2

OBSERVATIONS OF LOW ENERGY MAGNETOSPHERIC
PLASMA OUTSIDE THE PLASMASPHERE

Bengt Hultqvist

KGI PREPRINT
JANUARY 1985

KIRUNA GEOPHYSICAL INSTITUTE
KIRUNA SWEDEN

OBSERVATIONS OF LOW ENERGY MAGNETOSPHERIC PLASMA OUTSIDE THE PLASMASPHERE

by

Bengt Hultqvist
Kiruna Geophysical Institute
P.O. Box 704, S-981 27 Kiruna, Sweden

KGI Preprint 075
January 1985

Printed in Sweden
Kiruna Geophysical Institute
Kiruna, 1985
ISSN 0349-2656

OBSERVATIONS OF LOW ENERGY MAGNETOSPHERIC PLASMA OUTSIDE THE PLASMASPHERE

B. Hultqvist
Kiruna Geophysical Institute
P.O. Box 704
S-981 27 Kiruna
Sweden

ABSTRACT

After some introductory discussions about morphological concepts and limitations of various measurement techniques, existing low energy plasma data, orginating primarily from the GEOS, Dynamics Explorer, and Prognoz spacecraft, is described and discussed. The plasmasphere measurements are not included (but for some observations of plasmasphere refilling). It is finally concluded that we are very far from a complete picture of the low-energy plasma component in the magnetosphere and that this problem has to be given high priority in planning payloads of future space plasma physics missions.

1. INTRODUCTION

The distribution of density, characteristic energies, composition and flow of the plasma in the magnetosphere is the result of a complex interplay of source and loss processes, primarily at the outer (magnetopause) and inner (ionosphere) boundaries, as well as of transportation and energization/dissipation in various regions within the magnetosphere. One of the most important tasks of experimental magnetospheric research is to determine the main characteristics of the plasma in various parts of the magnetospheric system under different disturbance conditions. To know the plasma density in the magnetosphere is important because of the effect that plasma density has e.g. on wave-particle interactions, including those giving rise to auroral kilometric radiation and electrostatic ion cyclotron waves. The plasma density is also important for the propagation of waves of various kinds. So, besides being one of the main macroscopic characteristics of the magnetospheric plasma, the knowledge about the total plasma density is required for analysing most microphysical problems in the magnetosphere.

Although a most important task, which has been recognized since before the beginning of the space era, we are still far from the goal of being able to determine density, temperature or energy distribution, composition and flow for all energy ranges of importance to the physical processes in the magnetosphere. This is because it is quite a difficult task to measure the plasma parameters in some energy ranges and an extensive set of sofisticated measuring instruments are required. Mostly the set is not complete even on satellites which are devoted to space plasma physics research. When most of the parameter space of interest is covered by a set of such instruments, there are generally still intercalibration problems to overcame in order to arrive at resonably accurate fluid parameters for the plasma in question.

In the 1960's and 1970's whistler measurements in combination with some direct satellite measurements provided a fairly comprehensive picture of the cold plasma density distribution in and close to the plasmasphere (e.g. Carpenter, 1966, 1970; Chappell, 1972), but temperature, pitch angle and density distributions along the magnetic field lines were not known. Until the late 70's the magnetospheric plasma was thought to be composed of two basic particle populations, one of solar wind origin, with high characteristics energies, and one cold ($T < 1$ eV), of ionospheric origin, found mainly in the plasmasphere. The change of this picture started in fact already at the end of the 1960's with the first flight of an energetic ion mass spectrometer on a low polar orbiting satellite by the Lockheed group (Shelley et al., 1972) which demonstrated the existence in the ring current of energetic O^+ ions, by necessity of ionospheric origin. Also observations of the cold plasma component provided quite early results which were inconsistent with the two component (hot and cold) magnetospheric plasma picture. Serbu and Maier (1970), on the basis of ion trap measurements on OGO 5, derived temperatures of 5-10 eV for the outer plasmasphere. Gurnett and Frank (1974) obtained a temperature of 8 eV in the dayside plasma trough and Bezrukikh and Gringauz (1975) reported temperatures above 2 eV in the outermost plasmasphere.

That the simple picture of the magnetospheric plasma being composed basically of a cold ("thermal") component originating in the ionosphere with temperatures below 1 eV and a hot component of solar wind origin was completely false was definitely demonstrated in the 1970's by means of the S3-3 and GEOS spacecraft for higher energies and by means of the plasma experiment on ATS 6 for the low, but superthermal, energies. It was found that the hot magnetospheric plasma in disturbed conditions may be dominated by ions of ionospheric origin (Shelley et al., 1976, Geiss et al., 1978 and others) and that the cold component has a long "tail" tying it together with the hot component along the energy axis (Lennartsson and Reasoner, 1978, Horwitz et al., 1978, Horwitz and Chappell, 1979, Horwitz, 1980 and others).

In this lecture I will concentrate on the thermal and superthermal parts of the energy distribution of the magnetospheric plasma. Others will discuss the hot component.

It should be emphasized that the term thermal plasma is not very well defined. If we mean fairly well Maxwell-distributed plasma, we may find such both at the cold end of the energy spectrum and in the hot part (plasmasheet). In this lecture we will use the term thermal plasma for the part that has a temperature of less than 1-2 eV (alternatively named the cold component). For the superthermal plasma T is in the range from 1-2 eV to about a hundred eV and for the hot plasma the characteristic energies are of the order of a hundred eV or more. These definitions are those mostly used in the literature, but differences occur.

The plasmasphere will not be dealt with here (but for when discussing phenomena where it is related to the magnetospheric regions outside it). It is a large subject of its own.

The material is organized regionally. That is a natural way of presenting the present knowledge of the cold and superthermal plasma in the magnetosphere, as the different regions of the magnetosphere have different histories of plasma research, different spacecraft making the measurements and, to some extent, different dominating physical processes.

As this is a tutorial lecture the goal is not to present a complete review of the field but rather to present the basic characteristics of the plasma in the magnetosphere outside the plasmasphere and the most important known physical processes affecting it.

2. SOME MORPHOLOGICAL CONCEPTS

In the parts of the magnetosphere outside the plasmasphere the magnetic field lines are supposed to be periodically or permanently open to the distant tail and the interplanetary space, whereas they are closed and dipole-like within the plasmasphere. How big the plasmasphere is depends on the magnetospheric disturbance level (see e.g. Chappell, 1972). During magnetic storms its size is strongly decreased to the extent that the L-value of the plasmapause in the midnight sector ($L \lesssim 4$) may be less than half of the value for very quiet conditions ($L \sim 8$). There is thus an outer part of the plasmasphere region of the magnetosphere which sometimes is part of the plasmasphere and sometimes not. In periods after storms this part is characterized by refilling processes, during which ionospheric plasma fills up the emptied region in which at least part of the magnetic field lines are supposed to be temporarily open during the storm. The time scale for this replenishment of thermal ionospheric plasma has been found to be in the range 7-22 hours (e.g. Horwitz et al., 1984). The refilling of the plasmasphere is a field where we know very little of the basic physical processes and where very much remains to be investigated in the future.

Before going into the substance of this chapter we have to clarify another matter of nomenclature. The region of the magnetosphere next to the plasmasphere is usually called the plasma trough by researchers working in the field of thermal plasma. This name has come from observations that the ionosphere contains less electrons per unit volume in a region between the auroral oval and the plasmasphere than it does north and south of it. In the magnetosphere this trough region has been associated with a region in the dusk to midnight sector between the plasmapause and the inner edge of the plasmasheet (reported first by Vasyliunas, 1966). This intermediary region is difficult to understand on the basis of known magnetospheric processes. Some recent observations in fact indicate that it does not exist but the plasmapause and the inner edge of the plasma sheet, as seen in the electrons, coincide closely (Horwitz et al., 1982). On the dayside the trough region is located between the plasmapause and the magnetopause boundary layer (including the cusp region). It therefore appears likely - although not definitely demonstrated yet - that in the magnetosphere, as in the ionosphere, the trough is bounded on the outer side by the magnetic field lines connected with the auroral oval, i.e. by those in the plasma sheet boundary layer. In the trough there appears to occur generally a more or less intense electron precipitation associated with diffuse aurora (Horwitz et al., 1982) whereas the strong structured aurora is located on the field lines of the plasma sheet boundary layer.

The trough region of the researchers working with the thermal and superthermal components of the magnetospheric plasma, falls, for those working with the hot plasma, in the plasma sheet (on the nightside) and the ring current (on both day- and nightside). The ring current region overlaps with both the plasma sheet and the plasmasphere to some extent and it covers the trough region.

3. LIMITATIONS OF MEASUREMENT TECHNIQUES

To determine completely the characteristics of the magnetospheric plasma over the entire energy range from a tenth of an electron volt to hundreds of kiloelectron volts in the varying conditions found within the magnetosphere is, as mentioned in the introduction, a goal very difficult to reach and we are still in the early phase of approaching it. A number of different techniques have to be employed. Here we shall only briefly sketch the main characteristics and some problems associated with the different methods, which are important to understand in connection with the discussion of the measurement results presented below.

At the high energy end of the scale, i.e. in the hot region, the plasma is frequently far from Maxwell distributed. Therefore, the entire distribution function has to be determined for all major ion species in order to compute even the basic macroscopic variables, such as density, energy density, characteristic energies and flow vectors. At these energies each individual plasma particle entering the instrument is analysed and to cover all directions, energies and mass of interest in sufficiently short time requires so many different sensors that it has not yet been possible to measure in great detail but in limited parts of parameter space. Between or beyond the measured range interpolation and extrapolation have to be resorted to. Still, we have generally a better idea about density and characteristic energies of the hot plasma component than of the thermal and superthermal parts in most of the magnetosphere outside the plasmasphere.

The technique of measuring individual particles for determining density, temperature, composition and flow of the plasma has to be used also in the superthermal energy range (~1 eV - ~100 eV). It is, however, more difficult to apply such methods the lower the energy, mainly because of the spacecraft being charged up to several volts potential relative to the plasma in most of the magnetosphere outside the plasmasphere. Only very recently has it become possible to control the effect of an unknown spacecraft potential on the particle measurements reasonably well by varying the potential of the aperture of the measuring instrument (Sojka et al., 1983; Nagai et al., 1984). Still, the density values derived are subject to a number of assumptions which make the absolute accuracy of the measurements limited.

The best way to determine the total plasma number density (electron density) in the magnetosphere fairly accurately appears to be by deriving it from resonance effects in the surrounding plasma, which give rise to plasma waves detectable onboard the spacecraft. The technique may be passive or active, i.e. one may determine naturally excited waves or waves may be excited with a transmitter onboard. The passive method is generally more uncertain than the active methods because of difficulties under some conditions to identify the nature of the process producing the waves. Only from the late 1970's are observations in the magnetosphere, using active methods, available and only for limited regions (Decreau et al., 1982; Higel and Lei, 1984).

The relaxation sounding technique used for magnetospheric plasma density measurements first on the GEOS spacecraft is based on ionospheric plasma resonance phenomena discovered by the first topside sounder experiment (Calvert and Goe, 1963).

Passive methods of analysing plasma waves have provided magnetospheric plasma densities only in the 1970's and later (Gurnett and Shaw, 1973; Kurth et al., 1979; Persoon et al., 1983, and references therein).

The techniques using plasma waves for plasma density determination have the important limitation compared to the methods based on direct particle measurements that they only provide information about the density but not about the other characteristics of the plasma such as temperature, composition and flow.

The same is basically true for in situ probe techniques which have been used in the magnetosphere on several spacecraft since the middle of the 1970's but which have given rise to only little published results. The active wave mutual impedance probe onboard GEOS 1 and 2 have given electron densities from the geostationary orbit inwards (Decreau et al., 1982). The probe techniques have difficulties in hot low density plasma because of Debye length limitations and are therefore difficult to apply in many parts of the magnetosphere. A detailed comparison of most of the above techniques has been reported by Decreau et al. (1978).

After this summary of the limitations of the measurement techniques we proceed to the measurement results. The main problem everywhere outside the plasmasphere is to determine the density of a possibly present cold plasma component of ionospheric origion. This problem is bigger the lower the cold plasma density, the hotter the hot plasma and the higher the relative density of the hot plasma component.

4. THERMAL AND SUPERTHERMAL MAGNETOSPHERIC PLASMA ABOVE THE HIGH LATITUDE IONOSPHERE

A terrestrial contribution of cold plasma to the magnetosphere was hypothesized in 1961 by Dessler and Hanson. The theory of the "polar wind" (Axford, 1968) was initially discussed by Hanson and Patterson (1963), Dessler and Michel (1966), Axford (1968), Banks and Holzer (1968, 1969 a, b), Lemaire and Scherer (1970, 1973) and Marubashi (1970). The predictions of the decrease of the electron density with altitude above the ionosphere arrived at by Banks and Holzer (1969 b) from their polar wind theory are shown in Figure 1. For reasonable upper ionosphere temperatures only the light ions, H^+ and to a lesser degree He^+, flow out into the magnetosphere, whereas the O^+ ions do not overcome the gravitational force. The limiting flux is reached when the scale height of the escaping ion species is reduced to that of the friction-producing species at great altitudes.

Schunk and Watkins (1982) have developed a more advanced set of steady state solutions for the high-latitude plasma flow above 1500 km altitude from a 13-moment system of transport equations for a range of boundary conditions at 1500 km. Some of their predictions are shown in Figure 2 together with observational results from the Dynamics Explorer 1 satellite (Persoon et al., 1983).

Whereas the electron densities derived from whistler wave observations over the polar cap are an order of magnitude, or more, below the values predicted by Banks and Holzer (1969 b) on the basis of equal electron and ion temperatures, the measured values fall within the range expected on the basis of Schunk's and Watkins' (1982) calculations with different electron and ion temperatures and temperature gradients.

The electron density height distribution obtained with the DE 1 satellite is related to the topside sounder data at lower altitudes in the polar ionosphere in Figure 3. The Alouette and ISIS density data shown do, however, not include the very low electron density values that were observed in the upper winter

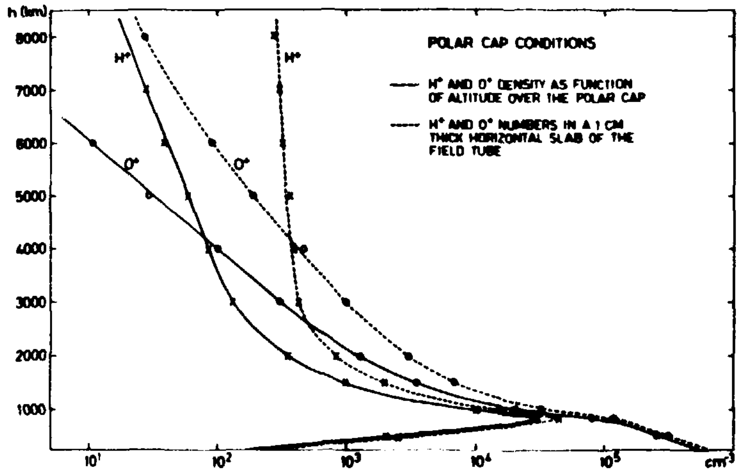

Figure 1. Altitude profiles for O^+ and H^+ ion densities under polar wind conditions, according to Banks and Holzer (1969b). In the figure are also given the corresponding variation with height of the numbers of O^+ and H^+ ions in a 1 cm thick horizontal slab of a typical auroral latitude field tube of 1 cm^2 cross section at 100 km (L=7) (after Hultqvist, 1983).

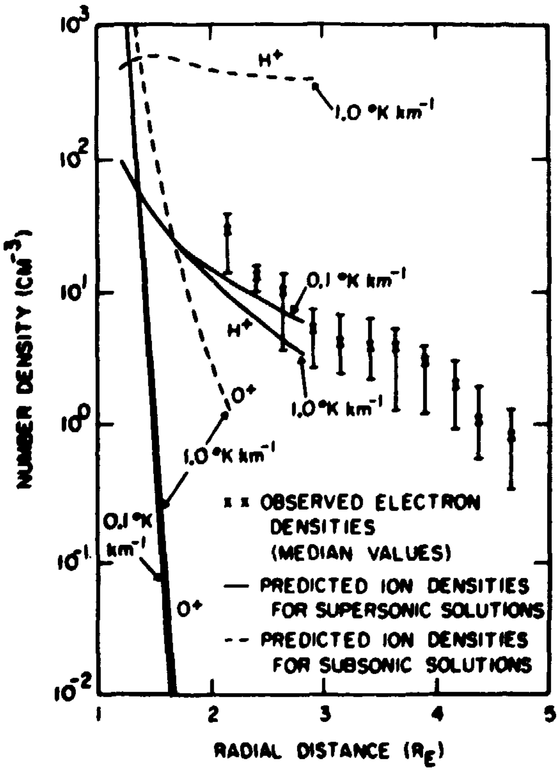

Figure 2. Predicted ion densities below 2.8 R_E based on solutions to the 13-moment transport equations (Schunk and Watkins, 1982). The subsonic outflow solutions correspond to higher H^+ and O^+ densities. These predicted densities exceed the DE 1 measured densities at 2 R_E by more than an order of magnitude. Supersonic outflow solutions correspond to lower H^+ and O^+ densities. An increase in the boundary electron temperature gradient (from 0.1°K km^{-1} to 1°K km^{-1}) corresponds to a slight increase in the predicted O^+ densities and a larger decrease in the predicted H^+ densities. Both sets of predicted ion densities for the supersonic outflow solutions are within 25% of the median density values observed by DE 1 (after Persoon et al., 1983).

night ionosphere in about 12% of the passes (Hagg, 1967, Timleck and Nelms, 1969). The inclusion of these very low densities on Figure 3 would lower the Alouette/ISIS density curve in Figure 3 by an order of magnitude above 1.2 R_e.

Mozer et al. (1979) have derived electron densities in the range 4 to 40 cm^{-3} from lower-hybrid-frequency measurements on-board the S3-3 satellite. Calvert (1981), from Hawkeye wave measurements, and Temerin (1984), from S3-3 wave data, have derived electron densities as low as 1 cm^{-3} at about an earth radius altitude. These very low densities appear to be unusual, however, except possibly in outflowing ion beams.

The reasonable agreement between the DE 1 measurements and the polar wind theory predictions shown in Figure 2 indicates that the theory for the 'cold' polar wind is basically correct. This has also been confirmed by the first direct observations of a supersonic ion outflow outside the plasmasphere recently reported by Nagai et al. (1984). However, there are other results, besides the mentioned extremely low densities sometimes found over the polar cap which are not consistent with the polar wind theory, namely the observations on DE 1 of sizable fluxes of superthermal or even hot (i.e. energy above 100 eV with our nomenclature) field-aligned ions out of the polar cap ionosphere (Shelley et al., 1982; Moore et al., 1984; Lockwood et al., 1984; Waite et al., 1984 and Yau et al., 1984), sometimes composed of practically only O^+ ions. An example of such an observation is shown in Figure 4 after Shelley et al. (1982). This phenomenon has been observed in about 50% of the DE 1 passages over the polar caps. The total flux into the magnetosphere of ions due to this process has been estimated by Shelley et al. (1982) and Lockwood et al. (1984) to amount to $\sim 10^{25}$ ions/s, which is comparable in number to the estimated total polar wind outflow (see e.g. Cowley, 1980) and represents a much larger energy input to the magnetosphere than that of the polar wind.

Attempts have been made to modify the polar wind theory in such a way that also O^+ ions can overcome the gravitational force (Barakat and Schunk, 1983). This requires, however, so high electron temperatures in the upper ionosphere ($>$ 10000 K) that they become unrealistic. In addition, it is doubtful that even so high electron temperatures will suffice to have the O^+ ions penetrating the neutral hydrogen gas in the outermost ionosphere without loosing its charge to the hydrogen atoms (Moore, 1980, 1984). In any case such mechanisms seem unable to account for the ion beams consisting of only O^+. Therefore, other mechanisms, most likely involving field-aligned potential differences and/or ion cyclotron resonances, appear to be at work more or less continuously also over the polar caps, as they are in the auroral zones.

5. DAYSIDE PLASMA TROUGH

The total plasma density well outside the plasmapause in the day-

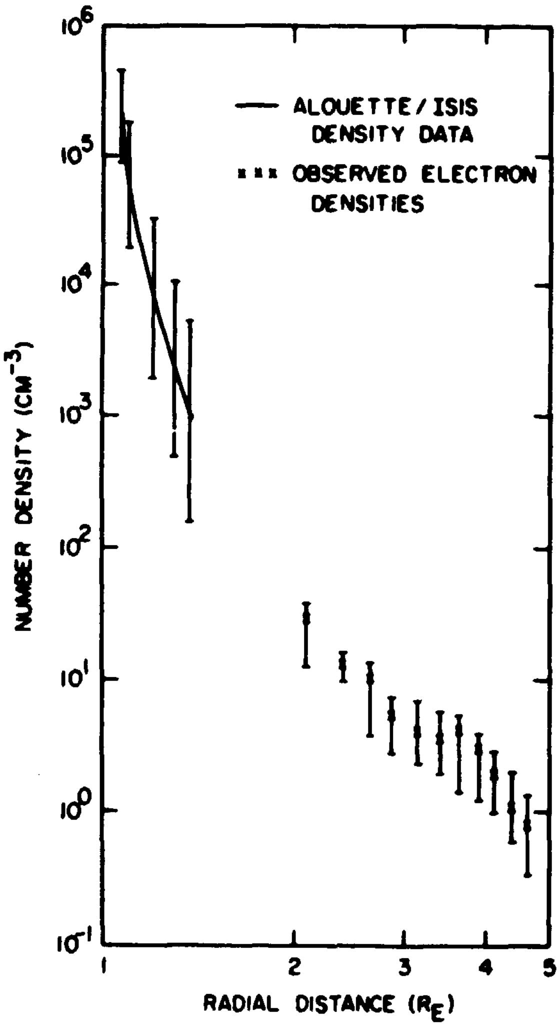

Figure 3. A log-log plot comparing low-altitude median electron densities obtained from the topside sounder data of Alouette II and ISIS 1 and high-altitude median electron densities obtained from the plasma wave instrument on DE 1 (after Persoon et al., 1983).

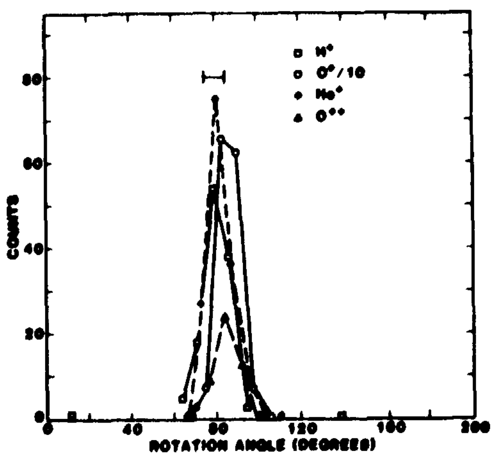

Figure 4. Counting rate as a function of mass and rotation angle for a portion of the DE 1 spin period beginning at 1241:00 UT on September 20, 1981. At this time the magnetic field direction was 88 degrees. The retarding potential difference was 7.2 V (after Shelley et al., 1982).

side of the magnetosphere has been determined for the first time with the active relaxation sounder and mutual impedance probe on GEOS 1 and 2 (Decreau et al., 1982; Higel and Lei, 1984). An example of the results obtained is shown in Figures 5 a, b. As can be seen the total electron density maximizes generally along the geostationary orbit on the dayside with values reaching ~10 electrons/cm^3. It builds up towards this value during the late morning hours from values around 1 cm^{-3} on night side. In the afternoon or early evening the spacecraft generally crosses the dusk-bulge of the plasmasphere containing appreciably higher electron densities.

What the energy and pitch angle distributions and the ion composition are cannot be determined with the wave methods used by Higel and Lei (1984) and Decreau et al. (1982). It turns out to be difficult to find answers in the litterature to the question what fractions of the plasma have energies in the thermal, superthermal and hot energy ranges. Sojka et al. (1983) report, from particle measurements on the DE 1 satellite, ion densities in the range 1-10 cm^{-3} both for ions of a few eV energy and for 10-15 eV ions, but Horwitz and Chappell (1979) derived much lower superthermal densities (0.1 - 0.4 cm^{-3}) from the ATS 6 measurements. Chappell (1983) stated that it is uncertain if there are <1 eV plasma in the plasma trough and Higel and Lei (1984) refer disagreements between wave measurements and particle measurements to a dominating cold component. The answer to the question formulated above is thus far from clear.

The DE 1 low energy particle experiment (RIMS) has recorded field-aligned ion beams (uni-or bidirectional) as well as conical distributions and isotropy.

The hot ion density for energies up to ~20 keV in the dayside trough region, i.e. in the outer ring current region from the hot plasma nomenclature point of view, can be seen from Figures 6 to be in the same density range (1-10 cm^{-3}) in storm conditions. As is evident in Figure 6, O^+ ions play a major role at keV energies in storms. In quiet conditions the H^+ ion density is not very much less than in Figure 6 but the O^+ density is an order of magnitude lower. Hultqvist (1983) has argued that the number densities of keV O^+ ions observed in the entire magnetosphere during disturbed conditions cannot have been produced by acceleration of cold O^+ ions existing in the magnetosphere when the disturbance set in. The amount of O^+ ions in the storm time magnetosphere is simply so large that it is equal to all cold O^+ ions above an altitude of the order of a thousand kilometers in the upper ionosphere in quite a wide latitude band on both hemispheres. It appears, therefore, that in disturbed magnetospheric conditions an effective extraction process works in the upper ionosphere over wide ranges in latitude and longitude. All ionospheric ion species are energized in this process, many to keV energies but others to lower (superthermal) energies.

It is still unclear in the literature what ion species dominate the trough region at lower energies during different distur-

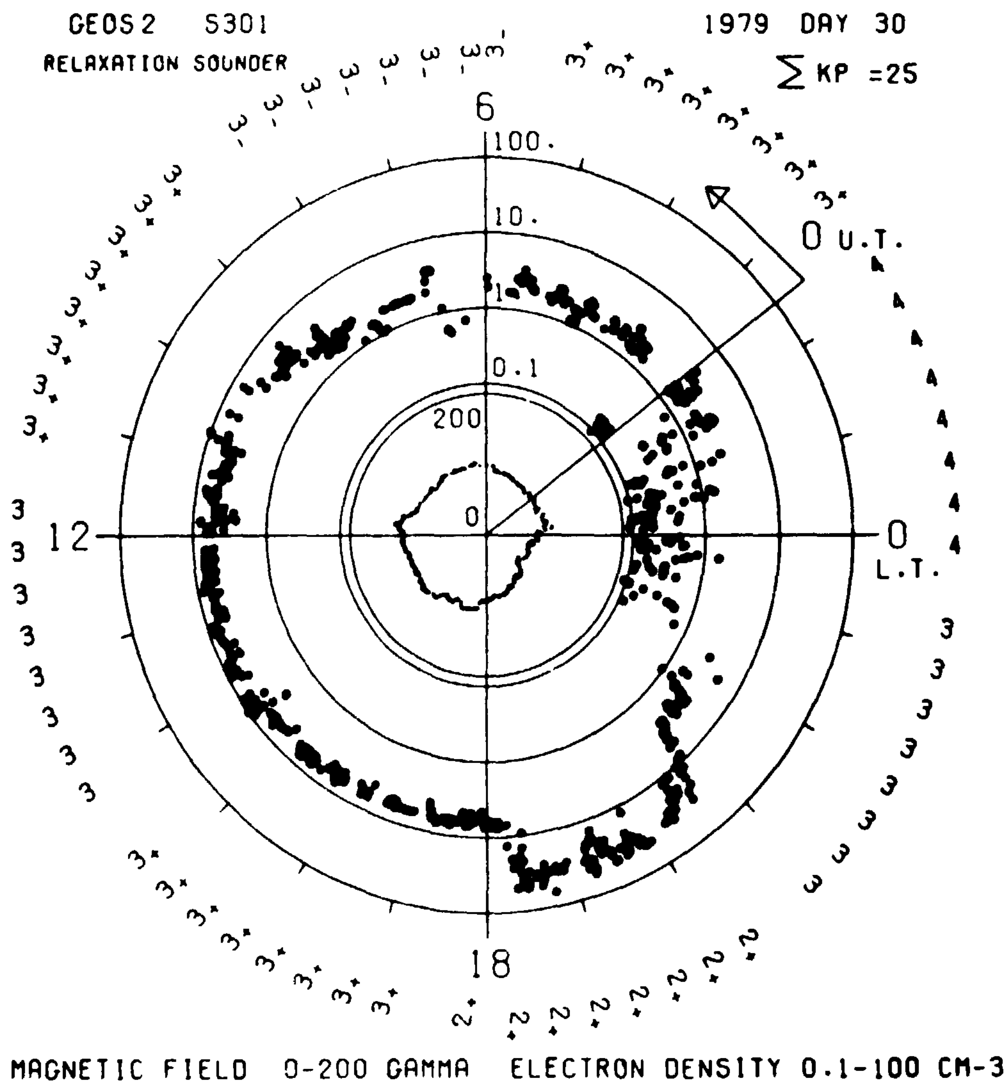

Figure 5a. Distribution versus local time of the magnetospheric plasma parameters measured by the GEOS 2 relaxation sounder (RS) along its 6.6 R_E orbit for one day (January 30, 1979). Electron density Ne and magnetic field strength B_0 are plotted radially, with time running as an angular coordinate starting from the 0000 UT radius. The electron density scale is logarithmic over the three decades (0.1-100 cm^{-3}) displayed by concentric rings. The magnetic field strength is plotted in the inner circle with a linear scale between 0 (center) and 200 nT (smaller circle). Ne and B_0 data are available in real time. Values of the three-hour Kp index are shown on the outer circumference (after Higel and Lei, 1984).

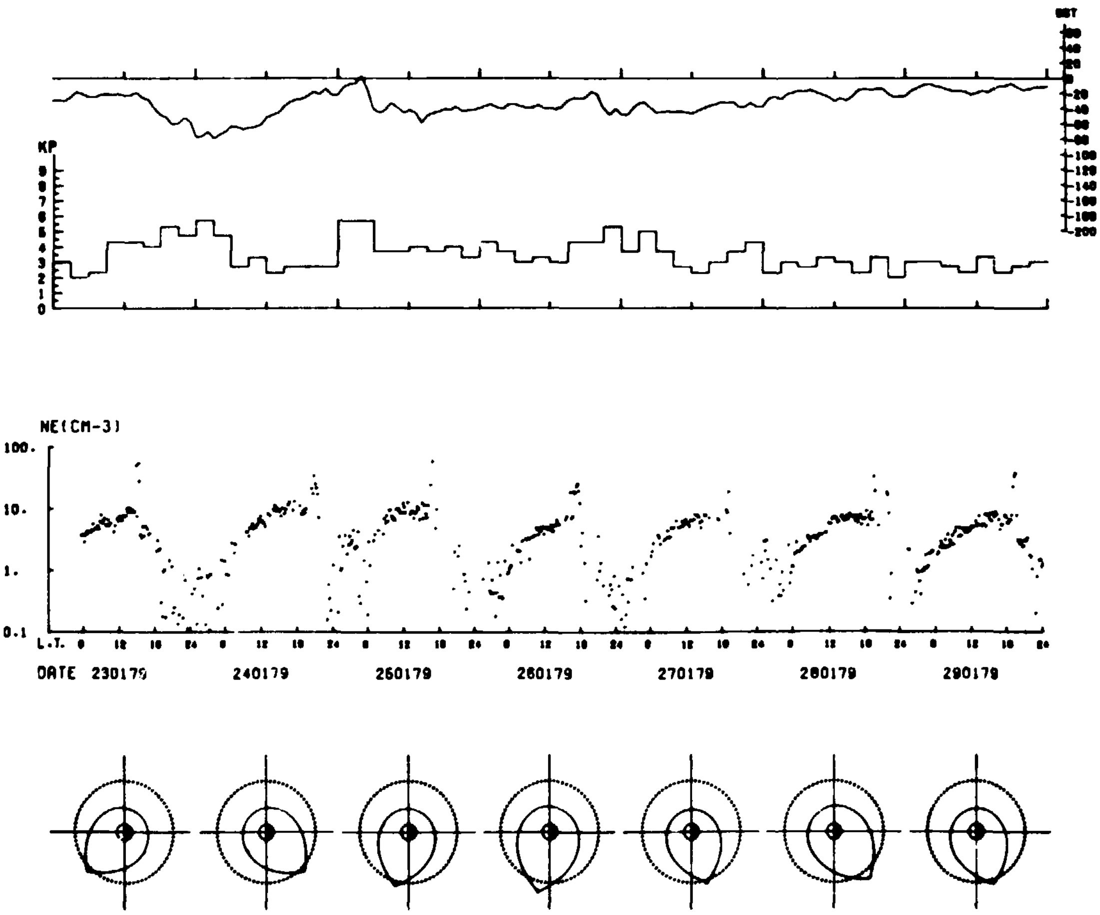

Figure 5b. Synoptic plot over seven consecutive days (January 23-29, 1979) of GEOS 2 RS electron density data. The center panel displays the density (vertical axis, log scale 0.1-100 cm^{-3}) versus local time (horizontal axis). Dates are given under the time axis. The top panel is devoted to geomagnetic activity indices (three-hour Kp with scale on the left, hourly Dst with scale on the right). The bottom panel shows, day by day, the orbit and the schematic equatorial section of the teardrop shaped model plasmapause that has the same bulge characteristics at 6.6 R_E as the actually measured profile displayed above (see text; after Higel and Lei, 1984).

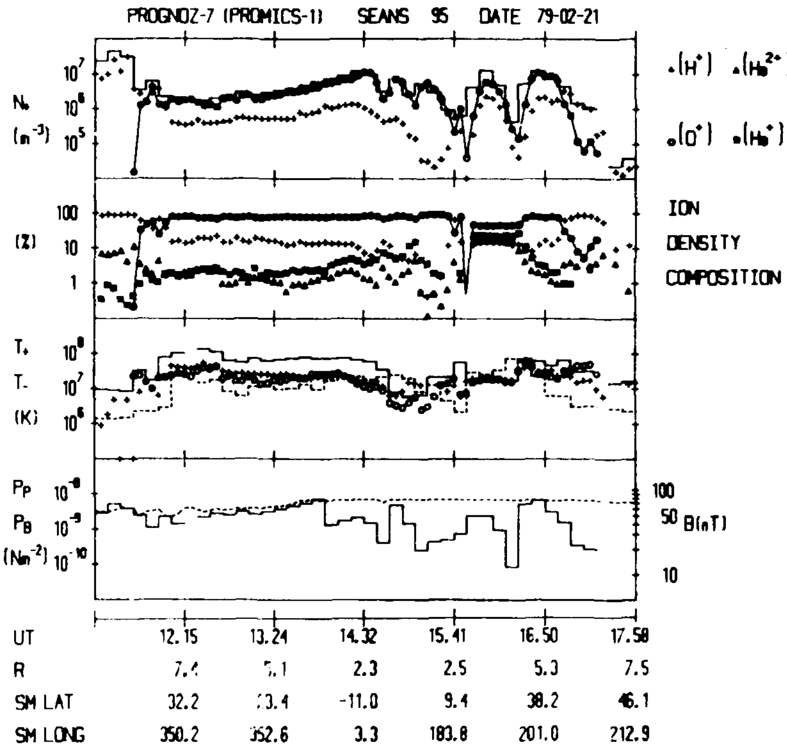

Figure 6. An example of observations in the dayside magnetosphere in magnetic storm conditions. At the lowest altitudes MeV electrons produce a dominating background which has not been eliminated from the data shown in the figure. The upper panel shows the ion number density (N_+) as deduced from the E/q spectrometers and assuming the ions were all protons (solid lines). Plus signs (+) represent the density of H^+ as deduced from the perpendicular ion mass spectrometers (assuming isotropy) and circles (o) represent the number density of O^+ using all mass spectrometers The second panel from the top represents the percentages of the four major ion constituents with respect to the total number density (logarithmic scale used). The third panel shows the temperatures of ions (solid line) and electrons (broken line) as deduced from the E/q electron and ion spectrometer data fitted onto Maxwellians. In the same panel the "perpendicular" H^+ (+) and O^+ (o) temperatures have been plotted. The fourth panel shows the ion plasma pressure (solid line) and magnetic field pressure (dotted line). The time and space coordinates (in Solar Magnetic, SM, coordinates) are given along the horizontal axis (after Hultqvist, 1983).

bance conditions. n_{H^+}/n_{He^+}=0.1-6 have been reported by Sojka et al. (1983) but no corresponding values for O^+ seem to have been published.

Chappell (1972) reported about detached plasma clouds in the dayside trough region and he suggested that they might originate in the dusk side bulge region and convect towards the dayside magnetopause. On the basis of the DE 1 measurements he concluded recently (Chappell, 1983) that these flux enhancements observed by the OGO 5 experiment may have been the equatorial manifestation of the out-flowing superthermal ion beams seen with DE 1 some ten years later.

6. THERMAL AND SUPERTHERMAL PLASMA IN THE PLASMAPAUSE REGION

The magnetospheric region just outside the plasmapause, as determined from the plasma density distribution, may in the recovery phase of disturbances in fact be located within a larger plasmasphere determined by the magnetospheric convection field at the moment in question. Horwitz et al. (1984) have investigated the formation of such a new outer plasmasphere near dusk. At the start the plasmapause was at L=4 (K_p=5-). K_p decreased then rapidly and the authors estimated that the new plasmapause was at L=8 during most of the period of investigation.

The time scale for filling up the outer plasmasphere was reported to be 7-22 hours. They saw $O^+/H^+>1$ at L=3-4 in the early period and a peak in the O^+ density just inside L=4, the so called "*heavy ions* torus" or "shell" or "cloak". The outer plasmasphere was O^+ enriched compared to the inner plasmasphere during the replenishment. There were indications that the O^+ ions were field-aligned at L~4 with 2-5 km/s speed along the field lines. The He^+/H^+ ratio was found to be in the range 0.2-0.5 in both the inner and the outer plasmasphere. The temperatures showed no overall evolution during the refilling of the outer part. The ion temperature they found was generally less than 2 eV between L=4 and L=8 and the various ion species had about the same temperatures. The "heavy ions torus" has also been discussed by Chappell (1983).

7. THE PLASMA SHEET

Higel and Lei (1984) have reported total electron density values from the region of the plasmasheet close to the plasmapause, the boundary of which is frequently crossed by the geostationary orbit in the late evening (except in very quiet periods when the entire geostationary orbit lies within the plasmasphere). Examples of measurement results from the midnight sector are also included in Figures 5a, b. The density values are lower and show a much larges spread than at other local times. As can be seen, the electron density is mostly between 0.1 and 1 cm^{-3} around midnight. Again it is difficult to say if there is any significant fraction of thermal or superthermal plasma in the inner plasmasheet. Considering that the hot plasma density in the plasmasheet generally is quoted to be in the density range mentioned, it seems likely that the low energy plasma components do not play a major role from a density point of view in this part of the magnetosphere, but better measurements are required before any firm conclusion can be drawn.

8. THE MAGNETOPAUSE BOUNDARY LAYERS AND THE CUSP

The dayside magnetopause boundary layer has been investigated in recent years by means of the ISEE 1,2 spacecraft (Peterson et al., 1982) and Prognoz 7 and 8 (Lundin and Dubinin, 1984a, b; Lundin, 1984).

The low latitude boundary layer appears to be a poor mix of solar wind and magnetosphere plasma. That is illustrated by Figure 7. Prognoz 7 crossed the magnetopause at 0619 on 9 February 1979 and encountered immediately inside it a magnetospheric kind of plasma without a low energy component. A few minutes later it saw a narrow beam of cold ionospheric ions, both H^+, He^+ and O^+, with a very narrow energy spectrum (at ~0625 in Figure 7). Three minutes later, within a region with a mixture of solar wind-like and magnetospheric plasma another beam of only He^+ was encountered. Another two minutes later a narrow beam composed of He^+ and O^+ ions was observed. Possibly it contained also ionospheric H^+ ions, but they could not be distinguished from those of solar wind origin. Figure 7 shows only the outermost part of the boundary layer. There were a number of transitions between magnetosphere-like and solar wind-like plasma regions similar to those shown in Figure 7. The solar wind-like "penetration" regions generally contain also ions of ionospheric origin as does the entire boundary layer. There are strong local increases of He^+ ion density in the solar wind penetration regions. These ions may be supposed to have reached the boundary layer from the plasmasphere. The reason that they are seen by the mass spectrometer on Prognoz 7 in the region of solar wind penetration is that the He^+ ions have been accelerated in those regions to energies above the lower threshold of the instrument.

These cold terrestrial ion beams in the boundary layer propagate perpendicularly to the magnetic field lines. The beam velocity is independent of ion mass. The thermal velocity is also roughly the same for all species and the beam velocity is generally higher than the thermal velocity by a factor of 2-4. The characteristic thermal energy falls in the superthermal energy range, but the lower threshold of the Prognoz-7 instrument of 200 eV did not make it possible to investigate in detail the thermal and superthermal plasma components, which may well be present in significant amounts. That thermal/superthermal ionospheric plasma exists in the boundary layer has, however, been clearly demonstrated by means of the PROMICS experiments on Prognoz 7 and 8. The observed independence of both beam velocity and thermal velocity on ion mass is a clear indication that the ions are accele-

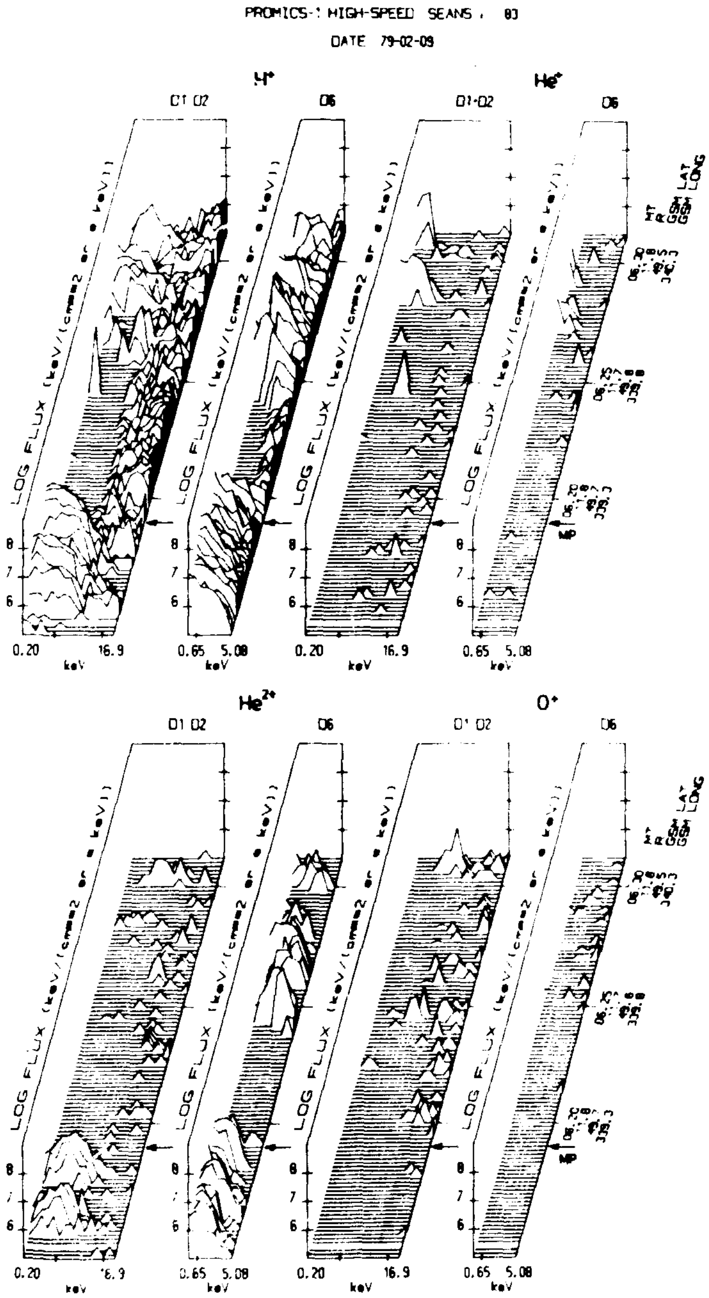

Figure 7. Spectrogram plot for H^+, He^{2+}, He^+ and O^+ during an inbound magnetopause crossing (marked MP) by Prognoz-7 on February 9, 1979. The D1D2-panels show energy spectra taken from the "perpendicular" spectrometers (scanning the YZ-ecliptic plane) whilst the D6 panels show energy spectra taken from the sunward oriented spectrometer. Time (MT = UT + 3) and orbital parameters are given along the inclined axis (after Lundin, 1984).

rated to an ExB velocity (Lundin and Dubinin, 1984b).

With the retarding potential ion mass spectrometer on DE 1 Chappell (1983) has observed outflowing H^+ and He^+ ions in the superthermal energy range in the cusp at altitudes of a few earth radii similar to what has been observed over the polar cap, but with more complex characteristics of the plasma energy distribution and flow than outside the cusp.

In discussing the boundary layers we have not emphasized density measurements as in previous sections. This is partly because it is more difficult to determine densities in a highly structured region such as a boundary layer and partly because the dominating physical processes in the boundary layers are likely to be more closely related to dynamical situations, structures and gradients than to averaged densities.

9. CONCLUDING REMARKS

Although the DE 1 satellite has provided us with very important new information about the low-energy plasma within a few earth radii altitude in the last few years, one general conclusion from the above presentation is that we still know very little about the magnetospheric plasma outside the plasmasphere at the very low end of the energy scale. The active wave instruments, flown for the first time in the late 1970's in the outer magnetosphere on the GEOS-satellites, which appear to be the best in including also the cold plasma component in the density measurements, have still only been used at and within the geosynchronous orbit. Systematic cold plasma density measurements remain to be carried out in the plasma sheet, boundary layers, lobes and tails. Even in regions where some measurements have been made a number of questions are unanswered.

The problem of how to make accurate measurements at or below a few eV of energy with particle detectors of various kinds in the presence of a potential difference of some volts between the spacecraft and the surrounding plasma is not a simple one, especially not in the presence of a large warm or hot plasma component. The good steps in the direction of solving that problem that have been taken by the Huntsville group (Chappell et al., 1981) are probably not the final ones needed. In any case an arsenal of different measurement techniques are required to cover the total range from cold to hot plasma in the magnetosphere and the low energy end requires particular care in planning the future space plasma physics payloads. Only when we master the determination of the density and temperature of the cold plasma component in those parts of the magnetosphere where there is a lot of high energy plasma will we have a basis for detailed investigations of microphysical processes, generation and propagation of many kinds of plasma waves and for answering questions about where some acceleration and heating processes take place. In other words, the answers to many fundamental questions in space plasma physics depend upon good measurements in the future of the low energy plasma in large parts of the magnetosphere.

10. REFERENCES

Axford, W.I., J. Geophys, Res., **73**, 6855, 1968.
Banks, P.M., and T.E. Holzer, J. Geophys. Res., **73**, 6846, 1968.
Banks, P.M., and T.E. Holzer, J. Geophys. Res., **74**, 6304, 1969a.
Banks, P.M., and T.E. Holqer, J. Geophys. Res., **74**, 6317, 1969b.
Banks, P.M., A.F. Nagy, and W.I. Axford, Planet. Space Sci., **19**, 1053, 1971.
Barakat, A.R., and R.W. Schunk, J.Geophys. Res., **88**, 7887, 1983.
Bezrukikh, V.V., and K.I. Gringauz, 'Hot zone in the outer plasmasphere of the earth', Techn. Rep. D-219, Acad. Sci. USSR, Space Res. Inst., Moscow, 1975.
Calvert, W., and G.B. Goe, J. Geophys. Res., **68**, 6113, 1963.
Calvert, W., Geophys. Res. Lett., **8**, 919, 1981.
Carpenter, D.L, J. Geophys. Res., **75**, 3887.
Carpenter, D.L., J. Geophys. Res., **71**, 693, 1966.
Chappell, C.R., Rev. Geophys. Space Phys., **10**, 951, 1972.
Chappell, C.R., C.R. Gaugher, and J.L. Horwitz, Rev. Geophys. Space Phys., **18**, 853, 1980.
Chappell, C.R., S.A. Fields, C.R. Baugher, J.H. Hoffman, W.B. Hanson, W.W. Wright, H.D. Hammack, G.R. Carignau, and A.F. Nagy, Space Sci. Instrum., **5**, 477, 1981.
Chappell, C.R., R.C. Olsen, J.L. Green, J.F.E. Johnson, and J.H. Waite, Jr., Geophys. Res. Lett., **9**, 937, 1982.
Chappell, C.R., in B. Hultqvist and T. Hagfors (Eds), High-Latitude Space Plasma Physics, p. 251, Plenum Press, N.Y., 1983.
Cowley, S.W.H., Space Sci. Rev., **26**, 217, 1980.
Decreau, P.M.E., J. Echeto, K. Knott, A. Pedersen, G.L. Wrenn, and D.T. Young, Space Sci. Rev., **22**, 633, 1978.
Decreau, P.M.E., C. Beghin, and M. Parrot, J. Geophys. Res., **87**, 695, 1982.
Dessler, A.J., and W.B. Hanson, Astrophys. J., **134**, 1024, 1961.
Dessler, A.J., and F.C. Michel, J. Geophys. Res., **71**, 1421, 1966.
de Ferandy, H., and B. Higel, Planet. Space Sci., **30**, 483, 1982.
Geiss, J., H. Balsiger, P., Eberhardt, H.P. Walker, L. Weber, D.T. Young, and H. Rosenbauer, Space Sci. Rev., **22**, 537, 1978.
Garrett, H.B., in W.P. Olson (Ed.), Quantitative Modeling of Magnetospheric Processes, p. 364, AGU, Washington, D.C., 1979.
Gurgiolo, C., and J.L. Burch, Geophys. Res. Lett., **9**, 945, 1982.
Gurnett, D.A., and R. Shaw, J. Geophys. Res., **78**, 8136, 1973.
Gurnett, D.A., and L.A. Frank, J. Geophys. Res., **79**, 2355, 1974.
Hagg, E.L., Can. J. Phys., **45**, 27, 1967.
Hanson, W.B., and T.N.L. Petterson, Planet. Space Sci., **11**, 1035, 1963.
Higel, B., and Wu Lei, J. Geophys. Res., **89**, 1583, 1984.
Hoffman, J.H., and W.H. Dodson, J. Geophys. Res., **85**, 626, 1980.
Horwitz, J.L., C.R. Baugher, E.G. Shelley, and D.T. Young, EOS, Trans. AGU, **59**, 1144, 1978.

Horwitz, J.L., and C.R. Chappell, J. Geophys. Res., **84**, 7075, 1979.
Horwitz, J.L., J. Geophys. Res., **85**, 2057, 1980.
Horwitz, J.L., J. Geophys. Res., **86** ,
Horwitz, J.L., Rev. Geophys. Space Phys., **20**, 929, 1982
Horwitz, J.L., W.K. Cobb, C.R. Baugher, C.R. Chappell. L.A. Frank, T.E. Eastman, R.R. Anderson, E.G. Shelley. and D.T. Young, J. Geophys. Res., **87**, 9059, 1982.
Horwitz, J.L., J. Atmos. Terr. Phys., **45**, 765, 1983.
Horwitz, J.L., R.H. Comfort, and C.R. Chappell, Geophys. Res. Lett., **11**, 701, 1984.
Hultqvist, B., Planet. Space Sci, **31**, 173, 1983.
Jackson, J.E., and E.S. Warren, Proc. IEEE, **57**, 861, 1969.
Kurth, W.S., J.D. Craven, L.A. Franck, and D.A. Gurnett, J. Geophys. Res., **84**, 4145, 1979.
Lemaire, J., and M. Scherer, Planet. Space Sci., **18**, 103, 1970.
Lemaire, J., and M. Scherer, Rev. Geophys. Space Phys., **11**, 427, 1973.
Lennartsson, W., and D.L. Reasoner, J. Geophys. Res., **83**, 2145, 1978.
Lockwood, M., J. Geophys. Res., **89**, 301, 1984.
Lockwood, M., J.H. Waite Jr., T.E. Moore, J.F.E. Johnson, and C.R. Chappell, 'A new source of suprathermal O^+ ions near the dayside polar cap boundary', Preprint, Space Sci. Lab. NASA Marshall Space Flight Center, Huntsville, 1984.
Lundin, R., Planet. Space Sci., **32**, 757, 1984.
Lundin, R., and Dubinin, E., Planet. Space Sci., **32**, 745, 1984a.
Lundin, R., and Dubinin, E.M., 'Solar wind energy transfer regions inside the dayside magnetopause-III Accelerated plasmaspheric ions as tracers for MHD-processes in the dayside boundary layer', Planet. Space Sci., in print, 1984b.
Marubashi, K., Rep. Ionos. Space Res., Japan, **24**, 322, 1970.
Moore, T.E., J. Geophys. Res., **85**, 2011, 1980.
Moore, T.E., Rev. Geophys. Space Phys., in print, 1984.
Moore, T.E., C.R. Chappell, M. Lockwood, and J.H. Waite, Jr., 'Superthermal ion signatures of auroral acceleration pro cesses', Preprint No. 85-101, Space Sci. Lab., NASA Marshall Space Flight Center, Huntsville, submitted to J. Geophys. Res., 1984.
Mozer, F.S., C.A. Cattell, M. Temerin, R.B. Torbert, S. von Glinski, M. Woldorff, and J. Wygant, J. Geophys.Res., **84**, 5875, 1979.
Nagai, T., J.H. Waite, Jr., J.L. Green, C.R. Chappell, R.C. Olsen, and R.H. Comfort, Geophys. Res. Lett., **11**, 669, 1984.
Persoon, A.M., D.A. Gurnett, and S.D. Shawhan, J. Geophys. Res., **88**, 10123, 1983.
Peterson, W.K., E.G. Shelley, H. Haerendel, and G. Paschmann, J. Geophys. Res., **87**, 2139, 1982.
Schunk, R.W., and D.S. Watkins, J. Geophys. Res., **87**, 171, 1982.
Serbu, G.P., and E.J.R. Maier, J. Geophys. Res., **75**, 6102, 1970.

Shelley, E.G., R.G. Johnson, and R.D. Sharp. J. Geophys. Res., **77**, 6104, 1972.

Shelley, E.G., R.D. Sharp, and R.G. Johnson, Geophys. Res. Lett., **3**, 654, 1976.

Shelley, E.G., W.K. Peterson, A.G. Ghielmetti, and J. Geiss, Geophys. Res. Lett., **9**, 941, 1982.

Sojka, J.J., R.W. Schunk, J.F.E. Johnson, J.H. Waite, Jr., and C.R. Chappell, J. Geophys. Res., **88**, 7895, 1983.

Temerin, M., J. Geophys. Res., **89**, 3945, 1984.

Timleck, P.L., and G.L. Nelms, Proc. IEEE, **57**, 1164, 1969.

Vasyliunas, V.M., 'Observations of low energy electrons with the OGO-A Satellite' Ph. D. Thesis. M.I.T., 1966.

Vasyliunas, V.M., (abstract) Trans. AGU, **47**, 142, 1966.

Waite,Jr. J.H., T. Nagai, J.F.E. Johnson, C.R. Chappell, J.L. Burch, T.L. Killeen, P.B. Hays, G.R. Carignan, W.K. Peterson, and E.G. Shelley, 'Escape of superthermal O^+ ions in the polar cap', J. Geophys. Res., in print. 1984.

Yau, A.W., P.H. Beckwith, W.K. Peterson, and E.G. Shelley, 'Long-term (solar-cycle) and seasonal variations of upflowing ionospheric ion events at DE-1 altitudes', Preprint, Herzberg Inst. Astrophys., NRC, Canada, 1984.