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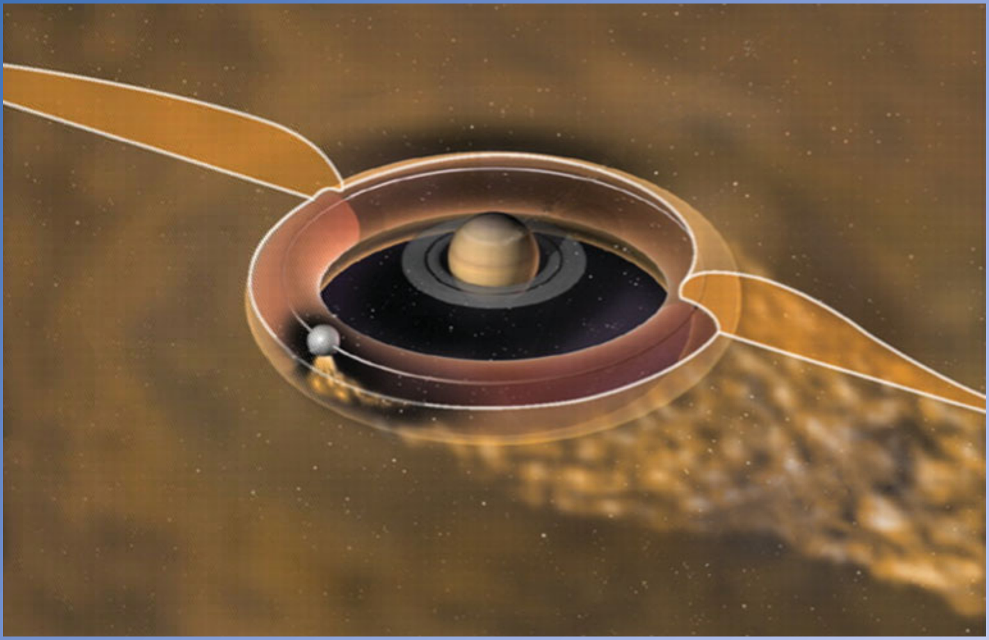
Plasma Sources of Solar System Magnetospheres



Andrew F. Nagy · Michel Blanc
Charles R. Chappell · Norbert Krupp *Editors*

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Editors

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Cover Image: Enceladus as a major source for Saturn's magnetosphere. Credit: Margaret Kivelson et al., Does Enceladus govern magnetospheric dynamics at Saturn? Science 311, 1391 (2006)

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Foreword

Michel Blanc[1] · **Andrew F. Nagy**[2]

In September 1999, ISSI published a volume entitled "Magnetospheric Plasma Sources and Losses", edited by Bengt Hultqvist and collaborators. This volume, which was the result of a two-year preparation and study process within the "ISSI Study Project on Source and Loss Processes", aimed at giving a comprehensive view of what we knew at that time of Earth's magnetospheric plasma sources and losses. To reach this ambitious objective, the team had divided the Earth's plasma environment into specific regions, and in each region the budget of sources and losses of plasma and energetic particles was established, based on the number of spacecraft investigations available. For the sources, essentially two were considered, the ionosphere and the solar wind, and the circulation paths by means of which these two sources feed each region were traced.

Approximately one and a half decade later, it seemed relevant to revisit this issue of plasma sources. Indeed, since the late 1990's comprehensive results from several orbital missions to the intrinsic planetary magnetospheres of the solar system have become available: Galileo at Jupiter, Cassini at Saturn, and more recently Messenger around Mercury. This is the reason why, following a suggestion by Andrew F. Nagy, the directors of ISSI decided to take advantage of this host of space missions to the planets to study the budget of plasma sources not only for the Earth, but this time for all intrinsic magnetospheres in our solar system. To this end, an ISSI workshop gathering over 40 of the best specialists working on these topics was held in Bern from September 23rd to 27th, 2013, with the task of performing a study of magnetospheric plasma sources in the solar system, and of preparing the writing of a comprehensive book on the subject.

In this perspective, the workshop participants had to face and manage the broad diversity of the subject: first, the diversity of the objects to be considered, from Mercury to Neptune, but also, and above all, the diversity in the sources of the plasmas themselves. While for Earth in 1999 we had, and still have a few years later, to consider only two plasma sources,

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ionosphere and solar wind, in our visit to all solar system magnetospheres we had to include new and complex plasma sources: satellites and rings (at the giant planets), or the planetary surface itself (for Mercury), some of which actually happen to be the dominant sources.

This book reports on our findings along this full tour of the solar system performed by the workshop participants. It starts with two introductory chapters which set the stage and provide the basic tools for our visit to solar system magnetospheres.

In the first introductory chapter, Rick Chappell provides a historical perspective on the study of plasma sources at Earth, showing in particular how our understanding of the ionospheric source evolved and how it became understood to be more and more important with time, and has to be considered now at least on equal footings with the solar wind source. His chapter teaches us how the availability of new space data and progress in simulations transformed our view of plasma sources: a lesson certainly to be kept in mind for all other magnetospheres.

In the second chapter, Kanako Seki and her co-authors provide an overview of the main physical processes that are at work in the expression of sources, transport and losses in the different regions of a magnetosphere and at various energies. The chapter also nicely summarizes the main equations used for the description of these processes, and the main types of modeling tools that have been developed to simulate them. In that way it provides us with the "tool box" that we need to start our exploration of the solar system and understand the data and models.

This exploration is performed from closest to the Sun outwards, and therefore starts with the planet Mercury. Jim Raines and co-authors use some of the latest data from the Messenger orbiter to visit the plasma sources and the dynamics of this tiny magnetosphere, where the influence of the solar wind is dominant, but also where the direct interaction of magnetospheric particles and fields with the exosphere and surface of the planet plays a role like nowhere in the solar system, except maybe at Jupiter's satellite Ganymede. The very short time scales within which the magnetospheric configuration and the plasma domains of this magnetosphere are reconfigured are also unique in the solar system.

The next object in our exploration is planet Earth: Dan Welling et al. review the progress made in our understanding of Earth's plasma sources and subsequent transport, acceleration and loss processes since the comprehensive ISSI book of 1999. They consider both the observational and the modelling advances achieved since that time, and establish a new reference for the description of Earth's basic plasma processes.

The book then moves on to the exploration of giant planets, starting with Jupiter. As Bolton et al. write in their introduction to this chapter, the Jupiter system is "a world of superlatives": biggest planet in the solar system, strongest magnetic field, largest magnetosphere, and with the most intense plasma sources. Jupiter is dominated by the Io plasma source, which under the effect of the planet's centrifugal action generates a large plasma disc. Given this, Jupiter is not just the largest magnetosphere, it is also the closest object to a proto-planetary disk we have at hand in our solar system, and to some extent it bridges the gap between planetary sciences and astrophysics. The chapter summarizes the different plasma sources associated with this fascinating object, and the way they are transported and lost from their regions of origin to the outer edges of the magnetosphere.

Saturn, Jupiter's sister planet and our solar system's second gas giant by its size, is described in the next chapter by Blanc et al. Just as the Saturn system is diverse in terms of the objects it includes, its plasma sources display a broad diversity, which has been explored in considerable detail by Cassini since it went into orbit around Saturn in July 2004. The rings and satellites all contribute to its plasma sources, but the space exploration of Saturn revealed, quite unexpectedly, that the dominant source is the tiny satellite Enceladus. Even

Titan, the largest moon in the system and the only one with a thick atmosphere, plays a minor role compared to it. So, like Jupiter, Saturn is dominated by a single source.

Uranus and Neptune, our two ice giants at the outskirts of the solar system, are described by Norbert Krupp in the final chapter of the book. These two planets are by far the least well known, since what we know of them only comes from the fly-bys of Voyager 2 in 1986 and 1989. The Voyager data suggest that plasma at Uranus is produced mainly by its hydrogen corona with a likely complement from its ionosphere, whereas at Neptune the dominant source seems to be associated with its satellite Triton.

In the remainder of his chapter, Norbert Krupp offers a final review of all the planetary plasma sources explored by the book, emphasizing the main similarities and differences between them. Overall, one sees that more or less all the same categories of sources are acting at the different planets, but the dominant ones vary strongly from one planet to another. We hope this book will provide the reader with a good opportunity to visit this variety of sources, and to contemplate the diversity of their expressions.

Before closing this foreword, we would like to thank the Directors and Science Committee of ISSI for their support to this project, and to express our warmest appreciation to the wonderful staff of ISSI, ISSI's science programme manager Maurizio Falanga, Jennifer Fankhauser, Andrea Fischer, Saliba F. Saliba, Irmela Schweizer, Silvia Wenger, and all their colleagues, whose kindness and dedication make ISSI such a convivial and effective place to interact, exchange ideas and work. This book would not have been possible without all of them.

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

Charles R. Chappell[1]

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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

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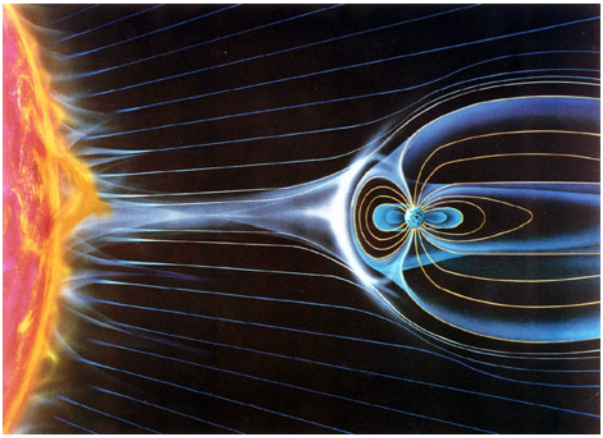

Fig. 1 A schematic image representing the early understanding of the primary role of the solar wind in populating the Earth's magnetosphere with plasma

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.

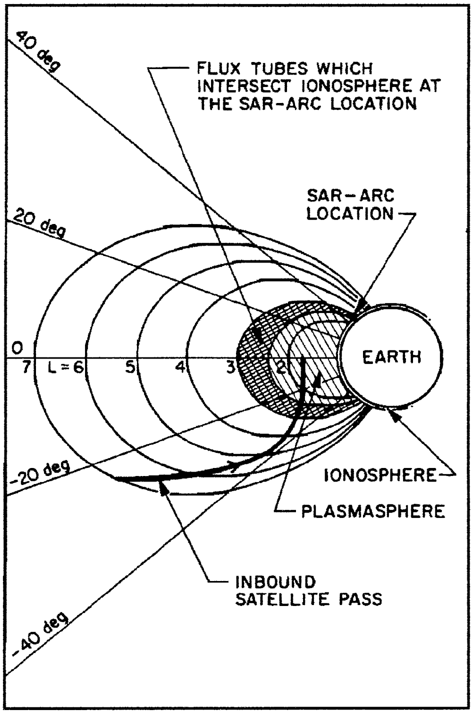

Fig. 2 A sketch of the inner magnetosphere plasma regions showing the overlap of the energetic ions of the ring current with the low energy plasma of the outer plasmasphere. The transfer of energy from the ring current to the plasmasphere results in heating which causes the formation of Stable Auroral 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 topside 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/cm^2 sec. 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 plasmapause 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/cm^2 sec.

In the early 1970s observations of stable auroral red arcs at the foot of field lines in the vicinity of the plasmapause first suggested an interaction between the energetic protons in the ring current and the low energy H^+ and He^+ ions and electrons near the plasmapause (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 A. 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

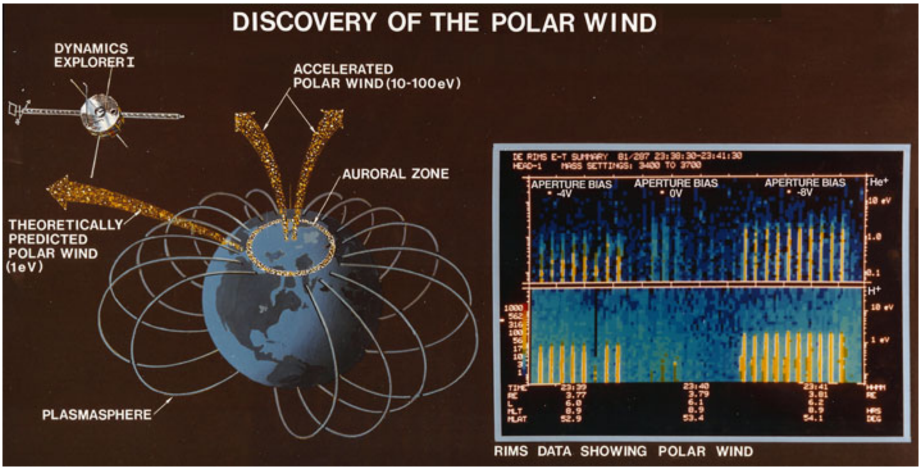

Fig. 3 A segment of data showing the DE Retarding Ion Mass Spectrometer measurements of the low energy polar wind ions flowing upward out of the ionosphere at MLT 8:54, $L = 6.1$, $3.8R_E$ geocentric altitude. By alternately placing bias potentials of -4, 0 and -8 volts on the entrance aperture of the 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 Bz component of the solar wind magnetic

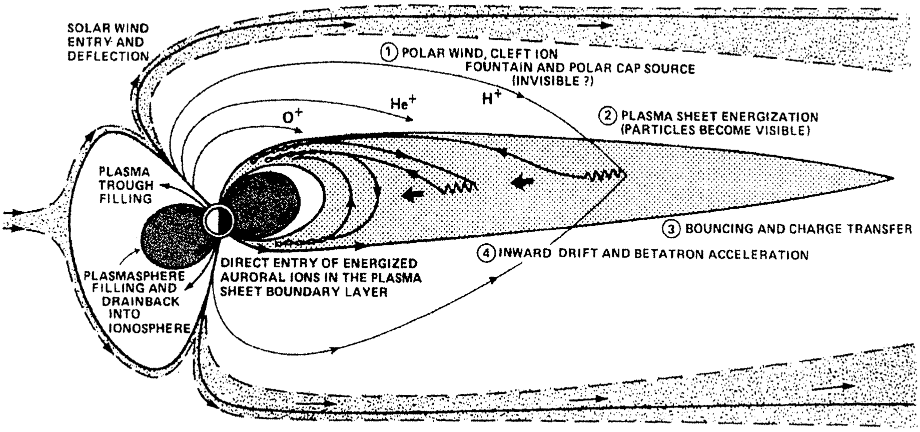

Fig. 4 A sketch of the flow of polar wind and auroral ions upward out of the ionosphere and into the outer magnetosphere. The polar wind ions move through the lobes of the tail into the downstream plasma sheet and the auroral zone ions move directly upward into the inner plasma sheet. In combination,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

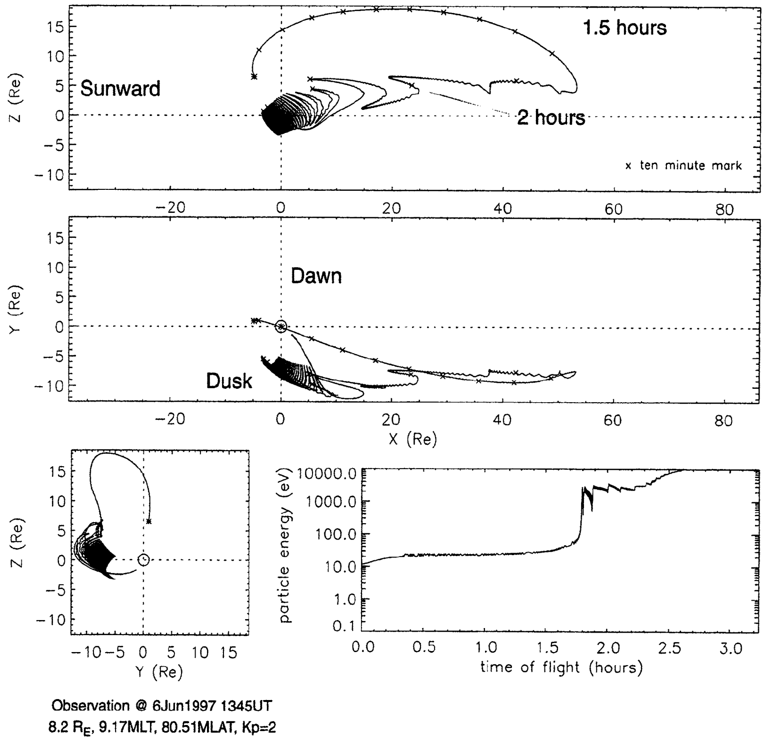

Fig. 5 Results of the tracing of the flow trajectories of a low energy ion which leaves the ionosphere and moves through the magnetosphere, gaining energy as it moves through the cross-tail potential in the magnetosphere. By following the time marks on the energy plot in the *lower right*, and matching 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