PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Antarctic Studies of the Coupled Ionosphere-Magnetosphere System [and Discussion]

A. S. Rodger, A. J. Smith and M. J. Rycroft

Phil. Trans. R. Soc. Lond. A 1989 **328**, 271-287
doi: 10.1098/rsta.1989.0036

Phil. Trans. R. Soc. Lond. A **328**, 271–287 (1989)
Printed in Great Britain

Antarctic studies of the coupled ionosphere–magnetosphere system

By A. S. Rodger and A. J. Smith

British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, U.K.

[Plate 1]

The southern polar region offers many significant advantages over its northern counterpart for studies of the interactions of the solar wind, magnetosphere, ionosphere and thermosphere. These mainly arise from the much wider separation of the geographic and geomagnetic poles in the south compared with the north. These displacements lead to hemispheric asymmetries and to considerable longitudinal structure in the high-latitude ionosphere and magnetosphere, which is particularly striking in the south. Examples of these effects are given. In addition, observations of geospace from Antarctica have made a valuable contribution *per se*. Suitable illustrations are provided from invariant latitude *ca.* 45° to the invariant pole. Possible areas for future research, and the experimental methods that are likely to be used to overcome the logistical difficulties, are discussed.

Introduction

Although Antarctica is encompassed by 60° geographic latitude, it is possible to make ground-based observations there from 45° invariant latitude to the pole. This results from the large offset of the geomagnetic pole (dip pole is offset by *ca.* 24°). Thus ground-based observations from Antarctica investigate all regions from the inner plasmasphere to the polar cap. It is impossible to review comprehensively the coupling between the ionosphere and magnetosphere over such a large region. Therefore attention will be focused upon the advantages that Antarctica offers for geospace research, the coupled system from the solar surface to the lower thermosphere and mesosphere. Key points will be illustrated with examples taken from the recent literature, which extends to more than 200 papers in the last eight years.

Antarctica offers four important advantages for geospace research.

1. Simultaneous observations from both hemispheres are required to understand more completely and quantitatively the processes coupling the solar wind to the magnetosphere, and to assess the energy transfer and deposition in the high-latitude ionosphere and thermosphere.

2. For studies of the conjugacy and non-conjugacy of geospace phenomena, Antarctic observations are essential.

3. The configuration of the geomagnetic field in the south is significantly different from that in the north and hence interactions of the magnetosphere and ionosphere can be widely different in the two hemispheres.

4. The dynamics of the lower atmosphere, stratosphere and mesosphere are very different in the two hemispheres, especially at high latitudes; thus different lower boundary conditions are imposed on the ionosphere and thermosphere.

In addition, many observations made from Antarctica have led to increased understanding of magnetosphere–ionosphere interactions, although they have not relied on any particular advantages of the Southern Hemisphere; appropriate illustrations will be provided.

There are a variety of good logistical and experimental reasons for using Antarctica as a platform for geospace science. For example, Antarctica is a land mass, albeit covered by ice, with no national boundaries, whereas the northern counterpart is mainly ocean at the highest latitudes; thus it can be easier to deploy experiments in the south. Electromagnetically, Antarctica is the quietest continent in the world owing to its remoteness and the very low level of human activity there. This is a great advantage for all active and passive radio experiments in which the signal-to-noise ratio is important, such as riometers (Hargreaves & Jarvis 1986), and very low-frequency or extremely low-frequency (VLF or ELF) experiments (Carpenter 1988), and for geomagnetic studies (Arnoldy *et al.* 1988*a*). Antarctica is also the continent most free from natural aerosols, such as dust and smoke, and tropospheric water vapour levels are very low over the majority of the continent. These factors, combined with the extended periods of darkness through austral winter owing to the high geographic latitude, make Antarctica an ideal site for many types of optical experiments, such as Fabry–Perot interferometers (Wardill *et al.* 1987), photometers (Eather 1984), all-sky camera and television (TV) systems (Ono *et al.* 1987).

The distribution of present and past geospace observatories has been described by Lanzerotti & Park (1978) and by Russell & Southwood (1982) (see figure 1). In recent years there has

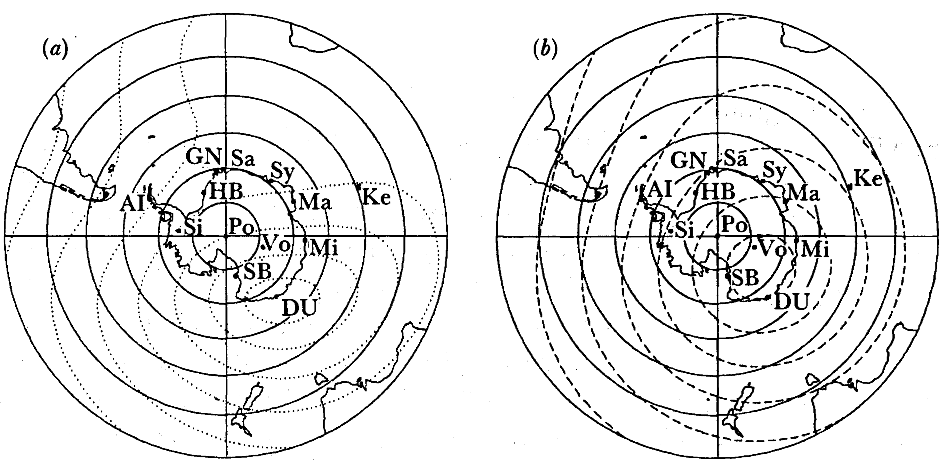


FIGURE 1. Polar projection of the Southern Hemisphere from 30° S to the pole with (*a*) magnetic dip latitude in 10° steps from 20–80° superposed with dotted curves, and (*b*) invariant latitude (dashed curves) in 10° steps from 20–80°, determined for 100 km altitude using the 1985 international geomagnetic reference field. Key to stations: AI, Argentine Islands; DU, Dumont d'Urville; GN, Georg von Neuymayer; HB, Halley Bay; Ke, Kerguelen; Ma, Mawson; Mi, Mirny; Po, Pole Station; Sa, Sanae; SB, Scott Base; Si, Siple; Sy, Syowa; Vo, Vostok.

been a steady increase in activities in Antarctica in all scientific disciplines. The stations in operation and the experiments that are performed there are described in some detail in national yearly reports to the Scientific Committee for Antarctic Research (SCAR). There are now 37 nations actively involved in Antarctic research, the majority of which carry out some research in the field of solar terrestrial physics. SCAR also successfully engenders a spirit of international cooperation and data exchange.

The geomagnetic field in the Southern Hemisphere

The configuration of the magnetic field in the Southern Hemisphere is significantly different from that in the north. The southern dip pole is nearly 24° from the geographic pole (see figure 1) and with the present secular trend this displacement is steadily increasing. In the north, the separation of the poles is less than 12°. This difference has profound effects, leading to pronounced hemispheric dissimilarities, as well as large longitudinal asymmetries, which are particularly marked in the south. The maximum plasma frequency of the F-layer (f_0F2) over Dumont d'Urville and Argentine Islands are often contrasted as an illustration (DU and AI on figure 1). These stations are at about the same geographic latitude (65° S) and thus receive the same diurnal variation of solar radiation. However, their dip angles are nearly 90° and 58° respectively; Dumont d'Urville is a deep polar cap station while Argentine Islands is normally located on an L-shell well within the plasmasphere. As a result of the significantly different production, loss and transport effects on the plasma experienced above the two sites, the f_0F2 values show completely different diurnal variations in summer. Although this difference is less marked in winter, the absolute values still differ by a factor of 2 through most of the day (see Dudeney & Piggott (1978) for a more detailed analysis).

It was as a direct result of this large southern displacement that the importance of thermospheric winds was recognized as a major dynamic force affecting the height and distribution of plasma in the F-region of the ionosphere. In the 1960s and early 1970s, the effects of neutral winds were inferred from the time variation of f_0F2 (see, for example, Rishbeth 1972), but more recently direct measurements have been made of thermospheric winds, both from the ground (Wardill *et al.* 1987) and from space (see, for example, Thayer *et al.* 1987; Killeen 1987). Thus for the first time it has been possible to compare observations with theoretical predictions from sophisticated three-dimensional time-dependent models (see, for example, Rees & Fuller-Rowell 1987). While the general patterns of the observed and modelled winds are usually rather similar, some significant differences have been identified. An

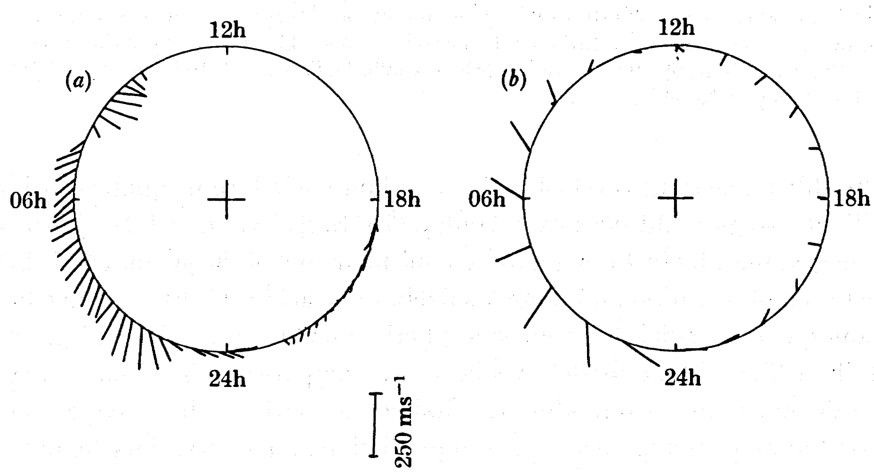


Figure 2. (*a*) Model simulation of winds over a 24 h period for Halley from the University College London, thermospheric general circulation model. Wind vectors are shown at hourly intervals. The solar and magnetospheric parameters are chosen to represent prevailing conditions for the 12–13 July 1983. (*b*) Neutral wind data determined from the Fabry–Perot interferometer at Halley. Vectors interpolated at 15 min intervals are shown, their tails lying on a circle describing the locus of Halley through a 24 h period. At Halley, LT = U.T. − 2 h (From Stewart *et al.* (1985).)

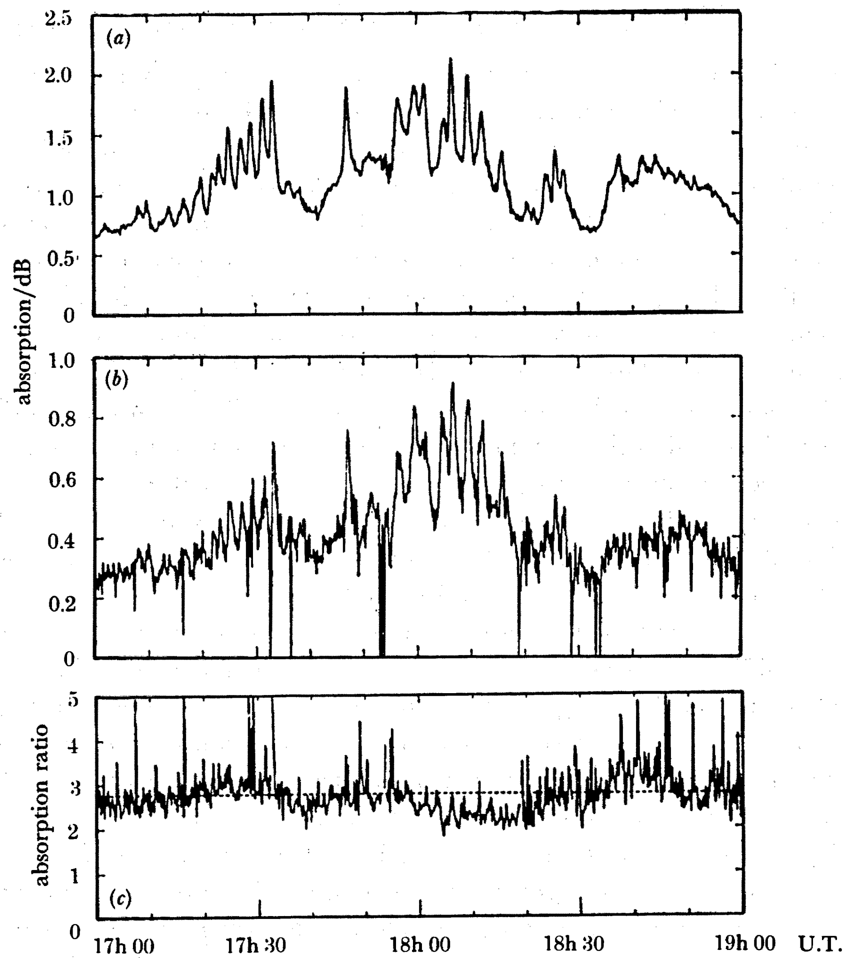


FIGURE 3. (*a*) Riometer data from Siple and (*b*) its geomagnetic conjugate station Roberval, Canada, between 17 and 19 h U.T. on 30 October 1983 (day 303). The ratio of the absorption at the two stations is shown in (*c*); the broken line represents the mean ratio for the period (*ca.* 2.8). The authors note that there is a significant deviation of the values from the mean between 18h00–18h20 U.T. when there is evidence of pulsation activity (from Krishnaswamy & Rosenberg (1987)).

example of this difference is the reversal in the meridional wind from equatorward to poleward near 08h U.T. at F-region altitudes over Halley (76° S, 27° W, $L = 4.2$) (figure 2). Stewart *et al.* (1985) suggest that, by including a more realistic model of the geomagnetic field, a better agreement between observation and theory is likely to be achieved. Efforts have been made to couple an ionospheric model to a thermospheric model (Fuller-Rowell *et al.* 1987) to produce a fully self-consistent model. While early comparisons between observations and predictions in the north are encouraging, the limited comparisons that have been made in the south show considerable discrepancies between prediction and observation. Again this has been attributed in part to limitations of the description of the magnetic field. Other aspects of the uniqueness of Antarctica for thermospheric dynamics, and the importance of magnetospheric processes in providing the principal driving forces of the thermosphere at high latitudes are given in the reviews by Killeen (1987) and by Smith *et al.* (1988).

An illustration of longitudinal effects arising from the significant displacement of the geomagnetic pole from the geographic pole is provided by the studies of the main ionospheric trough carried out using advanced ionospheric sounder data from Halley and Siple (Berkey & Jarvis 1985). The trough is a circumpolar region where the maximum electron concentration at F-region altitudes is anomalously low. Berkey & Jarvis showed that the motions of the trough could not be ordered either in a local-time (LT) frame, or a universal-time frame, or a magnetic-local-time (MLT) frame, but its dynamics was a complex combination of all three.

The South Atlantic geomagnetic anomaly (SAGA) is a region where the geomagnetic field is anomalously weak, a major consequence of which is to lower the mirroring point of energetic particles (see, for example, Sheldon *et al.* 1987). Thus the western edge of the SAGA is a preferential region for the precipitation of energetic electrons, which drift eastwards, resulting in increases of ionospheric absorption and probably also in enhanced VLF or ELF wave activity. The effects of the SAGA have been studied by a variety of techniques, such as riometers, satellite measurements, and by rockets (see, for example, Rosenberg & Dudeney 1986; Gledhill & Hoffman 1981; Sheldon *et al.* 1987). Corresponding arguments concerning energetic ions lead to the conclusion that they should be preferentially deposited on the eastern edge of the SAGA, but to date there is no experimental evidence to verify this suggestion.

Another consequence of the weaker field in the SAGA is that, in the longitude sector centred near 30° W, energetic particles are preferentially precipitated into the Southern Hemisphere. This is illustrated by Krishnaswamy & Rosenberg (1987), who compare 30 MHz riometer data from the conjugate stations of Siple and Roberval, Canada. Figure 3 shows the absorption for a two-hour interval on 30 October 1983. There are considerable temporal variations of the absolute levels of absorption but throughout the period the absorption (in decibels) is *ca.* 2.8 times more in the south than in the north.

Interhemispheric differences

The orientation of the interplanetary magnetic field (IMF) to the geomagnetic field in the two hemispheres is critical in determining the energy transfer from the solar wind into the magnetosphere. For a particular orientation of the IMF, the energy transferred into the magnetosphere will vary as the angle that the geomagnetic axis makes with respect to the IMF changes as a function of time of day and of season (Russell & McPherron 1973). One implication is that the energy deposited into one hemisphere can be very substantially different from that deposited in the other. This has been illustrated by Zanetti *et al.* (1982) using data from high-latitude geomagnetic observatories in both hemispheres (see figure 4). The magnetograms from the south, from sites which range in latitude from $L = 4$ to the invariant pole, show virtually no geomagnetic activity between 13 and 24 h U.T. on 29 July 1977. In the north over the same range of latitudes, there is a geomagnetic disturbance which reaches *ca.* 800 nT. For this event the IMF is northward; field lines from near Resolute Bay map out to near the noon cusp where the magnetospheric field and the IMF are antiparallel. Viscous interaction drives large field-aligned currents into the northern high latitudes; in the south the corresponding field lines map to the solar wind far down the magnetospheric tail where interactions drive very little field-aligned current. The combination of the orientation of the IMF, the U.T. of the observations and the time of northern summer solstice conspire to make these ideal conditions for the maximum asymmetry in field-aligned currents.

The hemispheric asymmetry described above results mainly from an interaction of the

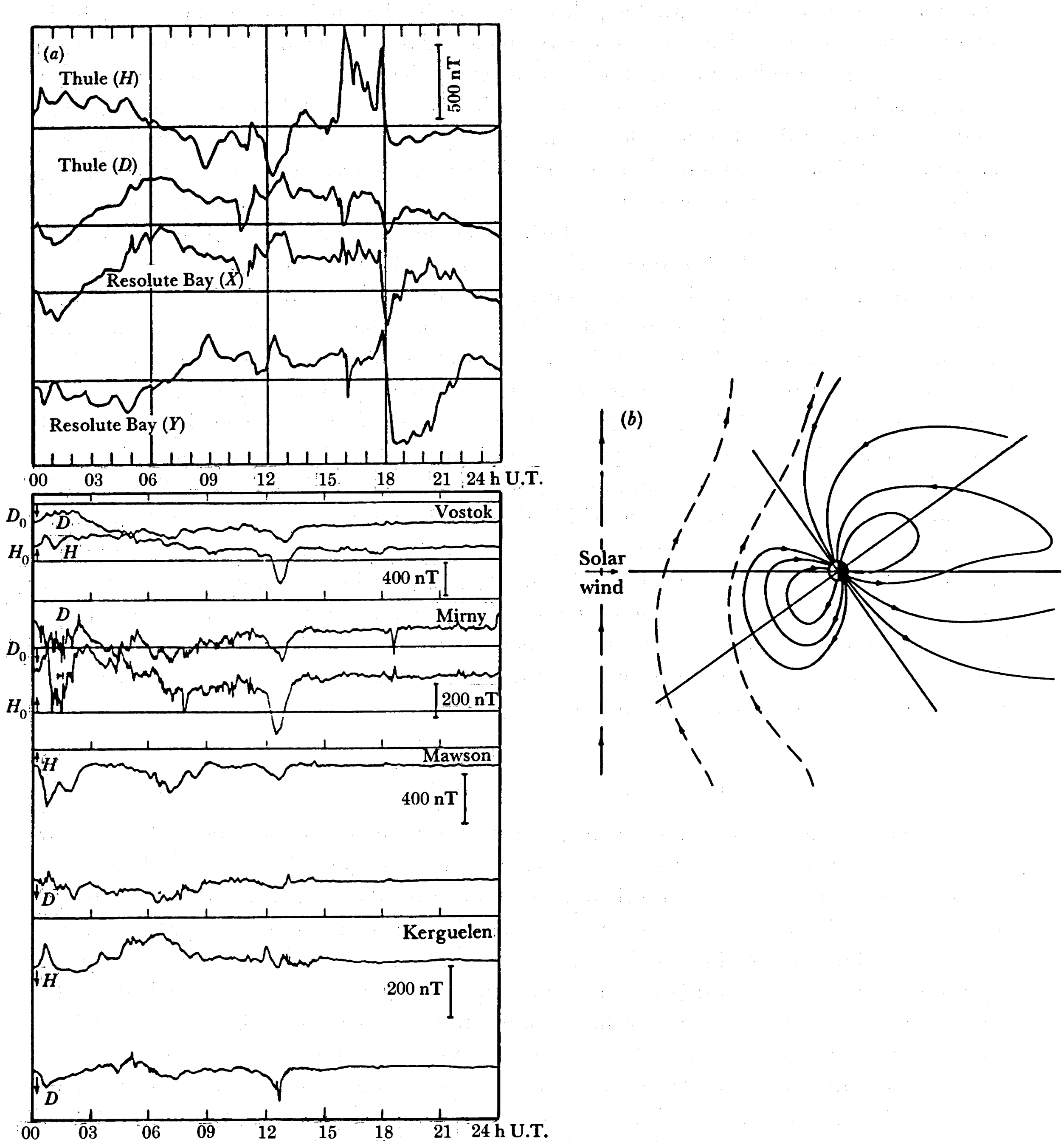


FIGURE 4. (*a*) Magnetograms from a selection of high-latitude geomagnetic observatories in both hemispheres for 29 July 1977. Note that the period between *ca.* 13h00 and 24h00 U.T. is relatively quiet in the south, but the north is very disturbed. (*b*) A schematic diagram of the geometry of the geomagnetic field lines at *ca.* 17h00 U.T. during the northern summer solstice. The Earth's north magnetic pole is tilted up to 35° from the ecliptic north pole toward the Sun. If the IMF is northward, regions of antiparallel magnetic field lines are evident in the Northern Hemisphere at the dayside boundary of the magnetospheric tail (from Zanetti *et al.* 1982).

north–south component of the IMF. The y-component of the IMF, B_y, also gives rise to very significant asymmetries between the two hemispheres which can manifest themselves through many processes. The effects include alteration of the local time of the cusp (Crooker *et al.* 1987) and of the field-aligned current systems associated with it (Friis-Christiensen *et al.* 1985), variations in the plasma convection patterns in the ionosphere in the polar cap and auroral oval (Reiff & Burch 1985), influencing the magnetic time of observations of the Harang discontinuity at a fixed location (Rodger *et al.* 1984). In each of these cases, the direction of the effect is opposite in the two hemispheres. For $B_y > 0$, the dusk plasma convection cell is enlarged at the expense of the dawn cell in the Northern Hemisphere, but the converse is true in the south. These processes in turn affect the dynamics of the thermosphere through ion–neutral coupling. This alters the direction of cross-polar flow of the neutral atmosphere at F-region altitudes, and appreciably changes the strength of the winds in the evening and morning sectors of the oval (Thayer *et al.* 1987).

Candidi & Meng (1988) have carried out a study involving 118 pairs of nearly simultaneous observations of the polar cusp in the two hemispheres. While the statistical average of their data-set shows no consistent variation between the hemispheres, there is considerable scatter in their data and there is an example where the latitude of the northern and southern cusps differs by up to 10°. While there are some problems in uniquely identifying the cusp through a low-altitude particle signature, their data do suggest that there are often differences of several degrees in the latitude of the cusp location in the two hemispheres, which do not appear to be ordered by the magnitude or direction of the IMF, or indeed by the auroral electrojet index, *AE*. There is still some controversy over the extent to which forces external or internal to the magnetosphere control the location of the cusp. These have been reviewed by Eather (1984; 1985) who reinterprets data of other authors and also provides a comprehensive keogram camera data-set from the South Pole.

Another very significant difference between the two hemispheres arises simply because at solstice one hemisphere is under winter conditions with little insolation at high latitudes whereas the summer pole is almost totally illuminated. While particle heating effects may in general be rather similar in the two hemispheres except under some of the conditions described above, solar heating and Joule heating in the two solstitial hemispheres are substantially different. The ratio of summer to winter heating at high latitudes is *ca.* 5:1. Consequences include very large differences in the thermospheric wind patterns at high latitudes at the two solstices (see, for example, Smith *et al.* 1988), and an interhemispheric wind pattern is established which alters the chemistry of the thermosphere significantly at all latitudes (Rishbeth *et al.* 1987). Also the time constant of coupling between ions and neutral particles is up to 10 times larger in the winter hemisphere (Killeen 1987).

Conjugacy

There are many studies of the conjugacy of magnetospheric and ionospheric phenomena which have led to a much greater understanding of the physics of the coupled magnetosphere–ionosphere system. Studies of conjugacy from all geomagnetic latitudes have gained considerable momentum over the last decade; several stations, such as Roberval and Frobisher Bay, both in Canada, and Husafell, Iceland, have been established in the north to be conjugate to Siple, South Pole and Syowa respectively. Antarctica is conjugate to major sources of thunderstorm activity which is ideal for VLF or ELF whistler studies of the plasmasphere, plasmapause and plasma trough (see Carpenter 1988). It is also conjugate to the major industrial activities in North America thus perfectly placed to investigate pollution of the magnetosphere by power line radiation (Tatnall *et al.* 1983). We shall highlight just a few examples ranging from the inner plasmasphere to the polar cap, involving a variety of experimental techniques, to illustrate the activity and importance in this research field.

(*a*) *Conjugacy near the polar cap boundary*

The study of flux transfer events (FTES) has been and continues to be a focus of much attention. Although these events were first identified by spacecraft, recent work has concentrated upon their ionospheric signatures (see, for example, Southwood 1987). Lanzerotti *et al.* (1986, 1987) have shown, with examples from South Pole magnetometer data, signatures of FTES, which correspond to their model of field-aligned Hall and Pedersen currents; however, other configurations of the field-aligned currents are possible. The signatures of FTES have been seen simultaneously at Sondre Stromfjord and South Pole station (see figure 5). The identification of the ground-based signatures may help to resolve some of the many problems concerning FTES such as their relative importance to steady-state reconnection in energy transfer from the solar wind and indeed what causes them.

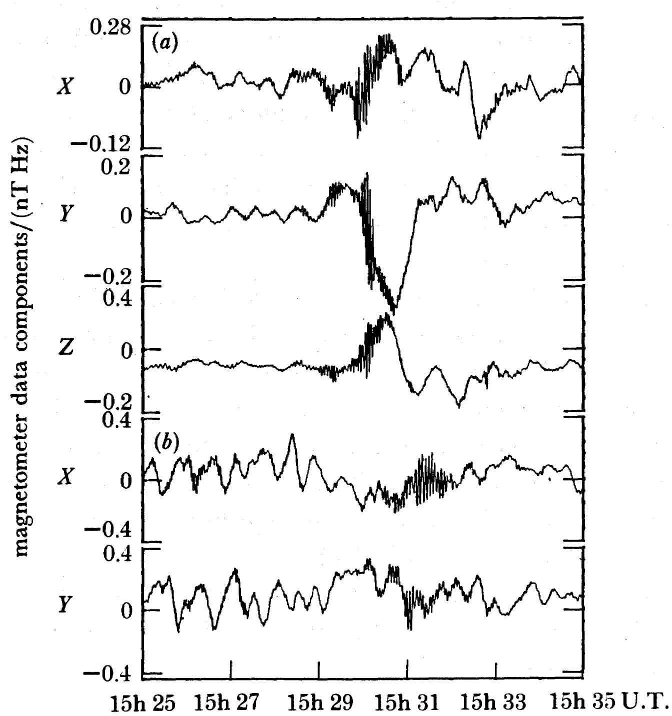


FIGURE 5. Magnetometer data from (*a*) Sondre Stromfjord and (*b*) South Pole Station between 15h25 and 15h35 U.T. on 15 October 1986 (from Arnoldy *et al.* 1988*b*). The flux transfer event signature, which is much clearer in the Sondre Stromfjord data occurs mainly in the minute from 15h30 U.T. The Pc1 activity starts at about 15h29 U.T.

One interesting feature of FTES is the frequent simultaneous presence of Pc 1 pulsation activity (figure 5). Pc 1s are thought to be caused by ion cyclotron waves which become unstable when hot and cooler magnetospheric and solar wind plasmas interact in a recently opened flux tube (see, for example, Arnoldy *et al.* 1988*b*). There is a whole zoo of different types of Pc 1 or Pc 2 and Pi(c) pulsation activity described by Cole and his coworkers from observations near the ionospheric footprint of the magnetospheric cusp (see, for example, Burns & Cole 1985; Morris & Cole 1987 and the references therein). These appear to be essentially the same phenomenon, but occurring under slightly differing geophysical conditions leading to the observed differences in their ground signatures.

(*b*) *Conjugacy within the auroral oval*

The well-instrumented stations at Syowa, Antarctica and Husafell, Iceland form a conjugate pair of stations at $L \approx 6$, which is ideal for studies of the conjugacy of phenomena in the auroral oval. A monochromatic, all-sky TV system (Ono *et al.* 1987) has been specifically developed to allow examination of many auroral phenomena such as the spatial relation between proton and electron auroras (see figure 6, plate 1). The results show that the proton auroras are consistently further equatorward at all stages through the course of a substorm and, to a first order, the intensities and dynamics both of the proton and of the electron auroras are remarkably similar at both ends of the field lines for the events studied to date (Sato *et al.* 1986; Sato & Saemundsson 1987). Conjugacy is normally observed in the diffuse, discrete and pulsating aurora, though occasionally with a latitudinal offset of up to 1° (Fujii *et al.* 1987*a*, *b*; Sato *et al.* 1981). The great similarity in the occurrence and shape of the aurora at both ends of the field line are attributed to there being particle acceleration processes at or very near the equatorial plane that cause particle precipitation simultaneously into both hemispheres. The differences that do occur tend to be small-scale features and are attributed to localized, field-aligned particle acceleration processes well away from the equatorial plane.

(*c*) *Near the plasmapause and within the plasmasphere*

Pc3–4 geomagnetic pulsations at conjugate locations near $L = 4$ have been used by Hamilton & Gough (1987) to show that there may be several standing mode oscillations on the same field line and that these frequencies differ substantially from those expected from its natural oscillation. There is often great similarity in the power spectra of pulsations from stations at $L = 4$ and near $L = 2$ resulting from the presence of fast-mode hydromagnetic waves which are of increasing importance in pulsation research. Some other aspects of conjugacy of Pc3–5 pulsations have been studied by Wolfe (1982).

The ionosphere at each end of the field line acts as a diffuse partial reflector to echoing ducted whistler mode waves. As a result there is some leakage of wave energy from efficient, but localized, VLF wave generation and amplification regions within a duct into a larger magnetospheric volume. This may occur through interduct coupling (Smith & Carpenter 1982) or through conversion into the unducted mode (Smith *et al.* 1985).

In the F-region of the ionosphere, irregularities of scale size 1–10 km have been shown to occur simultaneously in conjugate mid-latitude regions on many occasions, from analysis of ionogram and scintillation data-sets (see, for example, Rodger & Aarons 1988). These irregularities occur most frequently and with increased intensity during the recovery periods following geomagnetic storms. It has been suggested that the temperature gradient drift instability might be the formation mechanism for the irregularities, but that precipitation of the O^+ component of the ring current might play an important role in the formation of the necessary gradients of electron temperature and concentration (Aarons & Rodger 1989).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Lower-atmosphere forcing of the ionosphere and thermosphere

The energy transfer from the lower atmosphere into the ionosphere and thermosphere, through the propagation and dissipation of tides, planetary waves and gravity waves, is critically controlled by the temperature structure, aerosol distribution and dynamics of the stratosphere and mesosphere. There are many significant differences between the two hemispheres in the lower and middle atmosphere. Particularly striking is the change of zonal winds that occurs in spring between 80 and 100 km at Mawson, Antarctica, and Poker Flat in the north; both stations are near 66° geographic latitude (figure 7). In the north, this is a relatively gradual process, but in the south it occurs most dramatically in six days (Phillips & Vincent 1987*a*). The changeover in the north occurs one month earlier than in the south. There are also differences in the amplitude and phase of the diurnal and semidiurnal tides in the mesosphere, measured at Scott Base and at Mawson, from those predicted from various model simulations which have previously been adequate in comparison with observations from the north; the amplitude of the diurnal and semidiurnal tides are between 30–100% larger at Mawson than at Poker Flat (Phillips & Vincent 1987*b*).

Perhaps the most striking contrast is the well-known ozone hole which occurs over Antarctica in the austral spring. In 1987, 97% of ozone between 14–20 km altitude disappeared in October over Halley. No correspondingly large depletion has been reported in the north. The ozone hole must have a dramatic effect on lower atmospheric heating, hence

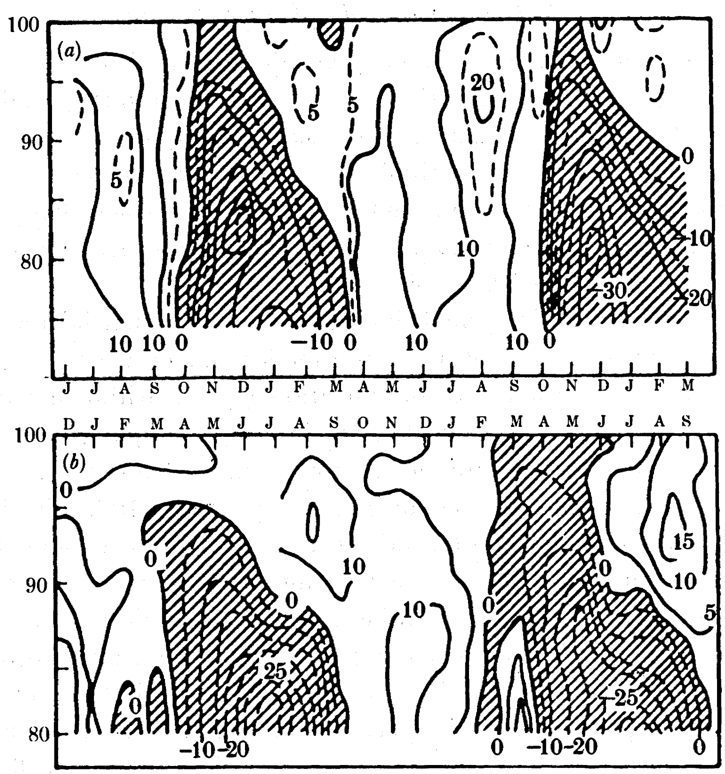


Figure 7. Comparison of the mean zonal winds measured at (*a*) Mawson (68° S, 63° E) and (*b*) Poker Flat (65° N, 213° E). Shaded regions indicate westward wind with contours drawn at 5 m s^{-1} intervals; unshaded regions indicate eastward wind. Note that the timescales are displaced by six months to compare seasons (Phillips & Vincent 1987*a*).

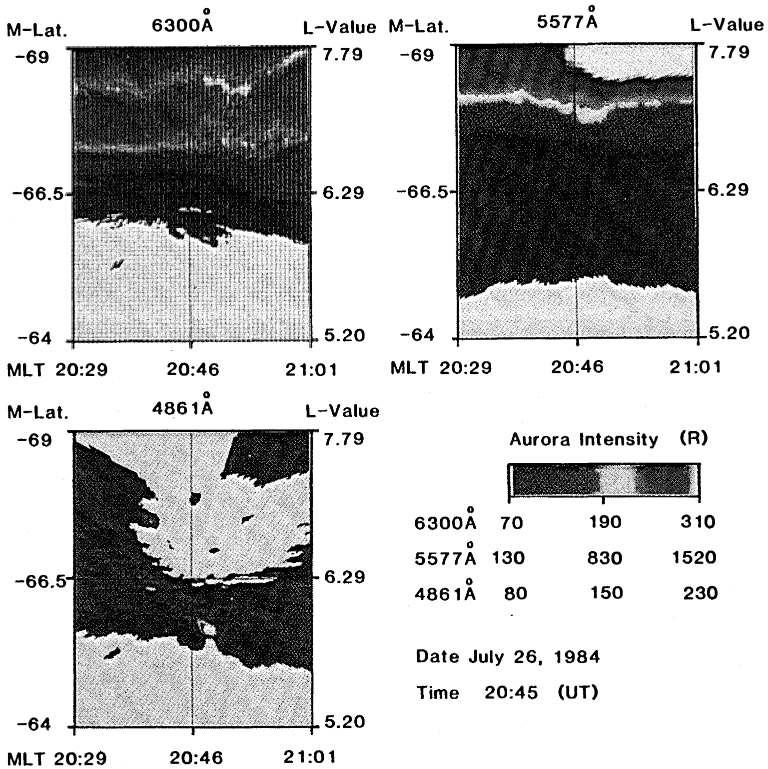


Figure 6

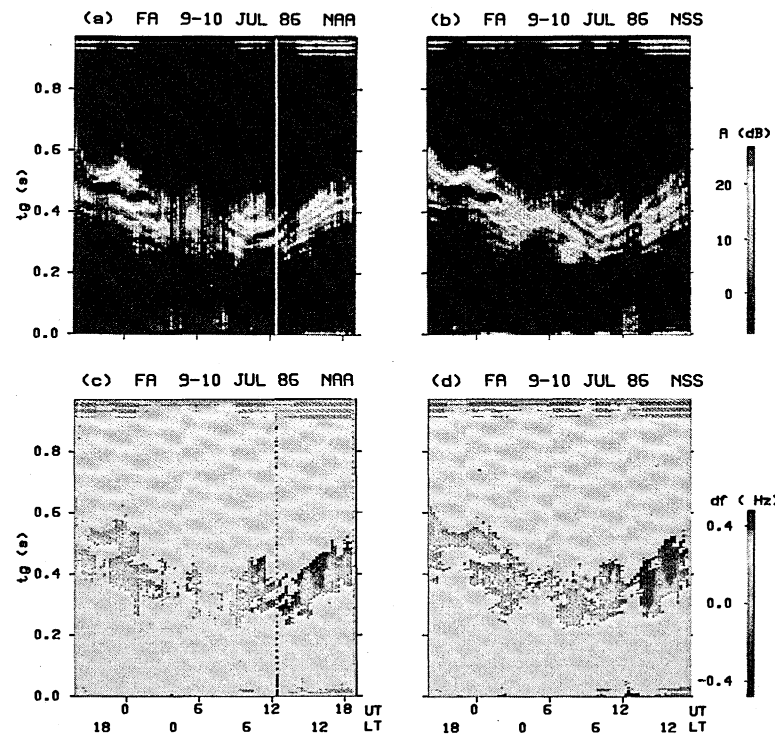


Figure 8

Figure 6. A stable aurora recorded by a three wavelength (630.0, 557.7 and 486.1 nm) monochromatic all-sky TV system at Syowa, Antarctica, on 26 July 1984 at 20h45 U.T. The 557.7 nm aurora includes a diffuse auroral band in the equatorward region of the stable arc. The distribution of H_{β} auroral emission has some contamination from the Milky Way but lies slightly equatorward of the 557.7 nm emission (from Ono *et al.* 1987).

Figure 8. Whistler mode signals from the NSS and NAA VLF radio transmitters located in the northeast U.S.A. recorded at Argentine Islands, Antarctica, on 9–10 July 1986. In (*a*) and (*b*) discrete paths, for which the intensity of the signals is greatest, appear as coloured traces. The group delay (tg) of these paths and the Doppler shifts of the signals ((*c*) and (*d*)) change as a function of U.T.

on the generation and propagation of tides to the upper atmosphere, but to date no upper atmosphere effects of the ozone hole have been conclusively shown.

Magnetosphere–ionosphere coupling studies from Antarctica

There are many studies of magnetosphere–ionosphere coupling that have used data-sets from Antarctica, and satellite observations over Antarctica which have not particularly exploited the advantages that the continent provides. It is impossible to review all these areas but a few highlights from various geomagnetic latitudes will be presented.

(*a*) *Middle latitudes*: $L \approx 2$–4

At Siple, a powerful VLF transmitter, which has good radiation efficiency because it is raised above the ground on an ice sheet *ca.* 2 km thick, has been deployed. A unique set of controlled, active experiments have probed the magnetosphere near $L = 4$, leading to considerable progress in the understanding of wave–particle interactions through stimulated emissions. As the topic has recently been comprehensively reviewed by Helliwell (1987, 1988), it will not be discussed further here.

Argentine Islands lie in the conjugate region to two powerful VLF transmitters which operate on slightly different frequencies. Radio waves from these transmitters can travel to Argentine Islands both through the Earth–ionosphere waveguide and in the whistler mode through the plasmasphere. The difference in the time of arrival of the signals and the Doppler shift of the plasmaspheric propagating signal are now being used to sense remotely the plasmasphere to determine the L-shell of paths, the cross-L drift of the paths and the total content of the plasmaspheric flux tube (Strangeways & Thomson 1986). Typical data are shown in figure 8, plate 1. The pronounced diurnal variations in group delay, and the changes from positive to negative Doppler shifts (08h U.T.) which occur at about the time of sunrise at Argentine Islands' conjugate point, are due partly to quiet time variations in cross L-shell drift of the ducts and partly to the solar controlled field-aligned fluxes of plasma (Smith *et al.* 1987*a*). Argentine Islands lie at a latitude where the relative importance of the ionospheric dynamo electric field and the cross-tail magnetospheric field vary as a function of geomagnetic activity. This experiment should further understanding of the penetration of the magnetospheric electric field, extending earlier Antarctic studies by a high-frequency Doppler experiment also centred on Argentine Islands (Crowley *et al.* 1984), particularly with high-altitude balloon observations (Bering & Benbrook 1987).

There have been many recent studies of the plasmapause (Carpenter 1988) and the feature which has frequently, but incorrectly, been regarded as its ionospheric footprint, the main ionospheric trough. This relation has now been studied experimentally (Smith *et al.* 1987*b*) and it was shown that the features are only likely to lie close to the same field line in the morning sector. In the evening sector, they can be displaced from each other by up to two L-shells. The local-time variation of the plasmapause during very quiet geomagnetic conditions shows that two bulges are observed, one near the expected time in the evening sector; the other is near midnight (Scourfield *et al.* 1985). No adequate explanation of the midnight bulge has been found. During geomagnetically active periods, the local-time evolution of the plasmapause is very complex and poorly understood (Corcuff *et al.* 1985).

Pc3–4 geomagnetic pulsations, combined with advanced ionospheric sounder (AIS) data

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

from Halley over a six-hour period in December 1982, have been used to show when Halley passes from the plasmatrough into the plasmasphere in the late afternoon. The plasmapause is marked on the AIS data by a change in the frequency of vertical motion of the F-layer determined from accurate phase measurements and short-lived particle precipitation events. The pulsation data show a clear change in the ellipticity of pulsations occurring simultaneously on three frequencies in a manner consistent with present theory. The amplitude of the AIS phase pulsations also shows a peak when the field line with that natural resonant frequency passes through Halley (Jarvis & Gough 1988). Multiple frequency pulsations occurring on the same field line have also been reported by Engebretson *et al.* (1986) and by Lin *et al.* (1986).

The formation and dynamics of the main ionospheric trough have been extensively studied in the last decade using data from AISs at Siple and Halley, and from total electron content data recorded near 90° E. The topics addressed include the morphology of the trough, the effects of the IMF, the response of the trough to substorm activity, the longitudinal structure of the trough, the relative importance of moderate-energy electron precipitation and the transport of plasma by the convection electric field in the evening and morning sectors for the formation of the poleward edge of the trough (see Lambert & Cohen 1986; Rodger *et al.* 1986; Rodger & Dudeney 1987 and the references therein).

Studies of the effects of F-region storms by using Antarctic ionosonde data from $L = 2$–4 extending over a solar cycle have provided a new insight into the causes of the changes to the maximum plasma concentration in the F-region (f_0F2) which occur as a result of geomagnetic activity. It has now been recognized that no single process can explain the observations which show generally a significant depletion in f_0F2 in summer, but an increase in winter resulting from storm activity (Wrenn *et al.* 1987). While alternative mechanisms have been proposed (Rishbeth *et al.* 1987), it is still necessary to establish the relative importance of the competing processes, which include the effects of the deposition of ring-current energy and of local heating through electric field effects, the transport of chemical energy from higher latitudes and modifications to the neutral wind régime. Storm effects at Slough (52° N, $L = 2.4$), which lies at a similar magnetic latitude to that of Argentine Islands (65° S, $L = 2.3$), are significantly smaller and do not show any positive effects in winter. This hemispheric asymmetry may result from the stations being at widely different geographic latitudes (13°). Hence the relative importance of processes ordered in magnetic latitude and those ordered in geographic latitude may be different at the two stations. Further study of this topic is required.

(*b*) *High latitudes*: $L > 4$

Pc3–4 pulsations have been used as a diagnostic of solar wind interactions with the magnetosphere. Analysis of South Pole magnetometer data and solar wind information by Yumoto *et al.* (1987) showed positive correlations between Pc3–4 occurrence and IMF direction, magnitude and solar wind velocity. These are similar results to those of Wolfe *et al.* (1987). However, these authors did not resolve the outstanding controversy of whether Pc3–4 pulsations were the result of surface waves on the magnetopause resulting from Kelvin–Helmholtz instabilities or due to upstream waves created in the ion-foreshock and subsequent convection to the subsolar point where they must be amplified.

Studies of the temporal relationship between irregular pulsations (Pi), VLF or ELF wave activity measured on the ground and the intensity of optical emissions, such as that at 427.8 nm, have been used by a variety of workers to infer ionospheric and magnetospheric

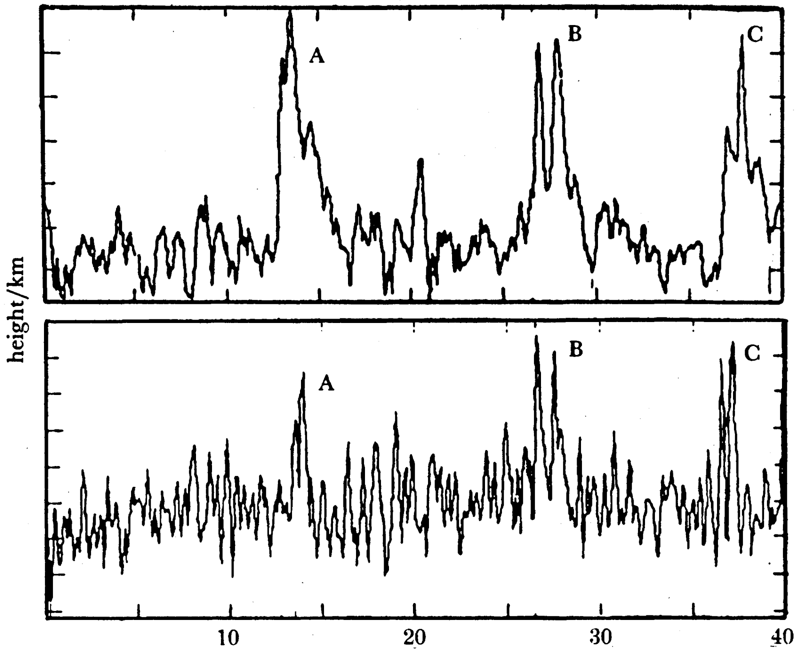


FIGURE 9. A 40 s segment of (*b*) VLF emission intensity at 3 kHz (± 500 Hz) and (*a*) optical intensity fluctuations recorded at Sanae, Antarctica on 23 August 1981. The time series start at 05h08:45 U.T. Peaks corresponding to events seen in both data-sets are labelled with letters (from Hansen 1988).

processes. For example, Hansen (1988) has used the relationship between the intensity of optical aurora and VLF activity near 3 kHz (figure 9), measured at Sanae, to suggest that the location of particle acceleration mechanisms are on occasions well displaced from the equatorial plane. However, observations of particle spectra, measured by the *NOAA*-6 satellite, associated with pulsating aurorae suggest that the moderate and energetic electron spectra behave in a rather different way from each other (Evans *et al.* 1987). Thus simple correlations between limited optical and VLF ground-based measurements may be misleading.

FUTURE IONOSPHERE–MAGNETOSPHERE INTERACTION STUDIES FROM ANTARCTICA

With the illustrations provided above, it has been shown that observations of the coupled ionosphere–magnetosphere system from Antarctica have played a critically important role in enhancing understanding. Many of the features that have been described have depended upon a series of measurements from a single instrument or a few instruments at one site or two sites. Theoretical models of the ionosphere, magnetosphere or coupled ionosphere–magnetosphere system (see, for example, Schunk & Sojka 1988; Killeen & Roble 1987; Fuller-Rowell *et al.* 1987) are now sufficiently advanced and flexible to be able to reproduce quasi-steady state observations with a reasonable degree of accuracy. Closer correspondence between model predictions and observations is expected if these models are to incorporate a more realistic geomagnetic field model for the south. However, the models still have difficulty in accurately determining the spatial and temporal variations of the modelled parameters. One major reason for this is that the necessary input parameters, such as the cross-tail electric field and quantitative estimates of particle precipitation fluxes as a function of space and time, are usually poorly known. Thus it is essential to make a series of spatially separate measurements of these parameters. New experiments, such as the over-the-horizon radar experiment deployed at Halley in 1988 which has a viewing area in the ionosphere of 3×10^6 km^2 is an ideal tool for providing such data. It can observe over the trough region, the auroral oval and well into the polar cap with high time resolution. With its counterpart in the north (Greenwald *et al.* 1985), these radars will be able to make unique contributions to studies of the interaction of the solar wind, magnetosphere and ionosphere through simultaneous observations of the effects of particle precipitation and electric fields in the two hemispheres in geomagnetically conjugate regions.

Over the next decade the manned and limited number of remote and comparatively simple observatories (see, for example, Papitashvili & Zaitzev 1986) will be supplemented by further automatic geophysical observatories with greater capability for making more measurements of geospace. These multipoint measurements from the ground, combined with complementary measurements from space by satellite, such as *Cluster* and other satellites of the *Global Geospace Science* mission, will provide the key data-sets to make further progress in understanding the medium-scale and large-scale processes in geospace. To understand microscale ionosphere–magnetosphere interactions, new experimental facilities, such as the imaging riometer system recently deployed at the South Pole station, and the network of stations to be deployed in the Southern Hemisphere at lower latitudes to monitor the phase and amplitude of Omega transmissions owing to transient particle precipitation, are likely to provide new insight.

The scientific topics that require to be addressed in addition to those identified above include the following.

1. The causes of the substorm onset phase, and the reconfiguration of the tail in the recovery phase (Rosenberg *et al.* (1987) and Gledhill *et al.* (1987) have identified some of the problems).
2. The importance of electron, proton and O^+ precipitation from the ring current as an ionization source and a heat source in the ionosphere and thermosphere, especially at middle latitudes.
3. Magnetospheric cavity modes of geomagnetic pulsations.
4. The relation between convection and precipitation boundaries under a wide range of geophysical conditions including IMF northward, when theta auroras are present (Gusev *et al.* 1987).
5. The interaction of microscale and mesoscale irregularities (1 m–100 km) on the structure and dynamics of the ionosphere and magnetosphere.

Antarctica should also continue to provide a platform for long-term studies of the ionosphere and magnetosphere to provide data-sets with which to assess the effects of the secular change of the geomagnetic field and to assess the effects of anthropogenic changes.

We gratefully acknowledge the cooperation of many scientists throughout the world who contributed reprints and preprints of papers, and who have given permission to reproduce figures.

References

Aarons, J. & Rodger, A. S. 1989 *Annls Geophysicae* (In the press.)

Arnoldy, R. L., Cahill, L. J., Engebretson, M. J., Lanzerotti, L. J. & Wolfe, A. 1988*a* *Rev. Geophys.* **26**, 181–207.

Arnoldy, R. L., Engebretson, M. J. & Cahill, L. J. 1988*b* *J. geophys. Res.* **93**, 1007–1016.

Bering, E. A. & Benbrook, J. R. 1987 *Annls Geophysicae* **5**, 485–502.

Berkey, F. T. & Jarvis, M. J. 1985 In *Propagation effects on military systems in the high-latitude region.* AGARD Conf. Proc. **382**, pp. 4.6.1–4.6.24.

Burns, G. B. & Cole, K. D. 1985 *J. atmos. terr. Phys.* **47**, 587–599.

Candidi, M. & Meng, C.-I. 1988 *J. geophys. Res.* **93**, 923–931.

Carpenter, D. L. 1988 *Rev. Geophys.* **26**, 535–549.

Corcuff, Y., Corcuff, P. & Lemaire, J. 1985 *Annls Geophysicae* **3**, 569–580.

Crooker, N. U., Berchem, J. & Russell, C. T. 1987 *J. geophys. Res.* **92**, 13467–13471.

Crowley, G., Dudeney, J. R., Rodger, A. S. & Jones, T. B. 1984 *J. atmos. terr. Phys.* **46**, 917–925.

Dudeney, J. R. & Piggott, W. R. 1978 In *Antarctic Research Series*, 29 (ed. L. J. Lanzerotti & C. G. Park). Washington, D. C.: American Geophysical Union.

Eather, R. H. 1984 *J. geophys. Res.* **89**, 1695–1700.

Eather, R. H. 1985 *J. geophys. Res.* **90**, 1569–1576.

Engebretson, M. J., Zanetti, L. J., Potemra, T. A. & Acuna, M. H. 1986 *Geophys. Res. Lett.* **13**, 905–908.

Evans, D. S., Davison, G. T., Voss, H. D., Imhof, W. L., Mobilia, J. & Chiu, Y. T. 1987 *J. geophys. Res.* **92**, 12295–12306.

Friis-Christiensen, E., Kamide, Y., Richmond, A. D. & Matsushita, S. 1985 *J. geophys. Res.* **90**, 1325–1338.

Fuller-Rowell, T. J., Quegan, S., Rees, D., Moffett, R. J. & Bailey, G. J. 1987 *J. geophys. Res.* **92**, 7744–7748.

Fujii, R., Sato, N., Ono, T., Fukunishi, H., Hirasawa, T., Kokubun, S., Araki, T. & Saemundsson, T. 1987*a* *Mem. natn Inst. Polar Res.* Special issue **48**, 72–80.

Fujii, R., Sato, N., Ono, T., Fukunishi, H., Hirasawa, T., Kokubun, S., Araki, T. & Saemundsson, T. 1987*b* *Geophys. Res. Lett.* **14**, 115–118.

Gledhill, J. A. & Hoffman, R. A. 1981 *J. geophys. Res.* **86**, 6739–6744.

Gledhill, J. A., Dore, I. S., Goertz, C. K., Haggard, R., Hughes, W. J., Scourfield, M. W. J., Smits, D. P., Stoker, P. H., Sutcliffe, P. R., Wakerly, P. A. & Walker, A. D. M. 1987 *J. geophys. Res.* **92**, 2461–2475.

Greenwald, R. A., Baker, K. B., Hutchins, R. A. & Hanuise, C. 1985 *Radio Sci.* **20**, 63–79.

Gusev, M. G., Nikolashkin, S. V., Samsonov, V. P. & Troshichev, O. A. 1987 Academy of Sciences, Yakutsk Branch, U.S.S.R.

Hamilton, R. A. & Gough, H. 1987 *Br. Antarctic Surv. Bull.* **77**, 131–144.

Hanson, H. J. 1988 Ph.D. thesis, University of Natal, South Africa.

Hargreaves, J. K. & Jarvis, M. J. 1986 *Br. Antarctic Surv. Bull.* **72**, 13–23.

Helliwell, R. A. 1987 *Mem. natn Inst. Polar Res.* Special issue **48**, 81–92.

Helliwell, R. A. 1988 *Rev. Geophys.* **26**, 551–578.

Jarvis, M. J. & Gough, H. 1988 *Planet. Space Sci.* **36**, 733–745.

Killeen, T. L. 1987 *Rev. Geophys.* **25**, 433–454.

Killeen, T. L. & Roble, R. G. 1987 *J. geophys. Res.* **92**, 10133–10139.

Krishnaswamy, S. & Rosenberg, T. J. 1987 *Mem. natn Inst. Polar Res.* Special issue **48**, 171–182.

Lambert, M. & Cohen, E. A. 1986 *Radio Sci.* **21**, 347–350.

Lanzerotti, L. H. & Park, C. G. 1978 Antarctic Research Series, no. 29. Washington, D.C.: American Geophysical Union.

Lanzerotti, L. J., Lee, L. C., Maclennan, C. G., Wolfe, A. & Medford, L. D. 1986 *Geophys. Res. Lett.* **13**, 1089–1092.

Lanzerotti, L. J., Hunsucker, R. D., Rice, D., Lee, L. C., Wolfe, A., Maclennan, C. G. & Medford, L. V. 1987 *J. geophys. Res.* **92**, 7739–7743.

Lin, N. G., Cahill, L. J., Engebretson, M. J., Sugiura, M. & Arnoldy, R. L. 1986 *Planet. Space Sci.* **34**, 155–181.

Morris, R. J. & Cole, K. D. 1987 *Planet. Space Sci.* **35**, 313–328.

Ono, T., Ejiri, M., Hirasawa, T., Kaya, N. & Mukai, T. 1987 *J. Geomagn. Geoelect., Kyoto* **39**, 119–128.

Papitashvili, V. O. & Zaitzev, A. N. 1986 *Antarctic Record*, 30, 1–10. Natn Inst. Polar Research, Tokyo, Japan.

Phillips, A. & Vincent, R. A. 1987*a* *Australian upper atmospheric and space physics research in Antarctica* (ed. G. B. Burns & M. Craven) (ANARE research notes no. 48), pp. 86–92.

Phillips, A. & Vincent, R. A. 1987*b* *Australian upper atmospheric and space physics research in Antarctica* (ed. G. B. Burns & M. Craven) (ANARE research notes no. 48), pp. 93–106.

Rees, D. & Fuller-Rowell, T. J. 1987 *Mem. natn Inst. Polar Res. Special issue* **48**, 134–160.

Reiff, P. H. & Burch, J. L. 1985 *J. geophys. Res.* **90**, 1595–1609.

Rishbeth, H. 1972 *J. atmos. terr. Phys.* **34**, 1–47.

Rishbeth, H., Fuller-Rowell, T. J. & Rodger, A. S. 1987 *Physica Scr.* **36**, 327–336.
Rodger, A. S. & Aarons, J. 1988 *J. atmos. terr. Phys.* **50**, 63–72.
Rodger, A. S. & Dudeney, J. R. 1987 *Adv. Space Res.* **7**(8), 65–74.
Rodger, A. S., Cowley, S. W. H., Brown, M. J., Pinnock, M. & Simmons, D. A. 1984 *Planet. Space Sci.* **32**, 1021–1027.
Rodger, A. S., Brace, L. H., Hoegy, W. T. & Winningham, J. D. 1986 *J. atmos terr. Phys.* **48**, 715–728.
Rosenberg, T. J. & Dudeney, J. R. 1986 *J. geophys. Res.* **91**, 12032–12040.
Rosenberg, T. J., Detrick, D. L., Mizera, P. F., Gorney, D. J., Berkey, F. T., Eather, R. H. & Lanzerotti, L. J. 1987 *J. geophys. Res.* **92**, 11123–11132.
Russell, C. T. & McPherron, R. L. 1973 *J. geophys. Res.* **78**, 92–108.
Russell, C. T. & Southwood, D. J. 1982 *The IMS source book*, Washington, D.C.: American Geophysical Union.
Sato, N. & Saemundsson, T. 1987 *Mem. natn Inst. Polar Res. Special issue* **48**, 58–71.
Sato, N., Fukunishi, H., Ozaki, T. & Yoshino, T. 1981 *J. geophys. Res.* **86**, 9953–9960.
Sato, N., Fujii, R., Ono, T., Fukunishi, H., Hirasawa, T., Araki, T., Kokubun, S., Makita, K. & Saemundsson, T. 1986 *Geophys. Res. Lett.* **13**, 1368–1371.
Schunk, R. W. & Sojka, J. J. 1988 *Eos Wash.* **69**, 153–165.
Scourfield, M. W. J., Hansen, H. J. & Rash, J. P. S. 1985 *J. atmos. terr. Phys.* **47**, 615–620.
Sheldon, W. R., Benbrook, J. R., Bering, E. A., Leverenz, H., Roeder, J. L. & Stansbury, E. G. 1987 *Adv. Space Res.* **7**(8), 49–52.
Smith, A. J. & Carpenter, D. L. 1982 *J. atmos. terr. Phys.* **44**, 973–984.
Smith, A. J., Carpenter, D. L. & Inan, U. S. 1985 *Annls Geophysicae* **3**, 81–88.
Smith, A. J., Yearby, K. H., Bullough, K., Saxton, J. M., Strangeways, H. J. & Thomson, N. R. 1987*a* *Mem. natn Inst. Polar Res.* Special issue **48**, 183–195.
Smith, A. J., Rodger, A. S. & Thomas, D. W. P. 1987*b* *J. atmos. terr. Phys.* **49**, 43–47.
Smith, R. W., Rees, D. & Stewart, R. D. 1988 *Rev. Geophys.* **26**, 591–622.
Southwood, D. J. 1987 *J. geophys. Res.* **92**, 3207–3213.
Stewart, R. D., Smith, R. W., Rees, D., Dudeney, J. R. & Rodger, A. S. 1985 *Nature, Lond.* **317**, 45–47.
Strangeways, H. J. & Thomson, N. R. 1986 *Special publication* 68, pp. 41–47. Institute of Electrical and Radio Engineers.
Tatnall, A. R. L., Matthews, J. P., Bullough, K. & Kaiser, T. R. 1983 *Space Sci. Rev.* **35**, 139–173.
Thayer, J. P., Killeen, T. L., McCormac, F. G., Tschan, C. R., Ponthieu, J. J. & Spencer, N. W. 1987 *Annls Geophysicae* A **5**, 363–368.
Wardill, P., Jones, N. & Jacka, F. 1987 *Australian upper atmospheric and space physics research in Antarctica* (ed. G. B. Burns & M. Craven) ANARE research notes no. 48), pp. 114–120.
Wolfe, A. 1982 *J. geophys. Res.* **87**, 10425–10431.
Wolfe, A., Kamen, E., Lanzerotti, L. J., Maclennan, C. G., Bamber, J. F. & Venkatesan, D. 1987 *J. geophys. Res.* **92**, 168–174.
Wrenn, G. L., Rodger, A. S. & Rishbeth, H. 1987 *J. atmos. terr. Phys.* **49**, 901–914.
Yumoto, K., Wolfe, A., Terasawa, T., Kamen, E. L. & Lanzerotti, L. J. 1987 *J. geophys. Res.* **92**, 12437–12442.
Zanetti, L. J., Potemra, T. A., Doering, J. P., Lee, J. S., Fennell, J. F. & Hoffman, R. A. 1982 *J. geophys. Res.* **87**, 5963–5975.

Discussion

M. J. RYCROFT (*British Antarctic Survey, Cambridge, U.K.*). Automated geophysical observatories (AGOS) in Antarctica offer particular advantages, especially in relation to large-area radar investigations and for geomagnetically conjugate studies. The region between the Australian Mawson station and the Soviet Vostok station could be especially suitable in conjunction with an additional EISCAT radar in Spitsbergen or a coherent radar there.

A. S. RODGER. The location where AGOS should be deployed is critically dependent upon the scientific objectives. For example, several closely spaced AGOS (*ca.* 100 km apart) would be preferable for studies of the structure and evolution of flux transfer events as identified by their ionospheric signature. A similar configuration might also be appropriate for deployment in the conjugate region to major research facilities in the Northern Hemisphere, such as EISCAT, or any new incoherent scatter radar at higher geomagnetic latitudes. If the focus of the science were to try to monitor continuously the location of the polar-cap–auroral-oval boundary, a

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

separation of AGOs of the order of 400 km might be better. Owing to the logistical and technical difficulties, and the comparatively high costs involved in building, deploying, and maintaining AGOs, national and international coordination is required to make the most cost effective use of AGOs, which should form a cornerstone of research facilities for making multipoint measurements of geospace in remote locations in both hemispheres during and beyond the Solar Terrestrial Energy Programme.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF

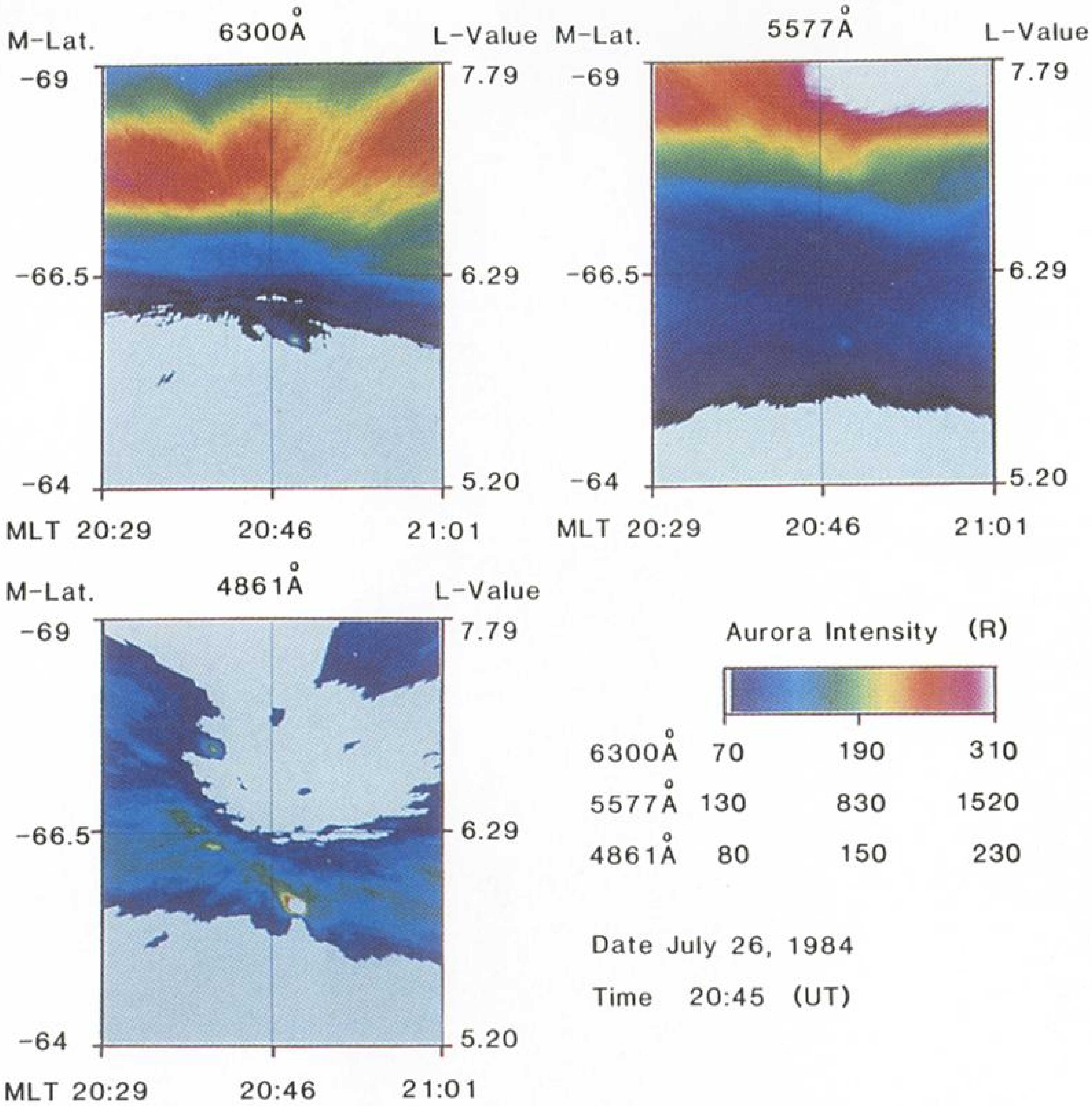
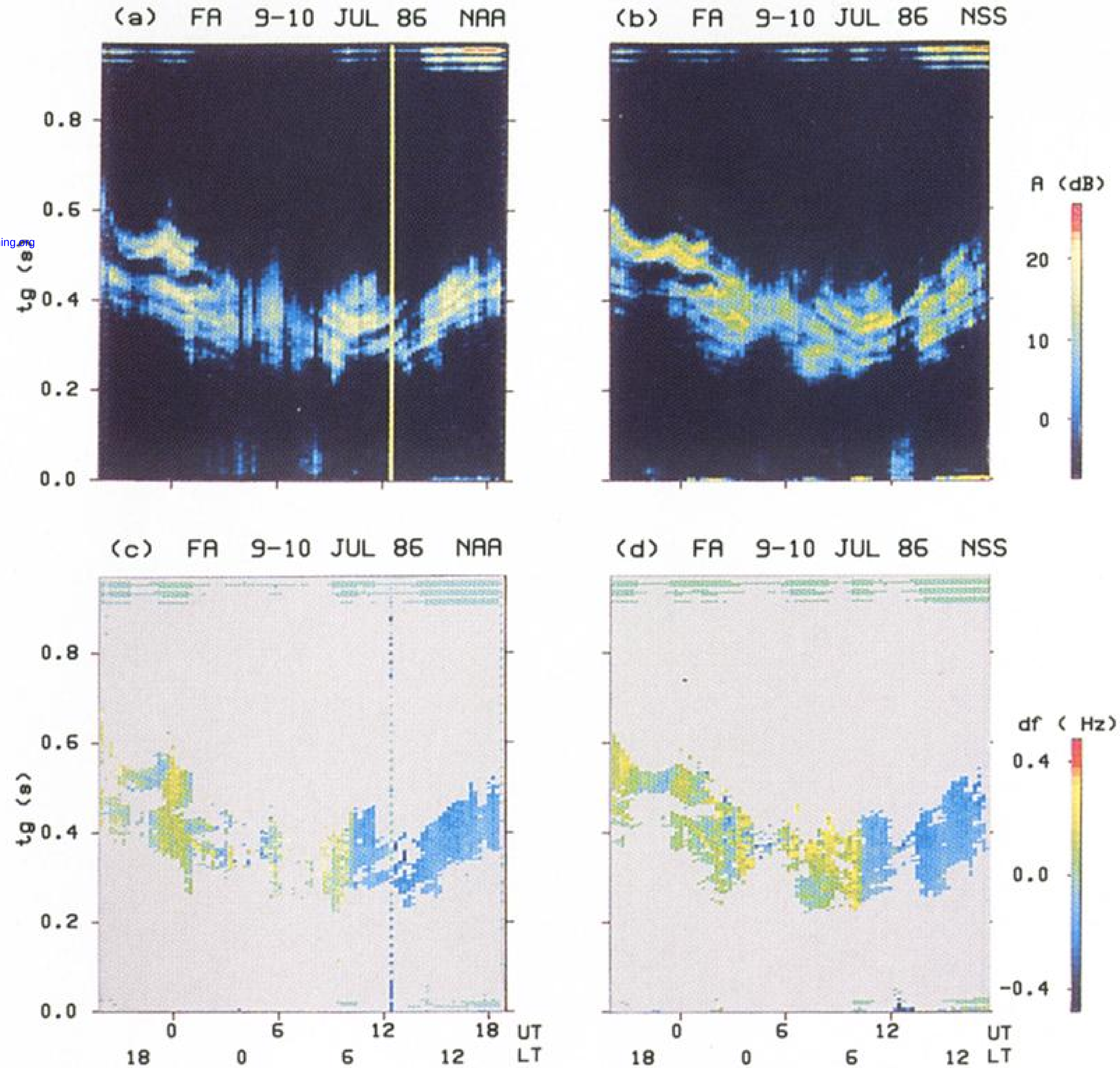


FIGURE 6. A stable aurora recorded by a three wavelength (630.0, 557.7 and 486.1 nm) monochromatic all-sky TV system at Syowa, Antarctica, on 26 July 1984 at 20h45 U.T. The 557.7 nm aurora includes a diffuse auroral band in the equatorward region of the stable arc. The distribution of H_{β} auroral emission has some contamination from the Milky Way but lies slightly equatorward of the 557.7 nm emission (from Ono *et al.* 1987).



PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

GURE 8. Whistler mode signals from the NSS and NAA VLF radio transmitters located in the northeast U.S.A. recorded at Argentine Islands, Antarctica, on 9–10 July 1986. In (*a*) and (*b*) discrete paths, for which the intensity of the signals is greatest, appear as coloured traces. The group delay (tg) of these paths and the Doppler shifts of the signals ((*c*) and (*d*)) change as a function of U.T.