Modeling Magnetospheric Plasma, ~~AGU~~ Geophysical Monograph #44
T.E. Moore + J.H. Waite, Jr. Editors, Am. Geophys Union, Wash. DC. 1988.

AURORAL ZONE ION COMPOSITION

W. K. Peterson

Lockheed Palo Alto Research Laboratory, Palo Alto, California 94304

Abstract. Ion composition measurements provide valuable information about the sources, energization, transport, and loss mechanisms of space plasmas. In the past 10 years the initial series of plasma composition measurements from the S3-3, GEOS, ISEE, SCATHA, PROGNOZ, AUREOL-3, DE, and AMPTE satellites have provided insights which have significantly improved our understanding and models of the magnetosphere and ionosphere. In particular, we now know that the auroral and polar ionosphere are important sources of the magnetospheric plasma. We have learned that the ionospheric source of magnetospheric plasma varies systematically in its mass and energy composition with respect to local time, season of the year, and the solar cycle, as well as with respect to magnetic activity. There is also some evidence that variations in the ionospheric source composition can lead to the initiation of plasma sheet instabilities. Today we realize that auroral field lines are the sites of many different types of acceleration and energization processes, some of which are known to be mass dependent. Detailed measurements of ion distribution functions have been useful in exploring the importance of various ion energization and thermalization processes. Some recent observational results obtained from satellite-borne ion mass spectrometers that are relevant to magnetosphere/ionosphere plasma models will be discussed.

Introduction

Understanding the physical processes involved in creating the spectacular visual displays called the aurora has been a goal for several centuries. Since the start of the systematic exploration of the near earth plasma environment using rocket and satellite probes, we have made rapid progress toward this goal. The in situ measurements of ion mass, energy, and angle distributions on auroral field lines have provided important insights that have lead us to our present understanding of the ionosphere and magnetosphere and the models we use to characterize them. Some recent observations of auroral ion composition that are relevant to magnetospheric and ionospheric models will be discussed.

The paper is organized as follows: The discussion begins with a description of the auroral zone and its role as the region of exchange of warm and hot plasmas between the magnetosphere and ionosphere. The ion mass, energy, and angle distributions observed on a typical mid-altitude auroral zone crossing are then presented and discussed, followed by a discussion on the central role of oxygen ions as a tracer of the processes involved in coupling of ionospheric and magnetospheric plasmas. Rather than review the extensive statistical studies of the upflowing ionospheric ions on auroral field lines, which are discussed in detail elsewhere (Ghielmetti et al., 1978; Gorney et al., 1981; Yau et al., 1985a, 1987), discussions will be given on some recent observations that have been made using the very high resolution ion mass spectrometer data that have improved our understanding of magnetosphere/ionosphere interactions. The thermal (i.e., less than ~10 eV) ion plasma observed on auroral field lines is not emphasized here since it is discussed elsewhere (Yau and Lockwood, 1987; Schunk, 1987). It is also important to note that the Swedish VIKING satellite was successfully operated in 1986. The first series of papers from the VIKING high resolution plasma instruments were not available at the time this paper was written.

Plasma Exchange in the Auroral Zone

Plasma is continuously exchanged at all latitudes between the ionosphere and magnetosphere. In fact the often sharp gradients in the energy and mass composition of the plasma exchanged between the ionosphere and magnetosphere as a function of latitude are used to identify distinct regions of the magnetosphere. The auroral zone can be thought of as the region where plasma is exchanged between the plasma sheet and ionosphere. This exchange of plasma on auroral field lines is, of course, directly associated with the visible aurora. The relationship between the

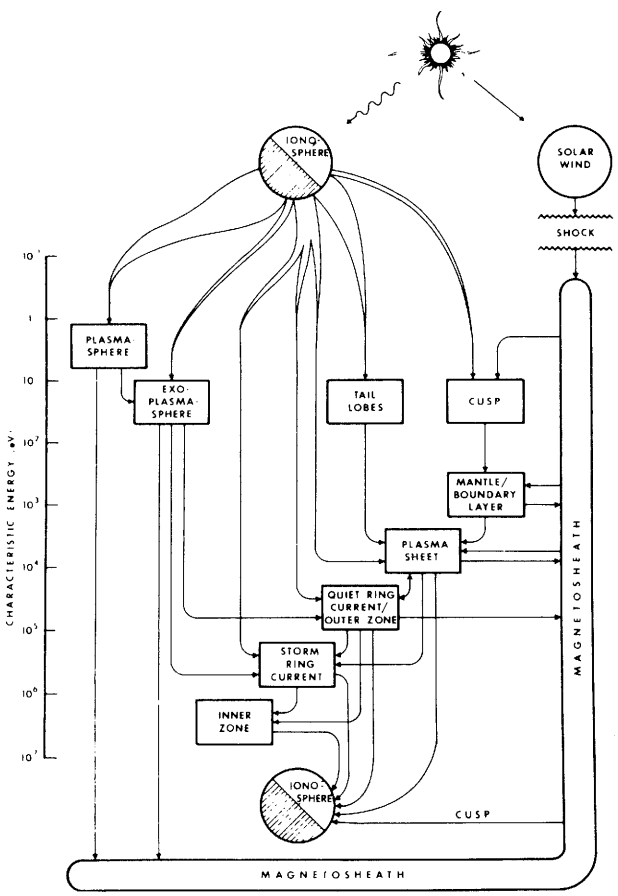

Fig. 1. Schematic relationship of magnetospheric particle populations from Young (1986). See text.

aurora, auroral zone particle populations, and magnetospheric plasma regions has been recently discussed by Feldstein and Galperin (1985) and Young (1983).

Figure 1 (reproduced from Young, 1986) schematically shows the relationship of magnetospheric particle populations to their source regions in the ionosphere and solar wind. The ionosphere and magnetosheath (solar wind) are shown as both sources (top) and sinks (bottom). The relative latitudes of ionospheric sources and sinks as well as the characteristic energies of the various particle populations are also indicated on this chart. At low magnetic latitudes there is the plasmaspheric (and exoplasmaspheric) exchange of thermal and warm plasmas of primarily ionospheric origin. Very high magnetic latitudes are characterized by the magnetospheric cusp, the escape of polar ionospheric plasma, and by the entry of solar wind (electron) plasma in the form of polar rain. The auroral zone is between the plasmasphere and magnetotail lobes (polar cap) and is characterized by heated and/or accelerated ionospheric plasma flowing up magnetic field lines, intermixed with trapped and precipitating energetic plasma sheet plasma.

Mass composition measurements in the auroral zone are used to sort out the complex physical processes that occur when cool ionospheric plasma and energetic plasma sheet plasma mix on auroral field lines. Because the energy and angular distributions of ions in the ionospheric and solar wind source regions are reasonably well known, and the result of plasma processes operating in the auroral zone is in general to modify the energy and angular distributions of the various plasma constituents, ion mass composition measurements can be a very powerful tool. Unfortunately the major species, hydrogen, is the dominant constituent of the solar wind (magnetosheath) and, above ~1000 km, is the dominant ionospheric ion. H^+ energy and angular distributions provide clues that can, at times, be used to identify its source. For example the relatively cool (~100 eV) H^+ beams moving up auroral field lines with streaming energies of ~1 keV could not have come from the magnetosheath or plasma sheet, while the very intense streams of H^+ with narrow energy distributions with energies of ~1 keV seen flowing downward in the cusp region (see, for example, Peterson, 1984) are definitely from the magnetosheath (solar wind).

Other singly charged ions encountered in the magnetosphere are generally of ionospheric origin; multiply charged ions are generally of solar wind origin. However, there are important qualifications to this simplified source identification rule. Young et al. (1977) identified an equatorial suprathermal plasma of ionospheric constituents that contains significant densities of low-energy, doubly charged ions, He^{++} and O^{++}. Chappell et al. (1982) also reported detectable fluxes of low-energy O^{++} and N^{++} flowing up auroral field lines.

The mass composition of both the solar wind and ionosphere is variable. The solar wind charge state distribution is one that is characteristic of variable solar coronal temperatures (see, for example, Bame et al., 1983). Helium is the most common minor constituent (typically a few percent of hydrogen) and oxygen the next most abundant (typically 10^{-4} as abundant as hydrogen). Other species are typically less common. Except for unusual impulsive events, solar wind helium is doubly charged. Ionospheric plasma composition is more variable than that of the solar wind; it depends on altitude, solar lighting (local time), and other energy inputs such as particle precipitation in the auroral region. Typical ionospheric constituents are H^+, He^+ (singly ionized), O^+, N^+, and NO^+.

As indicated in Figure 1, very little solar wind plasma flows directly from the magnetosheath onto auroral zone magnetic field lines. The trapped and precipitating energetic plasma sheet ions encountered in the auroral zone have resided for variable times in the plasma sheet after their entry from either the ionosphere or magnetosheath. In the plasma sheet, the energy, angle, and charge state distributions of the plasma are modified on various time scales, but a discussion of the processes acting in the plasma sheet is beyond the scope of this paper. (See, for example, the recent reviews by Cornwall, 1986, and Young, 1986.)

It is essential in constructing models of the magnetosphere to have an idea of the relative strengths of the ionospheric and solar wind contributions to magnetospheric plasmas. Shelley (1985, 1986) and Chappell et al. (1987) have recently addressed the question of the relative importance of what Shelley has called the "geogenic" and "heliogenic" plasma sources. Chappell et al. (1987) argued that the ionospheric source is fully adequate to explain observed plasma densities in all regions of the magnetosphere. In a recent presentation Shelley et al. (1986) extended the calculations presented in Shelley (1986) and calculated the ionospheric or geogenic fraction of the plasma sheet as a function of magnetic and solar activity. At high levels of magnetic and solar activity Shelley et al. (1986) found the plasma sheet to be dominated by ions of ionospheric origin and that most of these ions are transported along auroral field lines to the plasma sheet. Clearly, the composition of the magnetosphere is not static and models should reflect this.

Energetic Ion Plasma Typically Observed in the Mid-Altitude Auroral Zone

In addition to identifying the origin of the plasma, magnetospheric models must also concern themselves with the details of plasma transport. Ion composition measurements obtained on auroral field lines have provided several key insights into our current understanding of plasma transport in the magnetosphere. Figure 2 presents a typical example of the composition of the energetic ion plasma encountered in the evening auroral zone at a distance of about 3 earth radii (geocentric) by Dynamics Explorer 1 (DE 1). The data in Figure 2 were acquired on October 25, 1981, by the energetic ion composition spectrometer (EICS) (Shelley et al., 1981). The universal time (UT) and orbital information are displayed at the bottom. Figure 2 presents angle-time and energy-time spectrograms which are only briefly described here; a complete description of the spectrogram formats is given in Peterson and Shelley (1984). The top four angle-time spectrogram panels display hydrogen (first and third panels) and oxygen (second and fourth panels) number fluxes encoded in units of cm^{-2} s^{-1} sr^{-1} using the gray scale bar on the right. The number fluxes displayed in the top four panels are integrated over two different energy ranges (1 to 17 keV in the top two panels and 10 eV to 1 keV in the third and fourth panels) and are displayed as a function of instrumental look direction with respect to the satellite motion. In this spin-phase angle coordinate system, ions flowing up magnetic field lines from the ionosphere appear near 90°; ions flowing down magnetic field lines toward the ionosphere appear near 270°. The bottom two energy-time spectrogram panels display hydrogen and oxygen differential number fluxes for ions flowing upward with pitch angles that lie within 15° of the magnetic field direction. These differential fluxes are also encoded using the gray scale on the right, but the units are in cm^{-2} s^{-1} sr^{-1} keV^{-1}.

In Figure 2 the energy and angular distribution of the ion constituents of the plasma are seen to vary dramatically from the polar cap region before ~1700 UT to the plasmasphere ~1730 UT. In fact the particle distributions observed on DE 1 from ~1700 to ~1708 UT indicate that the satellite passed above the region of primary auroral acceleration. During this period relatively intense upward beams of kiloelectron volt ions were observed. (Particle beams are characterized by peaked energy distributions and narrow angular distributions centered on the magnetic field direction.) Electron data from the DE high altitude plasma instrument for this time presented by Persoon et al. (1987) show an energetic, quasi-isotropic electron distribution, similar to that found in the plasma sheet, rather than an electron inverted-V which is seen on auroral field lines below the primary auroral acceleration region. The rising and falling of the energy of the upward flowing hydrogen and oxygen beams from ~1700 to ~1708 UT (bottom two panels) reflects variations of the electrostatic potential seen by ions below the satellite. Ion beams accelerated upward and electron beams accelerated downward are in fact the basic, remote plasma signatures of the primary auroral acceleration region (see, for example, Sharp et al., 1983).

Not all of the ion distributions on auroral field lines shown in Figure 2 can be characterized as ion beams, however. Near 1708 and 1700 UT, the low-energy angular distributions in Figure 2 (center two panels) show the angular distribution peaking on either side of the magnetic field direction. These distributions have been called ion conic distributions and are indicative of ion accelerations process(es) acting perpendicular to the local magnetic field (see, for example, Sharp et al., 1977). Conic-type ion distributions are frequently found on the "edges" of ion inverted-V events, such as those shown in Figure 2, but are also observed in isolation, such as near 1650 UT in the data presented in Figure 2.

Auroral and sub-auroral field lines are also populated by energetic kiloelectron volt quasi-isotropic ions. The top two panels in Figure 2 show such distributions. After ~1712 UT, depletions of ions with pitch angles nearly aligned with the magnetic field direction are observed. (In the spin-phase angle coordinate system used in Figure 2, 90° corresponds to upflowing ions

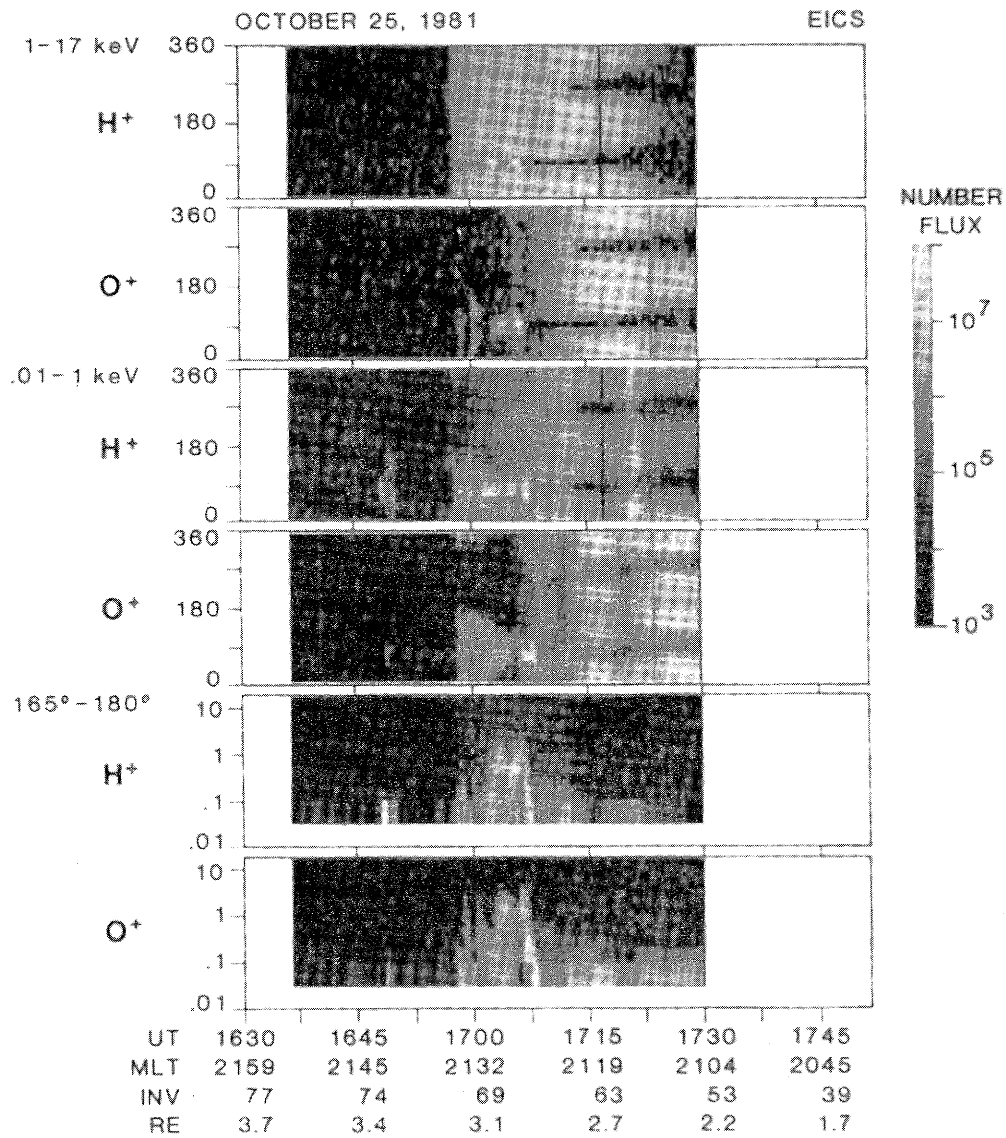

Fig. 2. Energetic ion composition data observed on mid-altitude auroral magnetic field lines from the DE 1 satellite on October 25, 1981. The universal time (UT) and orbital parameters, magnetic local time (MLT), invariant latitude (INVL), and geocentric distance in earth radii (R_E) are displayed given at 15-min intervals at the bottom. Angle-time spectrograms for two energy ranges are presented in the top four panels and energy-time spectrograms for hydrogen and oxygen ions flowing upward with pitch angles within 15° of the magnetic field are displayed in the bottom two panels. The spectrogram format is further described in the text.

with a pitch angle of 180°, and a 270° spin-phase angle corresponds to downflowing ions with pitch angles near 0°.) These depletions are the well-known particle "loss cones" caused by scattering and loss of ions in the ionosphere. Particles with pitch angles away from the loss cones mirror above the ionosphere and so are trapped. The upward accelerated ion beams seen from ~1700 to ~1708 UT appear in the downward looking loss cone, indicating their ionospheric origin.

The upward looking loss cone (i.e., the one at 270° spin-phase angle in Figure 2) is the result of ions being lost in the magnetically conjugate hemisphere, while the downward looking loss cone monitors particle losses as they mirror in the ionosphere below the satellite. From ~1700 to ~1712 UT, the upward looking loss cone is clearly filled. Our current understanding is that the ions are scattered into pitch angles within the loss cone by plasma waves as they follow magnetic

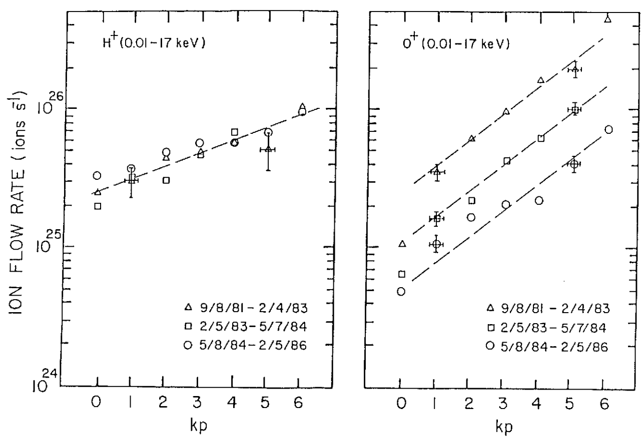

Fig. 3. Average ion outflow from the earth's auroral zones and polar caps observed from the DE 1 satellite for three time periods during the declining phase of the current solar cycle. Hydrogen data on the left and oxygen data on the right are presented as a function of the magnetic activity index Kp.

field lines between hemispheres, but as discussed below we really do not fully understand the processes involved.

The Excess Oxygen Problem

The intense fluxes of oxygen flowing up magnetic field lines out of the ionosphere first observed 10 years ago were unexpected. Subsequent investigation of the morphology of upflowing ions established that there were at least two broad classes of ion acceleration mechanisms operating on auroral field lines: one class accelerates ions primarily parallel to the local magnetic field and another class imparts energy to ions perpendicular to the magnetic field. The region of primary auroral acceleration parallel to the magnetic field was found to be at an altitude of 5000 to 10,000 km, while evidence for acceleration of ions perpendicular to the magnetic field line has been found at altitudes ranging from 400 km to deep in the magnetotail. These results have been discussed in detail by Sharp et al. (1983) and Johnson (1983). The beams of oxygen observed streaming parallel to the magnetic field above about 5000 km have on average comparable oxygen and hydrogen fluxes. However, ionospheric models predict that the hydrogen is the dominant thermal ion with little or no thermal oxygen present in the region of parallel acceleration above 5000 km. To account for the high-altitude parallel acceleration of large numbers of oxygen ions, a low-altitude (<1000 km) process is required to transport sufficient oxygen to the region of parallel acceleration. Experimental and theoretical work has now firmly established the existence of such low-altitude processes, although no single mechanism has been identified as the source of all or even a major part of the low-altitude preheating (see, for example, Whalen et al., 1978; Moore, 1980; Hultqvist, 1983; Moore et al., 1986; Chang et al., 1986).

One of the consequences of an ionospheric source for magnetospheric oxygen is a variation of oxygen ion outflow during the solar cycle. Young et al. (1982) demonstrated a long-term increase in oxygen ions near geosynchronous altitude with no associated increase in hydrogen ions during the rising phase of the current solar cycle. They suggested that these results are expected from the known increase in oxygen scale height in the ionosphere with solar activity if the auroral ionosphere is the source of magnetospheric oxygen. Yau et al. (1985a,b, 1987) investigated the long-term variation in outflowing hydrogen and oxygen ions from auroral and polar regions using data obtained since 1981 by the DE satellite and confirmed this hypothesis.

Figure 3 presents the observed hydrogen and oxygen ion outflow rates as a function of the magnetic activity index, Kp, obtained from three consecutive periods during the declining phase of the current solar cycle from DE. These data were compiled by Yau et al. (1987) and the method used is described there. The total ion outflow rate for both hydrogen and oxygen is seen to increase with the magnetic activity index, Kp. The total oxygen ion outflow rate retained approximately the same magnetic activity dependence, but the level observed in the 1984 to 1986 period had decreased by at least a factor of 5 from the near solar maximum level observed from 1981 to 1983. Young et al. (1982) noted that the daily solar radio flux index, $F_{10.7}$, is a good indicator of the total solar ultraviolet flux and is therefore the appropriate index with which to monitor solar cycle variations. Yau et al. (1987) extended their earlier report (Yau et al., 1985b) to include data obtained through the current solar minimum in early 1986 and have presented the data shown here in Figure 3 as a function of the solar radio flux index, $F_{10.7}$. They have shown that from minimum to maximum values of the solar radio flux index, at a given level of magnetic activity, the total oxygen outflow increases by a factor of ~5 while the hydrogen outflow rate decreases by less than a factor of 2. The result is that there is a significant variation in the average oxygen-to-hydrogen ratio of upflowing ions over the solar cycle.

In addition to the variation in mass composition of ionospheric ion outflow with solar cycle discussed above there is experimental evidence that suggests that the altitude of the primary auroral acceleration region rises with increasing solar activity and that microphysical processes on auroral field lines are modulated by the ionospheric response to variations in the input of solar energy. Ghielmetti et al. (1984) found that the frequency of occurrence of upward streaming hydrogen and oxygen ions with energies

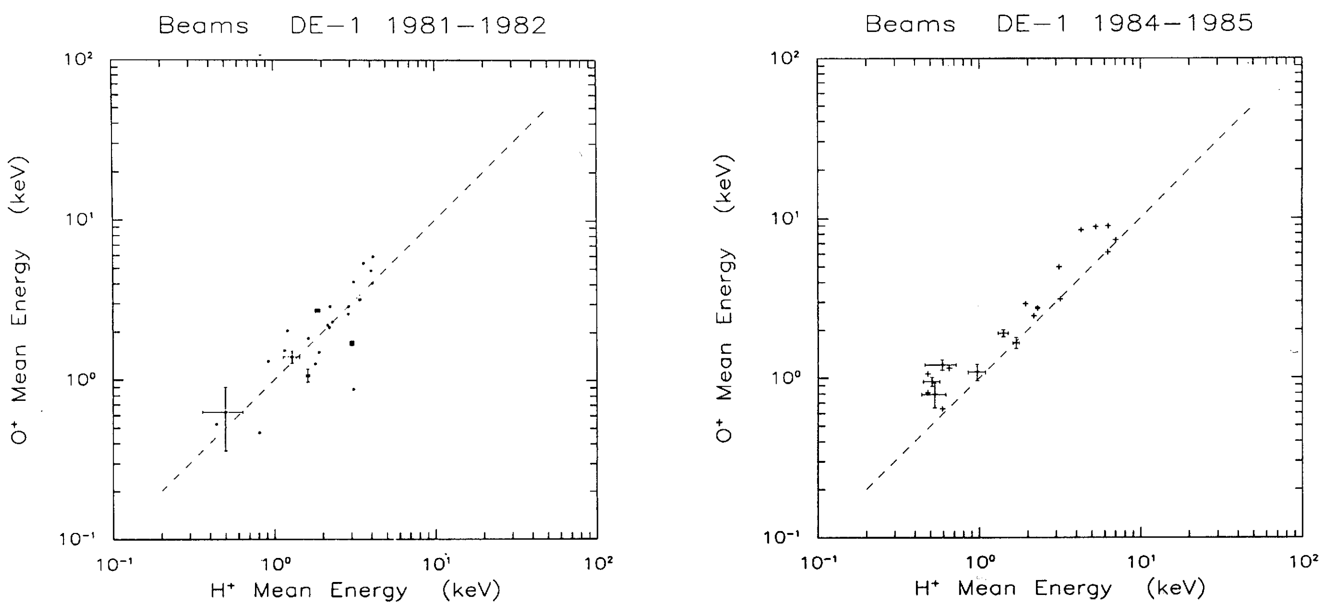

Fig. 4. Average energy of selected upflowing hydrogen and oxygen ion beams observed on the DE 1 satellite in two intervals. 1981-1982 was a period of high solar activity and 1984-1985 was a period of low solar activity. The average energy of oxygen beams is seen to be higher than that of the hydrogen beams during the 1984-1985 interval (from Collin et al., 1987).

greater than 500 eV and at altitudes less than 8000 km by the S3-3 satellite decreased from 1976 to 1979. Ghielmetti et al. (1984) also noted systematic changes in the composition, energy, and pitch angle characteristics of these upward streaming ions over this period of rising solar activity. During the same general time period (1979) of decreased S3-3 observations of upward flowing ions, field-aligned hydrogen and oxygen structures were commonly observed near geosynchronous orbit by the SCATHA satellite implying continuing injection from the ionosphere. The fluxes and energies of the ions detected by the SCATHA instrument were generally sufficient to have been detectable at the S3-3 orbit. Ghielmetti et al. (1984) concluded that these observations were consistent with the displacement of the principal auroral acceleration region to altitudes above 8000 km near the peak of the solar cycle.

There are some surprising consequences that follow from the variation in the number and energy of oxygen ions leaving the ionosphere. Measurements from the S3-3 satellite in 1976 and 1977 showed that oxygen beams observed above 5000 km had, on average, 1.7 times the energy of simultaneously observed hydrogen beams (Collin et al., 1981). Observations at higher altitude by Lundin et al. (1982) made in 1978 showed that both oxygen and the singly charged helium ion beams had more energy than accompanying hydrogen beams. These results contrast with the results of Reiff et al. (1987) who studied several beam events and reported that oxygen and hydrogen beams had nearly the same energy. The Reiff et al. observations were made in 1981, near solar maximum, from DE 1. Reiff et al. (1987) also showed that, in their beam events, there was a transfer of ion beam "streaming" energy into increased random thermal energy in the streaming frame of reference. Collin et al. (1987) examined the relative energies of many simultaneously observed oxygen and hydrogen beams observed by S3-3 at solar minimum and DE 1 at both solar maximum (1981-1982) and in the declining phase of the current solar cycle (1984-1985). Figure 4, reproduced from their paper, shows that the relative energies of the hydrogen and oxygen components of upflowing ion beams for the two periods are different. It shows that near solar maximum the oxygen and hydrogen ion beam components had comparable mean energies. Near the 1976-1977 solar minimum, Collin et al. (1986a) found that oxygen beams had more energy than could have been acquired from the potential drop determined from the simultaneously observed electron loss cone widening. No simultaneous electron loss cone measurements are available during the 1984-1985 period, but oxygen beams were found to have more energy than could have been acquired from the potential drop determined from the hydrogen beam energy.

Collin et al. (1987) suggested that the observations summarized in Figure 4 are consistent with the ion beams being partially thermalized through the two-stream instability between hydro-

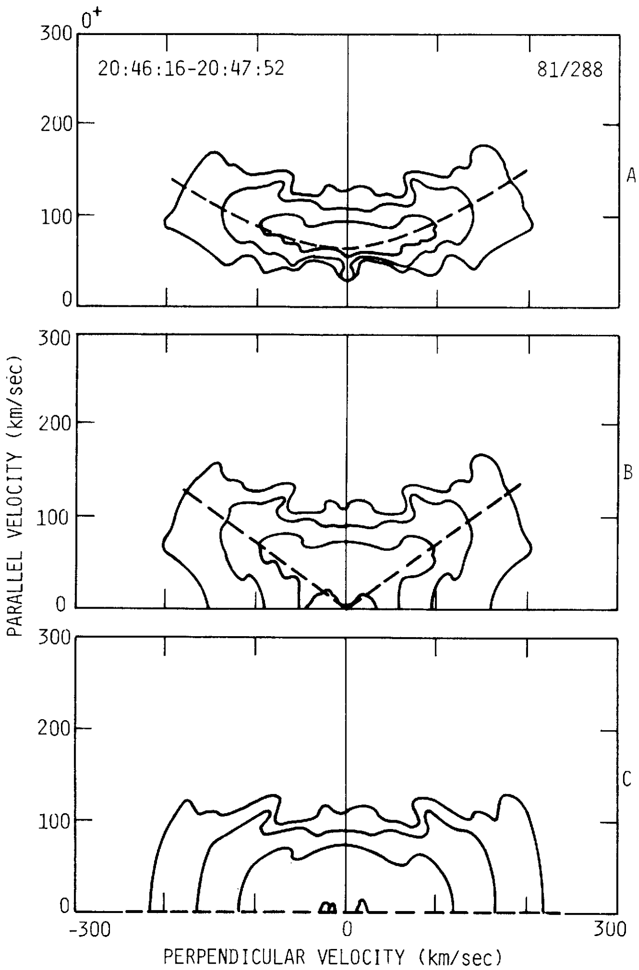

Fig. 5. Velocity space density contours reproduced from Klumpar et al. (1984). See text.

gen and oxygen with the effect being modulated by the beam composition. The two-stream instability arises because of the velocity difference between hydrogen and oxygen beams which, initially, acquire the same energy when they pass through a magnetic field-aligned potential drop (Kaufmann et al., 1986; Bergmann and Lotko, 1986). Collin et al. (1986b) examined the multi-species dispersion relation and showed how it is possible for oxygen to acquire extra energy from hydrogen beams with higher velocities when oxygen is a minor species.

Transverse Acceleration and Ion Conics

The early results from the S3-3 satellite (Sharp et al., 1977) clearly established that energization of ions perpendicular to the local magnetic field is an important process in the coupling of ionospheric and magnetospheric plasmas. Since this initial recognition, considerable work on both the macro- and microphysical aspects of perpendicular acceleration processes has been done. Klumpar (1986) compiled a comprehensive bibliography on this subject. It is beyond the scope of this report to discuss all aspects of transverse acceleration; instead discussions will concentrate on recent results that suggest that the expected ion energy-angle "signature" of transverse acceleration may not be unique and that more than one microphysical process is important for imparting transverse energy to significant numbers of ions on auroral field lines.

The starting point for this discussion is to note the extreme difficulty experimentalists have had in finding regions where transverse ion energization is the dominant process. The expected "signature" of such regions is the simultaneous occurrence of intense low-frequency plasma waves and energetic ions with their energy primarily perpendicular to the local magnetic field, a so-called 90° conic distribution. Kintner and Gorney (1984) were able to find only one such example in the entire S3-3 data set. Whalen et al. (1978), Yau et al. (1983), and Kintner et al. (1986) have been remarkably successful in observing the so-called 90° conics at ionospheric altitudes from rockets. However, mapping ion pitch angle distributions from ion conic distributions measured at satellite altitudes indicates that almost all such conical distributions have a source region at altitudes well above the ionosphere. This point is illustrated in Figure 5 from Klumpar et al. (1984). The top panel of Figure 5 presents the observations made at an altitude of ~22,000 km and shows contours of the logarithm of observed velocity space density. Considering, for the moment, the pitch angles of only the most energetic particles, Klumpar et al. showed that conservation of the first adiabatic invariant in the earth's magnetic field indicates that the energetic ions would have had 90° pitch angles where the strength of the magnetic field was ~1.49 times larger, or at ~18,200 km.

More importantly, because Klumpar et al. (1984) had observations of ion velocity distributions to low energies (i.e., ~50 eV), they were able to show, as indicated in the second two panels of Figure 5, that the observed ion distribution is inconsistent with simple adiabatic transport of ions from a source at 18,200 km to the observation altitude of ~22,000 km. The interpretation implied in Figure 5 is that a parallel acceleration of 310 eV and adiabatic transport, a two-step or bimodal process, is responsible for producing the observed ion distribution. There have been three other suggestions of processes that could produce ion distributions such as those shown in Figure 5. Chang et al. (1986) and Temerin and Roth (1986) showed how such distributions can be caused by a relatively weak transverse acceleration mechanism acting over a range of altitudes. Retterer et al. (1987) extended the work of Chang et al. and were able to reproduce the type of ion distribution discussed by Klumpar et al. (1984). It should also be noted that Horwitz (1986) has shown that some of the features of the observed ion distribution in Figure 5 can be explained by a velocity filter mechanism (i.e., simply particle kinematics).

The point of the above discussion is to show that our understanding of the microphysical processes that are responsible for the exchange of ionospheric and magnetospheric plasmas, in spite of the large number of papers devoted to the subject, is still incomplete and evolving. Lennartsson (1983) provided a short introduction to and catalog of the types of acceleration mechanism that have been considered to be operating in the auroral region. It is important to realize that most of the mechanisms cataloged by Lennartsson probably do occur on auroral field lines and it is difficult to distinguish among them using state-of-the-art in situ plasma diagnostics.

Ion Velocity Dispersion Events

In addition to ion "beams" and "conics," there is a third type of ion energy-pitch angle distribution observed on auroral field lines that has been less intensively studied. As noted below, some of these distributions are unstable and can lead to the emission of plasma waves. Observable velocity dispersion effects can be seen after the introduction in a localized region and/or in a short period (compared to ion travel times) of a plasma population with a rather broad energy and/or pitch angle distribution. The difference in travel times caused by the different spiral path distances traveled by ions with different pitch angles to a remote location leads to unique energy-pitch angle, or energy-latitude distributions at locations well removed from the source.

The first intensively studied ion velocity dispersion events were observed in the low-latitude magnetospheric cusp (Shelley et al., 1976; Reiff et al., 1977). In the cusp there is localized entry of a broad energy and pitch angle spectrum of magnetosheath ions and a well defined anti-sunward drift (independent of energy) of ions as they move down to the ionosphere. The spread in ion velocities parallel to cusp field lines coupled with anti-sunward drift, independent of parallel velocity, results in the characteristic energy-latitude signature identified by Shelley et al. (1976) and Reiff et al. (1977). At higher altitudes in the cusp Burch et al. (1982) showed that a characteristic "V" in ion energy-pitch angle distributions is explained by the same kinematic effects. Gorney (1983) noted that these downstreaming cusp ion distributions have a characteristic ring or shell shape in velocity space that could lead to plasma wave instabilities. Subsequently Roth and Hudson (1985) showed there is enough energy in these distributions to support significant ion heating.

A second velocity dispersion effect has also been found in the cusp region. The Marshall group has recently found in their DE 1 retarding ion mass spectrometer (RIMS) data an interesting and unexpectedly intense source of low-energy ion outflow from a limited latitudinal region in the dayside cusp/cleft which they have called the "upwelling ion region" (see, for example, Lockwood et al., 1985a). This spatially restricted low-energy ion source and the normal anti-sunward high-latitude plasma convection pattern result in effects which have been called a "fountain in a wind" (Lockwood et al., 1985a) where the upwelling ion energies are small compared to the gravitational potential energy at high altitudes, or a "geomagnetic ion mass spectrometer" (Lockwood et al., 1985b) where the energy of the upflowing low-energy ions is slightly higher. The further acceleration of some of these ions on auroral and cusp field lines by a mechanism such as that recently proposed by Cladis (1986) suggests that this upwelling ion region could be an important source of low-energy (~10-50 eV) plasma sheet ions (Chappell et al., 1987).

Ion velocity dispersion signatures not associated with the dayside cusp or cleft region have also been reported on auroral magnetic field lines. Figure 6 is from a presentation made by Klumpar et al. (1983) and shows in the middle panel an oxygen energy-pitch angle velocity dispersion feature. The data presented in Figure 6 were obtained by the EICS instrument on DE 1 and are in the form of mass resolved energy-time spectrograms. Data for about 7 min on July 14, 1982, when DE 1 was on mid-altitude ($R/R_E \sim 4$) auroral field lines ($L \sim 5.6$) near 1600 magnetic local time are shown. The top two panels display mass-resolved hydrogen and oxygen ion count rate presented at the highest time resolution encoded with the gray bar shown on the right. The EICS instrumental response function is such that the counting rate is approximately proportional to number flux. The bottom panel, labeled ED, is from an ion detector sensitive to all ion species. The EICS mode used during the interval presented in Figure 6 obtained complete pitch angle coverage for oxygen and hydrogen ions over the energy range (10 eV to 17 keV) every 24 s. The data in Figure 6 are displayed in pitch angle order for each measurement cycle instead of in strict time order. The pitch angle characteristic of each energy spectrum is displayed as a function of time in the bottom panel. Klumpar et al. (1983) analyzed the oxygen energy-time-pitch angle signature in Figure 6 and have found that it is consistent with an impulsive isotropic equatorial source with a broad energy and pitch angle spectrum which occurred for a short (compared to the ion bounce time) period at 23:26:25. Note that the low-energy trace (i.e., the slow ions) have come directly from the equator, while the higher energy dispersion signature starting near 23:34 comes from ions which have traveled through the opposite hemisphere, mirrored, and

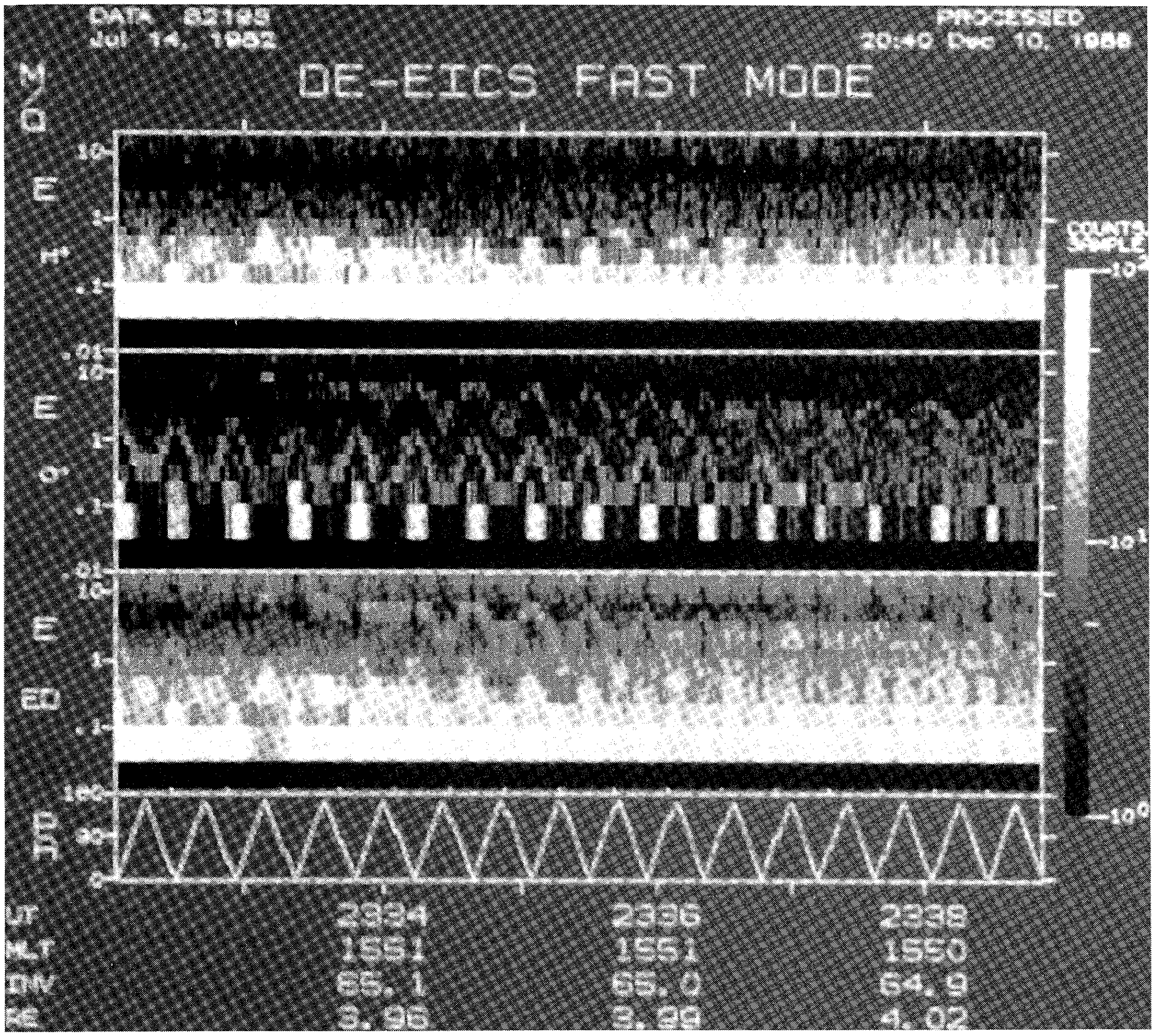

Fig. 6. Energy-time spectrograms of hydrogen (top panel) and oxygen (middle panel) illustrating an oxygen ion dispersion event. See text.

are coming back down magnetic field lines. Quinn and McIlwain (1979) reported the not infrequent occurrence of ion energy pitch angle dispersion signatures consistent with those shown in Figure 6 at geosynchronous altitudes. They analyzed the ion dispersion signatures for a number of events and found two classes of dispersion signature, one consistent with an equatorial source and the other with an ionospheric source for the initial population responsible for what they have called "bouncing ion clusters." In a subsequent paper Quinn and Southwood (1982) proposed a parallel ion acceleration mechanism for the equatorial ion source.

Quinn and McIlwain (1979) noted that a very large fraction of the "bouncing ion clusters" they observed survived multiple reflections at low altitudes with very little reduction in intensity. At the time of their observations this was consistent with the lack of detection of significant numbers of downflowing ion events (i.e., ion beams precipitating into the ionosphere) by instrumentation on the S3-3 satellite (Ghielmetti et al., 1979). Since that time there have been reports from the DE 2 and AUREOL-3 satellites of significant numbers of downflowing ion events (Winningham et al., 1984; Frahm et al., 1986; Bosqued et al., 1986).

Figure 7, reproduced from Bosqued et al. (1986), illustrates the observational details and interpretation of a downward flowing ion event observed on AUREOL-3 on June 27, 1982. The observations are of a precipitating ion distribution with a maximum intensity at an energy that

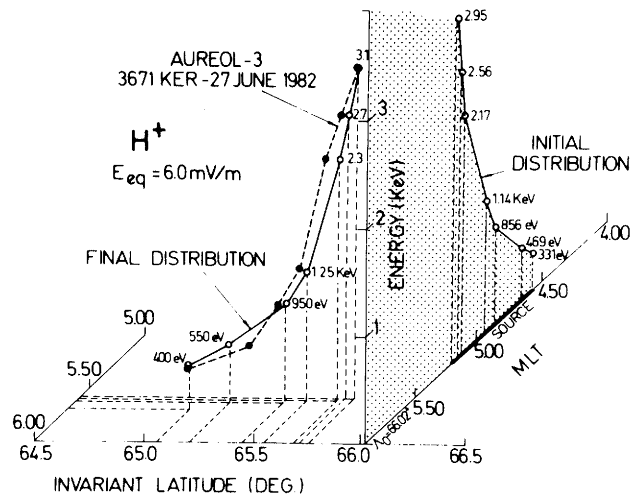

Fig. 7. Schematic representation of the observed energy-latitude dispersion (left) of an ion band observed from the AUREOL-3 satellite on June 27, 1982. The inferred source distribution is shown in the right-hand panel (from Bosqued et al., 1986).

systematically decreases with invariant latitude as the satellite moves across auroral field lines. The curve labeled "final distribution" in Figure 7 shows the observed peak energy as a function of invariant latitude. The interpretation is that the final energy-latitude distribution is the result of the transport of ions accelerated from a range of local times at more or less the same invariant latitude in the magnetically conjugate hemisphere, including the effects of ion drift in a uniform dawn-dusk electric field. The curve labeled "initial distribution" in Figure 7 shows the ion energies as a function of magnetic local time inferred using this interpretation.

Bosqued et al. (1986) had a data base consisting of 600 auroral zone crossings in 1982 and 1983. They found ion energy-latitude dispersion features similar to the one shown in Figure 7 in 68 auroral crossings (~11%). Frahm et al. (1986) analyzed 227 low-altitude auroral crossings of the DE 2 satellite from the fall of 1981 and found 40 such signatures (~18%). This contrasts with the results of Ghielmetti et al. (1979) who found only 20 downward flowing ion events in 570 auroral crossings of the S3-3 satellite between 1976 and 1979 (~4%). The relatively low number of downward flowing ion events seen by the S3-3 satellite might be explained by the large differences in sensitivity and energy threshold between the S3-3 instrument and the AUREOL-3 and DE 2 instruments. It is interesting to note however, that the DE 2 observations were obtained closer to the recent solar maximum than either the S3-3 or AUREOL-3. The ATS 6 results of Quinn and McIlwain (1979) were also obtained during relatively low levels of solar activity. It is, of course, not possible to demonstrate a solar cycle variation in the occurrence frequency of downward flowing ion events from the data discussed here, but since Yau et al. (1985a,b, 1987) have demonstrated a solar cycle dependence in upflowing ion events, a solar cycle dependence to the observation of downward flowing ion events would not be surprising.

The above discussion shows a large gap in our understanding of the physical processes involved in the coupling of ionospheric and magnetospheric plasmas. Ionospheric ions stream out of the ionosphere as collimated beams or, in the absence of other interactions, become collimated beams near the equator as the strength of the magnetic field decreases because of the conservation of the first adiabatic invariant. At some time in their transport through the plasma sheet, these directed ion streams are converted into the hot quasi-isotropic plasma sheet population. We do not understand, at this time, the processes occurring on auroral field lines in the plasma sheet well enough to be able to explain why some streams of ions retain their identity and perform multiple bounces, others precipitate into the ionosphere, and still others are pitch-angle scattered to become the quasi-isotropic plasma sheet population. Perhaps the key to understanding these complicated relationships will come from the detailed studies of counterstreaming ion populations observed on mid-altitude auroral field lines (see, for example, Horita et al., 1987; Sagawa et al., 1987) and near the equator (see, for example, Quinn and Johnson, 1985).

Concluding Remarks

In situ plasma diagnostics and particular energetic ion composition measurements on auroral field lines in the past 10 years have greatly improved our understanding of the magnetosphere and the ionosphere and their interactions, but we are still far from a complete picture. Current models of the magnetosphere and ionosphere are starting to reflect the importance and dynamic nature of the ionospheric contribution to magnetospheric plasmas. Our present level of understanding is illustrated by considering the recent suggestion by Baker et al. (1982) that variations in the ionospheric source composition can lead to the initiation of plasma sheet instabilities. We have observations that lead to such suggestions that large-scale physical processes are important in coupling ionospheric and magnetospheric plasmas, but we cannot confirm or rule out these suggestions because of the very global nature of the processes and the very limited, in space and time, simultaneous observational data available to test them. On a more fundamental level, the recent discovery of the frequent occurrence of cross polar cap emission features, the so-called "theta aurora," during extended periods of northward interplanetary magnetic field (see, for example, Frank et al., 1986; Peterson and Shelley, 1984) has raised some basic questions about our understanding of the topology of the magnetosphere.

On auroral field lines we also have a very incomplete understanding of the relative importance of the many possible mechanisms that could be involved in the transport of atomic oxygen from the ionosphere to the magnetosphere and why some ion populations pass through the equatorial magnetosphere to precipitate in the magnetically conjugate hemisphere and some populations become trapped.

Until we can answer questions such as these, there will have to be doubts about the generality of any empirical models we use to describe the magnetosphere/ionosphere system. We are making progress, however. The Dynamics Explorer project has illustrated the importance and difficulty of looking at the complete range of in situ parameters. The continued analysis of the high resolution Dynamics Explorer data, the very recent successful operation of the Swedish VIKING satellite with its complement of high resolution plasma instruments, and multi-satellite collaboration such as the recently initiated PROMIS campaign (Hones, 1985) should continue to provide new insights into both the micro- and macrophysics involved in the interaction of magnetospheric and ionospheric plasmas on auroral field lines.

Acknowledgments. Thanks go to D. Klumpar, A. Ghielmetti, H. Collin, J. Drake, and A. Yau for their helpful comments. This work has been supported by NASA under contracts NAS5-28710 and NAS8-36323.

References

Baker, D. N., E. W. Hones, Jr., D. T. Young, and J. Birn, The possible role of ionospheric oxygen in the initiation and development of plasma sheet instabilities, Geophys. Res. Lett., 9, 1337, 1982.

Bame, S. J., W. C. Feldman, J. T. Gosling, D. T. Young, and R. D. Zwickl, What magnetospheric workers should know about solar wind composition, in Energetic Ion Composition in the Earth's Magnetosphere, edited by R. G. Johnson, p. 73, Terra Scientific Publ. Co., Tokyo, 1983.

Bergmann, R., and W. Lotko, Transition to unstable flow in parallel electric fields, J. Geophys. Res., 91, 7033, 1986.

Bosqued, J. M., J. A. Sauvaud, K. Delcourt, and R. A. Kovrazhkin, Precipitation of suprathermal ionospheric ions accelerated in the conjugate hemisphere, J. Geophys. Res., 91, 7006, 1986.

Burch, J. L., P. H. Reiff, R. A. Heelis, J. D. Winningham, W. B. Hanson, C. Gurgiolo, J. D. Menietti, R. A. Hoffman, and J. N. Barfield, Plasma injection and transport in the mid-altitude polar cusp, Geophys. Res. Lett., 9, 921, 1982.

Chang, T., G. B. Crew, N. Hershkowitz, J. R. Jasperse, J. M. Retterer, and J. D. Winningham, Transverse acceleration of oxygen ions by electromagnetic cyclotron resonance with broad band left-hand polarized waves, Geophys. Res. Lett., 13, 636, 1986.

Chappell, R. C., C. R. Olsen, J. L. Green, J.F.E. Johnson, and J. H. Waite, Jr., The discovery of nitrogen ions in the earth's magnetosphere, Geophys. Res. Lett., 9, 937, 1982.

Chappell, C. R., T. E. Moore, and J. H. Waite, Jr., The ionosphere as a fully adequate source of plasma for the earth's magnetosphere, J. Geophys. Res., 92, 5896, 1987.

Cladis, J. B., Parallel acceleration and transport of ions from polar ionosphere to plasma sheet, Geophys. Res. Lett., 13, 893, 1986.

Collin, H. L., R. D. Sharp, E. G. Shelley, and R. G. Johnson, Some general characteristics of upflowing ion beams and their relationship to auroral electrons, J. Geophys. Res., 86, 6820, 1981.

Collin, H. L., E. G. Shelley, A. G. Ghielmetti, and R. D. Sharp, Observations of transverse and parallel acceleration of terrestrial ions at high latitudes, in Ion Acceleration in the Magnetosphere and Ionosphere, Geophys. Monogr. Ser., vol. 38, edited by T. Chang, p. 67, AGU, Washington, D.C., 1986a.

Collin, H. L., E. G. Shelley, and R. Bergmann, The heating of upflowing ion beams by an H^+/O^+ two-stream instability (abstract), Eos Trans. AGU, 67, 1164, 1986b.

Collin, H. L., W. K. Peterson, and E. G. Shelley, Solar cycle variation of some mass dependent characteristics of upflowing beams of terrestrial ions, J. Geophys. Res., 92, 4757, 1987.

Cornwall, J. M., Magnetospheric ion acceleration processes, in Ion Acceleration in the Magnetosphere and Ionosphere, Geophys. Monogr. Ser., vol. 38, edited by T. Chang, p. 3, AGU, Washington, D.C., 1986.

Feldstein, Y. I, and Yu. I. Galperin, The auroral luminosity structure in the high-latitude upper atmosphere: Its dynamics and relationships to the large-scale structure of the earth's magnetosphere, Rev. Geophys., 23, 217, 1985.

Frahm, R. A., P. H. Reiff, J. D. Winningham, and J. L. Burch, Banded ion morphology: Main and recovery storm phases, in Ion Acceleration in the Magnetosphere and Ionosphere, Geophys. Monogr. Ser., vol. 38, edited by T. Chang, p. 98, AGU, Washington, D.C., 1986.

Frank, L. A., J. D. Craven, D. A. Gurnett, S. D. Shawhan, D. R. Weimer, J. L. Burch, J. D. Winningham, C. R. Chappell, J. H. Waite, R. A. Heelis, N. C. Maynard, M. Sugiura, W. K. Peterson, and E. G. Shelley, The theta aurora, J. Geophys. Res., 91, 3177, 1986.

Ghielmetti, A. G., R. G. Johnson, R. D. Sharp, and E. G. Shelley, The latitudinal, diurnal, and altitudinal distributions of upward flowing energetic ions of ionospheric origin, Geophys. Res. Lett., 5, 59, 1978.

Ghielmetti, A. G., R. D. Sharp, E. G. Shelley, and R. G. Johnson, Downward flowing ions and evidence for injection of ionospheric ions into the plasma sheet, J. Geophys. Res., 84, 5781, 1979.
Ghielmetti, A. G., J. M. Quinn, E. G. Shelley, R. D. Sharp, and R. G. Johnson, Decreased auroral acceleration below ~2 R_E altitude--A solar cycle effect? (abstract), Eos Trans. AGU, 65, 1061, 1984.
Gorney, D. J., An alternative interpretation of ion ring distributions observed by the S3-3 satellite, Geophys. Res. Lett., 10, 417, 1983.
Gorney, D. J., A. Clark, D. Croley, J. Fennell, J. Luhmann, and P. Mizera, The distribution of ion beams and conics below 8000 km, J. Geophys. Res., 86, 83, 1981.
Hones, E. W., Jr., Project PROMIS to coordinate satellites (abstract), Eos Trans. AGU, 66, 1369, 1985.
Horita, R. E., E. Ungstrup, E. G. Shelley, R. R. Anderson, and R. J. Fitzenreiter, Counter-streaming ion (CSI) events in the magneto-sphere, J. Geophys. Res., in press, 1987.
Horwitz, J. L., Velocity filter mechanism for ion bowl distributions (bimodal conics), J. Geophys. Res., 91, 4513, 1986.
Hultqvist, B., On the origin of the hot ions in the disturbed dayside magnetosphere, Planet. Space Sci., 31, 173, 1983.
Johnson, R. G., The hot ion composition, energy, and pitch angle characteristics above the auroral zone ionosphere, in High-Latitude Space Plasma Physics, edited by B. Hultqvist and T. Hagfors, p. 271, Plenum Publ. Co., New York, 1983.
Kaufmann, R. L., G. R. Ludlow, H. L. Collin, W. K. Peterson, and J. L. Burch, Interaction of up-going auroral H^+ and O^+ beams, J. Geophys. Res., 91, 1080, 1986.
Kintner, P. M., and D. J. Gorney, A search for the plasma processes associated with perpen-dicular ion heating, J. Geophys. Res., 89, 937, 1984.
Kintner, P. M., J. LaBelle, W. Scales, A. W. Yau, and B. A. Whalen, Observations of plasma waves within regions of perpendicular ion accelera-tion, Geophys. Res. Lett., 13, 1113, 1986.
Klumpar, D. M., A digest and comprehensive bibli-ography on transverse auroral ion acceleration, in Ion Acceleration in the Magnetosphere and Ionosphere, Geophys. Monogr. Ser., vol. 38, edited by T. Chang, p. 389, AGU, Washington, D.C., 1986.
Klumpar, D. M., W. K. Peterson, E. G. Shelley, and J. M. Quinn, Localized magnetospheric ion injection outside the cusp (abstract), Eos Trans. AGU, 64, 297, 1983.
Klumpar, D. M., W. K. Peterson, and E. G. Shelley, Direct evidence for two-stage (bimodal) acceleration of ionospheric ions, J. Geophys. Res., 89, 10,779, 1984.
Lennartsson, W., Ion acceleration mechanisms in the auroral regions, general principles, in Energetic Ion Composition in the Earth's Mag-netosphere, edited by R. G. Johnson, p. 23, Terra Scientific Publ. Co., Tokyo, 1983.
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, J. Geophys. Res., 90, 4099, 1985a.
Lockwood, M., T. E. Moore, J. H. Waite, Jr., C. R. Chappell, J. L. Horwitz, and R. A. Heelis, The geomagnetic mass spectrometer--Mass and energy dispersions of ionospheric ion flows into the magnetosphere, Nature, 316, 612, 1985b.
Lundin, R., B. Hultqvist, E. Dubinin, A. Zackarov, and N. Pissarenko, Observations of outflowing ion beams on auroral field lines at altitudes of many earth radii, Planet. Space Sci., 30, 715, 1982.
Moore, T. E., Modulation of terrestrial ion escape flux composition (by low-altitude acceleration and charge exchange chemistry), J. Geophys. Res., 85, 2021, 1980.
Moore, T. E., C. J. Pollock, R. L. Arnoldy, and P. M. Kintner, Preferential O^+ heating in the topside ionosphere, Geophys. Res. Lett., 13, 901, 1986.
Persoon, A. M., D. A. Gurnett, W. K. Peterson, J. H. Waite, Jr., J. L. Burch, and J. L. Green, Electron density depletions in the nightside auroral zone, J. Geophys. Res., in press, 1987.
Peterson, W. K., Ion injection and acceleration in the polar cusp, in The Polar Cusp, edited by J. A. Holtet and A. Egeland, p. 67, Reidel Publ. Co., Dordrecht, Holland, 1984.
Peterson, W. K., and E. G. Shelley, Origin of the plasma in a cross-polar cap auroral feature (theta aurora), J. Geophys. Res., 89, 6729, 1984.
Quinn, J. M., and C. E. McIlwain, Bouncing ion clusters in the earth's magnetosphere, J. Geophys. Res., 84, 7365, 1979.
Quinn, J. M., and D. J. Southwood, Observations of parallel ion energization in the equatorial region, J. Geophys. Res., 87, 10,536, 1982.
Quinn, J. M., and R. G. Johnson, Observation of ionospheric source cone enhancements at the substorm injection boundary, J. Geophys. Res., 90, 4211, 1985.
Reiff, P. H., T. W. Hill, and J. L. Burch, Solar wind plasma injection at the dayside magneto-spheric cusp, J. Geophys. Res., 82, 479, 1977.
Reiff, P. H., H. L. Collin, J. D. Craven, J. L. Burch, J. D. Winningham, E. G. Shelley, L. A. Frank, and M. A. Friedman, Determination of auroral electrostatic potentials using high- and low-altitude particle distributions, J. Geophys. Res., in press, 1987.
Retterer, J. M., T. Chang, G. B. Crew, J. R. Jasperse, and J. D. Winningham, Monte Carlo modeling of large-scale ion-conic generation, this volume, 1987.
Roth, I., and M. K. Hudson, Lower hybrid heating of ionospheric ions due to ion ring distribu-

tions in the cusp, J. Geophys. Res., 90, 4191, 1985.
Sagawa, E., A. W. Yau, B. A. Whalen, and W. K. Peterson, Pitch-angle distributions of low-energy ions in the near-earth magnetosphere, J. Geophys. Res., in press, 1987.
Schunk, R. W., The polar wind, this volume, 1987.
Sharp, R. D., R. G. Johnson, and E. G. Shelley, Observations of an ionospheric acceleration mechanism producing energetic (keV) ions primarily normal to the geomagnetic field direction, J. Geophys. Res., 82, 3324, 1977.
Sharp, R. D., A. G. Ghielmetti, R. G. Johnson, and E. G. Shelley, Hot plasma composition results from the S3-3 spacecraft, in Energetic Ion Composition in the Earth's Magnetosphere, edited by R. G. Johnson, p. 167, Terra Scientific Publ. Co., Tokyo, 1983.
Shelley, E. G., Circulation of energetic ions of terrestrial origin in the magnetosphere, Adv. Space Res., 5, 401, 1985.
Shelley, E. G., Magnetospheric energetic ions from the earth's ionosphere, Adv. Space Res., 6(3), 121, 1986.
Shelley, E. G., R. D. Sharp, and R. G. Johnson, He^{++} and H^+ flux measurements in the dayside cusp: Estimates of convection electric field, J. Geophys. Res., 81, 2363, 1976.
Shelley, E. G., D. A. Simpson, T. C. Sanders, E. Hertzberg, H. Balsiger, and A. Ghielmetti, The energetic ion mass spectrometer (EICS) for the Dynamics Explorer-A, Space Sci. Instrum., 5, 443, 1981.
Shelley, E. G., H. L. Collin, J. F. Drake, W. Lennartsson, and A. W. Yau, Origin of plasma sheet ions: Substorm and solar cycle dependence (abstract), Eos Trans. AGU, 67, 1133, 1986.
Temerin, M., and I. Roth, Ion heating by waves with frequencies below the ion gyrofrequency, Geophys. Res. Lett., 13, 1109, 1986.
Whalen, B. A., W. Bernstein, and P. W. Daly, Low altitude acceleration of ionospheric ions, Geophys. Res. Lett., 5, 55, 1978.
Winningham, J. D., J. L. Burch, and R. A. Frahm, Bands of ions and angular V's: A conjugate manifestation of ionospheric acceleration, J. Geophys. Res., 89, 1749, 1984.
Yau, A. W., and M. Lockwood, Vertical ion flow in the polar ionosphere, this volume, 1987.
Yau, A. W., B. A. Whalen, A. G. McNamera, P. J. Kellogg, and W. Bernstein, Particle and wave observations of low-altitude ionospheric ion acceleration events, J. Geophys. Res., 88, 341 1983.
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, J. Geophys. Res., 90, 6395, 1985a.
Yau, A. W., E. G. Shelley, W. K. Peterson, and L. Lenchyshyn, Energetic auroral and polar ion outflow at DE 1 altitudes: Magnitude, composition, magnetic activity dependence, and long-term variations, J. Geophys. Res., 90, 8417, 1985b.
Yau, A. W., W. K. Peterson, and E. G. Shelley, Quantitative parametrization of energetic ionospheric ion outflow, this volume, 1987.
Young, D. T., Near-equatorial magnetospheric particles from ~1 eV to ~1 MeV, Rev. Geophys. Space Phys., 21, 402, 1983.
Young, D. T., Experimental aspects of ion acceleration in the earth's magnetosphere, in Ion Acceleration in the Magnetosphere and Ionosphere, Geophys. Monogr. Ser., vol. 38, edited by T. Chang, p. 17, AGU, Washington, D.C., 1986.
Young, D. T., J. Geiss, H. Balsiger, P. Eberhardt, A. Ghielmetti, and H. Rosenbauer, Discovery of He^{++} and O^{++} ions of terrestrial origin in the outer magnetosphere, Geophys. Res. Lett., 4, 561, 1977.
Young, D. T., H. Balsiger, and J. Geiss, Correlations of magnetospheric ion composition with geomagnetic and solar activity, J. Geophys. Res., 87, 9077, 1982.