

The Role of the Ionosphere in Providing Plasma to the Terrestrial Magnetosphere—An Historical Overview

Charles R. Chappell¹

Received: 10 March 2015 / Accepted: 25 May 2015 / Published online: 10 July 2015

© Springer Science+Business Media Dordrecht 2015

Abstract Through the more than half century of space exploration, the perception and recognition of the fundamental role of the ionospheric plasma in populating the Earth's magnetosphere has evolved dramatically. A brief history of this evolution in thinking is presented. Both theory and measurements have unveiled a surprising new understanding of this important ionosphere-magnetosphere mass coupling process. The highlights of the mystery surrounding the difficulty in measuring this largely invisible low energy plasma are also discussed. This mystery has been solved through the development of instrumentation capable of measuring these low energy positively-charged outflowing ions in the presence of positive spacecraft potentials. This has led to a significant new understanding of the ionospheric plasma as a significant driver of magnetospheric plasma content and dynamics.

1 Introduction

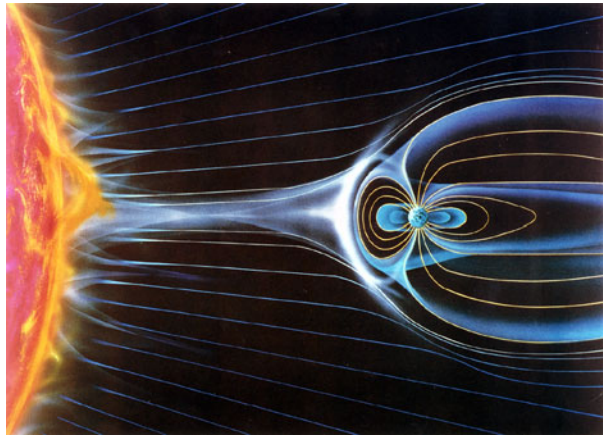
The early instrumentation used on satellites that probed the Earth's space environment was able to measure the fluxes of the low density, high energy particles found in the magnetosphere or the high density, very low energy particles typical of the ionosphere. Measurements of the high energy radiation belts originally were made with Geiger counters, while the low energy plasma of the ionosphere was measured with retarding potential analyzers and Langmuir probes. As miniaturized channel electron multipliers were developed, the measurement of the full energy range of particles from a few electron volts up to ten's of keV became possible.

As these new instruments were flown on satellites into the magnetosphere and solar wind, it was recognized that there was a similarity in energy between the solar wind particles and particles found in the Earth's plasma sheet and aurora. Early instrumentation did not have the ability to determine ion composition at this medium energy range, and it was assumed that the plasmas in the solar wind and the magnetosphere were both dominated by protons and electrons. Hence the conceptual picture shown in Fig. 1 was developed. In this understanding

✉ C.R. Chappell
rick.chappell@vanderbilt.edu

¹ Vanderbilt University, Nashville, TN, USA

Fig. 1 A schematic image representing the early understanding of the primary role of the solar wind in populating the Earth's magnetosphere with plasma



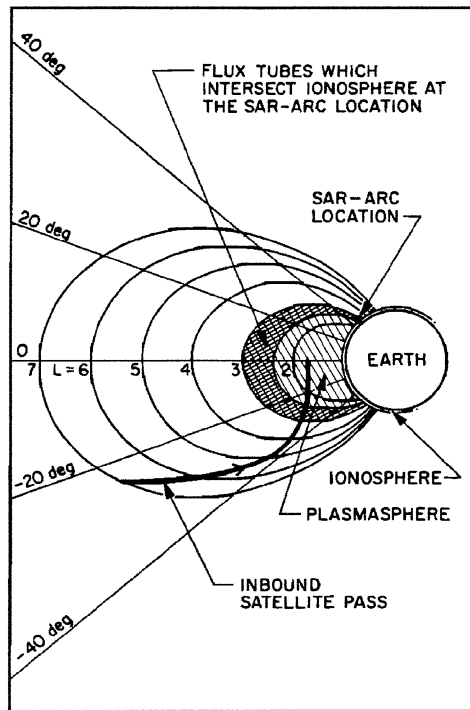
of our space physics “childhood” the solar wind was seen as the sole source of plasma for the magnetosphere with solar wind particles gaining access into the magnetosphere through the polar cusp on the dayside and through the flanks of the magnetotail into the plasma sheet on the nightside. These keV ions and electrons were thought to be channeled through the magnetic field down into the auroral zone where they collided with the atoms and molecules of the upper atmosphere to create the auroral emissions. The Van Allen radiation belts which were the first major discovery of a magnetospheric plasma population are shown in this figure as a toroidal shaped region surrounding the Earth in the inner magnetosphere.

In this early view of the solar wind/magnetosphere system, the low energy plasma was thought to be confined to the low altitudes of the ionosphere with an extension upward only in the plasmasphere, a roughly donut-shaped region with an outer average boundary of about $L = 4$, extending outward to $L = 6$ in the dusk sector. The plasmasphere was seen to vary with magnetic activity moving inward during disturbed times and growing larger during magnetically quiet times (Gringauz 1963; Carpenter 1963). Early theoretical work by Nishida (1966) and Brice (1967) suggested ways in which the convection electric field in the magnetosphere, combined with the corotation of plasma with the Earth could begin to explain the presence and shape of the plasmasphere. Later measurements from the Orbiting Geophysical Observatory series of spacecraft verified the earlier whistler and satellite measurements and enhanced the understanding of plasmasphere dynamics (Taylor et al. 1965; Brinton et al. 1970; Grebowsky 1970; Chappell 1972).

Although the plasmasphere represented a region of magnetospheric plasma, it was thought to be only an upward extension of the ionosphere and to be of too low an energy to contribute to the dynamic magnetospheric processes that created magnetic storms, the aurora and the radiation belts. Hence, discussions of the plasmasphere in those years were usually placed in ionospheric sessions at the national and international meetings and not in the magnetospheric sessions.

This was the space physics community perception of the solar wind-magnetosphere system through the decade of the 1960s. The locations of the magnetospheric regions of more energetic particles, their energies and unknown composition showed an excellent fit to the idea that the solar wind provided both the energy and the particles for driving the dynamic processes that were observed in the magnetosphere by both space-borne and ground-based measurements. This is what graduate students of that time were taught and these ideas have not gone away easily.

Fig. 2 A sketch of the inner magnetosphere plasma regions showing the overlap of the energetic ions of the ring current with the low energy plasma of the outer plasmasphere. The transfer of energy from the ring current to the plasmasphere results in heating which causes the formation of Stable Auroral Red arcs in the upper atmosphere



2 The Decade of the 1970s

At the end of the 1960s theoretical work at the University of California, San Diego led to the realization that there could be a supersonic escape of light ions from the top-side ionosphere. This very low energy ambipolar outflow of H^+ and He^+ ions and electrons was called the polar wind (Axford 1968; Banks and Holzer 1968; Nagy and Banks 1970; Banks et al. 1971, 1974a, 1974b) and predicted significant upward fluxes of the order of 3×10^8 ions/cm²sec. This outflow results from the charge separation electric field that is set up between the dominant ionospheric O^+ and the electrons which would then accelerate the minor ions, H^+ and He^+ upward. The polar wind was predicted to be present on all flux tubes in which the plasma content above the ionosphere was still filling and had not yet reached diffusive equilibrium. Given the fact that flux tubes from the pole to the inner plasmopause boundary at $L \sim 2.5$ were predicted to have polar wind outflow, the total magnitude of mass transport into the magnetosphere could be very large, of the order of 10^{25} – 10^{26} ions/sec (Moore et al. 1997; Ganguli 1996; Andre and Yau 1997). Measurements by Hoffman et al. (1970) from the ion mass spectrometer on the ISIS satellite confirmed the polar wind outflow showing H^+ and He^+ velocities of 10–20 km/sec and upward fluxes of a few times 10^8 ions/cm² sec.

In the early 1970s observations of stable auroral red arcs at the foot of field lines in the vicinity of the plasmopause first suggested an interaction between the energetic protons in the ring current and the low energy H^+ and He^+ ions and electrons near the plasmopause (Chappell et al. 1971; Cole 1965; Cornwall et al. 1971). This was the first identification of a mechanism in which the low energy plasma could potentially affect the dynamics of the energetic plasmas of the magnetosphere. As shown in Fig. 2, energy from the ring current

particles could be transformed into heating the cold plasma through coulomb collisions or wave particle interactions and the heat could be transmitted down the flux tube into the atmosphere resulting in heating and causing a resulting emission at 6300 Å. Hence, the motion of the plasmapause could influence the dynamics of the inner edge of the ring current.

One of the most significant influences in the magnetospheric community's perception of the role of the ionosphere as a source of plasma for the magnetosphere came from measurements in the early 1970s by the Lockheed group. These measurements showed energetic, keV ions of H^+ , He^+ and then O^+ streaming up the magnetic field lines above the auroral zone (Shelley et al. 1972; Sharp et al. 1977). The idea that energetic ions could flow upward into the magnetosphere and that some of them (He^+ and O^+) were definitely of ionospheric origin, was a transforming one. Suddenly, the door was opened to the realization that the low energy plasma of the ionosphere could become energized to the energies characteristic of the magnetosphere and could flow upward into the principal regions of magnetospheric dynamics—the ring current and plasma sheet. This spurred the need for measurements of the composition of energetic particles in the magnetosphere, a need that was met on the ISEE and GEOS set of satellites later in the decade (Shelley et al. 1978; Lennartsson et al. 1979; Young et al. 1982). These new plasma composition instruments verified the presence of ionospheric O^+ in the plasma sheet and ring current. The energy range of this instrument, however, did not effectively include ions with energies below 100 eV, both because of limited geometric factors and because of the typically positive charging of satellites at high altitudes, where surrounding ambient electron densities were not large enough to give a return current to the satellite that could offset the escaping photoelectron current. The resulting positive spacecraft charge prohibited the measurement of the lower energy polar wind ions and hence could not verify their presence out in the magnetosphere.

Thus, at the end of the 1970s interest in the influence of low energy plasma in the magnetosphere had grown. However, its influence was limited to its potential role in destabilizing the hot plasmas of the ring current and radiation belts, which was considered to be a secondary influence on magnetospheric dynamics. It was also accepted that energetic ions of ionospheric origin could contribute to the ring current and plasma sheet populations and could influence magnetospheric dynamics in certain circumstances. However, the ion outflow that was considered was limited to the more energetic outflows that are directly connected to the auroral oval precipitation processes and not to the low energy polar wind fluxes.

3 The Decade of the 1980s

As a result of increasing interest by the atmosphere-ionosphere-magnetosphere community regarding the coupling of these regions in terms of both particles and fields, a new mission, Electrodynamics Explorer, was planned. It grew out of community discussions that were focused by two AGU Chapman Conferences held at Yosemite National Park in 1974 and 1976. As the mission planning progressed, budget decisions led to a limiting of the scope of the mission, becoming Dynamics Explorer (DE). The two spacecraft, one ionospheric and one magnetospheric in coplanar polar orbits, were launched in 1980. They were designed to probe all of the elements of the coupling between the ionosphere and the magnetosphere.

One particular goal of DE was to measure the upward flow of particles from the ionosphere toward the magnetosphere. This goal was realized through measurements such as those from the Lockheed and Marshall Space Flight Center (MSFC) groups, which showed the broad presence of upward flowing ions with energies ranging from the few electron volt polar wind shown in Fig. 3 (Nagai et al. 1984) to the auroral energies of 100's of

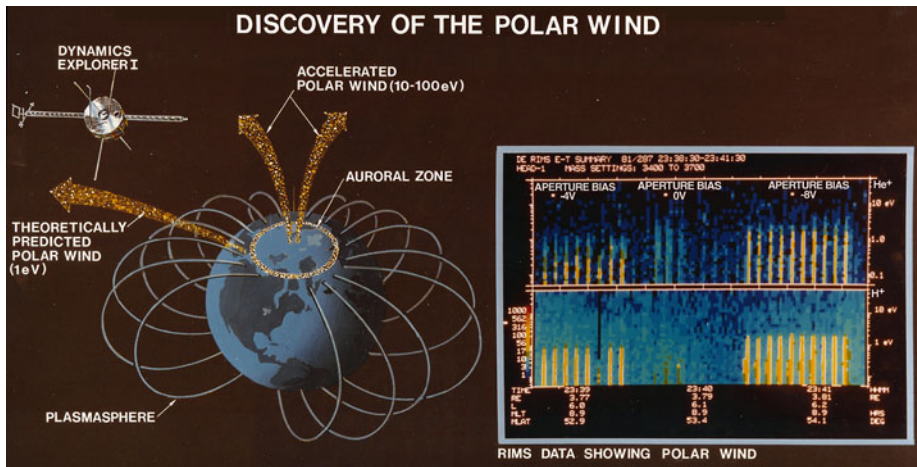


Fig. 3 A segment of data showing the DE Retarding Ion Mass Spectrometer measurements of the low energy polar wind ions flowing upward out of the ionosphere at MLT 8:54, $L = 6.1$, $3.8R_E$ geocentric altitude. By alternately placing bias potentials of -4 , 0 and -8 volts on the entrance aperture of the instrument, the low energy polar wind positive ions with energies of 1 eV can be seen when the spinning instrument looked down the magnetic field line (yellow bars, He^+ top panel and H^+ bottom panel)

eV to 10 's of keV (Gurgiolo and Burch 1982; Yau et al. 1985; Lockwood et al. 1985; Chandler et al. 1991). The low energy polar wind was found to be flowing out of the polar cap where it was intermixed with more energetic particles flowing up from the polar cusp. The ions associated with the auroral zone were easier to measure than the polar wind because of their higher energies which could overcome the positive potential of the spacecraft.

In this same time period, Cladis (1986) showed theoretically how very low energy outflowing ions could become energized to >10 eV through a centrifugal acceleration caused by the ions flowing along the curving magnetic field in the polar cap and through the cross-tail convection electric field. This energization allowed the low energy ions to be pushed farther out into the magnetospheric tail where other acceleration processes could energize them even more. The lower and higher energy outflows overlapped, especially in the polar cap and were sent outward into the lobes of the magnetotail and possibly the plasma sheet. In sum, there was a large amount of outflow when the polar wind and the auroral zone outflows were added together. Initial estimates showed total fluxes out of the ionosphere of 10^{25} – 10^{26} ions per second.

The magnitude of the total ion outflow, both the low energy polar wind and the higher energy auroral zone ions, led to the first idea that there might be enough ions flowing from the ionosphere to the magnetosphere to fill up the different regions of the magnetosphere to the observed levels. Chappell et al. (1987) looked into this possibility; their concept is shown in Fig. 4. In the inner magnetosphere, the upward flowing polar wind would fill up the flux tubes inside of the plasmapause location as the tubes continued to circulate with the Earth and not intersect the magnetopause where plasma could be lost. Just outside of the plasmapause, upward flowing polar wind particles could be convected to the magnetopause and lost to the magnetosheath on the dayside.

At higher L -shells, the outward flowing polar wind ions would be swept over the polar cap where they could become energized as they drifted through the polar cusp or later by the higher altitude centrifugal acceleration process. These ions would flow out through the lobes of the magnetotail and, depending on the B_z component of the solar wind magnetic

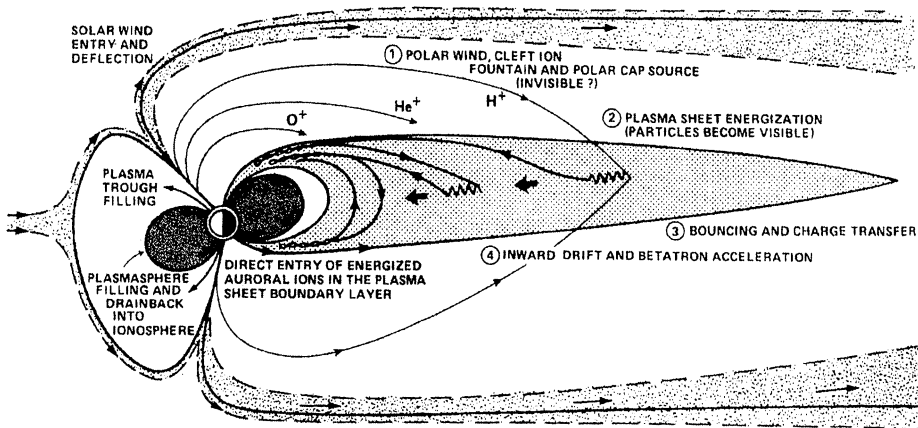


Fig. 4 A sketch of the flow of polar wind and auroral ions upward out of the ionosphere and into the outer magnetosphere. The polar wind ions move through the lobes of the tail into the downstream plasma sheet and the auroral zone ions move directly upward into the inner plasma sheet. In combination, they represent a significant ionospheric source of plasma for the magnetosphere

field at the magnetopause, could drift into the plasma sheet or escape anti-sunward through the lobes of the tail. The low energy polar wind portion of these outflowing ions would not be measurable because of the positive potentials that develop on spacecraft in the tail lobes and outer plasma sheet. These particles would only become visible after they became energized in the plasma sheet because of their movement through the cross-tail potential or because of magnetic reconnection processes. After their energization they would “appear” in the plasma sheet with higher energies. In addition to the polar wind particles, the more energetic upflowing ions from the polar cusp could also be swept across the polar cap into the plasma sheet with the upflowing ions from the nightside auroral zone moving directly upward into the more near-Earth plasma sheet.

Chappell et al. (1987) utilized the DE information on the magnitude of the polar wind and auroral zone outflow and followed the approximate motion of the ions out through the magnetotail lobes, into the plasma sheet, and subsequently into the ring current. Using the approximate volumes of the plasma sheet and ring current and estimating the residence time that an ion would spend drifting through these regions, the densities of the plasma sheet and ring current ions caused by ion outflow could be calculated. It was found that the densities predicted for the lobes of the magnetotail, the plasma sheet and the ring current matched the observed densities very well.

In summary, there appeared to be enough plasma flowing out of the ionosphere to adequately fill up the major regions of the magnetosphere. But does this really happen? Since it was virtually impossible to measure the low energy polar wind ions in the lobes of the tail because of the positive spacecraft potential, this filling mechanism from the ionosphere was not significantly embraced by the magnetospheric community. Consequently, the concept of solar wind access through the polar cusp and the flanks of the magnetotail remained the dominant explanation of the magnetospheric plasma source mechanism at the end of the 1980s.

4 The Decade of the 1990s

One of the uncertainties of the Chappell et al. (1987) paper had been not knowing the more exact trajectories of the ions as they flowed upward through the changing magnetic field and

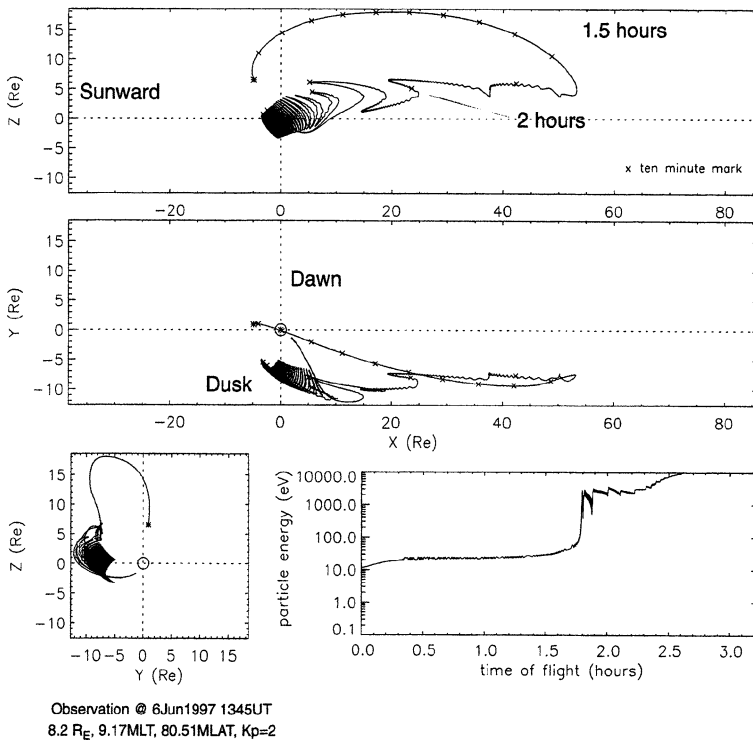
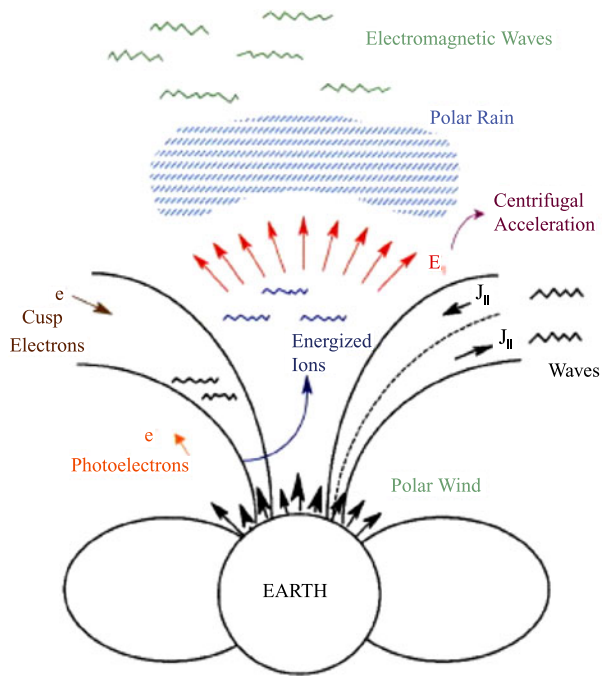


Fig. 5 Results of the tracing of the flow trajectories of a low energy ion which leaves the ionosphere and moves through the magnetosphere, gaining energy as it moves through the cross-tail potential in the magnetosphere. By following the time marks on the energy plot in the *lower right*, and matching them with the two time tags on the trajectory in the *upper plot*, one can see how the initially low energy ion gains energies representative of the plasma sheet and ring current

convection electric field. Delcourt et al. (1993) completed a set of ion trajectory calculations that showed more clearly how ions starting at different locations in the mid and high latitude ionosphere would move into the different regions of the magnetosphere. An example of this trajectory study is shown in Fig. 5. In this figure, an H^+ ion which represents a classical polar wind ion that has been centrifugally accelerated flows out through the lobe of the tail and into the duskside plasma sheet. As it curvature drifts from midnight toward dusk in the cross-tail potential, it is accelerated to energies characteristic of the plasma sheet after it enters that region. As it drifts farther earthward, its energy is increased to 10 keV, characteristic of the ring current region. The first three plots in the figure show the XZ, XY and YZ planes respectively. The times shown on the first plot can be matched with times in the fourth plot of energy versus time to see how the particle gains energy as it moves through the plasma sheet and ring current regions.

The surprising result of this analysis by Delcourt et al. (1993) is not only that the ions drift through the different major regions of the magnetosphere, but that they become energized to the level of energy characteristic of each region. Hence, the same particle can become part of several different major magnetospheric regions as it drifts through the magnetosphere. The Delcourt et al. (1993) ion trajectories were run for the different major upflowing ions, H^+ , He^+ and O^+ to demonstrate how they move through the magnetosphere. Different initial pitch angles for the outflowing particles can also be used. The different masses and pitch

Fig. 6 A sketch illustrating the different acceleration processes that can come into play as a “classical” polar wind ion moves along its flow path through the ionosphere and magnetosphere, becoming the “generalized” polar wind



angles have a significant influence on the energization and fate of each individual particle. This suggests that ionospheric exit location, energy, pitch angle and mass are important in calculating where the particle will go in the magnetosphere and what different energies it will obtain.

Another advancement that took place in this decade was the further development of the polar wind models by scientists at Utah State University (Demars and Schunk 1994; Barakat et al. 1995; Schunk and Sojka 1997). They continued to add important elements to the equations that explained the origin of the outflowing ions and the subsequent energization as the ions moved upward and across the polar cusp, polar cap and nightside auroral oval as shown in Fig. 6. The model was run for different flux tubes that are convecting through the high latitude magnetosphere from sunlight to darkness at the foot of the field line and for different magnetic activity levels, seasons and solar activity conditions. This modeling work began to close the identity gap between the initial classical polar wind results and the polar cusp and auroral zone related outflow. It also filled in the understanding of how a single ion can be influenced by a number of different flow and energization mechanisms as it moves upward into the magnetosphere.

In concert with these modeling advancements, the International Solar Terrestrial Physics (ISTP) mission gave multi-point measurements of the magnetosphere and solar wind from the Polar, Geotail and Wind spacecraft. The Polar satellite in particular measured the major outflow region from mid to high latitudes at altitudes of 5000 km to more than 9 earth radii. This spacecraft was instrumented in a way that covered both the low energy and more energetic ion composition and dynamics. The MSFC Thermal Ion Dynamics Experiment (TIDE) design was optimized to measure the mass composition and dynamics of the low energy polar wind plasma (Moore et al. 1995). The spacecraft also contained a plasma neutralizer that successfully limited the satellite positive potential when it was operated. The TIDE instrument had six opening apertures that were quite large (2 cm by 5 cm) in order to

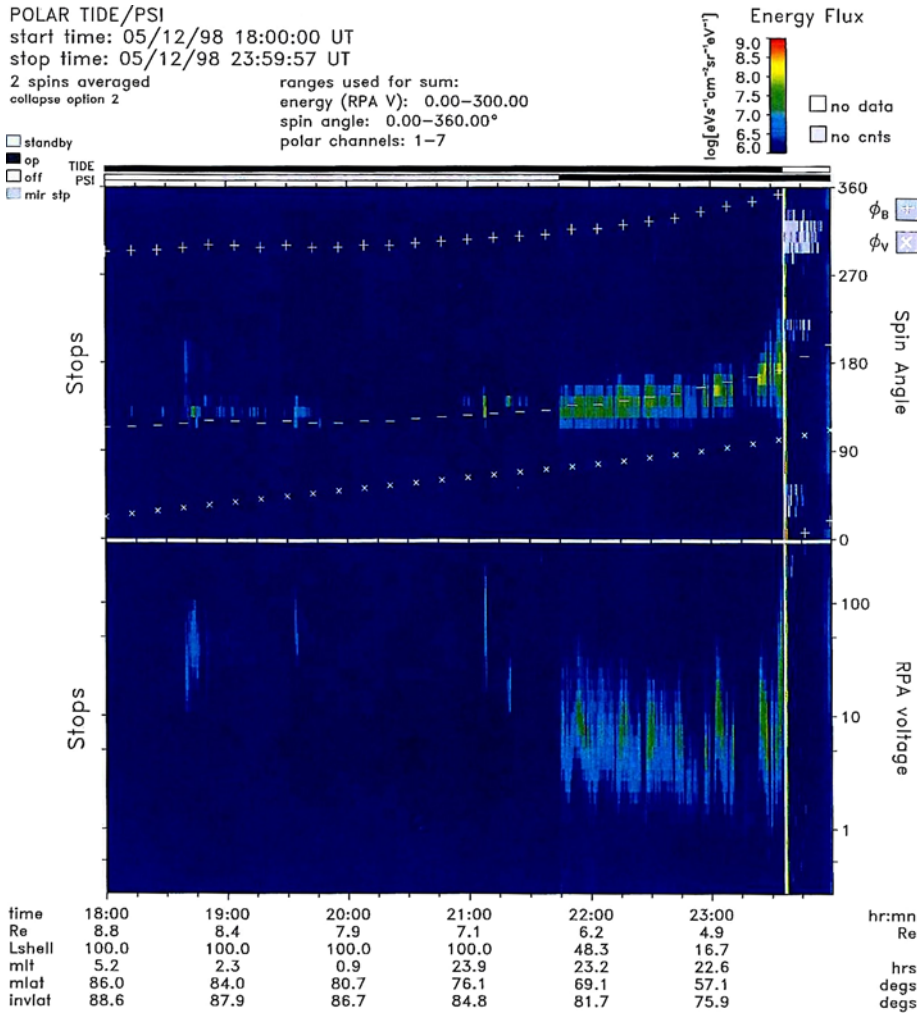


Fig. 7 A TIDE pass across the polar cap and magnetotail lobe with the Plasma Source Instrument turning on during the pass at 2145 UT. Outflows along the field line (*upper panel*) of less than 10 eV (*lower panel*) are hidden view until PSI is activated

get a geometric factor that is large enough to be able to measure the angular distribution of the low velocity polar wind ions. This necessarily large geometric factor makes it difficult if not impossible to use a single instrument to measure the full energy spectrum of ions from an eV to 10's of keV. It has been the case that many succeeding missions have not included an instrument that is specifically designed to measure the characteristics of the low energy plasma; hence this area of knowledge has not been as effectively advanced.

It is important to note that the Polar spacecraft potential was typically positive by 1 or 2 volts even at the low altitudes of 5000 km and this is large enough to prevent the full measurement of the outflowing polar wind. At high altitudes, spacecraft potentials reached 10's of volts positive in the lobe of the tail. With the spacecraft potential control, the TIDE measurements have demonstrated that the polar wind is present in this broad altitude range as shown in Fig. 7 (Moore et al. 1997; Su et al. 1998; Chappell et al. 2000). However, it was

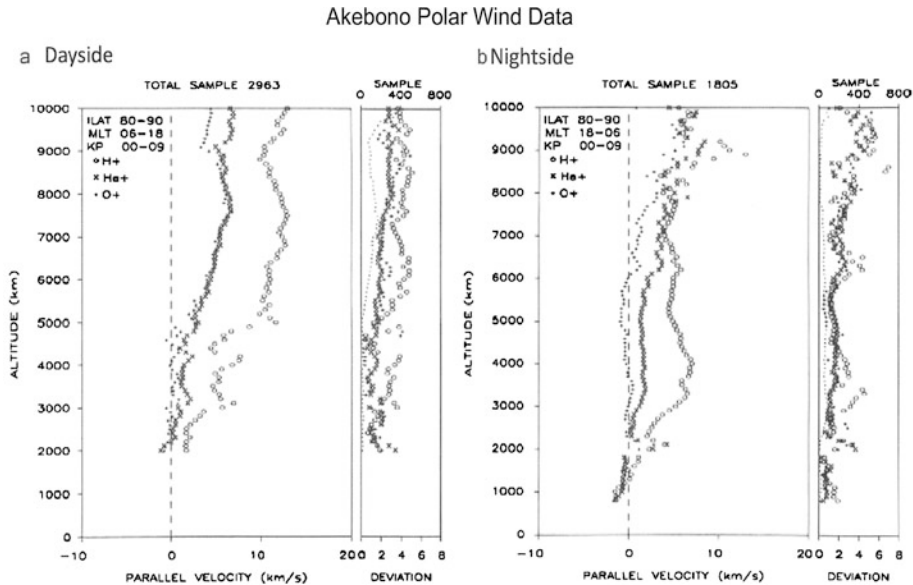


Fig. 8 Akebono SMS data on the outflow velocities of the polar wind versus altitude on the dayside and nightside of the ionosphere

only possible to get glimpses of the polar wind when the plasma source neutralizer was operating. The neutralizer operation was limited during the mission because of the concern by other experimenters about interference from the ionized xenon plasma cloud created by the neutralizer source. Any future spacecraft without potential control will have its direct measurements of the cold flowing particle characteristics compromised.

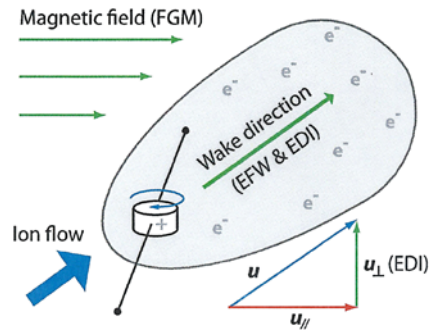
An extensive set of measurements of outflowing H^+ , He^+ and O^+ ions was also made by the suprathermal mass spectrometer (SMS) ion mass spectrometer on the Akebono satellite in this time period. Akebono had a lower altitude orbit than Polar. Figure 8 shows example results from Akebono with upward velocities in the 5–15 km per second range. The Akebono results showed very large fluxes of O^+ , which probably reflects the contribution from energization processes in the polar cusp and subsequent drift across the polar cap (Abe et al. 1993, 1996; Yau and Andre 1997; Andre and Yau 1997; Cully et al. 2003a). The measured outflow fluxes were $1\text{--}3 \times 10^8$ ions/cm² sec, as theory had predicted, with a total flux estimated at $10^{25}\text{--}10^{26}$ ions/sec.

Therefore, the experimental verification of the presence of the low energy polar wind at low and high altitudes continued. In addition the increasingly effective modeling of the polar wind generation in the topside ionosphere and its transit upward into the magnetosphere became more accurate. This transit was found to take the low energy ions to regions which strongly influence magnetospheric dynamics and thus set an even stronger foundation for needing to understand the role of the ionosphere as a source of magnetospheric plasma. Yet, somewhat surprisingly, the magnetospheric community acceptance of this idea still remained limited.

5 The Decade of the 2000s

The enhanced measurement techniques for characterizing outflowing ions combined with the better modeling understanding of their origin in the ionosphere and their transport to the

Fig. 9 A schematic drawing of the Cluster spacecraft showing the wake of the spacecraft and the two independent electric field measurements which could be combined with the magnetic field data to determine the flow velocity (u parallel) of the very low energy plasma in the magnetotail. Combining the flow velocity with the measured density gives the flux of the low energy ions



magnetosphere were used in two studies to do a more refined assessment of how effectively the ionosphere can act as a source for magnetospheric plasmas. Cully et al. (2003b) used the Akebono measurements of ion outflow together with some basic transport trajectories and calculated the adequacy of the ionospheric source to fill the magnetosphere. He found the ionosphere to be a significant source of magnetospheric plasma, which varied depending on the level of magnetic activity.

Huddleston et al. (2005) refined the Chappell et al. (1987) calculations by using the new TIDE data from Polar with adjustments for spacecraft potential influences coupled with the ion trajectory mapping of Delcourt et al. (1993). Measured fluxes and pitch angles of ions in different invariant latitude/magnetic local time boxes at 5000 km altitude were transported using the Delcourt et al. (1993) trajectory mapping and summed to show how the filling of the magnetosphere could take place. The low energy polar wind outflows combined with the more energetic auroral zone ion outflow showed again that the ionosphere was a significant source of plasma to the magnetosphere, which could be the dominant source under certain magnetic storm conditions. However the question of whether the low energy plasma really flows up through the “empty” lobes of the magnetotail and intersects the plasma sheet still remained unanswered. Limited measurements from Polar showed the presence of this “lobal wind” (Liemohn et al. 2005), so there was reason for optimism about the presence and influence of the polar wind out in the magnetosphere.

Then came the Cluster mission with its 4 spacecraft flying in relatively close formation through the magnetosphere with perigee of $4R_E$ and apogee of $19R_E$. These spacecraft carried the Composition and Distribution Function Analyzer (CODIF), a mass spectrometer capable of measuring the H^+ , He^+ and O^+ with energies ranging from 40 eV to 40 keV, (Reme et al. 2001) as well as two independent measurements of the electric field using a set of probes on wire booms (Gustafsson et al. 1997) and a new energetic electron emitting device which could inject and “catch” the electrons after they had spiraled back to the spacecraft (Paschmann et al. 1997). By measuring their spatial displacement during their spiral motion in the magnetic field, the electric field could be derived. In addition there was a spacecraft potential control device which was operated periodically (Tokar et al. 2001). It was this unique, complete set of instruments (see Fig. 9) combined with some impressive scientific detective work examining the location of the spacecraft wake shape that led to the clear demonstration of the extensive presence of the cold flowing polar wind ions moving throughout the lobes of the geotail and then into the plasma sheet at distances that depended on the character of the solar wind flow and magnetic field direction (Engwall et al. 2006, 2009a, 2009b; Nilsson et al. 2010; Haaland et al. 2012; Andre and Cully 2012). This suite of measurements was able to successfully determine the density, flow velocity, and fluxes of the low energy outflowing ions and to pull back the

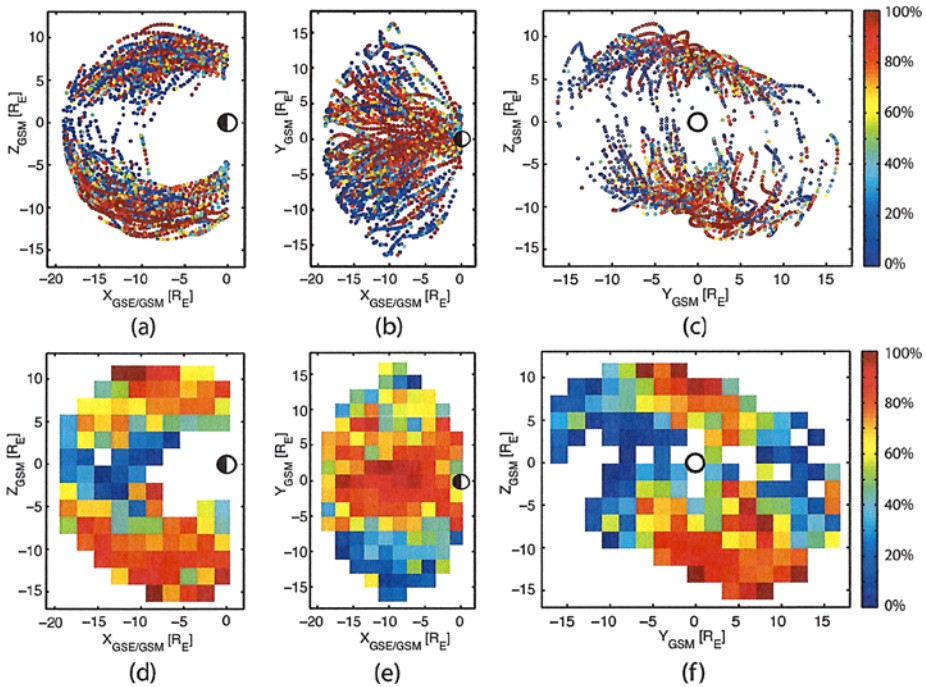


Fig. 10 Shows a collection of Cluster orbits through the magnetotail in the three orthogonal planes. These orbits are *color coded* to show the percentage probability that low energy outflow was seen (see *color bar*). The lower set of orbits have been averaged over a larger spatial area

curtain of spacecraft potential that had obscured the measurement of the presence of these ions in the magnetosphere for four decades.

Figure 10 of Engwall et al. (2009a) shows the portions of the cluster orbits where the low energy polar wind was seen. The orbits are shown in the XZ, XY and YZ planes with a color scale along the orbit that shows the probability that the low energy flowing ions have been measured. The probabilities are significant and the ions are located where the trajectory models would predict. The lower part of the figure shows an average of the individual measurements presented in larger spatial blocks with the probability of observing the outflowing ions shown by the color scale. Figure 11 shows the ion density and flow directions of the low energy polar wind flows in the XZ and XY planes averaged into spatial blocks. Again, the flow directions and densities are as expected from the ionospheric polar wind and ion trajectory calculations. The measured fluxes in the geotail lobes are also as expected from the polar wind models. Mapped back to the topside ionosphere along the flux tubes, the outflow fluxes are in the $1\text{--}3 \times 10^8$ ions/cm² sec range, as predicted by the theory, with the total outflowing flux of ions at $10^{25}\text{--}10^{26}$ as shown in Fig. 12.

Do these newly unveiled polar wind outflows in the lobe of the magnetospheric tail enter the plasma sheet? Fig. 13 from Haaland et al. (2012) shows the flow pattern for polar wind ions that are injected from the ionosphere for three different cases. In each case, the north/south component of the solar wind magnetic field is changed, increasing more southward from case a to case c. Note that with the southward component increasing as would be expected during magnetic storms, progressively more of the polar wind outflow is transported into the plasma sheet region where it can become energized, populating the plasma

Fig. 11 A cut through the tail of the magnetosphere in the XZ plane with arrows showing the magnitude and direction of the low energy ion outflow

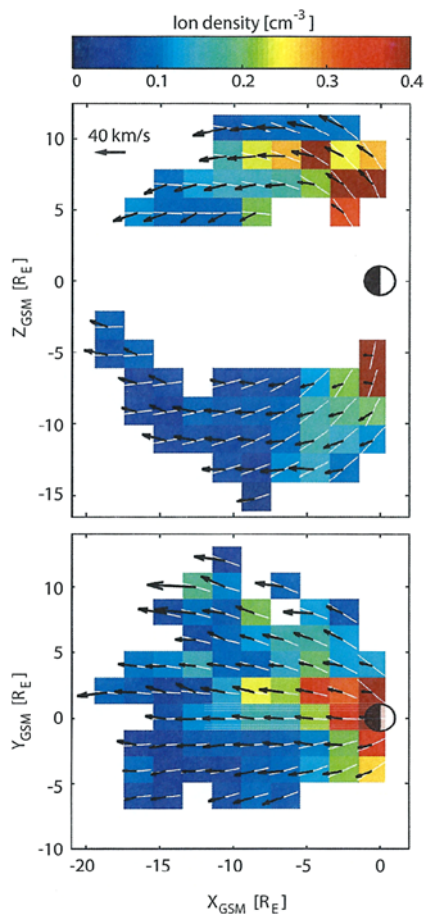


Fig. 12 A plot of the total ion outflow in the magnetotail as a function of K_p as measured by Cluster, Akebono and DE-1. The measured outflow is very similar for the three spacecraft

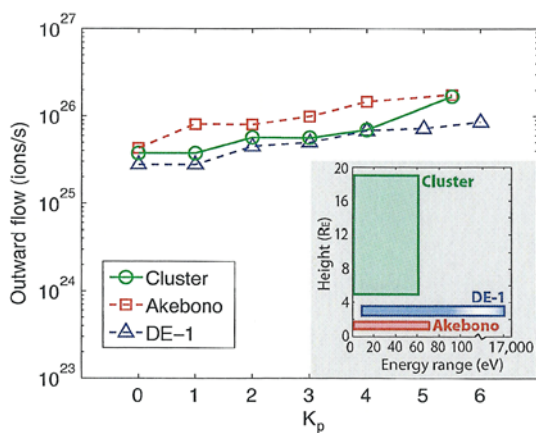
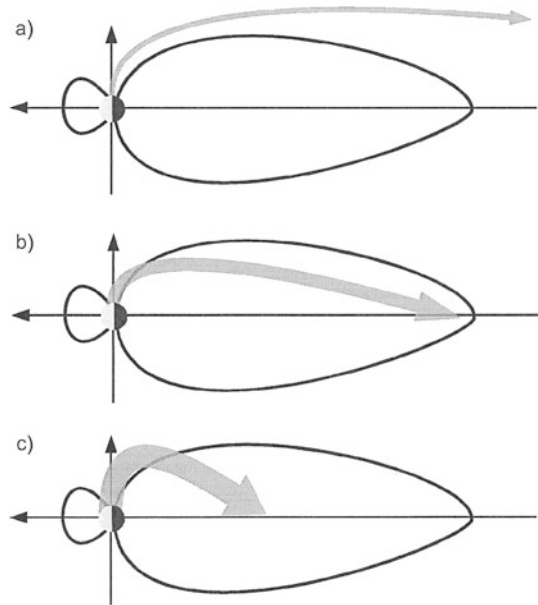


Fig. 13 Shows the calculated flow direction of the low energy ion outflow based on the flow velocity and the cross-tail potential. Based on the increasing strength of the southward component of the solar wind magnetic field from case (a) to (c), more of the outflow goes into the plasma sheet and less is lost down the tail



sheet. During southward IMF, more than 90 % of the polar wind ions enter the plasma sheet where they can gain energy typical of the plasma sheet particles and become “visible” to the medium energy range instruments given that the spacecraft potential no longer prohibits their observation.

The strength of the ionospheric outflow is known to be affected by the variation in the characteristics of the solar wind as it impinges on the magnetosphere. Changes in solar wind pressure can enhance the magnitude of the outflow (Pollock et al. 1990; Moore et al. 1999, and Cladis 2000) and will play a role in the future determination and modeling of the ion outflow. In addition to the H^+ and He^+ ions expected in the classical polar wind, extensive Cluster measurements using the CODIF instrument by Kistler et al. (2010), show large amounts of O^+ flowing out of the ionosphere caused by a variety of energization processes such as energization from particle precipitation and waves related to the polar cusp (Liao et al. 2010; Mouikis et al. 2010). Although this paper has concentrated on the outflow related more to the classical polar wind, it is clearly the sum of polar wind, polar cusp and nightside auroral zone outflows that combine to make up the total ionospheric mass transport outward into the magnetosphere.

With the flight of new instrumentation that has been able to image the characteristics of the low energy He^+ ions using their emission in 304 angstrom radiation, an enhanced perspective of the more dense low energy plasma the plasmasphere has become possible (Burch 2001). By following the changes in the distribution of these emissions, the evolution of the plasmasphere shape can be determined. During changing magnetic storm times, the plasmasphere is seen to be compressed in the nightside region and distended into tail-like plumes on the dusk side (Goldstein et al. 2003; Goldstein and Sandel 2005). These plumes which range from large and smooth to highly spatially variable extend out toward the magnetopause and have been measured as they cross geosynchronous orbit by the LANL spacecraft (Borovsky and Denton 2008). These “motion picture” images of the changing plasmasphere have verified dynamics measurements that were derived from the earlier spacecraft such as OGO, ISEE, and Polar and give a broader understanding of their evolving nature. Addi-

tional measurements showed that these regions of enhanced density were able to drift out to the dayside magnetopause where they are expected to effect the rate of magnetospheric reconnection with the incoming solar wind (Su et al. 2012). As the low energy plasma drifts outward toward the magnetopause, the ionospheric signature of these enhanced density flux tubes can be seen simultaneously (Foster et al. 2014) and their motion can be tracked as they move northward in the ionosphere and through the cusp region.

Hence, the low energy ionospheric-origin plasma can not only act as a source for the more energetic plasma in the magnetosphere; its presence in the magnetopause reconnection region can influence the rate of reconnection and the resultant strength of the magnetospheric convection electric field. Elphic et al. (1997) have shown that the low energy plasma that was convected sunward to the magnetopause and magnetosheath can be carried back toward the tail where it may re-enter the magnetosphere and contribute to the plasma sheet.

In summary, the low energy ionospheric plasma can flow upward from the polar regions directly into the plasma sheet region where it is energized to populate the plasma sheet and ring current or it can flow upward at lower latitudes where it initially fills the low energy plasmasphere and subsequently can be peeled off of the outer dusk region during storms, convected to the magnetopause, can enter the magnetosheath, and be carried back into the tail where it is available to become energized and to contribute to the population of the plasma sheet and ring current in a different way. This latter process adds a new dimension to the ionospheric source through the process of possible recirculation of the low energy plasma through the magnetosphere.

In addition to these new measurements, results from the NSF Geospace Environment Modeling program have brought the modeling of the mass coupling between the ionosphere and the magnetosphere more into focus. The generalized polar wind models, which include all of the energization elements that affect the outflowing ions, are being developed by several groups (Barakat and Schunk 2006; Glocer et al. 2009). The outflow models are now being coupled to the magnetospheric models with the generalized polar wind outflow becoming the source input to the magnetospheric models with promising results (Winglee 2000; Moore et al. 2005; Fok 1999; Welling and Ridley 2010; Welling et al. 2011; Nilsson et al. 2013; Glocer et al. 2009; Brambles et al. 2010).

As an example, the work of Welling and Ridley (2010) adds the ionospheric source to the magnetospheric models and gives an important result that shows the dominant role that the ionosphere can play during southward B_z conditions in the solar wind. In Fig. 14 the relative contribution of the ionosphere (blue) and the solar wind (red) can be seen in two cuts through the magnetosphere—the $Y = 0$, and the $Z = 0$ planes. The two panels on the left show the case in which the IMF B_z is southward and on the right when the IMF B_z is northward. In the two panels on the left, the ionospheric source is dominant in contrast to the two panels on the right where the solar wind contribution is more dominant. In addition to the issue of the plasma population, the inclusion of the ionospheric source in these models brings about a better agreement with a number of measured magnetospheric parameters such as the magnitude of the cross polar cap potential. The prospects for these merged modeling studies are very positive.

6 Summary

The advancement of both measurement and modeling of the ionospheric outflow and its transport throughout the magnetosphere has led to a new understanding of this fundamentally important mass coupling process in the Earth's space environment. Not only does the

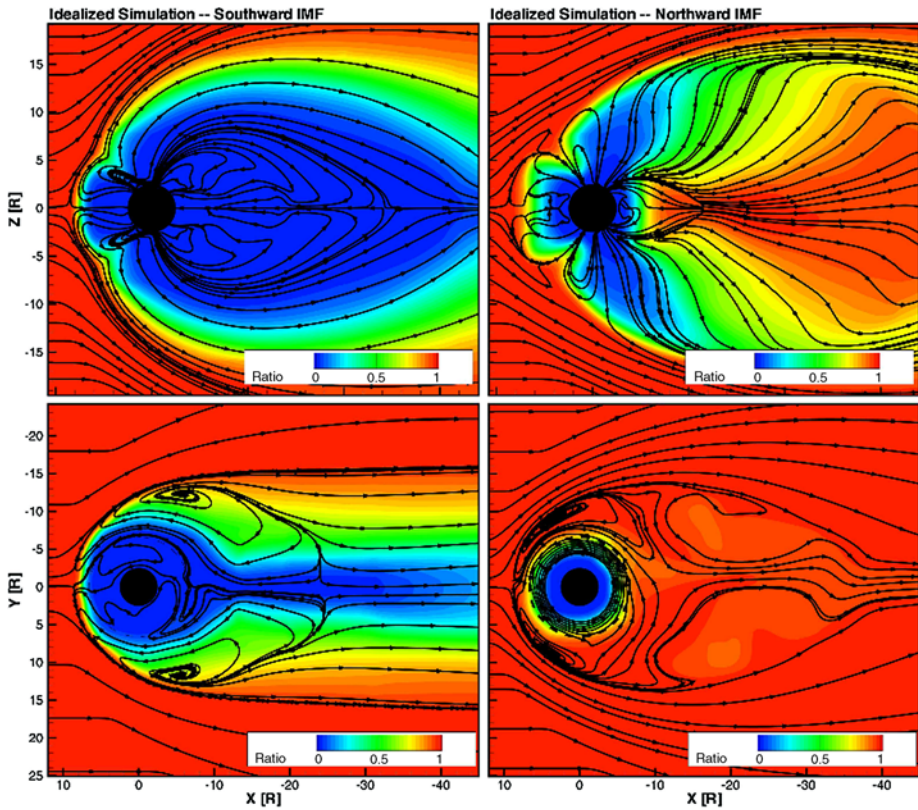


Fig. 14 Shows modeling results which include an ionospheric source. The *top panels* show the $Y = 0$, XZ plane and the *bottom panels* show the $Z = 0$, XY (equatorial) plane. The *two panels on the left* show the case for IMF B_z southward and *on the right* for IMF B_z northward. The *color contours* represent the ratio of the ionosphere to solar wind plasma as shown on the *color bar with blue indicating all ionosphere and red indicating all solar wind*. *Black lines* show plasma streamlines

low energy polar wind plasma flow upward from the ionosphere to the magnetosphere as predicted by early measurements and models more than 30 years ago; it is found that as it moves through the magnetosphere, it becomes energized to the levels that are characteristic of the regions through which it moves. This transport and energization is in agreement with the plasma characteristics found in the polar cap, magnetotail lobes, plasma sheet, ring current and warm plasma cloak. This filling process is shown in Fig. 15 from Chappell et al. (2008). The general motion from the ionosphere upward through the polar cap and lobe of the geotail and into the plasma sheet region can be seen. The ultimate fate of an upflowing ionospheric ion is determined by the location of its exit from the ionosphere, its energy, pitch angle and mass, and the action of acceleration processes that affect it as it flows into the magnetosphere. The energy that it gains as it moves through the polar cap (blue) and lobes (green) will determine how far back into the tail it flows and where it enters the plasma sheet. This entry point then determines its future energization.

As indicated in Fig. 15, ions which enter the plasma sheet closer to the Earth and on the dawn side of the tail, will be energized less and will drift earthward to form the warm plasma cloak region as indicated in yellow. Ions which are carried farther back into the tail

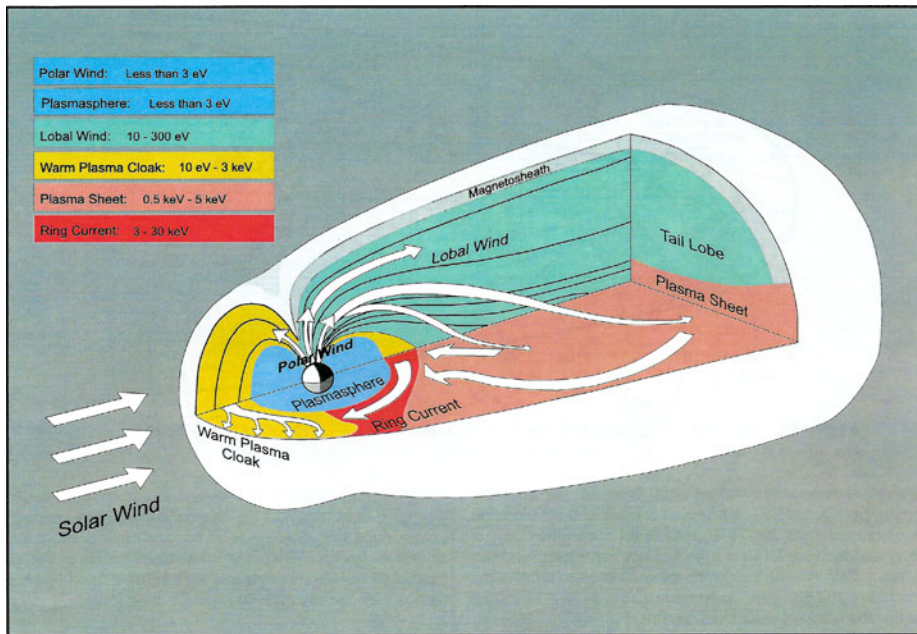


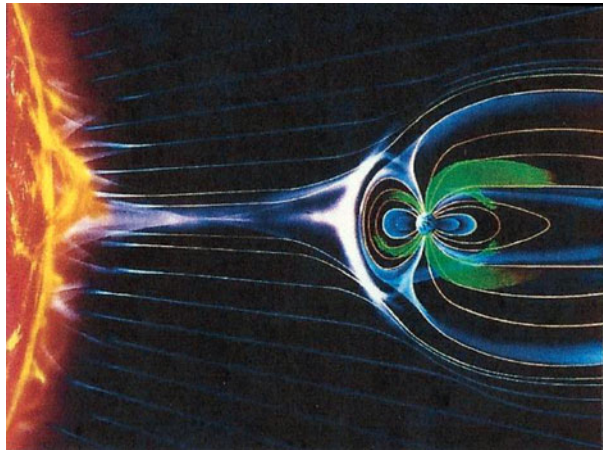
Fig. 15 A sketch of the magnetosphere showing the motion and energization of low energy ionospheric plasma as it moves through the magnetosphere. Beginning at a few eV of energy in the ionosphere, it is transported from the polar cap, through the lobes of the tail into the plasma sheet and then into the warm plasma cloak or the ring current depending on the point of entry into the plasma sheet

enter the plasma sheet region at greater distances. These ions move through the neutral sheet region at points where the magnetospheric magnetic field is more distended (non-dipolar) which causes them to have more curvature drift and hence more movement across the cross-tail potential drop. These ions are energized to plasma sheet energies (pink) and then drift earthward gaining further energy through betatron acceleration to become part of the ring current (red). This view of magnetospheric filling is still not widely understood or appreciated within the space physics community. The recent Engwall et al. (2009a) measurements that have thoroughly solved the mystery of the invisible low energy plasma transport into the magnetosphere regrettably remain unknown to many magnetospheric physicists.

Given the progress with understanding the role of the ionosphere in populating the magnetosphere, there is a different image evolving of the Earth's magnetosphere as shown in Fig. 16. The role of the solar wind in shaping the magnetosphere and delivering energy to the magnetosphere through merging at the nose, convection throughout the magnetosphere and reconnection in the tail is still in place. However, the source of the magnetospheric plasmas now takes on a different perspective. As shown by the green areas, representing ion outflow, the contributors to filling the magnetosphere now include the ionosphere in combination with the solar wind. The dominance of the ionosphere is a function of the characteristics of the solar wind at the nose of the magnetosphere. Both the plasma pressure, which has been statistically related to the amount of polar outflow, and the direction of the IMF, which determines the magnitude of the convection, influence the strength and ultimate energy of the ionospheric source particles.

As a corollary to the more realistic merged modeling, the future measurement of low energy plasma in the magnetosphere must be done more effectively than recent missions

Fig. 16 A revised sketch of the solar wind-magnetosphere region reflecting the addition of the ionospheric source *in green* flowing upward in the polar regions. In contrast to our earlier ideas about the solar wind origin of magnetospheric plasma, the ionosphere is now understood to make a significant and often dominant contribution



have done. It will be imperative that future missions have an instrument with a large enough geometric factor to be able to measure the mass, pitch angle and energy distributions of the very low energy (less than a few eV) ions so that the nature of the processes that transform them can be observed. In addition, there will have to be a potential control device on the spacecraft that will permit the low energy particles to reach the spacecraft without phase space distortion so that their measurement can be made. Combining the very low energy ion measurements into a single instrument with the medium to high energy measurements will most likely not be an acceptable approach. In times of tight budgets for NASA missions, the fundamental role that the ionosphere plays in populating the magnetosphere will have to be taken into consideration when the instruments are selected for the spacecraft.

Finally, it should be noted that the lessons learned from the terrestrial magnetosphere about the role of the ionosphere, should be remembered when considering the plasma sources of other solar system magnetospheres. In the case of Jupiter, the moon Io is certainly a very important source of magnetospheric plasma, but there are some indications from model calculations (Nagy et al. 1986) and measurements (McComas et al. 2007) that Jupiter's ionosphere is also playing a role in populating its magnetosphere. Since this is the case, it becomes very important to facilitate the interaction of those scientists who work on ionosphere-magnetosphere coupling at the Earth with those planetary scientists involved in understanding the coupled plasma and field environments of the planets. This ISSI Workshop has been an important step in bringing these groups together in order to share knowledge on measuring and modeling the fundamentally important coupling within the ionosphere and magnetosphere of different planetary systems.

References

- T. Abe et al., EXOS D (Akebono) suprathermal mass spectrometer observations of the polar wind. *J. Geophys. Res.* **98**, 11,191 (1993)
- T. Abe et al., Observations of polar wind and thermal ion outflow by Akebono/SMS. *J. Geomagn. Geoelectr.* **48**, 319 (1996)
- M. Andre, C.M. Cully, Low-energy ions: A previously hidden solar system particle population. *Geophys. Res. Lett.* **39**, L03101 (2012)
- M. Andre, A.W. Yau, Theories and observations of ion energization and outflow in the high latitude magnetosphere. *Space Sci. Rev.* **80**, 27 (1997)

- I. Axford, The polar wind and terrestrial helium budget. *J. Geophys. Res.* **73**(21), 6855 (1968)
- P.M. Banks, T.E. Holzer, The polar wind. *J. Geophys. Res.* **73**, 6846 (1968)
- P.M. Banks, A.F. Nagy, W.I. Axford, Dynamical behavior of thermal protons in the mid-latitude ionosphere and magnetosphere. *Planet. Space Sci.* **19**(9), 1053 (1971)
- P.M. Banks, R.W. Schunk, W.J. Raitt, Temperature and density structure of thermal proton flows. *J. Geophys. Res.* **79**(31), 4691 (1974a)
- P.M. Banks, R.W. Schunk, W.J. Raitt, NO^+ and O^+ in the high latitude F-region. *Geophys. Res. Lett.* **1**(6), 239 (1974b)
- A.R. Barakat, R.W. Schunk, A three-dimensional model of the generalized polar wind. *J. Geophys. Res.* **111**(A12), 1978 (2006)
- A.R. Barakat, I.A. Barghouthi, R.W. Schunk, Double-hump H^+ velocity distribution in the polar wind. *Geophys. Res. Lett.* **22**, 1857 (1995)
- J.E. Borovsky, M.H. Denton, A statistical look at plasmaspheric drainage plumes. *J. Geophys. Res.* **113**, A09221 (2008)
- O.J. Brambles et al., Effects of causally driven cusp O^+ outflow on the storm time magnetosphere-ionosphere system using a multifluid global simulation. *J. Geophys. Res.* **115**, A00J04 (2010)
- N.M. Brice, Bulk motion of the magnetosphere. *J. Geophys. Res.* **72**, 5193 (1967)
- H.C. Brinton et al., Altitude variations of ion composition in the midlatitude trough region: Evidence for upward plasma flow. *NASA Preprint*, X-621-70-311 (1970)
- J.L. Burch, Views of the Earth's magnetosphere with the IMAGE satellite. *Science* **291**, 619 (2001)
- D.L. Carpenter, Whistler evidence of a "knee" in the magnetospheric ionization density profile. *J. Geophys. Res.* **68**, 1675 (1963)
- M.O. Chandler, T.E. Moore, J.H. Waite, Observations of polar ion outflows. *J. Geophys. Res.* **96**, 1412 (1991)
- C.R. Chappell, Recent satellite measurements of the morphology and dynamics of the plasmasphere. *Rev. Geophys. Space Phys.* **10**(4), 951 (1972)
- C.R. Chappell, K.K. Harris, G.W. Sharp, Ogo 5 measurements of the plasmasphere during observations of stable auroral red arcs. *J. Geophys. Res.* **76**, 2357 (1971)
- C.R. Chappell, T.E. Moore, J.H. Waite Jr., The ionosphere as a fully adequate source of plasma for the Earth's magnetosphere. *J. Geophys. Res.* **92**, 5896 (1987)
- C.R. Chappell et al., The adequacy of the ionospheric source in supplying magnetospheric plasma. *J. Atmos. Sol.-Terr. Phys.* **62**, 421 (2000)
- C.R. Chappell et al., Observations of the warm plasma cloak and an explanation of its formation in the magnetosphere. *J. Geophys. Res.* **113**, A09206 (2008)
- J.B. Cladis, Parallel acceleration and transport of ions from polar ionosphere to plasma sheet. *Geophys. Res. Lett.* **13**, 893 (1986)
- J.B. Cladis, Observations of centrifugal acceleration during compression of magnetosphere. *Geophys. Res. Lett.* **27**, 915 (2000)
- K.D. Cole, Stable auroral red arcs, sinks for energy of Dst main phase. *J. Geophys. Res.* **70**(7), 1689 (1965)
- J.M. Cornwall, F.V. Coroniti, R.M. Thorne, Unified theory of SAR arc formation at the plasmopause. *J. Geophys. Res.* **76**(19), 4428 (1971)
- C.M. Cully et al., Akebono/Suprathermal Mass Spectrometer observations of low-energy ion outflow: Dependence on magnetic activity and solar wind conditions. *J. Geophys. Res.* **108**, 1093 (2003a)
- C.M. Cully et al., Supply of thermal ionospheric ions to the central plasma sheet. *J. Geophys. Res.* **108**, 1092 (2003b)
- D.C. Delcourt, J.A. Sauvaud, T.E. Moore, Polar wind ion dynamics in the magnetotail. *J. Geophys. Res.* **98**, 9155 (1993)
- H.G. Demars, R.W. Schunk, A multi-ion generalized transport model of the polar wind. *J. Geophys. Res.* **99**, 221 (1994)
- R.C. Elphic et al., The fate of the outer plasmasphere. *Geophys. Res. Lett.* **24**, 365 (1997)
- E. Engwall et al., Low-energy (order 10 eV) ion flow in the magnetotail lobes inferred from spacecraft wake observations. *Geophys. Res. Lett.* **33**, 6110 (2006)
- E. Engwall et al., Survey of cold ionospheric outflows in the magnetotail. *Ann. Geophys.* **27**, 3185 (2009a)
- E. Engwall et al., Earth's ionospheric outflow dominated by hidden cold plasma. *Nat. Geosci.* **2**, 24 (2009b)
- M.-C. Fok, Storm time modeling of the inner plasma sheet/outer ring current. *J. Geophys. Res.* **104**, 14557 (1999)
- J.C. Foster et al., Storm time observations of plasmasphere erosion flux in the magnetosphere and ionosphere. *Geophys. Res. Lett.* **41**, 762 (2014)
- S.B. Ganguli, The polar wind. *Rev. Geophys.* **34**, 311 (1996)
- A. Gloer et al., Modeling ionospheric outflows and their impact on the magnetosphere: Initial results. *J. Geophys. Res.* **114**, A05216 (2009)

- J. Goldstein, B.R. Sandel, The global pattern of evolution of plasmaspheric drainage plumes, in *Inner Magnetosphere Interactions: New Perspectives from Imaging*. AGU Geophysical Monograph Series, vol. 159 (2005)
- J. Goldstein et al., IMF-driven plasmasphere erosion of 10 July 2000. *Geophys. Res. Lett.* **30**, 1146 (2003)
- J.M. Grebowsky, Model study of plasmopause motion. *J. Geophys. Res.* **75**, 4329 (1970)
- K.I. Gringauz, The structure of the ionized gas envelope of Earth from direct measurements in the USSR of local charged particle concentrations. *Planet. Space Sci.* **11**, 281 (1963)
- C. Gurgiolo, J.L. Burch, DE-1 observations of the polar wind—A heated and an unheated component. *Geophys. Res. Lett.* **9**, 945 (1982)
- G. Gustafsson et al., The electric field and wave experiment for the cluster mission. *Space Sci. Rev.* **79**, 137 (1997)
- S. Haaland et al., Estimating the capture and loss of cold plasma from ionospheric outflow. *J. Geophys. Res.* **117**, A07311 (2012)
- J.H. Hoffman et al., Studies of the composition of the ionosphere with a magnetic deflection mass spectrometer. *Int. J. Mass Spectrom. Ion Phys.* **4**, 315 (1970)
- M. Huddleston et al., An examination of the process and magnitude of ionospheric plasma supply to the magnetosphere. *J. Geophys. Res.* **110**, 12,202 (2005)
- L.M. Kistler et al., Cusp as a source for oxygen in the plasma sheet during geomagnetic storms. *J. Geophys. Res.* **115**, A03209 (2010)
- W. Lennartsson et al., Some initial ISEE-1 results on the ring current composition and dynamics during the magnetic storm of December 11, 1977. *Geophys. Res. Lett.* **6**, 483 (1979)
- J. Liao et al., Statistical study of O⁺ transport from the cusp to the lobes with Cluster CODIF data. *J. Geophys. Res.* **115**, A00J15 (2010)
- M.W. Liemohn et al., Occurrence statistics of cold, streaming ions in the near-earth magnetotail: Survey of Polar-TIDE observations. *J. Geophys. Res.* **110**, A07211 (2005)
- M. Lockwood et al., A new source of suprathermal O⁺ ions near the dayside polar cap boundary. *J. Geophys. Res.* **90**, 4099 (1985)
- D.J. McComas, F. Allegrini, F. Bagenal, Diverse plasma populations and structures in Jupiter's magnetotail. *Science* **318**, 5848, 217 (2007)
- T.E. Moore et al., The thermal ion dynamics experiment and plasma source instrument. *Space Sci. Rev.* **71**, 409 (1995)
- T.E. Moore et al., High altitude observations of the polar wind. *Science* **277**, 349 (1997)
- T.E. Moore et al., Ionospheric mass ejection in response to a CME. *Geophys. Res. Lett.* **26**, 2339 (1999)
- T.E. Moore et al., Plasma sheet and (nonstorm) ring current formation from solar and polar wind sources. *J. Geophys. Res.* **110**, A02210 (2005)
- C.G. Moukikis et al., H⁺ and O⁺ content of the plasma sheet at 15–19 Re as a function of geomagnetic and solar activity. *J. Geophys. Res.* **115**, A00J16 (2010)
- T. Nagai et al., First measurements of supersonic polar wind in the polar magnetosphere. *Geophys. Res. Lett.* **11**, 669 (1984)
- A.F. Nagy, P.M. Banks, Photoelectron fluxes in the ionosphere. *J. Geophys. Res.* **75**(31), 6260 (1970)
- A.F. Nagy, A.R. Barakat, R.W. Schunk, Is Jupiter's ionosphere a significant plasma source for its magnetosphere? *J. Geophys. Res.* **91**, 351 (1986)
- H. Nilsson et al., Centrifugal acceleration in the magnetotail lobes. *Ann. Geophys.* **28**, 569 (2010)
- H. Nilsson et al., Hot and cold ion outflow: Observations and implications for numerical models. *J. Geophys. Res.* **118**, 1 (2013)
- A. Nishida, Formation of plasmopause, or magnetospheric plasma knee, by the combined action of magnetospheric convection and plasma escape from the tail. *J. Geophys. Res.* **71**, 5669 (1966)
- G. Paschmann et al., The electron drift instrument for Cluster. *Space Sci. Rev.* **79**, 233 (1997)
- C.J. Pollock et al., A survey of upwelling ion event characteristics. *J. Geophys. Res.* **95**, 18,969 (1990)
- H. Reme et al., First multispacecraft ion measurements in and near the Earth's magnetosphere with the identical Cluster ion spectrometry (CIS) experiment. *Ann. Geophys.* **19**, 1303 (2001)
- R.W. Schunk, J.J. Sojka, Global ionosphere-polar wind system during changing magnetic activity. *J. Geophys. Res.* **11**, 625 (1997)
- R.D. Sharp et al., Observation of an ionospheric acceleration mechanism producing energetic (keV) ions primarily normal to the geomagnetic field direction. *J. Geophys. Res.* **82**, 3324 (1977)
- E.G. Shelley, R.G. Johnson, R.D. Sharp, Satellite observations of energetic heavy ions during a geomagnetic storm. *J. Geophys. Res.* **77**, 6104 (1972)
- E.G. Shelley et al., Plasma composition experiment on ISEE-A. *Trans. Geosci. Electron.* **16**, 266 (1978)
- Y.J. Su et al., Polar wind survey with the thermal ion dynamics Experiment/Plasma source instrument suite aboard POLAR. *J. Geophys. Res.* **103**(29), 305 (1998)
- Y.J. Su et al., Plasmaspheric material on high-latitude open field lines. *J. Geophys. Res.* **106**, 6085 (2012)

- H.A. Taylor et al., Positive ion composition in the magnetosphere obtained from the OGO-A satellite. *J. Geophys. Res.* **70**, 5769 (1965)
- K. Tokar et al., Active spacecraft potential control for Cluster-implementation and first results. *Ann. Geophys.* **19**, 1289 (2001)
- D.T. Welling, A.J. Ridley, Exploring sources of magnetospheric plasma using multispecies MHD. *J. Geophys. Res.* **115**, A04201 (2010)
- D.T. Welling et al., The effects of dynamic ionospheric outflow on the ring current. *J. Geophys. Res.* **116**, A00J19 (2011)
- R.M. Winglee, Mapping of ionospheric outflows into the magnetosphere for varying IMF conditions. *J. Atmos. Terr. Phys.* **62**, 527 (2000)
- A.W. Yau, M. Andre, Sources of ion outflow in the high latitude ionosphere. *Space Sci. Rev.* **80**, 1 (1997)
- A.W. Yau et al., Energetic auroral and polar ion outflow at DE 1 altitudes: Magnitude, composition, magnetic activity dependence, and long-term variations. *J. Geophys. Res.* **90**, 8417 (1985)
- D.T. Young, H. Balsiger, J. Geiss, Correlations of magnetospheric ion composition with geomagnetic and solar activity. *J. Geophys. Res.* **87**(A11), 9077 (1982)

Plasma Sources of Solar System Magnetospheres

Nagy, A.F.; Blanc, M.; Chappell, C.R.; Krupp, N. (Eds.)

2016, V, 295 p. 134 illus., 89 illus. in color., Hardcover

ISBN: 978-1-4939-3543-7