Space physics: Achievements and prospects

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A number of examples relating to important achievements of space physics research in the Earth's magnetosphere are presented. The questions that could be addressed by studying the environments of other bodies of the solar system rather than our own magnetosphere are briefly discussed. Finally, future space physics missions are listed.

SPACE physics, or rather space plasma physics, was the first new scientific discipline to be conceived by the space age. It has now, more than 30 years after the launch of *Sputnik I*, reached a certain amount of maturity, although it is still a young research field in the way that the unexpected, 'surprising' results continue to be the most important ones from practically all space missions uptil now.

Let us consider briefly some major achievements from the three decades that have elapsed. The examples presented below do not constitute a complete list of major scientific results that have been obtained hitherto from the large number of ground-based and space-borne measurements of variables in the plasma environment of our blue planet, but they are some of the more spectacular ones.

In a later section, plans for future research in the field of space physics are outlined.

Major achievements in space physics

Magnetospheres

The magnetosphere concept is a result of space research. Before the launch of the first satellite the Chapman–Ferro[1] cavity in the solar wind plasma was the closest that one had come to a magnetosphere. The magnetopause was first identified by Cahill and Amazeen[2]. The concept as such was introduced by Thomas Gold[3] in 1959.

The magnetosphere is bounded by a thin boundary layer, which separates the comparatively dense and warm plasma of the solar wind from the thinner and hotter plasma in the magnetosphere. One of the important results of space plasma physics research is that it has demonstrated that this kind of thin boundary layers between plasma of quite different properties characterizes not only the vicinity of the Earth but the solar system as a whole. The solar system thus, has a cellular structure and it is quite likely that this is also true for the Universe as a whole. The 'cell walls' cannot be observed with remote sensing techniques but only through *in situ* measurements. A number of 'cells', i.e. magnetospheres, widely different in size and even in nature are shown in Figure 1.

The bow shock

The bow shock in front of the Earth's magnetosphere was discovered by Ness *et al.*[4]. What Ness and his colleagues observed was a physical phenomenon which had never been seen before: a collisionless shock wave. In shock waves known earlier collisions play a very important role. Collisionless shock waves are difficult to produce in a laboratory and most of what we know about them has been obtained from space measurements. Large efforts have since been made to investigate such shock waves in great detail both experimentally and theoretically. Collective plasma processes take the place of collisions in scattering and randomizing the velocities of the solar wind ions and electrons. There are still many features of the collisionless shocks which are very poorly understood. An example of bow shock data is shown in Figure 2.

Solar wind-driven plasma convection within the magnetospheres

The solar wind drives the plasma within the magnetosphere in a convection pattern which is illustrated in Figure 3. Figure 3*a* shows schematically the convection in the magnetic equatorial plane if the co-rotation of the plasma with the Earth is not taken into account. The corresponding convection pattern in the high latitude ionosphere is shown in Figure 3*b*. Figure 3*c* illustrates the equatorial plane flow when the co-rotation with the Earth is included. The general convection pattern was first proposed by Axford and Hines[5]. In the same year Dungey[6] proposed the open magnetospheric model which has, as a consequence, the same general convection pattern (see Figure 4). It has been later confirmed by numerous kinds of observations.

The understanding of the general large scale convection of the magnetospheric plasma is one of the major stepping stones for our understanding of many branches of magnetospheric physics.

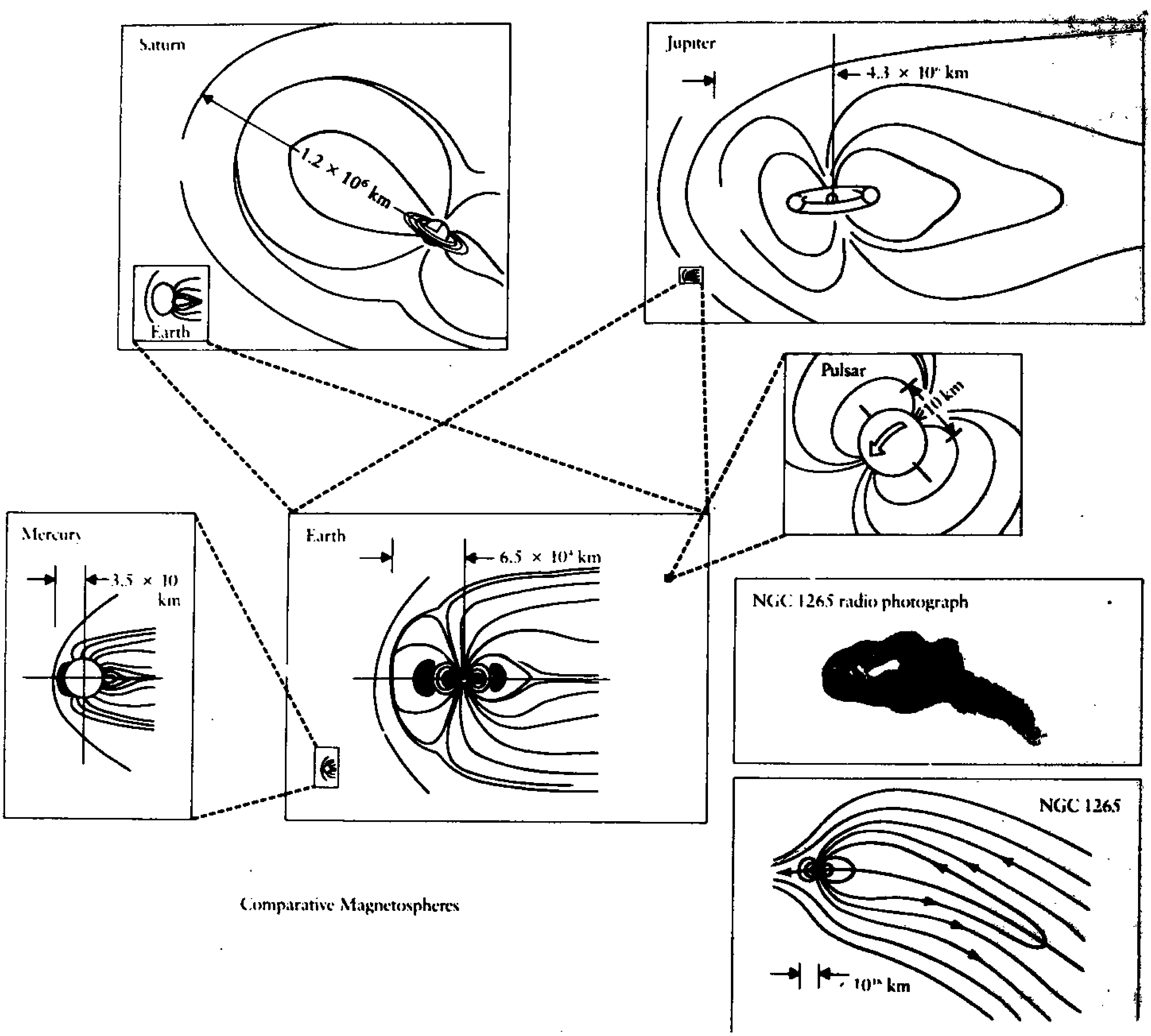

Figure 1. Comparative magnetospheres on the largest scale, NGC 1265 is a galaxy that exhibits a tail millions of light years long (after H. Friedman[22])

The magnetospheric boundary layer

The thin 'cell wall' of the magnetosphere, the magnetospheric boundary layer, is associated with a magnetic discontinuity and has plasma properties which have been studied only in recent years because of earlier spatial resolution problems. It appears that the boundary layer has quite a complex physics. Figure 5 shows the ion observations from the passage of Prognoz 7 from the magnetosheath into the boundary layer (at 1619). The plasma in the boundary layer appears to consist of both magnetosheath and magnetosphere plasma, poorly mixed. This can be seen in Figure 5, where the spacecraft came into typical magnetospheric plasma as soon as it passed the magnetopause. Further into the boundary layer it passed a region with mixed magnetosheath and magnetosphere plasma. In that region there was also present some plasma of ionospheric origin (O^+, He^+ and H^+).

A closer study has shown that the ionospheric plasma motion is sometimes different from that of the solar wind plasma in the boundary layer. This is illustrated in Figure 6, where it can be seen that the flow velocity of O^+ ions differed from that of the dominating H^+ ions

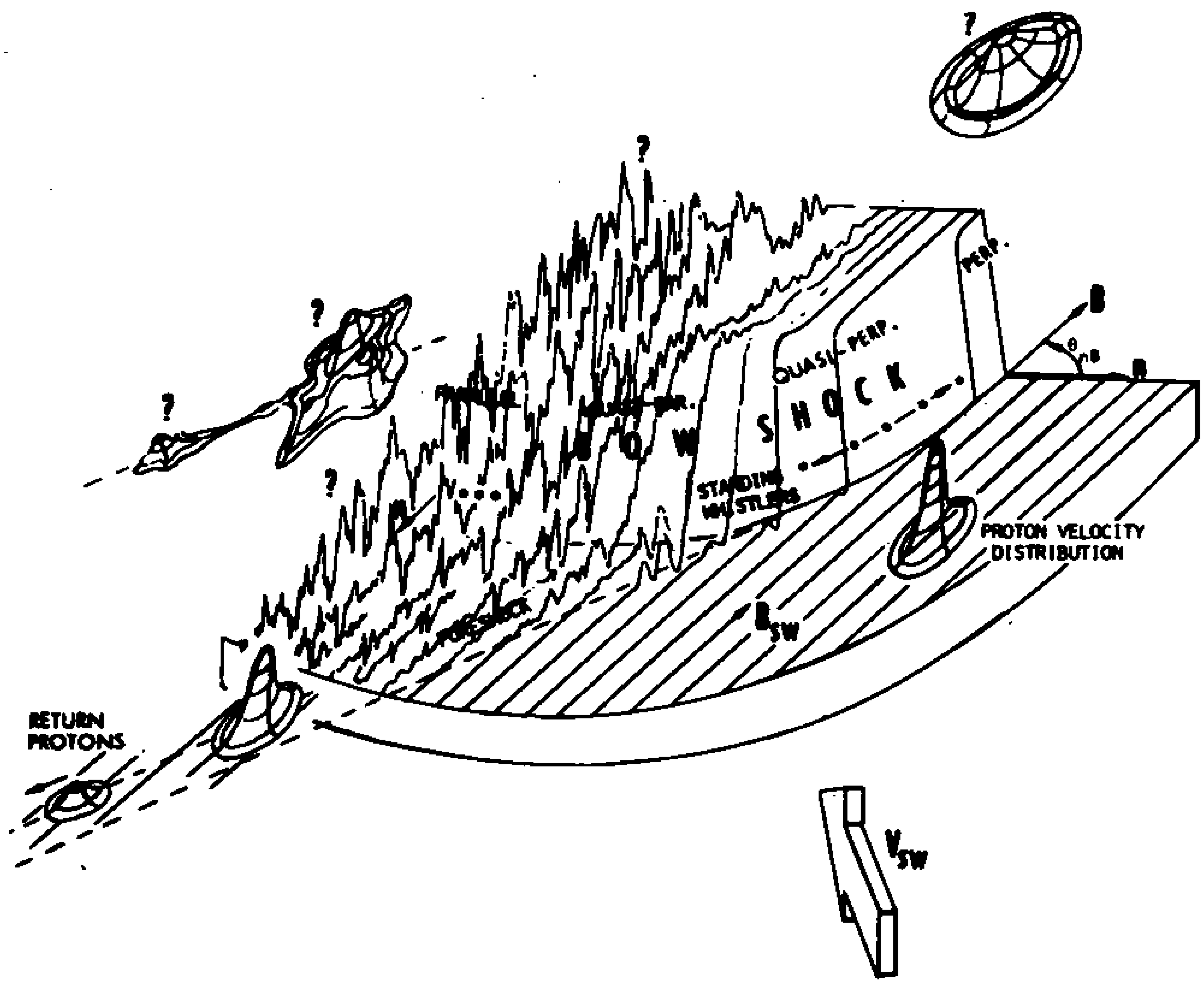

Figure 2. Schematic representation of magnetic field profiles at different locations of the Earth's bow shock (after Greenstadt and Fredricks[23])

from the solar wind both in magnitude and direction. Obviously, fluid theories do not work in the boundary layer but kinetic theories are required.

Auroral particle acceleration

The very first observation of primary auroral electrons[7] resulted in a peaked energy spectrum, indicating acceleration of the electrons in the direction of the magnetic field lines. An example of such an energy spectrum is shown in Figure 7*a*. It fits well with a spectrum model derived by Evans[8] (see Figure 7*b*), in which the low energy part of the spectrum consists of secondary electrons produced in the interaction with the atmosphere. These secondary electrons cannot escape upward because of the accelerating potential change along the magnetic field lines.

The existence of a field-aligned electric field component has also been demonstrated directly with electric field-measuring instruments. An example of that can be seen in Figure 8.

The potential difference along the magnetic field lines is generally maximal in the central part of an auroral electron precipitation region and decreases on both equatorward and poleward sides, as illustrated in Figure 9. Such distributions are generally called inverted Vs, (after Frank and Ackerson[9]).

Even though acceleration along the magnetic field lines of both electrons (downward) and ions (upward) is an important characteristic of the auroral latitude magnetosphere, there are also present there, very important processes which accelerate in the direction perpendicular to the magnetic field lines. This gives rise to so-called conical distributions (or conics) at altitudes well above the height range where the acceleration takes place[10]. This is because the increase of the perpendicular energy is equivalent to an increase of the magnetic moment which, in the upward diverging magnetic field, gives the charged particle an upward velocity component. An example of a conical distribution is shown in Figure 10. Ion conics can also be seen in Figure 11 around UT 1725, but there the conics are elevated, i.e. all ions have parallel energies above a certain minimum value (of almost 1 keV in the figure). In the same period narrow upward flowing electron beams can be seen in the upper panel. We thus see in Figure 11 electrons and ions flowing in the same direction along the magnetic field lines with similar energies and with pitch angle distributions which clearly indicate acceleration in a potential difference along the magnetic field lines for both positively and negatively charged particles. In the period shown in Figure 11 the electric field showed slow large amplitude fluctuations. It appears that both the ions and electrons are accelerated electrostatically in this fluctuating field[11].

We thus see that acceleration of electrons and ions in the auroral regions is due to a complex set of processes,

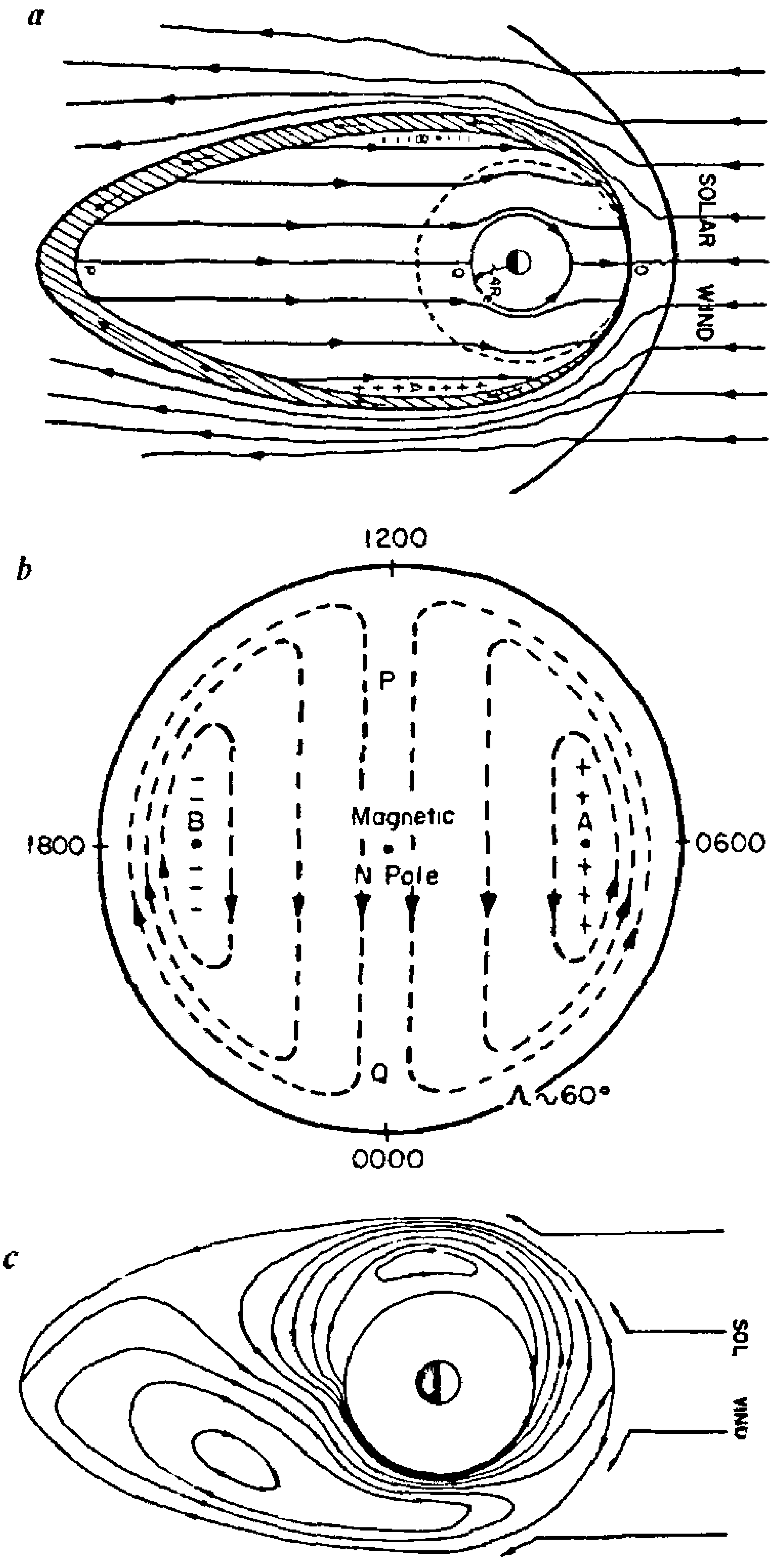

Figure 3. Convection patterns *a*, In the equatorial region without co-rotation taken into account, seen from above the North Pole (after Axford[24]) *b*, Corresponding convection in the north polar ionosphere (after Axford[24]). *c*, In the equatorial region with co-rotation taken into account (after Axford and Hines[5]).

and we are still far from anything like a complete understanding of all the important ones.

Macroscopic instabilities in magnetospheres

The magnetospheres have been found to be characterized by a kind of macroscopic instability which was

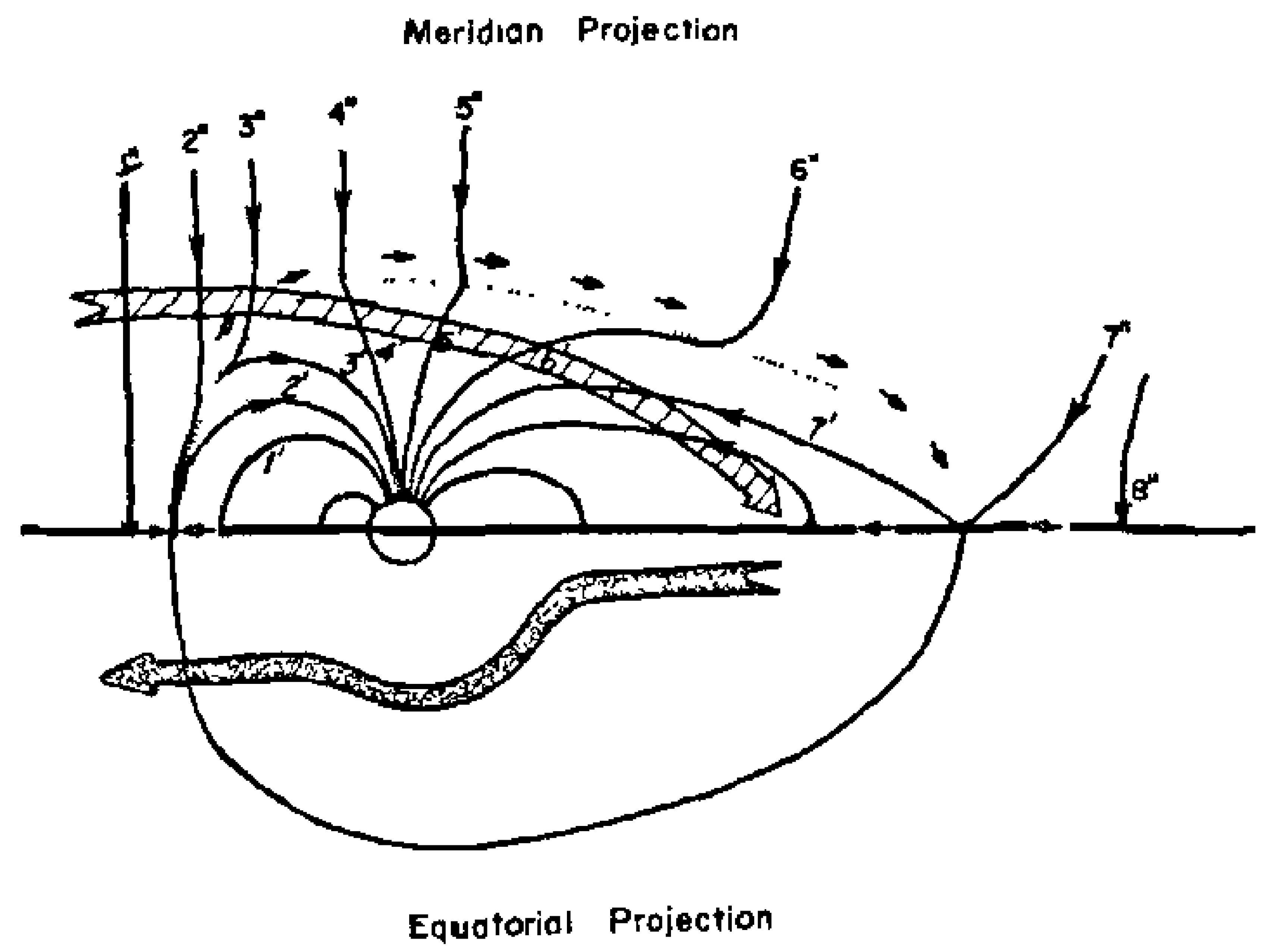

Figure 4. Convection in the open magnetosphere model as proposed by Dungey[6].

named substorms by Chapman. These can be seen in all plasma and field variables in the magnetosphere and they are probably physically similar to the solar flares. Although there are still somewhat different opinions about several aspects of the magnetospheric substorms, it appears to be clear that reconfiguration of the magnetic field and currents occurs in the tail with the crosstail current being partly rerouted to the ionosphere and out again. The aurora intensifies and spreads eastward and westward and also northward as determined by Akasofu and coworkers on the basis of the data collected in the International Geophysical Year, 1957–58, and thereafter. Akasofu's development scheme for the auroral substorm is shown in Figure 12. This scheme has been confirmed in most respects by recent satellite imaging experiments on DE1 and Viking.

What Akasofu and other substorm investigators could not find in the IGY data base was the substorm effects in the magnetospheric tail. Recent satellite measurements in the tail have shown that the plasma sheet becomes very thin, some 15 to 20 earth radii from the Earth and that a large plasma element, a so-called plasmoid, is released from the inner tail in the direction of the distant tail and out of the magnetosphere, as indicated by Hones in Figure 13. Although a lot of data supporting the process illustrated by Figure 13 have been presented the available data from distances beyond 25 R_e are very limited in amount and not quite conclusive. Some kind of plasma loss from the near tail toward the distant tail appears to be required for continuity reasons. More direct measurements are expected in the first half of the nineties from the Soviet Interball and the Japan-USA Tail satellites.

Microscopic instabilities

Satellite measurements in and near the atmospheric loss cone at auroral latitudes have demonstrated that the

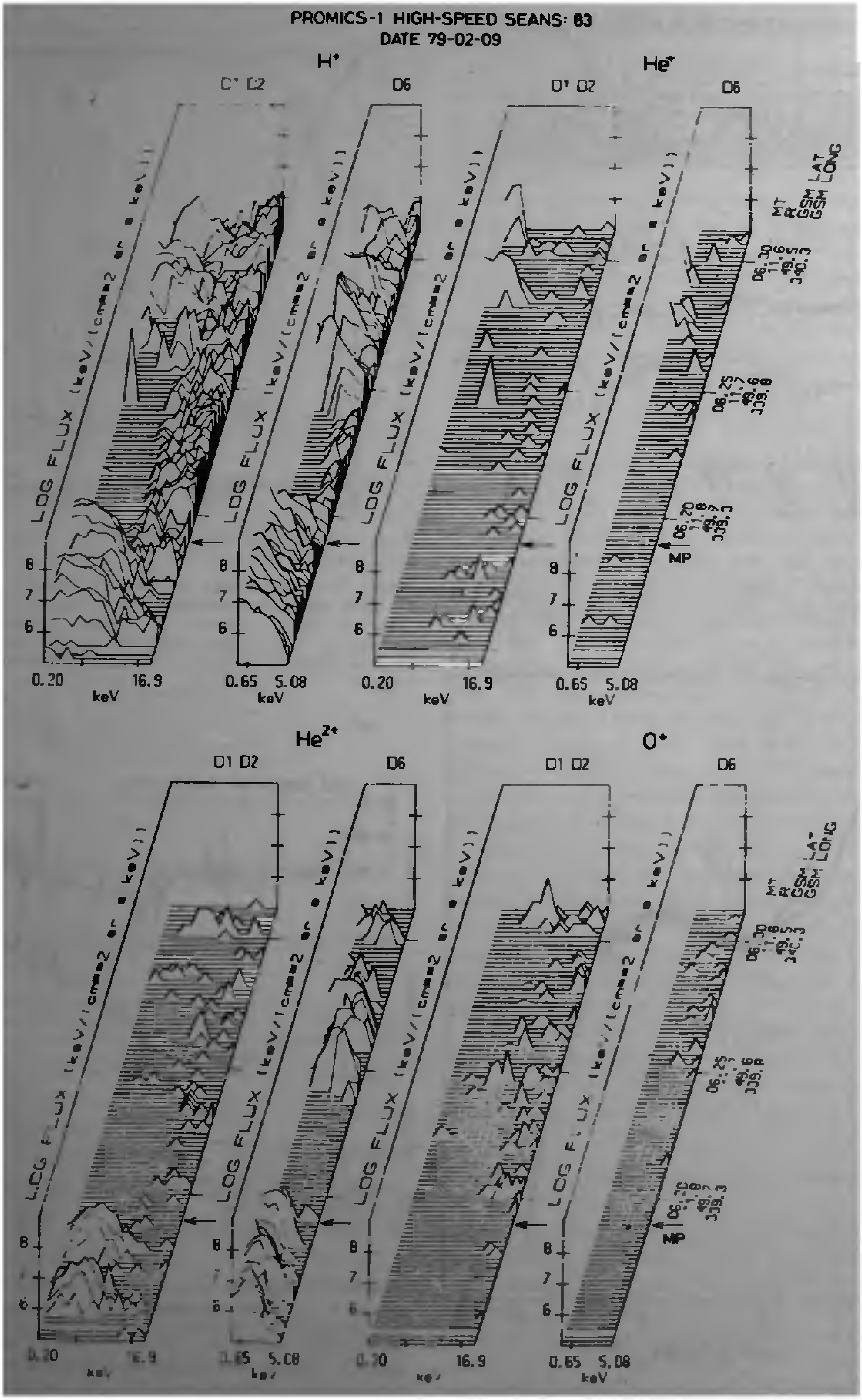

Figure 5. Energy spectra as function of time for H^+, He^{2+}, He^+ and O^+ ions during an inbound magnetopause (marked MP) crossing by Prognoz-7 on 9 February 1979. The D1 D2 panels show data from perpendicular ion mass spectrometers, which scan the GSE YZ plane and the D6 panels show data from the sunward oriented spectrometer (after Lundin[25])

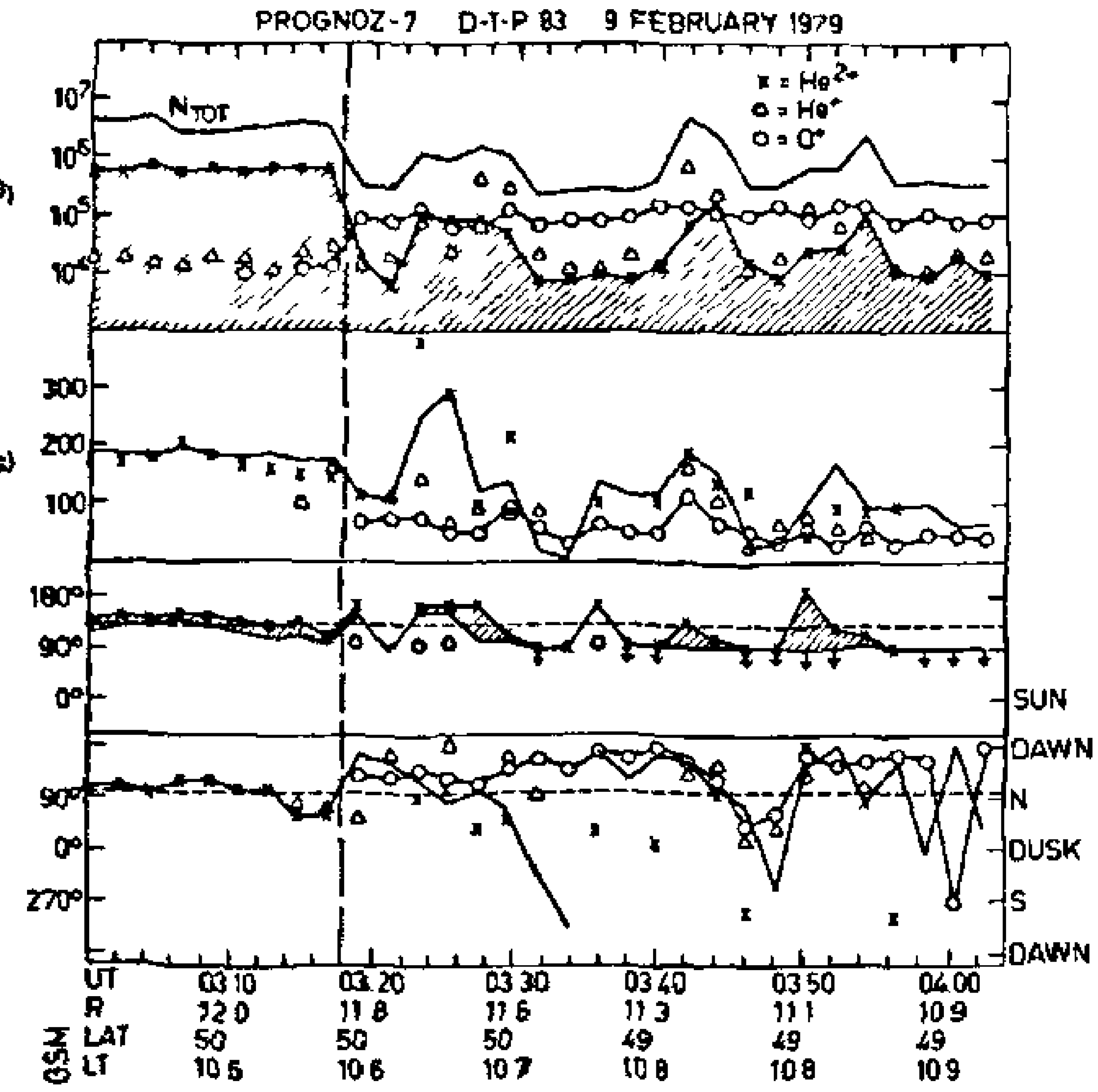

Figure 6. Density and flow velocities during an inbound magnetopause crossing by Prognoz-7. The magnetopause is shown by *the vertical dashed line Panels 2–4 show the magnitude and* direction of the flows of the various ion species (the solid line is for H$^+$) (after Lundin[25])

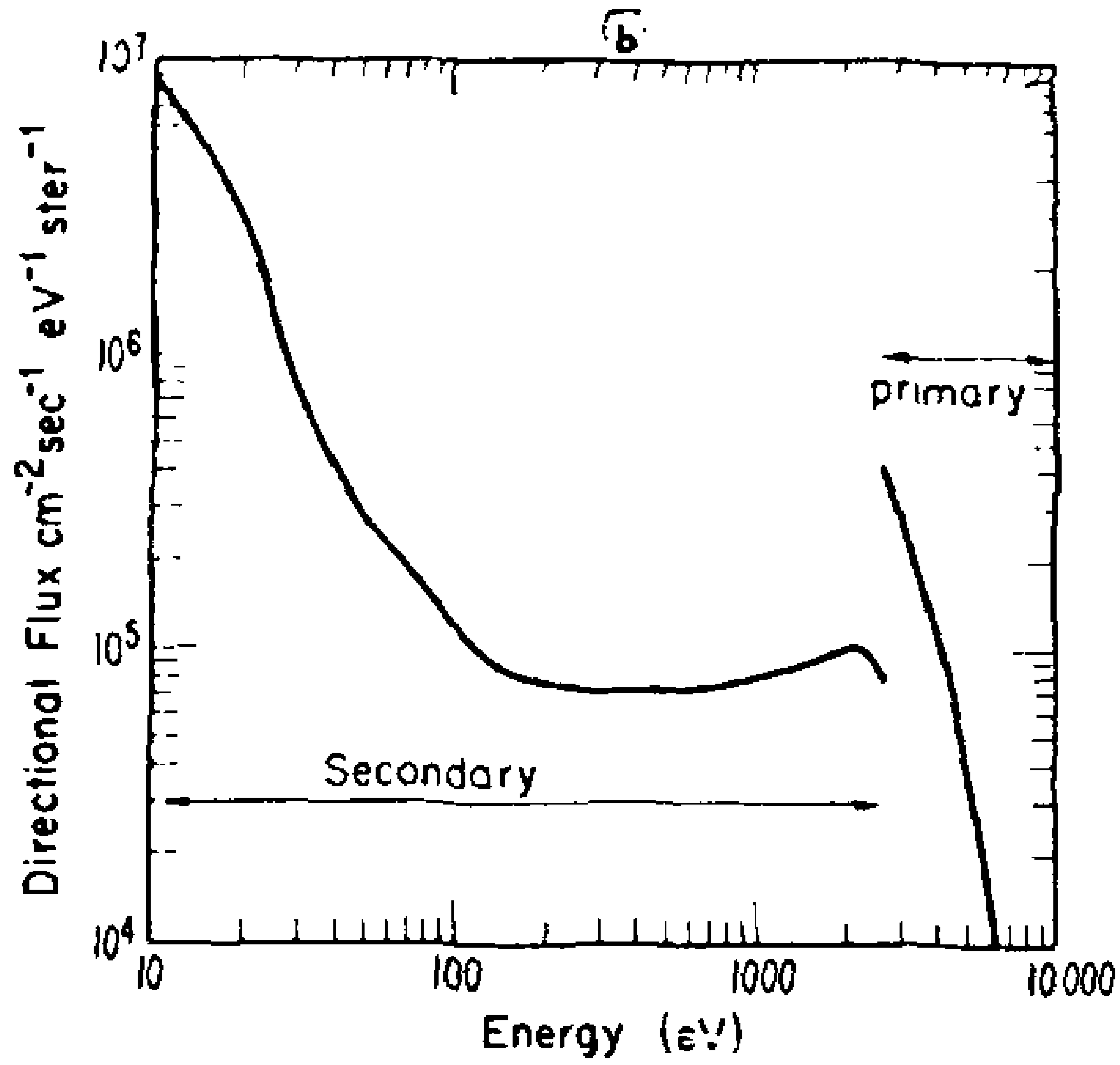

Figure 7 *b*. Model energy spectrum of precipitating electrons at 45° pitch angle The electrons were assumed to have originated from an 800 eV plasma of density 1 5 cm^{-3} and were assumed to have been accelerated by a total field-aligned potential difference of 2000 V located at 2000 km altitude (after Evans[8])

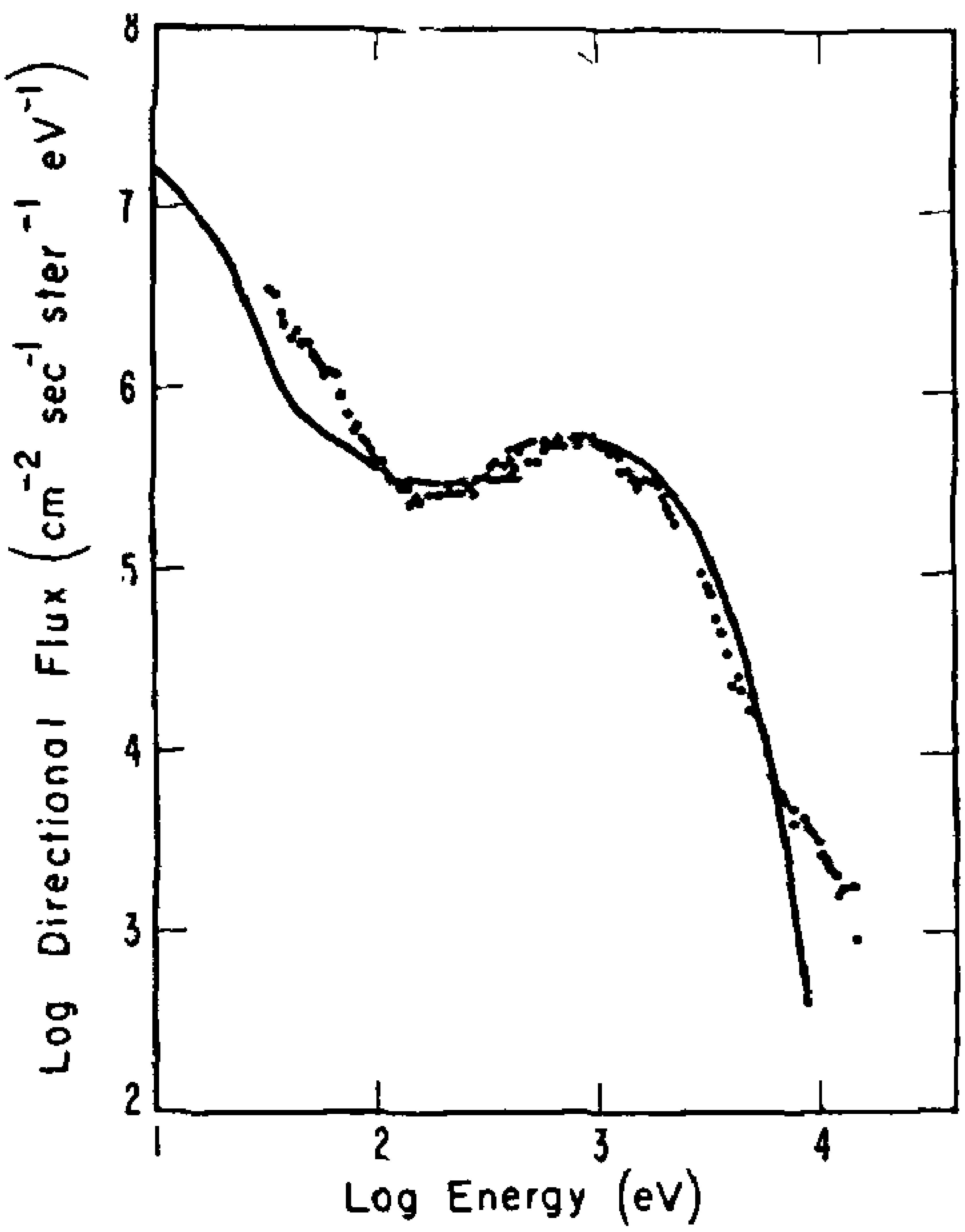

Figure 7 *a*. Comparison of Evan's model with observations from Frank and Ackerson[9] The electrons were assumed to have originated from an 800 eV plasma of density 5 cm^{-3} and the field-aligned potential difference was taken to be 400 V (after Evans[8])

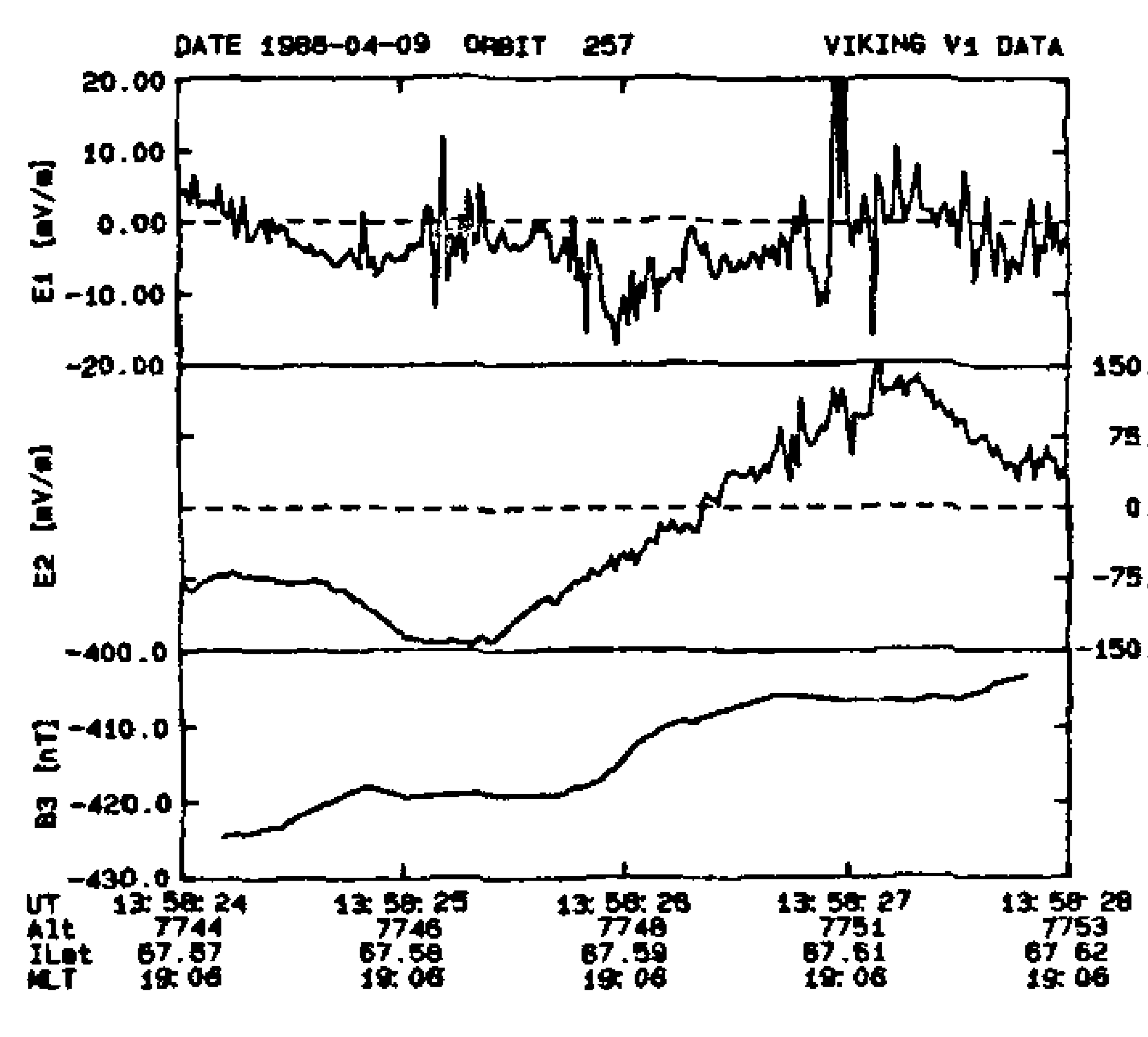

Figure 8. Electric and magnetic field variations during a Viking pass over an evening side auroral arc E1 is almost parallel to the local magnetic field, positive downward E2 is perpendicular to the magnetic field and positive in the southward direction B3 is the westward magnetic field component perpendicular to the main magnetic field An upward parallel electric current of about 17 μA/m is colocated with the maximum B3 variation, corresponding to a Birkeland current density of 50 μA/m^2 in the ionosphere (after Block[26])

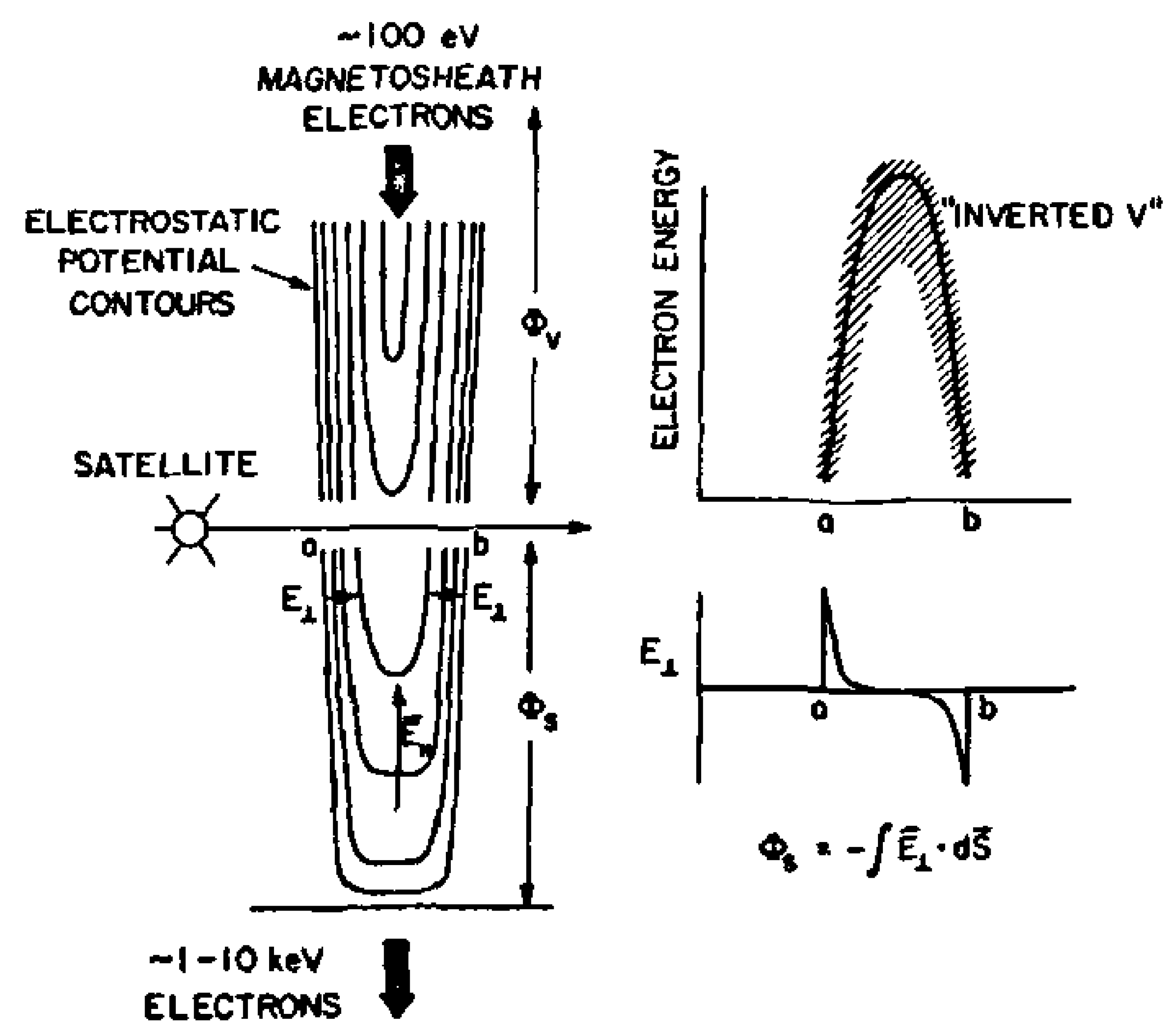

Figure 9. Qualitative form of the electrostatic potential contours associated with an inverted V electron–precipitation event (after Gurnett[27])

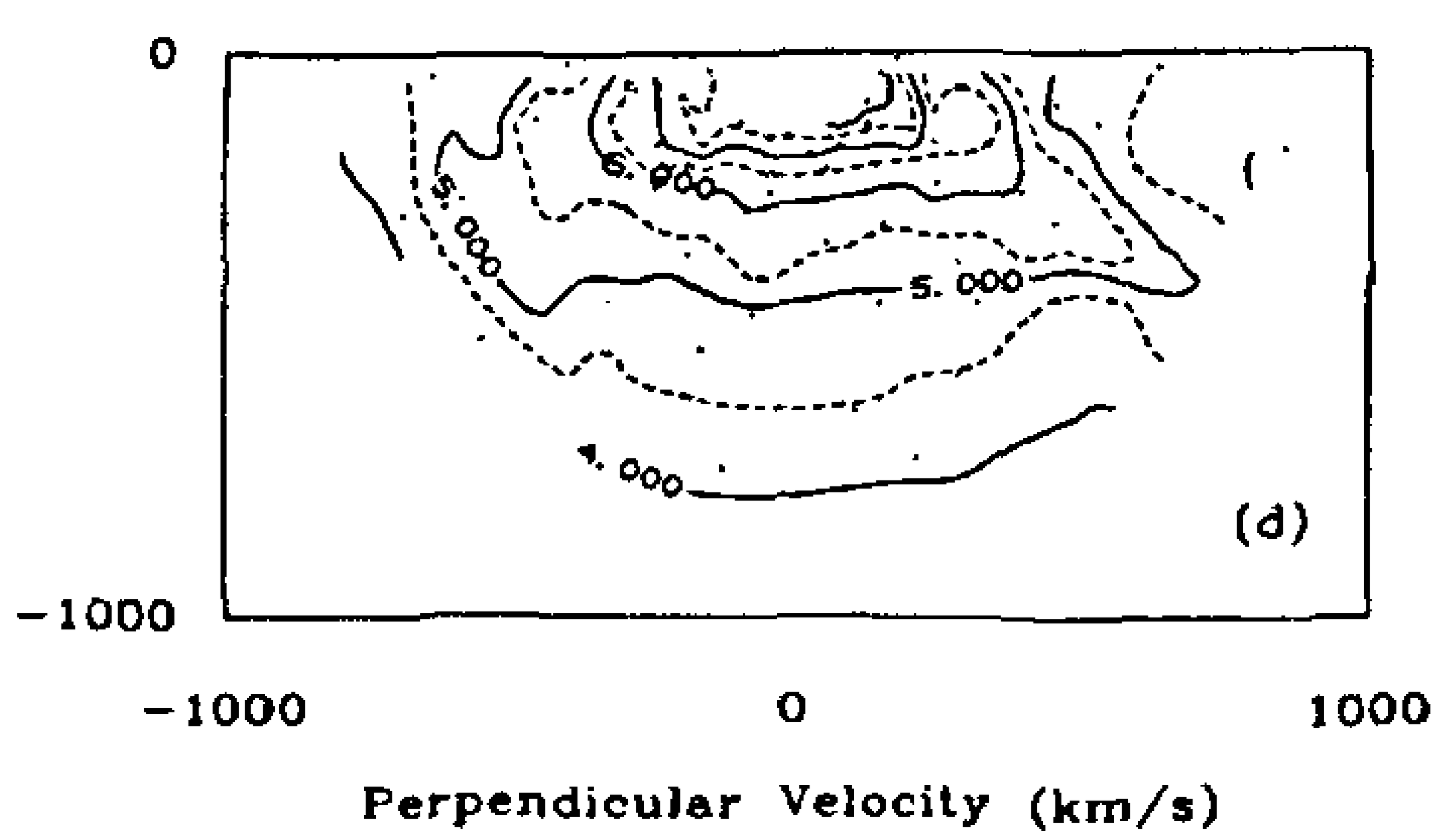

Figure 10. Contour plot of the logarithm of the velocity space density showing a conical distribution of He^+ ions Perpendicular velocity is along the horizontal axis and parallel velocity along the vertical axis (after Collin *et al* [28])

plasma sheet and its boundary layer are always turbulent to the extent that the diffusion of electrons and ions into the loss cone is rather strong. This is illustrated in Figure 14, where data obtained from ESRO I are displayed. The diagrams in Figure 14 show that on the nightside both ion and electron fluxes are of the same order of magnitude in the loss cone (10°) as outside it (80°) in the keV to tens of keV energy range. In the central part of the dayside the angular distributions are generally, fairly far from isotropic, with a depleted loss cone both for keV energies and below one keV. The electrons show more deviations from isotropy than the ions The electron angular distributions are generally closer to isotropy, the higher the fluxes and the lower the energies.

The first direct comparison of observations of electrostatic waves with the theory of wave generation by electron distributions with a loss cone was made in space by Rönnmark *et al* [12]. The satellite that took the data was GEOS 1.

New mechanisms of radio wave generation have been found, in which the relativity factor plays a role even at non-relativistic electron energies[13]. This mechanism explains the most intense radio wave emission that is produced in the Earth's environment, the so-called Auroral Kilometric Radiation (AKR). The Earth transmits these radio waves with an intensity of up to 10^9 W, more or less continuously.

An astonishing new result from Viking is that there exist density depletions in the upper ionosphere/lower magnetosphere at auroral latitudes, which appear to be solitary depletion waves. An example of this is shown in Figure 15. As can be seen there, the density may be depleted so that the remaining density is only about half of the original one. Boström *et al.*[14] have determined from data obtained with a plasma wave E-field and plasma density variations interferometer flown on Viking, that such depletions are quite common at intermediate altitudes (in about 10% of observations), they have characteristic sizes of 100 m both along and perpendicular to the magnetic field lines and they move upward along the field lines with velocities of 5–50 km s^{-1}. Finally, but most importantly, they are associated with a potential change in the direction along the field lines of the order of one volt. Since they are quite common we may assume that many of them may be piled along a field line and thereby create considerable potential differences which accelerate electrons downward and ions upward. It is thus believed that these rarefactive solitary waves are identical with the so-called weak double layers which were discovered by means of the S3–3 satellite[15].

It is still unclear how the depletions are produced, but there are some ideas about 'hole instabilities' being investigated[16, 17]. Our knowledge about the production mechanisms is, however, still rudimentary.

Ion composition in the magnetosphere

The very first measurements of magnetospheric ion composition carried out by the Lockheed group gave such astonishing results of precipitating energetic O^+ ions that the experimenters awaited the confirmation on a second spacecraft before publishing them[18]. The S3-3 discovery in 1976 of outward flowing O^+ ion beams above the auroral zone ionosphere[19, 20] was, towards the background of the earlier observations of precipitating energetic O^+ ions, *not quite so unexpected*, but it was in some respects even more important (again obtained by

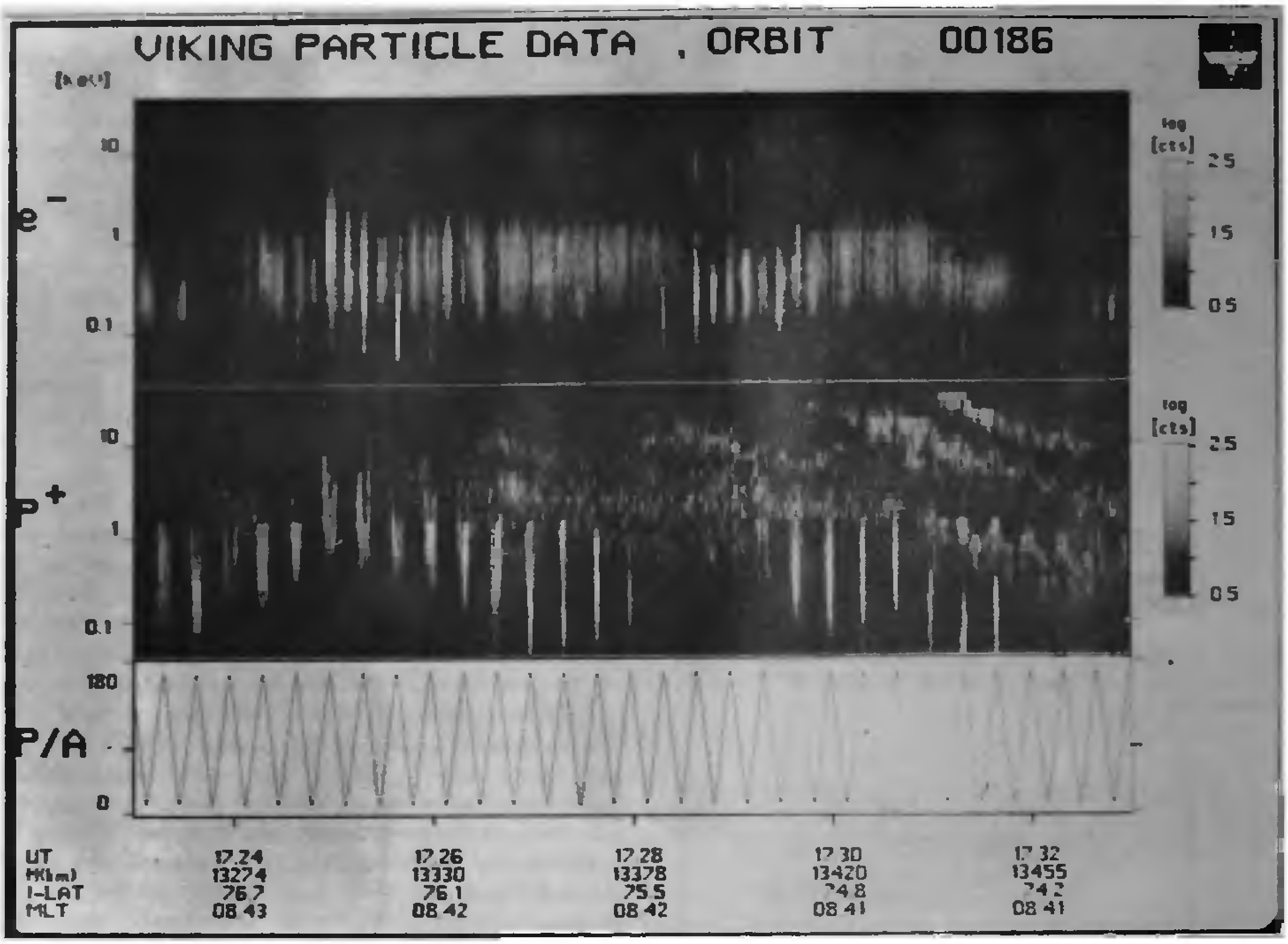

Figure 11. Energy time spectrogram for ions and electrons obtained in the cleft regions of the dayside auroral oval (orbit 186). Each spectrogram displays counts accumulated versus energy in 32 energy steps within 0.6 s corresponding to a pitch angle resolution of 5°. The lower panel shows pitch angle versus time (0° corresponds to downcoming particles)

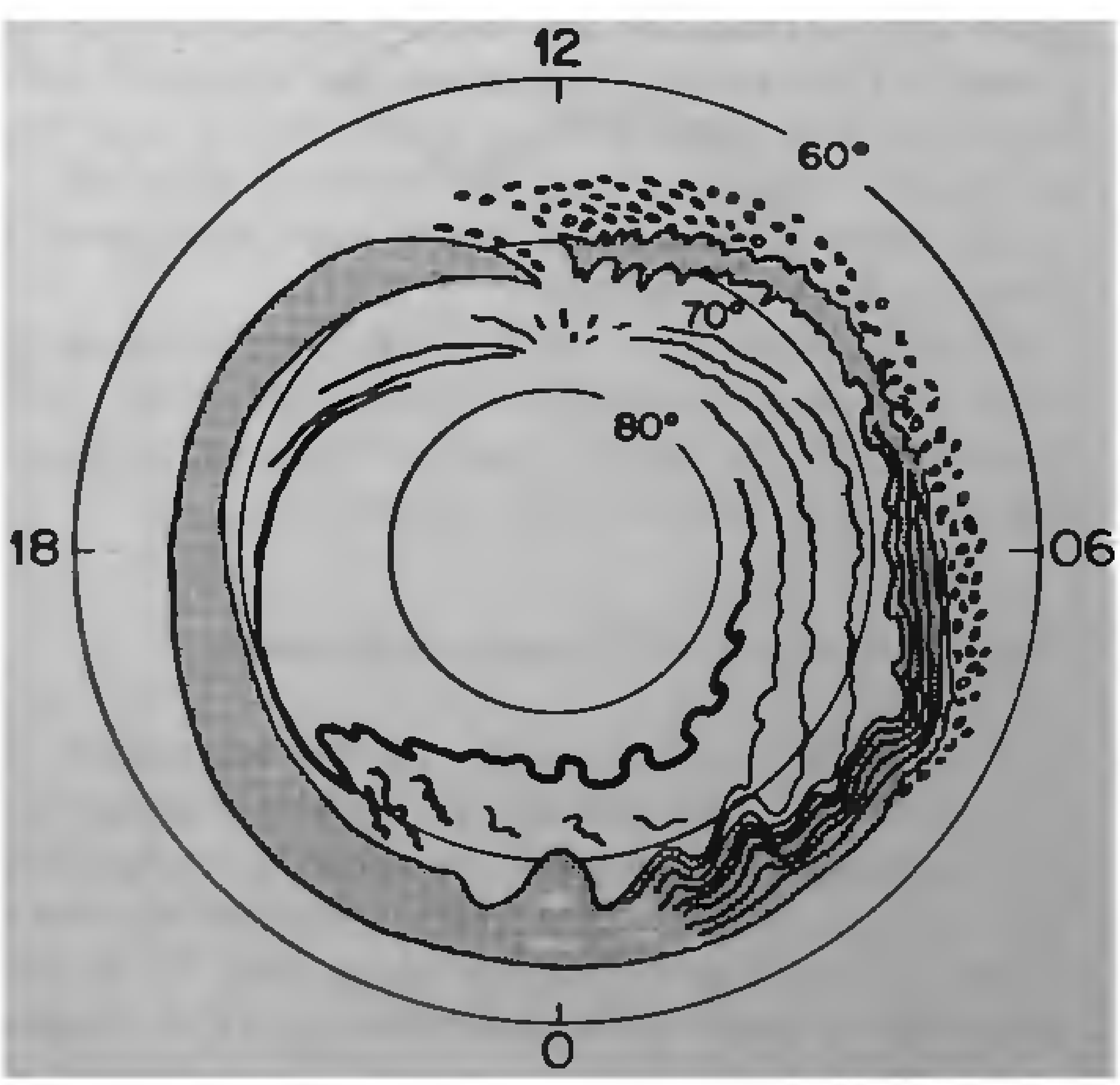

Figure 12. Schematic diagram showing the main characteristics of auroras during an auroral substorm in dipole-MLT coordinates. Discrete arcs are indicated by lines and diffuse auroral regions are shaded (after Akasofu[29])

the Lockheed group). When the first ion mass spectrometer was sent to great altitudes on GEOS-1 in 1977 by the Bern group, many research workers expected that significant abundances of ionospheric ions would be found in the outer magnetosphere. Still, the discovery by the Bern group[21] that the ionosphere is a source for the magnetospheric plasma of comparable importance to the solar wind came as a surprise. Sometimes the ionospheric source completely dominates, as shown in Figure 16, where there is an order of magnitude higher number density of O^+ ions than of H^+ ions in the entire dayside of the magnetosphere. Such situations occur only in magnetic storms. We have thus had in the last decade a complete revolution of our knowledge and understanding of the interaction between the ionosphere and the magnetosphere in regard to ion exchange.

Phenomena not found in the Earth's environment

The Earth's magnetosphere is our main laboratory for investigation of physical processes which are of importance in many other parts of the solar system and most

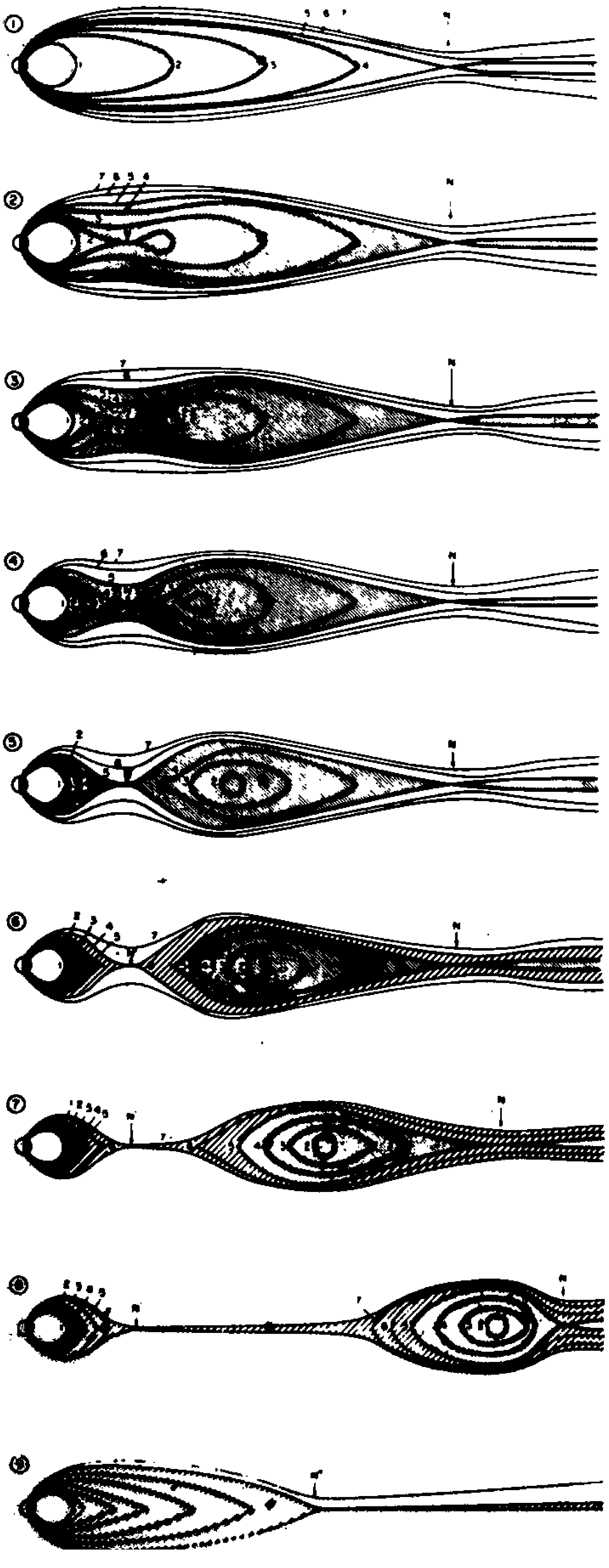

Figure 13. Development of a magnetic field line configuration and the plasma sheet in the magnetospheric tail through a substorm according to Hones[30]

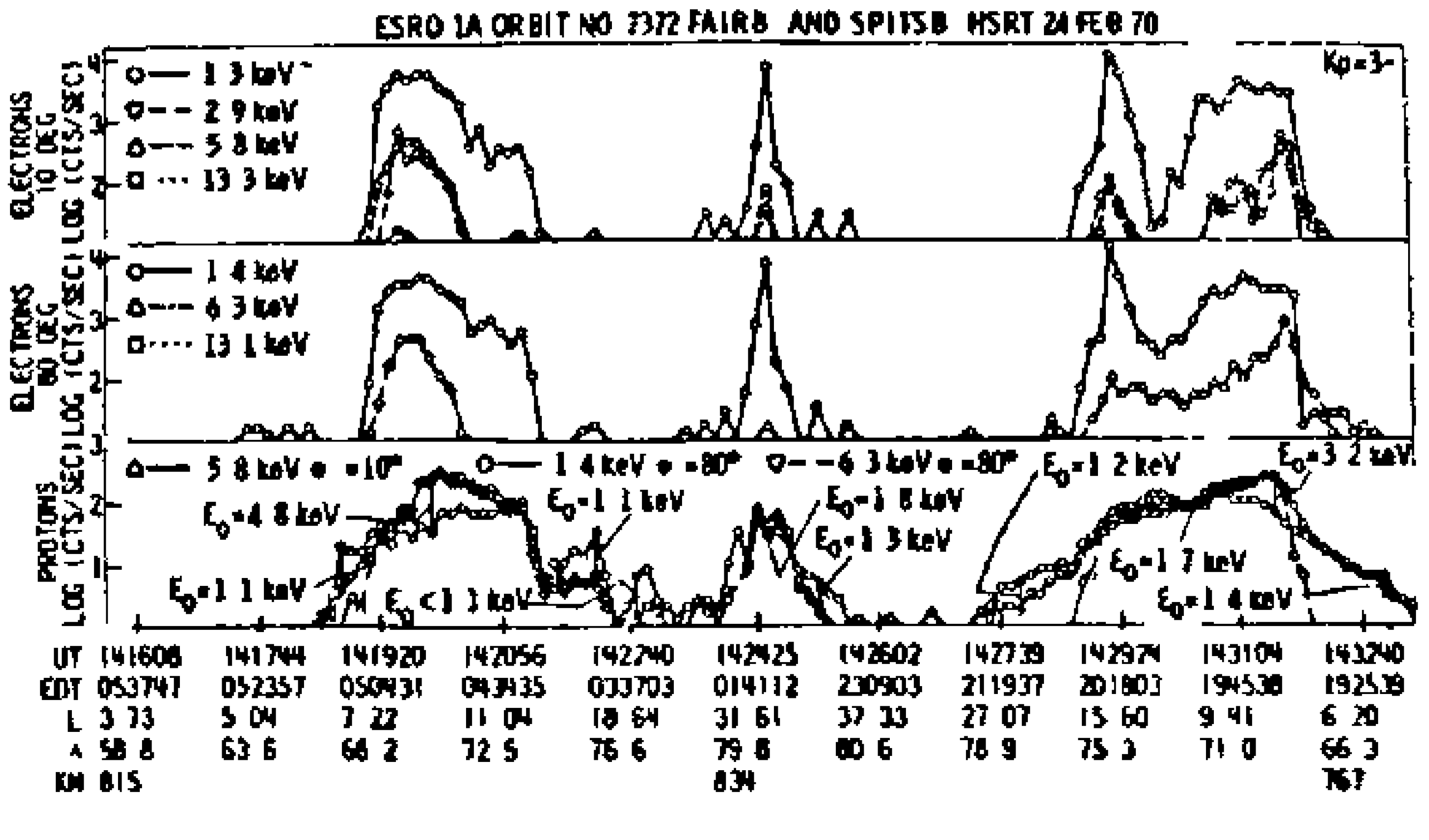

Figure 14. KeV electron and ion data from ESRO 1A orbit 7372 (after Hultqvist et al[31]). The figure clearly illustrates that fluxes in the loss cone (10°) and outside it (80°) are not very different (also when the calibration factors are taken into account).

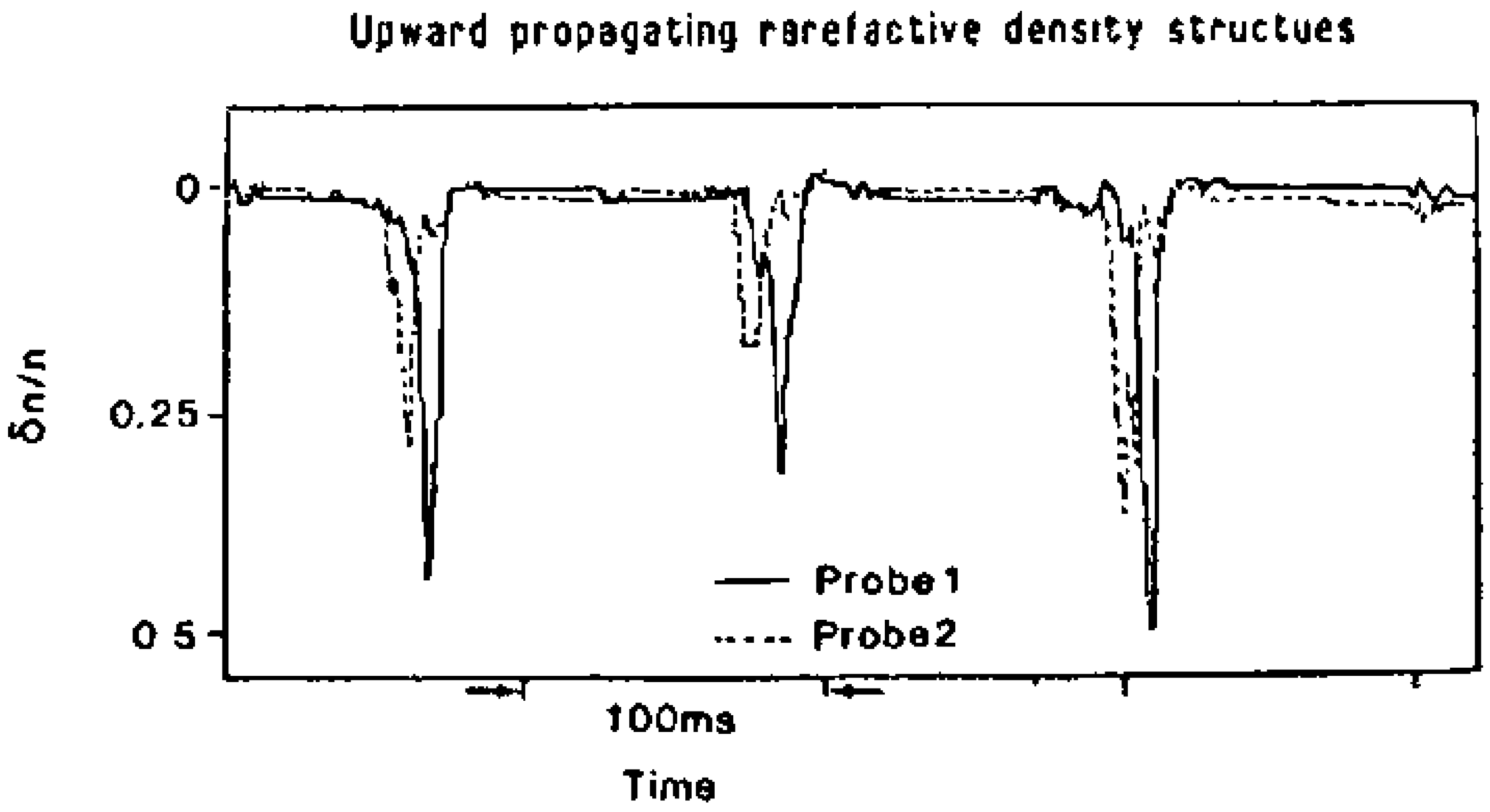

Figure 15. Wave form data for two $\Delta n/n$ probes displaying rarefactive solitary waves. The time delay between the two signals corresponds to an upward motion of the wave (after Gustafsson et al[32]).

likely in the Universe as a whole. There are, however, a number of important phenomena which we cannot study in our own magnetosphere but at other bodies in the solar system. Examples of such phenomena are the following:

Magnetospheric disk with internal powering (Jupiter).
Hot magnetospheric wind downtail (Jupiter)
Aurora excited entirely by energetic ions (Jupiter)

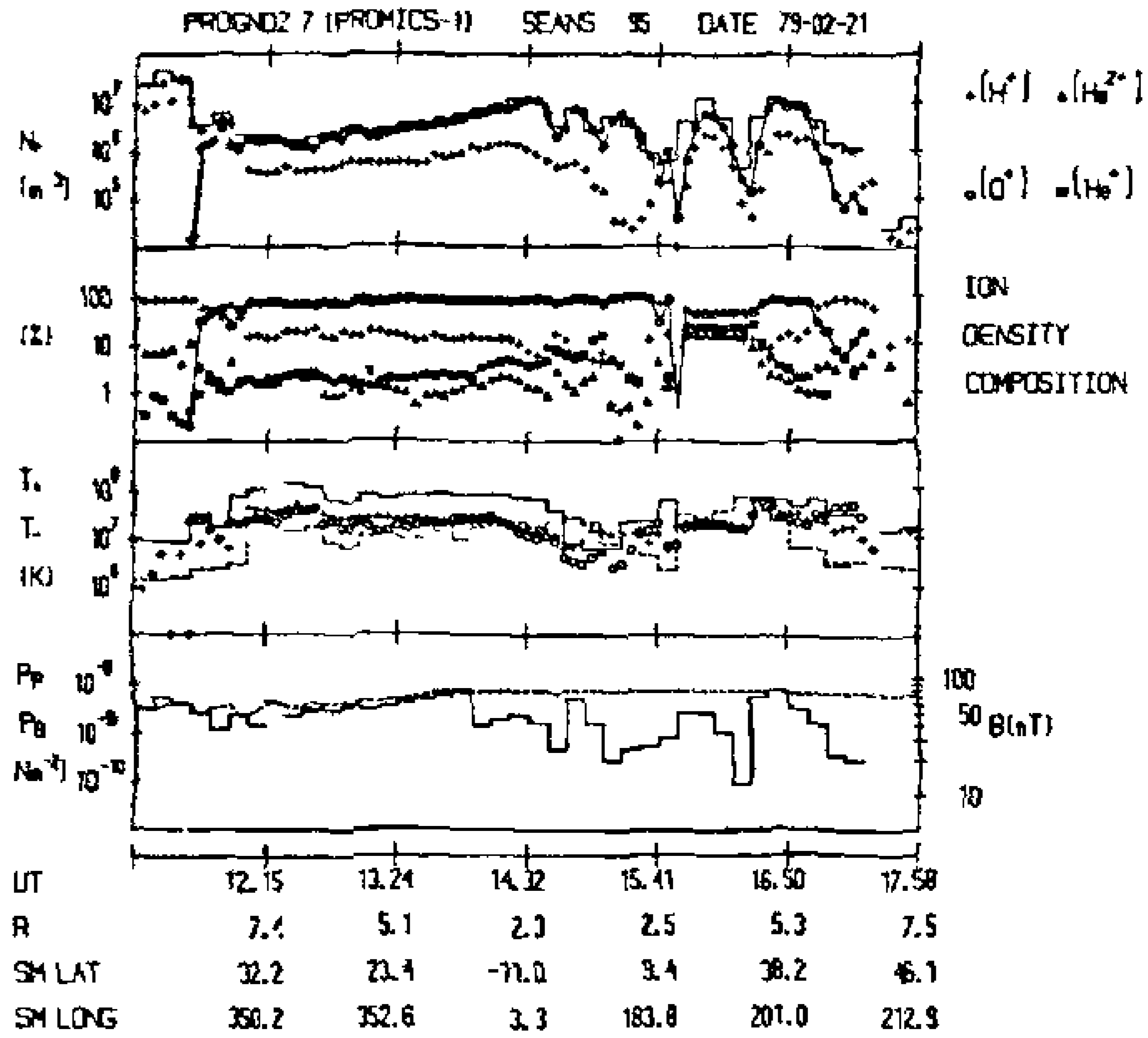

Figure 16. An example of complete dominance of O^+ ions in the dayside magnetosphere during a magnetic storm (after Hultqvist[33])

- Dominant role of a moon on the magnetosphere (Jupiter, Io).
- Magnetospheric plasma dominated completely by heavy ions (S^+, O^+; Jupiter).
- Interaction of the solar wind directly with the ionosphere (Venus).
- 'Soft' interaction of the solar wind with an ionosphere/neutral atmosphere in the absence of significant gravitational field (Halley).
- Effect of large angle between rotation axis and magnetic axis (Uranus).
- Orders of magnitude faster time scales than at the Earth for macroscopic disturbances in the magnetosphere (Mercury).

We can thus conclude that we need to extend our 'laboratory' so that it includes the plasma systems around most of the bodies of the solar system in order to be able to investigate all kinds of physical processes of importance for the formation of all these different plasma systems. That is one of the reasons (but not the dominant one) behind the existing plans for future planetary missions.

Plans for future space physics missions

From 1990 on the international cooperative research programme STEP (Solar Terrestrial Energy Programme), which is organized by SCOSTEP, will coordinate extensive investigations of the energy transfer within the solar-terrestrial system down to the middle atmosphere. This programme will involve a large number of space missions. Before the start of STEP there are already some space projects in the pipeline and a number of missions now being planned will fly after STEP has finished.

Table 1. Future missions which have been decided

Phobos (1988)	(USSR + many European groups)
EXOS D (1989)	(Japan + Canadian group)
Galileo (1989)	(USA + FRG)
Ulysses (1990)	(ESA + USA)
Interball (1991)	(USSR + many European groups)
Wind and Polar (1992–1993)	(USA)
Geotail (1993)	(Japan + USA)
Cluster + SOHO (1995–1996)	(ESA + USA)

Table 2. Missions not yet decided

Freja (1991 or 1992)	(Sweden with several European and American groups)
IMPACT (1993 or 1994)	(FRG, USSR, and others)
Delta and Scout Explorers (from 1992 on)	(USA, partly in cooperation with other countries)
Additional Cluster satellites (1996)	(USSR, possibly with non-Soviet research groups)

Table 1 contains a list of decided missions which are in various stages of execution. In the first one, Phobos, the two spacecraft are on their way towards Mars and its moons when this is being written. Table 2 lists a number of projects which are in the early-planning phase. The first project in the list is a follow-up of the Viking satellite project.

Concluding remarks

As mentioned earlier, space physics is still a young discipline. It therefore has a long way to go before the research field is well worked through. It is reassuring to observe that at least the next decade is likely to offer good opportunities for the research community to continue, extend and deepen its research programme. It is difficult to predict beyond ten years for any research field but there appears to be good reason for optimism regarding the future of space physics research, even after the passage into the next millennium.

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