passengers and astronauts, particularly).

Before proceeding to describe several well-defined periods of space weather activity, we next attempt to integrate the above lists in a more physical way.

Increases in solar X-rays, UV and other radiation during solar flares constitute space weather events for at least two reasons. First, the increased radiation levels can be dangerous to astronauts (e.g., by damaging biological tissue) and can damage ("radiation damage") spacecraft materials and sensors. Second, the ionosphere expands and heats due to absorption of the increased radiation fluxes, leading to increased drag for spacecraft, increased transport of ionospheric plasma into the magnetosphere, and increased conductivity in the ionosphere (particularly the auroral ionosphere).

Space weather associated with energetic particles includes the following. First, damage by energetic particles ("penetrating radiation") to spacecraft and humans, both near Earth and in the solar wind (Figure 15.1). Second, energetic particles can implant themselves in non-conducting spacecraft materials, causing dielectric charging, arcing, and eventually destruction of spacecraft electronics and components once the potential becomes large enough. Third, particles accelerated by solar flares or by CME and CIR shocks can cause these problems in the solar wind and, due to transport through the cusps and enhanced magnetic reconnection at the magnetopause, in the magnetosphere. Fourth, energetic particles are injected near geosynchronous orbit ($R < 10\ R_E$) and midnight during magnetic substorms. These particles enter the ring current and radiation belts, with associated changes in magnetic field near Earth and enhanced precipitation into the ionosphere.

Compression of the magnetosphere and entry of plasma particles from flares and the solar wind leads to a number of space weather phenomena. First, the decreased distance to the magnetopause current layer leads to a small increase in the magnetic field observed at Earth's surface, the so-called sudden impulse or sudden storm commencement (Lecture 13). Second, increased auroral displays and particle precipitation due to plasma funnelling down the cusp field lines to the auroral regions. Third, enhanced plasma densities and energies and magnetic field energy densities stored in the plasmasheet and the magnetotail, which are subsequently

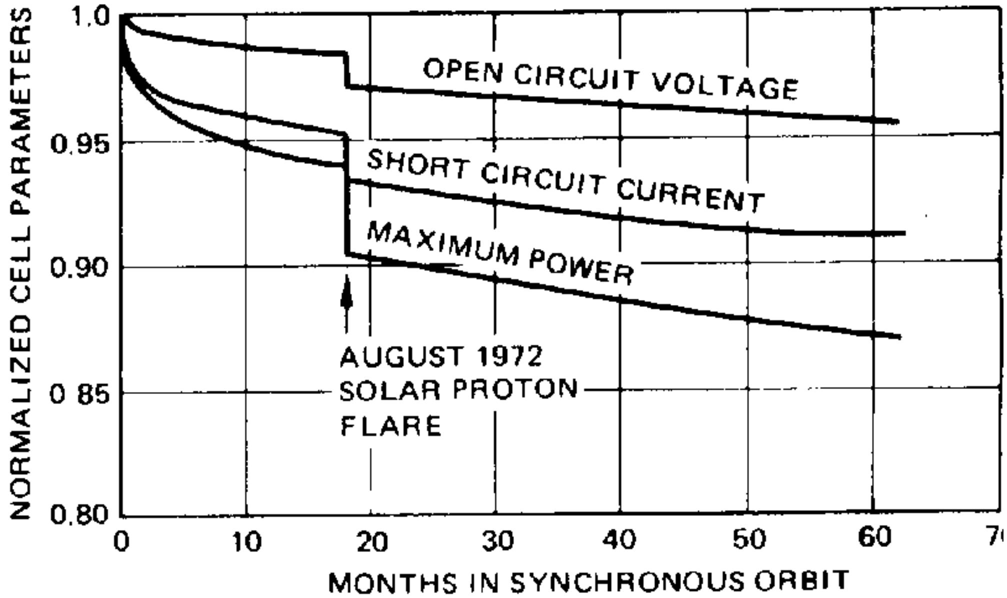

Figure 15.1: Degradation of the solar cell array on a spacecraft with time due to damage by energetic particles [Goldhammer et al., 1976]. The step function decrease was due to the protons from one large solar flare.

released in magnetic substorms. Fourth, radiation damage and dielectric charging etc. as described above.

Changes in magnetic field and associated currents cause many effects in space and on the ground. First, the induction of electromotive forces and currents in long (e.g., transoceanic and transcontinental) cables (Figure 15.2). Second, the induced currents can overload the transformers of electric utilities, leading to widespread power blackouts on Earth. The March 1989 event, for instance, involved over 6 million people being without power for over 9 hours in Canada and Sweden. Third, the fluctuating magnetic fields can lead to difficulties in operating prospecting and communications equipment and high-tech manufacturing equipment. Fourth, these currents can cause increased corrosion in long pipelines.

Finally, changes in the ionosphere due to space weather effects are important in at least the following ways. First, difficulties in radio communications, navigation, and use of GPS systems due to increased radio scintillations (caused by increased density turbulence) and the creation of plasma density holes and enhancements in the ionosphere (which affect the propagation of signals) that move poleward and/or equatorward. Second, difficulties in maintaining satellite orbits and orientations due to increased drag from the expanded and denser ionosphere. Third, increased auroral displays and particle precipitation affect the ionospheric density, both in magnitude and in inducing density turbulence. Fourth, the auroral region and associated displays can move to dramatically different locations rather rapidly. Fifth, the enhanced current and flow of the auroral electrojets leads to large, rapidly changing magnetic fields and associated induced currents on Earth.

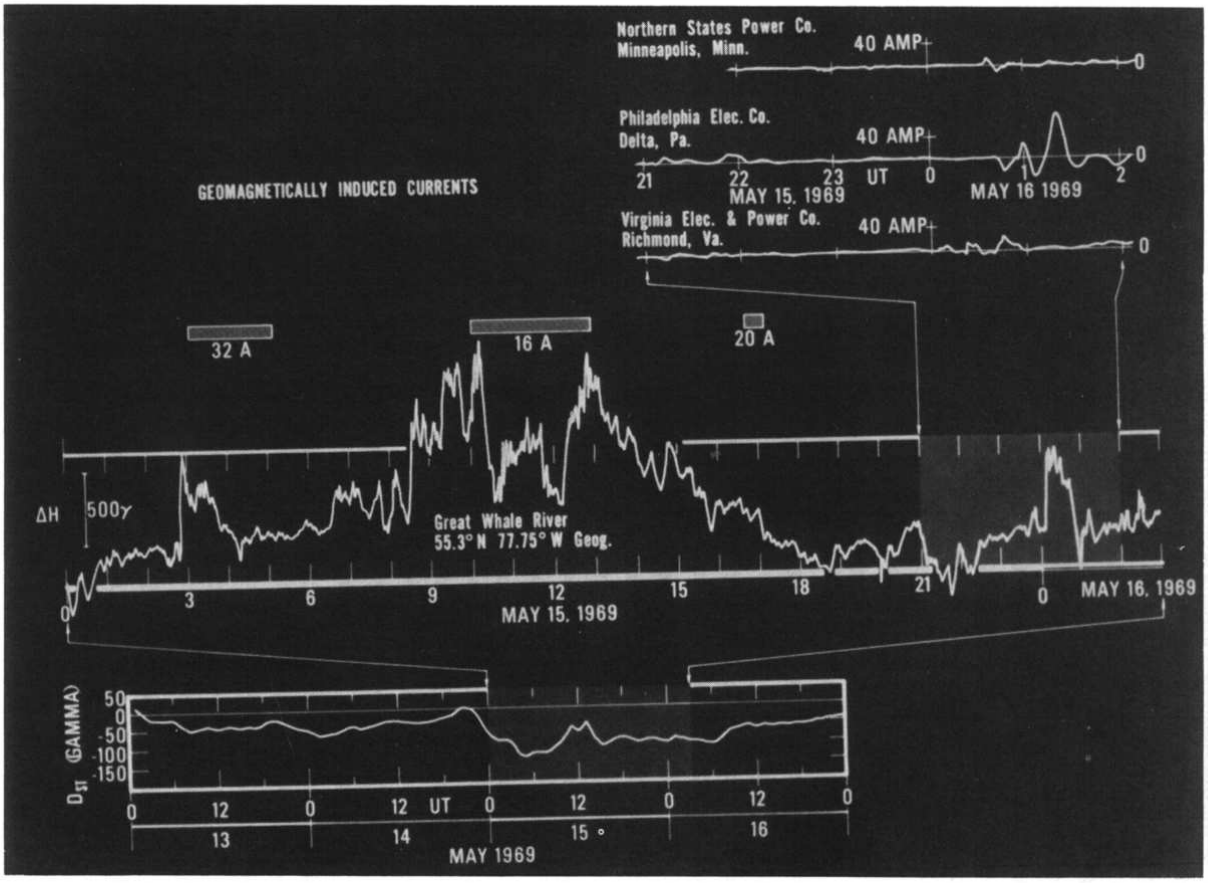

Figure 15.2: Currents induced in transformer windings of power stations in the northern USA (top), a magnetogram trace from Canada for the same period (middle), and time variations in the index D_{st} for the ring current associated with a substorm [Williams, 1979].

15.2 Indices of Space Weather Events

A large number of indices exist to categorize space weather in statistical, global, time- and space-averaged ways. The reasons for attempting to develop approximate indices include the following: (1) the details of most phenomena differ from event to event, so that only approximate representations are sought at first, (2) many of the phenomena depend strongly on the observer's location and local time, so that both a large number of observers and approximate global descriptions are necessary, (3) rapid time variations occur and attempts must be made to disentangle the effects of movement of the phenomenon from intrinsic time variations.

Here only a small number of indices are mentioned. One is the D_{st} index, which measures the strength and time variations of the ring current in terms of the associated changes measured in Earth's magnetic field at latitudes near to (but not at) the magnetic equator. Another is the K_p (or Kp) index which nominally measures the range of variation of particular magnetic field components associated with phenomena other than diurnal changes, yearly variations, and the slow recoveries associated with longterm storm variations. Both D_{st} and K_p are averaged over many observation sites to obtain "planetary" measures of activity. Figure 15.3 illustrates the regions where K_p, D_{st}, and the AE (see below) indices are measured.

The AE (Auroral Electrojet) index measures changes in the magnetic field observed at Earth's surface at auroral latitudes. Related indices are the AU and AL indices, which measure the upper and lower envelopes of the disturbance at a given site, which are then averaged together to form AE. These indices all measure geomagnetic activity; i.e., variations in the magnetic field observed at Earth.

15.3 A Brief Physical Explanation of Geomagnetic Activity

A necessary (but not sufficient) condition for geomagnetic activity to occur is that B_Z be southwards for at least a $30-60$ minute interval beforehand. This is shown conclusively, in a statistical sense at least, in Figure 15.4 [Muruyama et al., 1980].

At its lowest level geomagnetic activity is due to magnetic reconnection and the opposite senses of $\mathbf{E} \times \mathbf{B}$ convection of plasma for northward and southward B_z. This is illustrated in Figure 15.5, following on from Section 14.4. When the solar wind magnetic field is northward it can be seen that magnetic reconnection occurs at greater magnetic latitudes than the cusp and that one of the reconnected field lines adds to the closed field region sunward of the magnetopause while the other is entirely connected to the solar wind with no connection to Earth. Under these conditions, then, the total flux of closed magnetic field lines sunward of Earth is increased, the tail flux is decreased, the magnetopause is enhanced, plasma in the sunward portion of the inner magnetosphere convects Earthward, while plasma convects out of the tail. The situation is entirely reversed when the magnetic field is southward. Under these conditions closed field lines are lost from the dayside and transported to the tail, many more terrestrial field lines are magnetically open to the solar wind, the sunward magnetopause is eroded, the tail plasma flows Earthward and toward the center of the plasmasheet, and the tail magnetic field increases. Put another way, under southward conditions, energy is loaded into the tail, the ring current, and the cross-tail current sheet, while the cusp and magnetosphere as a whole are much better magnetically connected to the solar wind.

Geomagnetic activity can arguably be separated into auroral magnetic activity and magnetic substorms. Auroral magnetic activity involves the enhanced auroral light displays, currents, and magnetic perturbations associated with times when

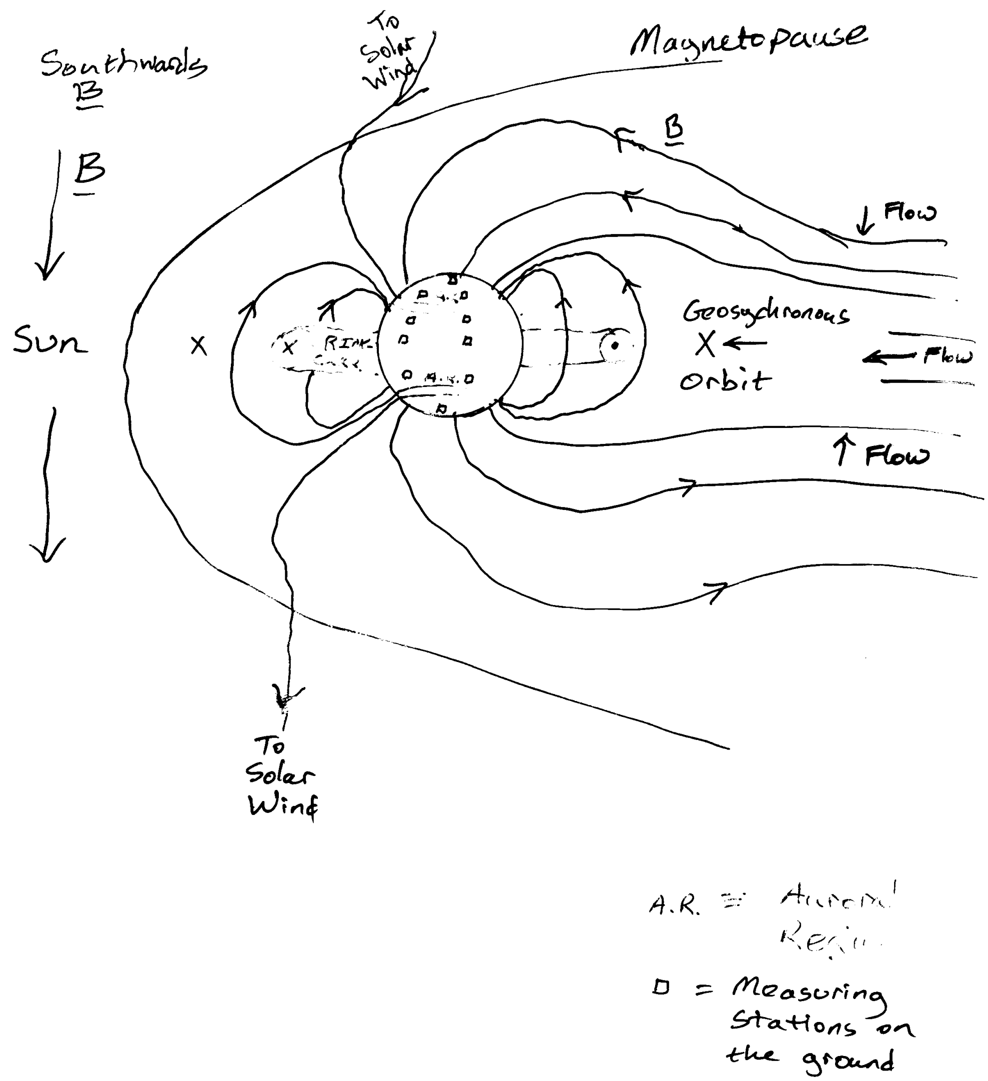

Figure 15.3: Illustration of the auroral ovals and ring current, as well as the regions where measurement stations are well placed to observe the magnetic field perturbations associated with the AE, K_p and D_{st} indices for geomagnetic activity. The characteristic connections of magnetic field lines for southwards IMF are also shown, together with the approximate location of geosynchronous orbits ($R \sim 6.6\ R_E$).

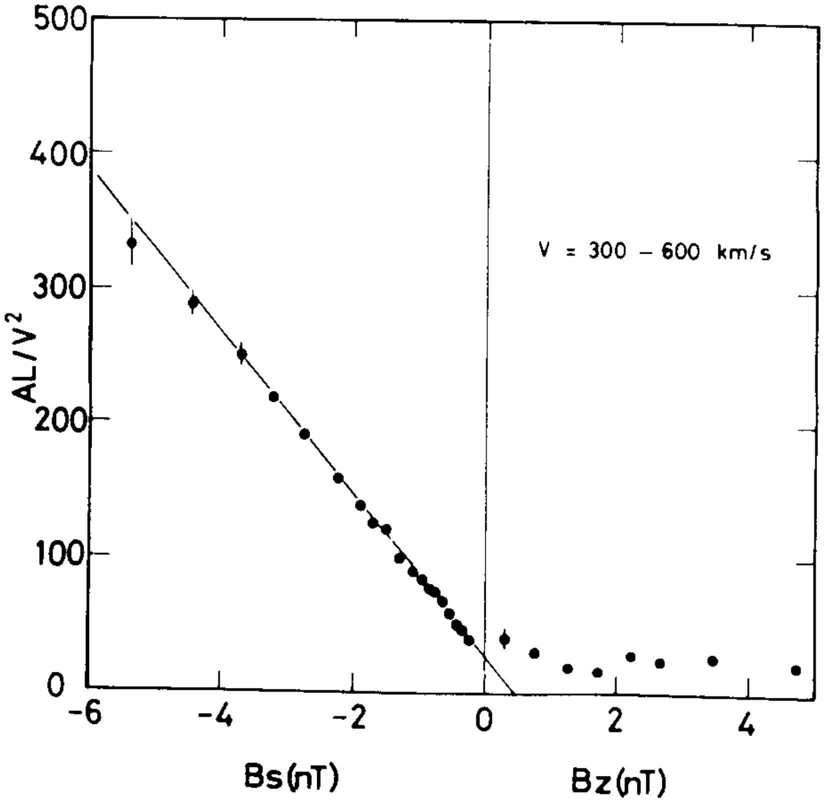

Figure 15.4: Dependence of the AL index for substorm magnetic activity on v_{sw} and B_z [Muruyama et al., 1980; McPherron, 1995]. The abscissa is the value of AL normalized by v_{sw}^2, while the ordinate is either the hourly average of B_z when $B_z > 0$ or else a duration-weighted value of B_z called B_s for $B_z < 0$. Statistically, substorm activity is clearly associated with long duration and/or large values of southward B_z.

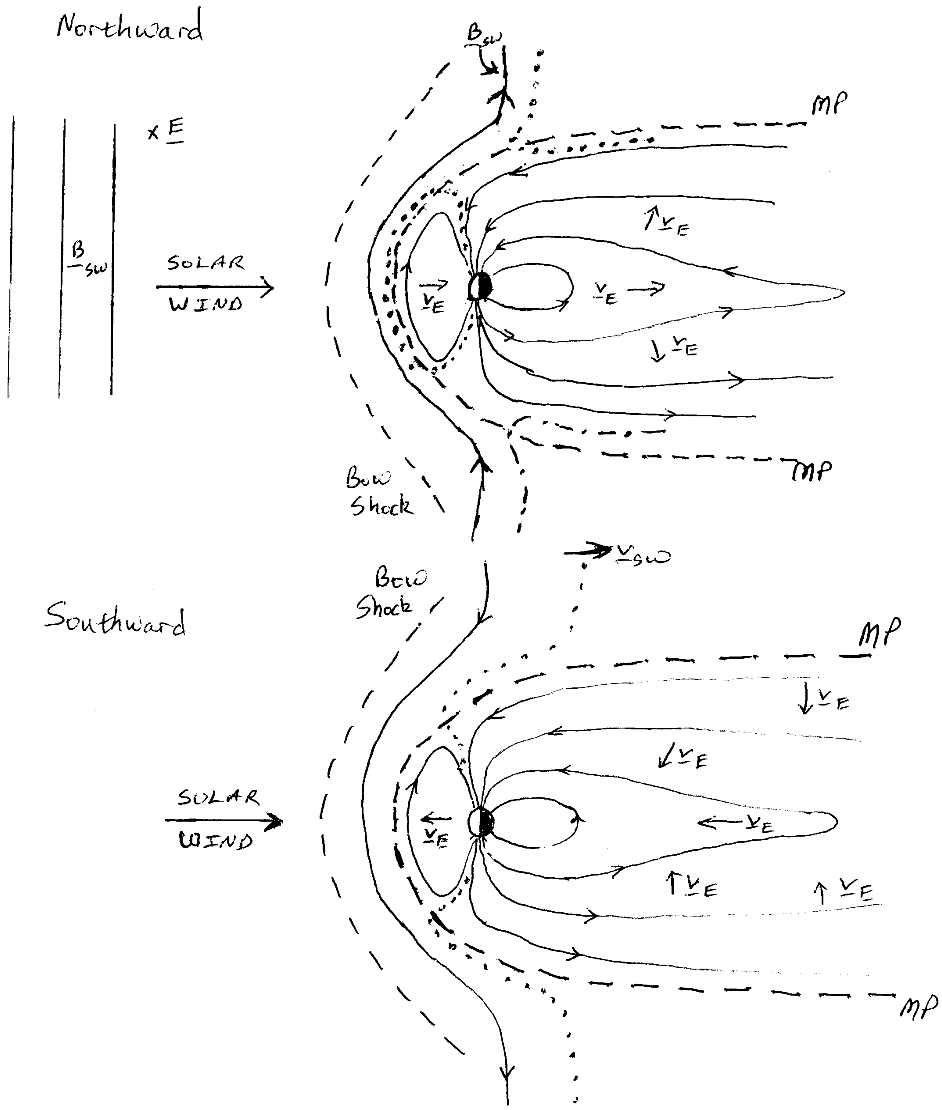

Figure 15.5: Magnetic topologies and $\mathbf{E} \times \mathbf{B}$ convection velocities for Earth's magnetosphere under northwards and southwards solar wind magnetic field conditions. Dashed lines show the locations of the bow shock and magnetopause. Solid lines show illustrative magnetic field lines in the solar wind, magnetosheath, and magnetosphere either before or well after reconnection. Dotted lines show magnetic field lines fairly soon after reconnection.

favorable magnetic coupling causes enhanced plasma flows down the field lines into the auroral regions (on both the cusp and night sides). Magnetic substorms occur, however, when (1) the tail has been loaded with excess energy during a period with southwards B_z and the solar wind turns northward, or (2) the tail is loaded into such a high energy state that even with continued southward driving it must relax. Magnetic substorms occur when B_z remains southwards for extended periods; they involve convection of tail plasma Earthward to cause the ring current to grow with time, continual auroral activity due to plasma transport along cusp field lines and from the plasma sheet boundary layer, the thinning of the plasmasheet, the formation of a second magnetic reconnection site about 10 R_E downtail from Earth, the injection of energetic particles (and their subsequent acceleration by the dawn-to-dusk electric field as the particles drift in the ring current) from the near-Earth reconnection site, and the ejection of the tail plasma as a "plasmoid" which convects tailward with the solar wind.

Figure 15.6 (and Figure 15.9 below) illustrates the main phases of a substorm: the "growth" and "expansion" phases involve the initial slow growth and then faster intensification of the ring current and the main auroral current systems, while the "recovery" phase involves the slow decay of the ring current and the auroral current systems and the disappearance downtail of the plasmoid in the absence of further driving. The near-Earth reconnection site is believed to become active just at the spike of the substorm. Figure 15.7 illustrates the ejection of a plasmoid.

Many details of the above physical model are unclear and are the subject of active international research now, as they have been for about 100 years. Details of some of the popular models can be found in McPherron's [1995] article and Cravens' [1997] book.

15.4 Space Weather Events in January 1997

This section illustrates space weather events using the unusually large and geoeffective event observed during the period 6 - 11 January 1997. This event was one of the largest substorms on record. The news article by Allen et al. [1989] describes the even larger and more geo-effective event for 6 - 19 March 1989 in detail, some of which is paraphrased and other parts supplemented in the 1999 SSP notes. The ISTP web site contains a more detailed discussion of the January 1997 events.

Figure 15.8 shows the solar wind data for the January 1997 space weather event, identifying the CME's shock and rotating magnetic field, as well as a CIR. Note that the magnetic field has a strong southwards B_z component during the CME (magnetic cloud) itself. Figure 15.9 shows the D_{st} and K_P indices for the period, as well as the flux of protons with energies ≥ 1 MeV (as a proxy for solar activity). A clear SSC is visible in D_{st} near about 0200 UT on 10 January, associated with the magnetopause (and associated currents) being pushed closer to Earth by the CME and so increasing the magnetic field measured at the Earth's surface. The main decrease in D_{st} occurs over about the next 12 hours on that same day (associated with changes in the ring current), primarily after the CME-shock system arrives and compresses the magnetosphere, followed by a slower recovery over another 24 hours. K_p started to increase prior to these changes in D_{st}. These increases in geomagnetic activity started (and continued) while B_z was southwards. The peak in D_{st} early on day 11 may be another SSC, this time associated with compression of the magnetosphere by the very dense "filament" at the end of the CME. The final panel in Figure 15.9 shows an increase in the flux of ≥ 1 MeV protons early on 6 January and weak evidence for another after about 1200 UT on 8 January, the second likely associated with a solar flare occurring when the CME lifted off from the Sun.

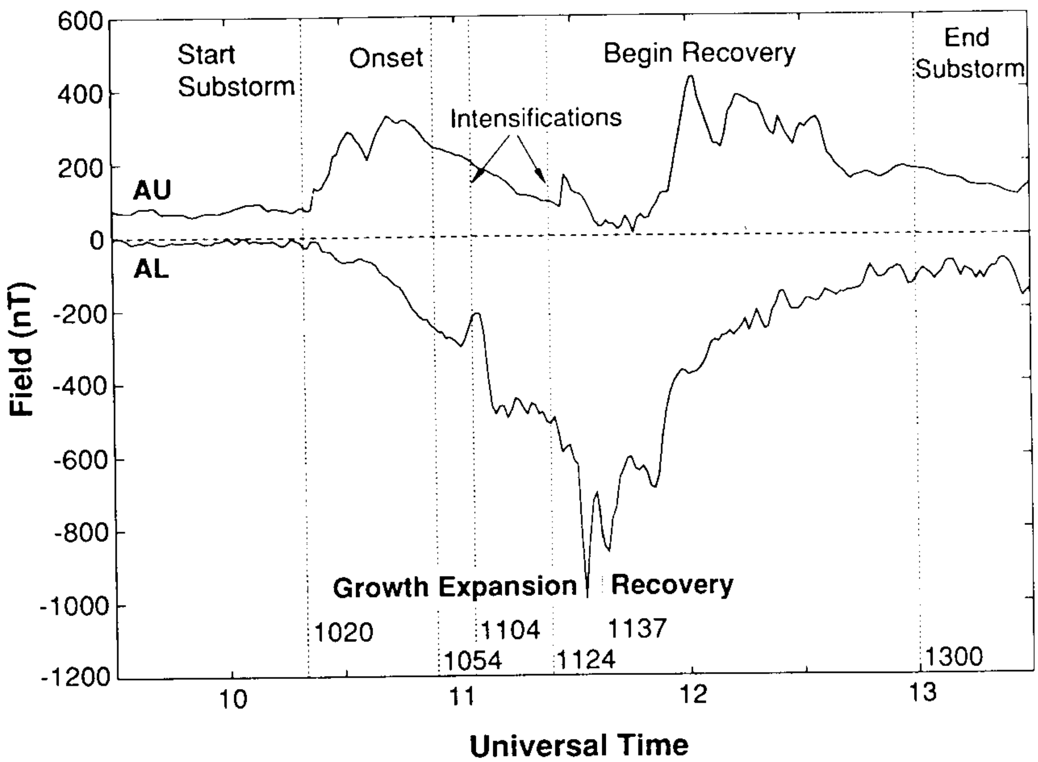

Figure 15.6: Definitions of the main phases of a magnetic substorm in terms of two auroral activity indices AU and AL [McPherron, 1995].

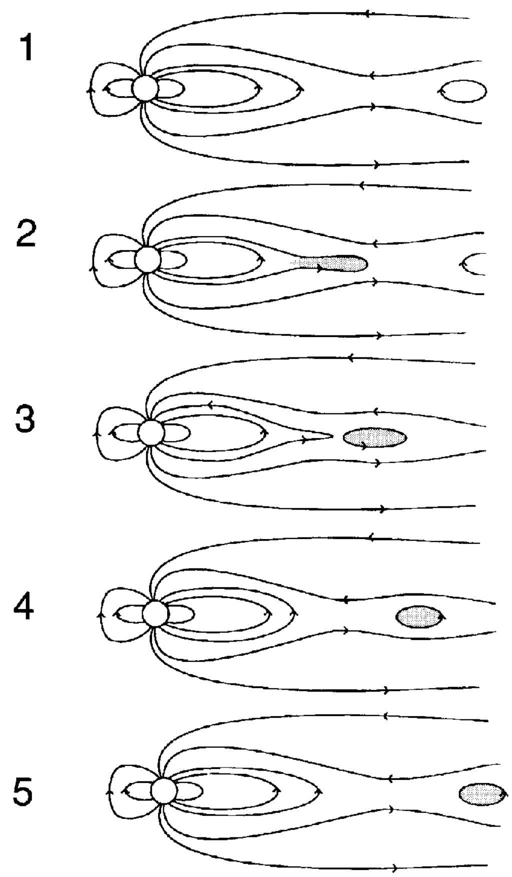

Figure 15.7: The main stages in the ejection of a plasmoid during a magnetic substorm. [Hones, 1984; Cravens, 1997].

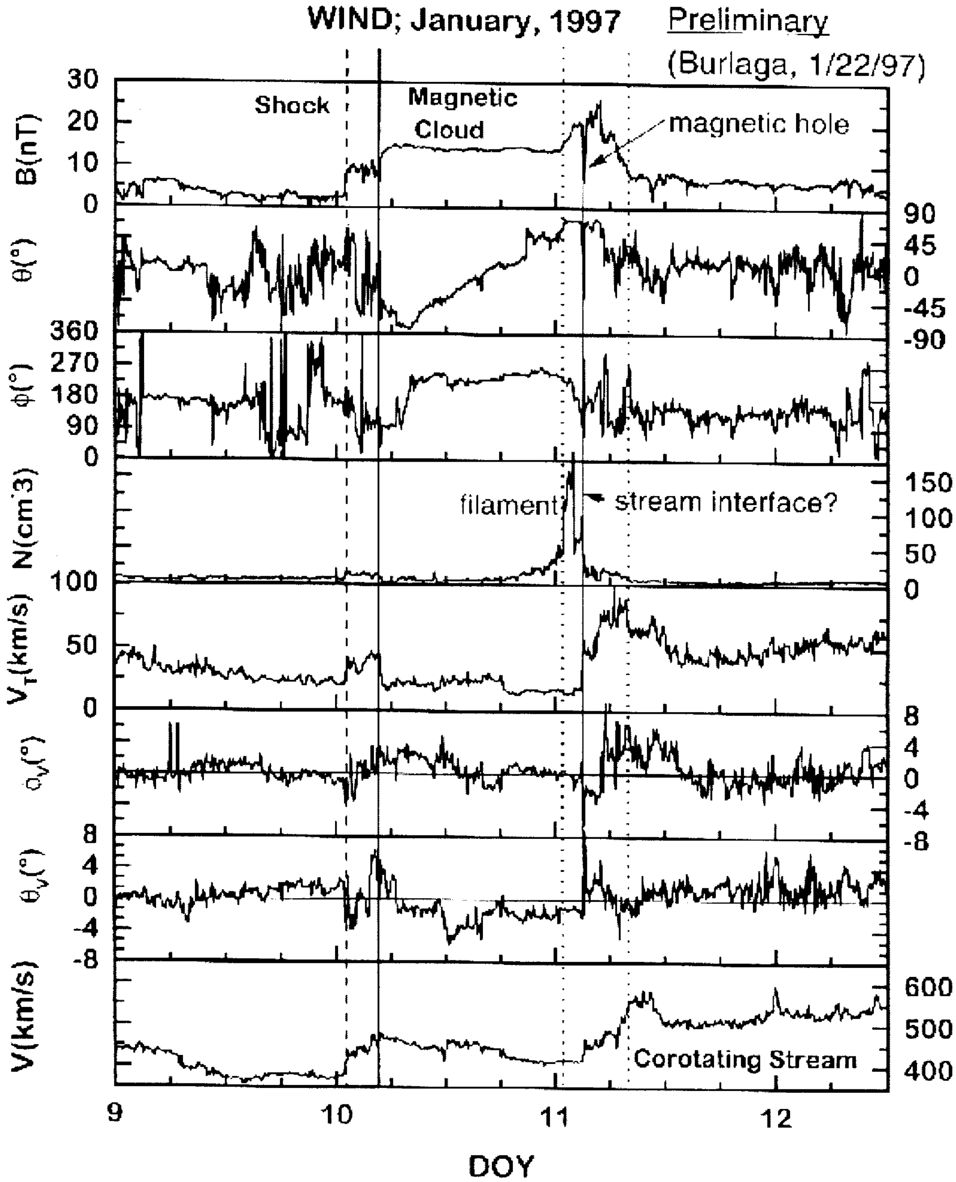

Figure 15.8: Solar wind data for the January 1997 storm period, as presented by L.F. Burlaga on the ISTP web site. The CME shock and cloud, plus a subsequent CIR, are clearly identified.

OMNIWeb Data Explorer Results

Plot for OMNI data from 19970106 to 19970111

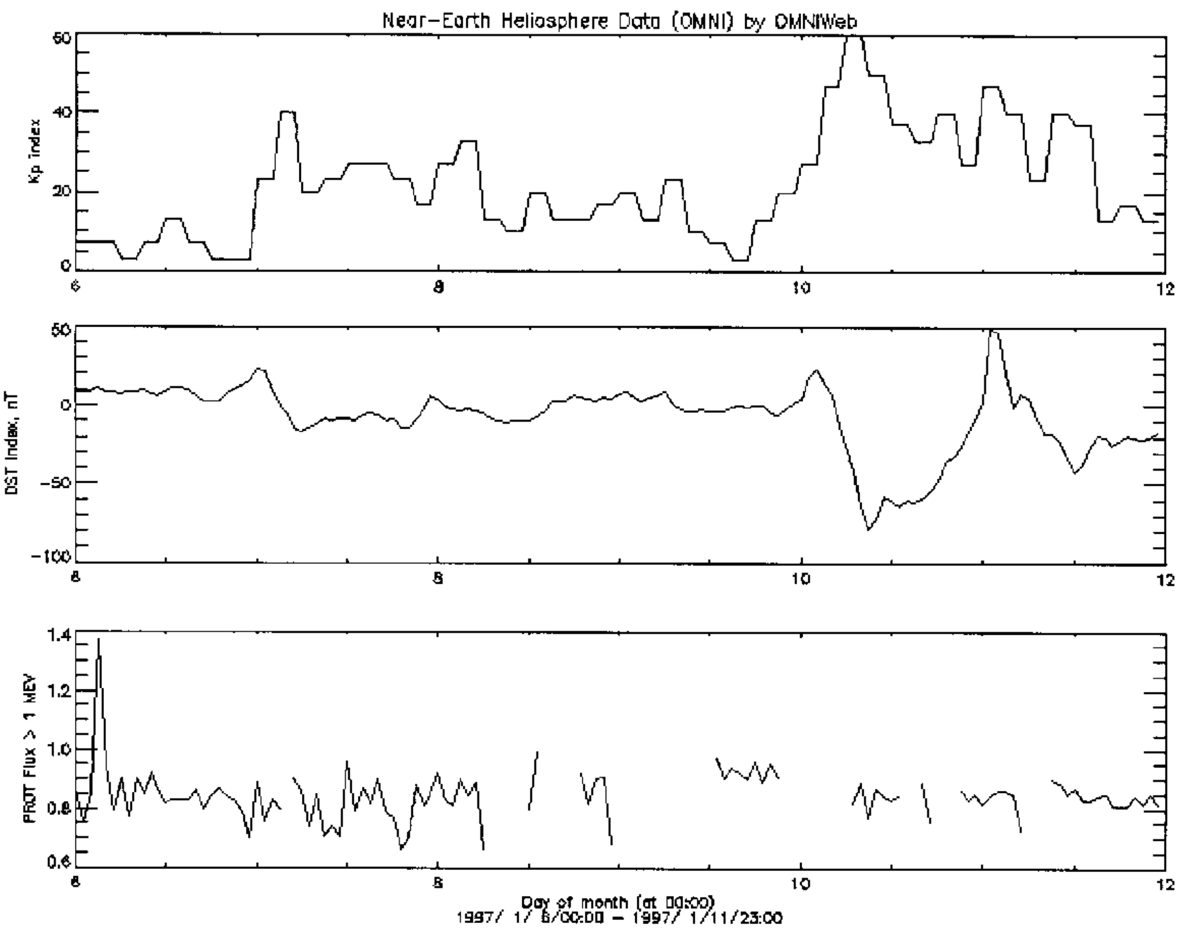

Figure 15.9: Geomagnetic activity indices $10 \times K_p$ and D_{st} for the period 6 – 12 January 1997, obtained from the OmniWeb site.

Figure 15.10 presents more detailed data for this period, showing the rather complex and strongly time varying nature of much geomagnetic activity. The figure shows magnetic field perturbations associated with the auroral oval and auroral electrojets (top panel), intense, time-localized injections of energetic electrons near geosynchronous orbit (second panel), perturbations in the magnetic field observed by the SESAME magnetometer chain (third panel) which are related to changes in the ring current, D_{st}, and the auroral perturbations, and the magnetic field observed in the solar wind by the Wind magnetometer (bottom panel). Note that the most intense activity occurs during and is part of the 10 January substorm. However, other, more localized disturbances occur during other times when B_z is southwards.

The aurorae during this storm covered an unusually large area, were unusually bright, and varied unusually quickly. Figure 15.11 shows these data.

The Telstar 401 satellite failed during this space weather event, possibly (but not certainly) due to radiation damage and dielectric charging. Space weather has also been responsible for several other satellite failures in the last 10 years, including the Galaxy IV satellite whose loss led to most American pagers being unusable for about 1 day from 20 May 1998.

15.5 References and Bibliography

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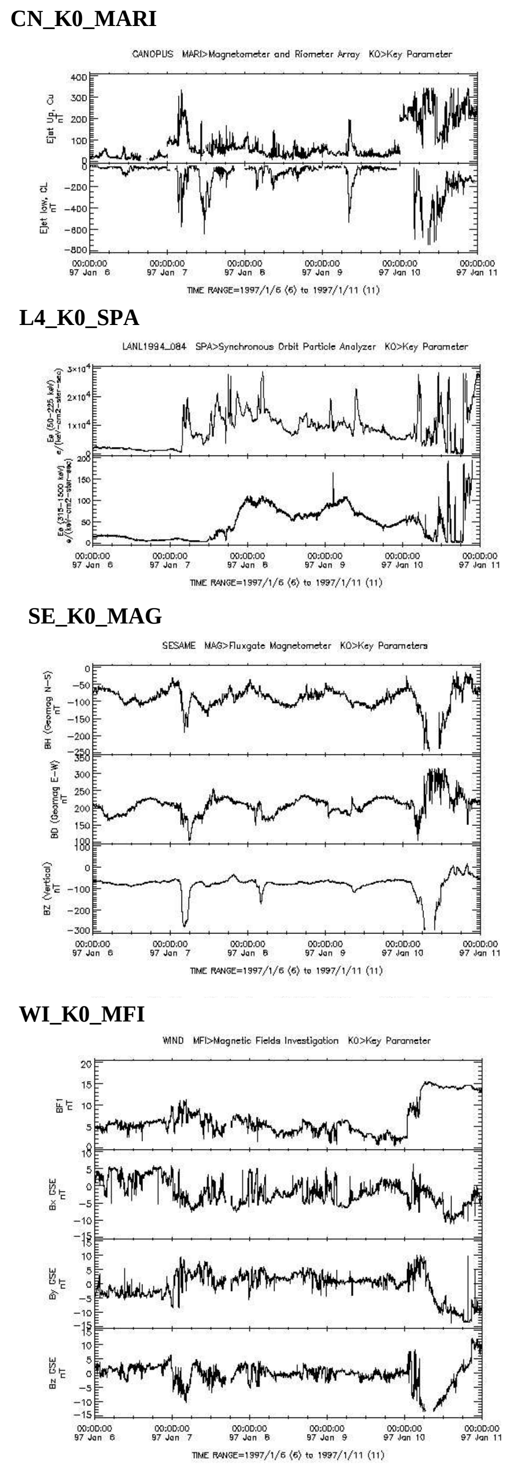

Figure 15.10: Ground-based and spacecraft data showing different aspects of geomagnetic activity for the January 1997 space weather events: (top) ground-based Canopus magnetometer data showing the magnetic perturbations of the auroral electrojets as a proxy for AE, (second) energetic electron fluxes measured at geosynchronous orbit, showing discrete injections on day 10 and before, as well as the general increase due to enhanced solar fluxes, (third) ground-based SESAME magnetometer data as a proxy for D_{st}, and (bottom) magnetometer data from Wind, showing how these geomagnetic activites are associated with southwards B_z.

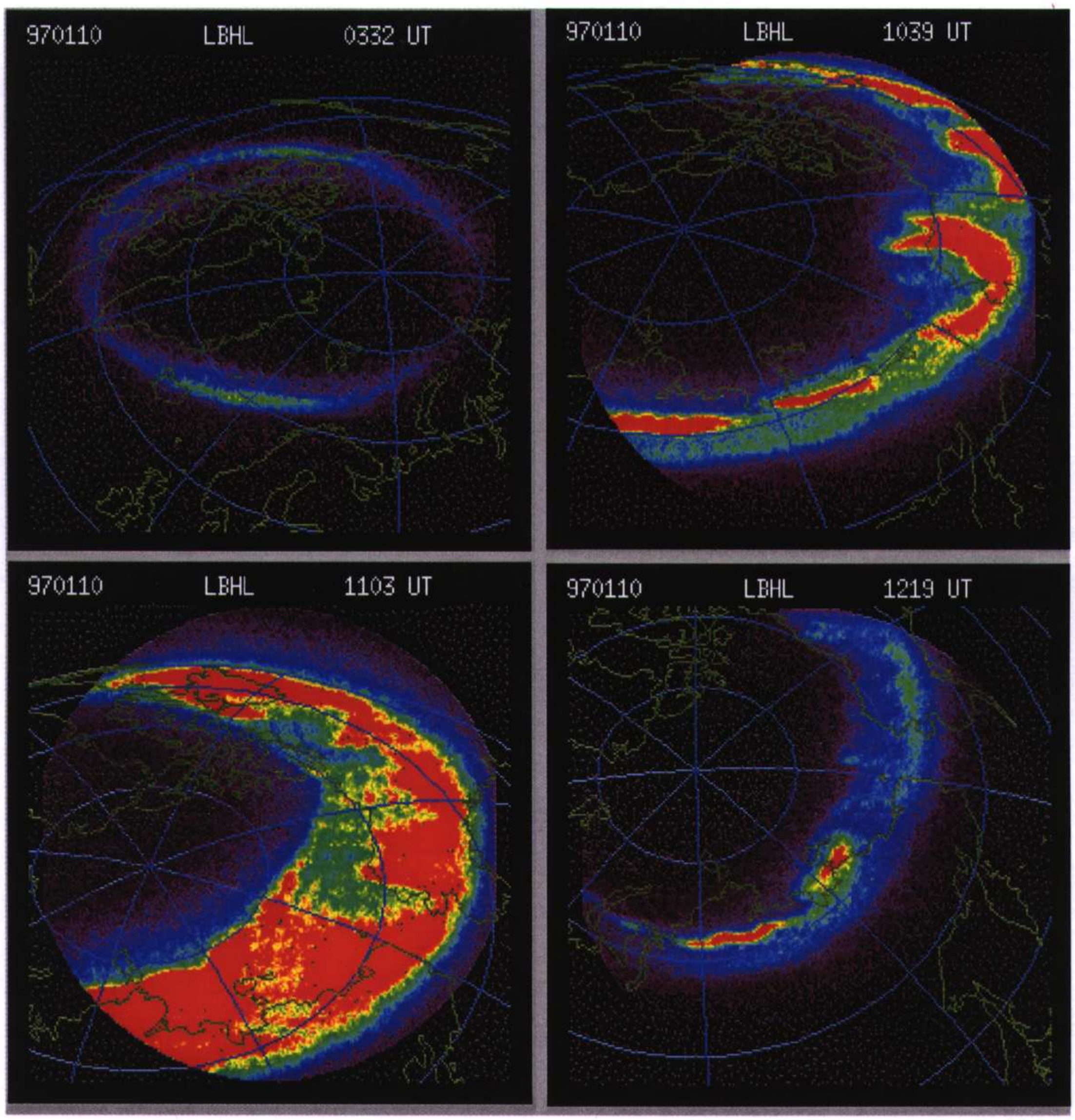

Figure 15.11: Auroral displays on 10 January 1997. Top-left, the quiet auroral oval before the storm. Top-right and bottom-left images are during the height of the storm, showing the large expansion, broadening and brightening of the auroral emissions. The final image shows how quickly auroral displays can disappear.