PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Features of Terrestrial Plasma Transport [and Discussion]

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Features of terrestrial plasma transport

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A review is given of the development of ideas concerning the transport and distribution of ionospheric plasma in the magnetosphere. An unresolved dichotomy in these ideas is identified, in which two incompatible explanations have been given for the low plasma densities outside the plasmasphere, the convection/hot solar plasma model, and the convection/loss model. This dichotomy reveals a fundamental unresolved problem in magnetospheric physics whose resolution is essential if we are to adequately understand the transport of mass, momentum and energy through the magnetosphere, and the resulting contributions of terrestrial and solar plasma sources. Recent progress in understanding global ionospheric outflows is reviewed for clues which might help resolve this problem. Observations are compared with theoretical concepts dealing with (1) the low-altitude collisional and chemical processes affecting the character of ionospheric outflow, (2) the ambipolar outflow of plasma in the collisionless region above, and (3) the acceleration of ionospheric plasma by macroscopic magnetospheric electric fields associated with structured convection. We appear to need a hybrid model of magnetospheric plasma in which terrestrial plasma is both lost into the solar wind, and energized and trapped within the magnetosphere, inflating the geomagnetic field and excluding cold plasma from conjugate regions.

Introduction

One of the consequences of an open magnetosphere identified by Dungey (1961) was that solar wind plasma would mix with the terrestrial plasma on the open field lines, upsetting equilibrium in the polar regions. The whistler data showing reduced densities in the outer magnetosphere, dating back to Storey (1953), suggested to Dungey that plasma was being lost to the solar wind along the open field lines. It is clear that Dungey perceived the magnetosphere as a region of terrestrial plasma for which the open field-line regions represented a potential escape route. Dungey was far ahead of his time in this view. The prevailing thinking at that time was that the ionosphere was a massive and dense medium, passively absorbing the precipitation of energetic particles of solar origin while remaining roughly in hydrostatic equilibrium. The primary direction of mass flow was thought to be Earthward, with the ionosphere collecting some matter but primarily energy in the form of a heat flow from the passing solar wind.

Nishida (1966) developed Dungey's hypothesis into a convection/loss model with the goal of accounting for the presence of Carpenter's (1963) 'knee' in the plasma density. The overall plasma circulation pattern within the magnetosphere was invoked. Flux tubes were assumed to empty out during their convection over the polar cap by exhausting their contents to the solar wind. They would subsequently refill with ionospheric plasma to an extent dependent upon a competition between the speed of convection and that of plasma outflow. Depleted flux tubes would circulate more deeply within the magnetosphere when convection was more rapid. The plasmapause was to be formed at the boundary between flux tubes subjected to loss and those which remained closed.

Brice (1967) suggested an alternative explanation of Carpenter's 'knee' observations in which the corotation boundary was taken as the boundary between solar (i.e. hot) and terrestrial plasma. The hot solar plasma was presumed to enter the magnetosphere and circulate throughout the convecting region, establishing a new equilibrium in which terrestrial plasma was confined to low altitudes and did not escape to interplanetary space. Brice noted the remarkable difference between this and the Dungey–Nishida hypothesis that the open convection region was occupied by escaping terrestrial plasma.

These two models seem to have been accepted as complementary even though a major inconsistency exists between them. The first appeals to a low-pressure solar plasma into which the ionosphere would freely vent along open field-lines, while the other appeals to a high-pressure solar plasma which would freely expand into the magnetosphere along open field-lines occupying the convecting magnetosphere to the exclusion of terrestrial plasma. Interpretations of Chappell and coworkers' subsequent observations of plasmapause dynamics (Chappell *et al.* 1970*a*, *b*) were cast largely in terms of the convection/loss model, for example in the work of Banks *et al.* (1971), which neglected hot plasma effects. Interpretations of plasma-sheet and ring-current dynamics have correspondingly been cast in terms of the convection/hot plasma model (Harel *et al.* 1981), neglecting low-energy plasma from the ionosphere at the feet of the field lines.

Perhaps a justification for separate treatments of hot and cold plasmas was derived from the work of Lemaire & Scherrer (1973), who described the interaction of hot and cold plasmas along plasma-sheet field-lines using a fully kinetic steady-state formalism. They found that the presence or lack of hot plasma had little effect upon the kinetic polar wind flow of H^+ in their model, in spite of the fact that the equatorial plasma pressure was dominated by the hot plasma by a factor of 10^3–10^5. This result appears entirely incompatible with the results of a hydrodynamic description of plasma dynamics, but this incompatability does not appear to have been resolved.

Concepts of polar wind and polar breeze flows arose in parallel with the convection/loss model (Dessler & Michel 1966), requiring a low-pressure solar wind region on open field-lines. Detailed treatments of the polar wind followed soon after (Banks & Holzer 1968, 1969*b*). This theory predicts supersonic bulk outflow and significant decrease in scale height for those species light enough or hot enough to have equilibrium scale heights comparable with the planetary radius, and not otherwise confined by a closed magnetic field. Such a polar wind flow is driven by subequilibrium plasma pressure, and would tend toward establishment of equilibrium. In those regions containing larger pressures, slower (breeze) or even reversed flows would be expected. Estimates of the solar wind pressure (thermal, not ram pressure) were low enough that Banks & Holzer were able to make a case not just for a slow polar breeze, but for supersonic polar wind at the limiting flux derived by Hanson & Patterson (1963).

Once the polar wind had been predicted as a consequence of the convection/loss model of terrestrial plasma transport, its observation became a crucial test of the open magnetosphere hypothesis in conjunction with the assumption that terrestrial plasma pressure would overwhelm the solar wind pressure along open field-lines. Light-ion upflows at low altitudes were inferred from the observations of Brinton *et al.* (1971), and Hoffmann *et al.* (1974), showing that polar wind outflow was almost certainly present at high altitudes and latitudes, thus confirming the polar wind concept, and indicating low pressure, as well as low density, in the polar regions of the magnetosphere.

A hot plasma with pressure comparable with ionospheric equilibrium values is present in the plasma-sheet and ring-current regions of the magnetosphere and may influence the transport of ionospheric plasma in the way envisioned by Carpenter and Brice. However, the findings by Shelley *et al.* (1972), Lundin *et al.* (1982), Balsiger *et al.* (1980), Lennartsson & Shelley (1986) and others that this hot plasma often contains significant quantities of terrestrial O^+ alerted us to the problem concerning the origin of the hot plasma and the inconsistency between the plasma models. Subsequent work of Shelley *et al.* (1976), Sharp *et al.* (1977), Ghielmetti *et al.* (1978) and Gorney *et al.* (1981), among others, showed that ionospheric ions are accelerated far above thermal energies and flow upward in the auroral zone. The work of Whalen *et al.* (1978) and Klumpar (1979) showed that this acceleration was primarily transverse at lower energies and ubiquitous at lower altitudes in the auroral zone.

Against this backdrop, we wish to present a synopsis of recent observations and modelling efforts. A more comprehensive review of observations has been given by Yau & Lockwood (1988). In the present review, we stress the comparison of recent observations and modelling work which bear upon the degree to which the ionosphere contributes to the magnetospheric hot plasma. We briefly review observations of terrestrial plasma flows which were not well known at the time of Cowley's (1980) comprehensive review of magnetospheric plasma circulation. We then review some recent modelling efforts aimed at describing terrestrial plasma transport. Finally, we address the relative contributions of terrestrial and solar plasmas to magnetospheric hot plasma, and comment on the question of convection/loss against convection/hot plasma behaviour in the magnetosphere.

Observations of terrestrial plasma transport

Subauroral magnetosphere

Observing the low energy plasma is fundamentally different from observing the hot magnetospheric plasma, the data being organized at least as much by the direction of spacecraft motion as by the local magnetic field. The retarding ion mass spectrometer (RIMS) on *Dynamics Explorer* 1 (*DE*1) has provided detailed information on this plasma, an example of which is shown in figure 1. Plasma flows appear as shifts in the apparent wind (flux) direction. In the subauroral region (figure 1*c*), one in fact observes the subsonic outflows expected from the convection/loss model, with only the light ions participating. New features observed in this region include counterstreaming between the light ion species, the presence of downward ion heat flows indicating a high-altitude heat source in the outer plasmasphere (visible in figure 1*c* as an asymmetry of the angular distributions), and supersonic outflow equatorward of the polar cap. These and other features of the plasmapause and trough region have been reported by, for example, Biddle *et al.* (1985) and Chandler & Chappell (1986).

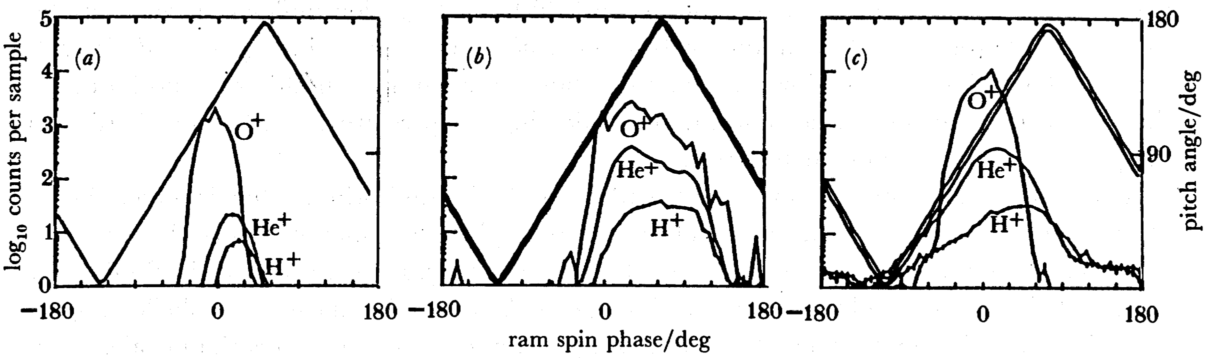

FIGURE 1. *DE*1 RIMS spin curves showing species count rates against spin phase angle with the ram direction at centre, and positive angles corresponding to upward flow. (*a*) Polar cap; 19h21:30–19h22:30, altitude (alt.) = 1.26 R_E†, local time (LT) = 05h13, *L*-value (L) = ∞. (*b*) Dayside cleft region; 19h33:30–19h34:30, alt. = 0.85 R_E, LT = 09h24, $L = 18.9$. (*c*) Subauroral trough; 19h39:30–19h40:30, alt. = 0.64 R_E, LT = 10h08, $L = 7.0$. All data taken on day 071, 1981. (After Moore *et al.* (1985).)

Cusp/cleft

The polar-cap boundary is marked not by a simple field-aligned acceleration of the light ion outflow into a supersonic polar wind, but rather by a region of intense ion heating and outflow in which all observed species participate (figure 1*b*). These heated flows have been referred to as upwelling ion events (Lockwood *et al.* 1985*a*; Moore *et al.* 1986*a*), and include appreciable fluxes of H^+, He^+, O^{2+}, N^+, O^+ and at times molecular ions (Craven *et al.* 1985). Bulk heating to temperatures a factor of 30 higher than typical ionospheric temperatures is often observed in these events. The O^+ ions are transversely heated with thermal energies on the order of 5–10 eV transverse and 2–3 eV parallel to the local magnetic field. Moreover, a non-maxwellian superthermal tail is often observed in the ion-species distribution functions, which can sometimes be characterized as containing an additional population with an e-folding energy several times larger again than the heated core temperature. It appears that this higher energy tail distribution is closely related to the transversely accelerated ions of Whalen *et al.* (1978) and Klumpar (1979).

As indicated in figure 2 (after Lockwood *et al.* 1985*a*; Pollock *et al.* 1988), statistical studies of these events have shown that such upwelling ion flows are a nearly continuous feature of a region centred before local noon in the dayside auroral zone (figure 2*a*). O^+ fluxes are $0.3–1.0 \times 10^9\ cm^{-2}\ s^{-1}$ in typical events, with $0.3–1.0 \times 10^8\ cm^{-2}\ s^{-1}$ of H^+, and smaller fluxes of other species (figure 2*b*). The largest fluxes of O^+ approach $10^{10}\ cm^{-2}\ s^{-1}$ at 1000 km. The heating signature is generally embedded within lower and higher latitude regions of polar wind or polar breeze.

The heating and outflow is associated with strong convection channels and with associated field-aligned current and transverse electric field systems, as shown in figure 3. Figure 3*a* illustrates an example of the strong convection features observed in coincidence with an upwelling event, while figure 3*b* shows the close association of the location of the associated field-aligned current system with the heating signature. Low-frequency auroral noise is also characteristic of these regions (Gurnett *et al.* 1984); and Curtis *et al.* (1985) have noted that electron heating to *ca.* 10000 K is typical of the cusp region near 1000 km altitude, as well as a strong upward temperature gradient. We still need measurements of electron pressure at

† $R_E = 6.37 \times 10^6$ m.

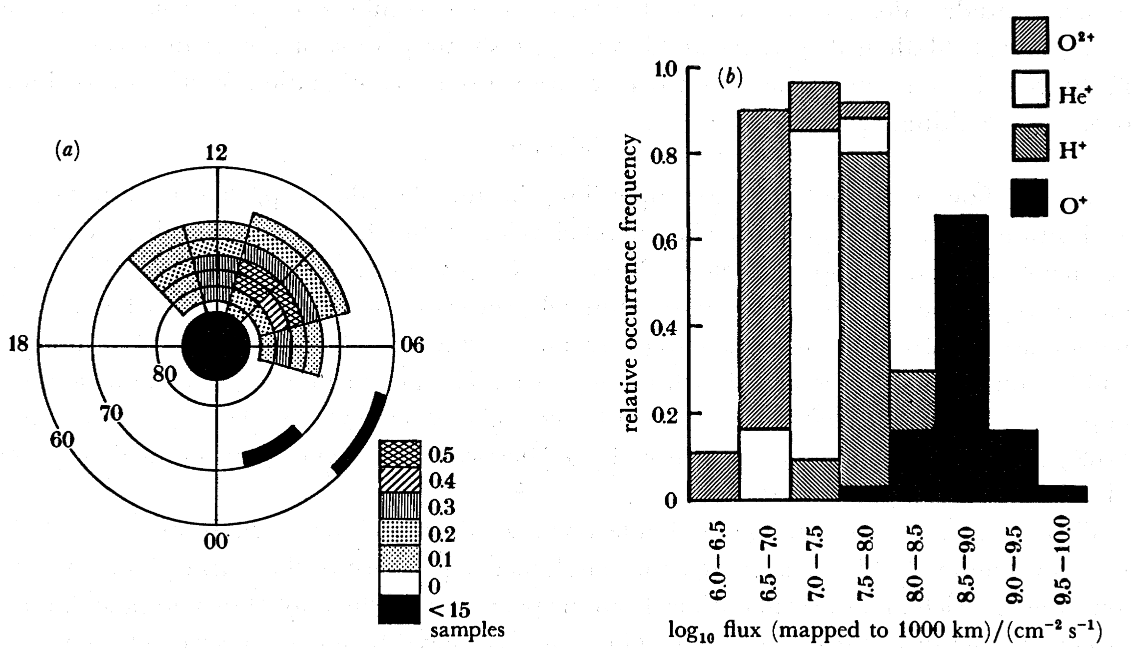

FIGURE 2. (*a*) Spatial distribution of upwelling O^+ ion events in local time and invariant latitude ($r < 3R_E$), after Lockwood *et al.* (1985*a*). (*b*) Relative frequency of occurrence of field-aligned flux magnitudes in upwelling ion events for four species, after Pollock *et al.* (1988).

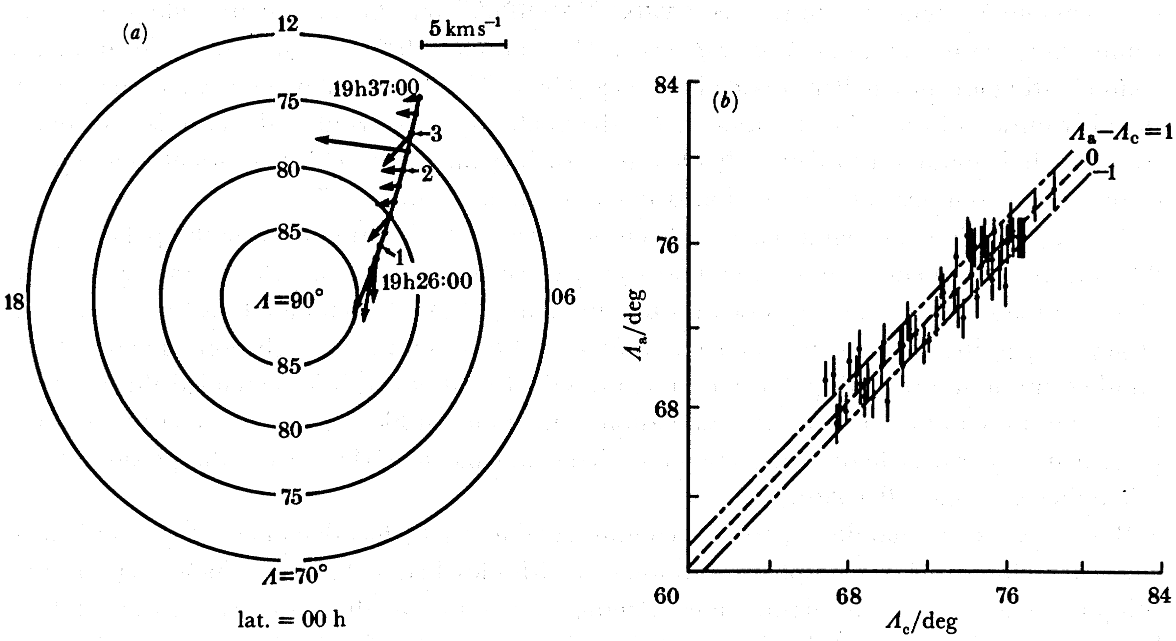

FIGURE 3. (*a*) *DE*1 12 March 1982 (day 071); orbit projection of invariant latitude against magnetic local time. Association of a strong plasma convection jet with an upwelling ion event, after Moore *et al.* (1986*a*). (*b*) Equatorward heating boundary against equatorward current boundary. Association of upwelling events with dayside auroral field-aligned current system, each of which have clearly defined equatorward boundaries, after Lockwood *et al.* (1985*a*).

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higher altitudes along cusp field-lines. Owing to the combination of strong convection, appreciable field-aligned currents, and hot magnetosheath plasma present in the cusp, it seems likely that the ionospheric heating observed arises from a combination of effects distributed over a large altitude range.

Polar cap

The outflow resulting from ion upwelling in the dayside cusp/cleft is dispersed by antisunward convection according to parallel velocity and hence mass forming at times a geomagnetic mass spectrometer effect (Moore *et al.* 1985; Lockwood *et al.* 1985*c*). The lower-energy component of the heavy ions ultimately reverses and falls back toward the Earth, having acquired insufficient energy to overcome gravitation. The more energetic component will be convected into the near-Earth plasma sheet. The net result is a gas dynamic fountain of planetary scale, the cleft ion fountain of Lockwood *et al.* (1985*b*) and Horwitz & Lockwood (1985). The plasma plume is swept through the polar-cap region where the nominally expected plasma flow is the polar wind.

Figure 1*a* shows an example of simple polar wind outflow observed below the cleft ion fountain plume. At higher altitudes, the simultaneous presence of the warm plume of heavy ions from the cleft and the cold outflow from the polar cap was first noted by Gurgiolo & Burch (1982). In fact, it was really the plume of plasma, as viewed by a mass spectrometer revealing its large O^+ content, which was the most evident clue to the presence of the fountain. This relationship of the polar O^+ outflow to a dayside cusp/cleft source was deduced by Waite *et al.* (1985). We can now assemble a picture of mixed plasma with the warm, heavy ion-rich component originating in the cleft region (or in transpolar auroral features) and the cold light-ion component originating in the polar cap. O^+ outflux from the dayside upwelling region is comparable with the total *polar cap* wind H^+ outflux ($10^{25}\ s^{-1}$), the larger local fluxes compensating for the smaller area. It has been shown (Waite *et al.* 1986; Lockwood 1986) that the distribution of the plasma plume across the polar cap downwind of the cusp is controlled by solar wind characteristics, notably the interplanetary magnetic field (IMF) orientation. Quite complex distributions can be envisioned in cases of northward IMF.

The supersonic polar wind has now been observed at high altitudes over the polar cap, a difficult measurement due to the positive spacecraft charging in which the spacecraft photoplasma excludes the very low-pressure ambient plasma. Careful analysis by Nagai *et al.* (1985), exploiting the aperture bias capability of *DE*1 RIMS, shows that light-ion flux and Mach number are in accord with polar wind theory. Subsequent efforts have extended this work to lower latitudes and permitted the observation of the more subtle (i.e. lower velocity) outflows present nearly everywhere in the magnetosphere, but particularly outside the plasmasphere (Chandler & Chappell 1986).

Recent work of Chandler (personal communication 1988) has documented the statistical character of the polar ionospheric outflows at altitudes below 4000 km, including the O^+ component as well as the lighter ions. Among the results of this work is a clear relation between the O^+ content of the flows and the flow energy flux of the O^+ ions. Figure 4 shows this effect in comparison with a relevant modelling result which will be discussed below. Clearly, the increasing participation of O^+ in the total ion outflow is tightly associated with the energization of the O^+. The existence of this relatively smooth curve suggests that there is a correspondingly smooth transition between classical polar wind behaviour and heavy-ion outflows. This work also makes it clear that the polar wind is routinely present throughout the

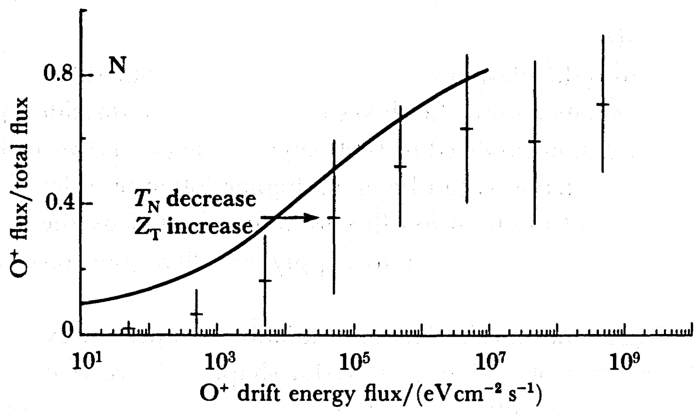

FIGURE 4. Ion outflow composition against demand. The average (error bars indicate the standard deviation of samples) dependence of the composition of ionospheric outflows on the level of demand for ions as parameterized by the O^+ drift energy flux, as measured by *DE*1 RIMS. The period of this database is late 1981 and early 1982. (Lat.: 65°–90°; alt.: 10^3–4×10^3 km; local time: 0–24 h; day: 284–120; $F_{10.7}$: 0–400.) For comparison, a solid curve derived by Barakat *et al.* (1987) is also shown. The curve's dependence on model parameters is indicated by the arrow. ($T_N = 900$ K, $Z_T = 10^3$ km.)

subauroral trough region as well as the polar cap. We may therefore conclude that outflowing terrestrial plasma dominates the polar cap and lobe regions, in support of the convection/loss model.

Nightside auroral zone/plasma sheet

As the ionospheric polar plasma convects into the nightside auroral zone where hot plasma-sheet material is present, it tends to disappear, at least in the low-energy range characteristic of the ionosphere. Where low-energy plasma is observed in this region, it is usually flowing upward along the local magnetic field with energies of tens of electronvolts to several kiloelectronvolts in discrete auroral structures. Although positive spacecraft potential may in some cases create the erroneous appearance of low plasma densities, it is clear that plasma densities at a given altitude are much lower than in the dayside auroral zone (Persoon *et al.* 1988). Since this is a region of hot auroral plasma, the Brice hypothesis may account for some measure of confinement of the terrestrial plasma at low altitude.

The outflows observed in the nightside auroral zone may be characterized as a combination of conic and beam angular distributions, occurring in close association with auroral 'inverted V' events. In the low-energy ions, a common signature is the X-shaped spin angle distribution, which corresponds to a broad conic, narrowing to a beam and then opening out into a conic again (Moore *et al.* 1985). This represents a progression from transverse heating, to field-aligned accelerated ions and back again to transverse heating. Simultaneous electron measurements from the *DE*1 high altitude plasma instrument (HAPI) show that this X-shaped pattern is coincident with an inverted V electron event, the apex of the V coinciding with the intersection of the 'X'. At higher angular resolution, as provided by HAPI (J. D. Winningham, personal communication 1985), the field-aligned flow at the crossing of the 'X' can be resolved as the parallel acceleration of an ion conic to energies reaching the order of kiloelectronvolts, forming the auroral ion-beam signature.

It seems clear from this behaviour that regions of convection shear of the correct sense to produce upward field-aligned currents and downward electron acceleration also produce ion transverse heating below and adjacent to the region of enhanced parallel potential drop. One forms an impression of a region from which the cold terrestrial plasma is excluded, except where field-aligned currents simultaneously heat at low altitude and accelerate a flow of terrestrial plasma upward into the plasma sheet. The ion flux associated with these accelerated outflow events is generally smaller than the fluxes observed in the dayside upwelling events, typically 10^7–10^8 cm^{-2} s^{-1} when normalized to 1000 km altitude (Yau *et al.* 1985), but the final energies of the parallel accelerated ions can be much higher (often of order kiloelectronvolts). However, Yau *et al.* (1985) find the total ion flux to be dominated by the ions below 1 keV, so that regions of higher acceleration tend to supply less flux (see also Ghielmetti *et al.* 1987).

Transverse heating of the ionospheric ions occasionally assumes an extremely interesting velocity distribution form, that of a ring or toroidal shape (Moore *et al.* 1986*b*). Though uncommon, these distributions may offer important clues to the mechanisms responsible for the ion transverse heating so evident both on the dayside and nightside auroral zones. These distributions have been coherently accelerated in the direction transverse to ***B***, so as to develop a ring shape, with a depression at the centre near the frame of reference of the plasma taken as a whole. Other measurements obtained at lower altitudes from the European incoherent scatter (EISCAT) radar have been interpreted in terms of distribution functions tending toward such a ring or toroid shape (Lockwood *et al.* 1987). The production of such distributions has been attributed to large relative flows between the ions and the neutral atmosphere, an interesting case where classical collisions produce a free energy source for lower hybrid plasma waves (St-Maurice & Schunk 1979).

Subauroral magnetosphere: revisited

The convecting flux tubes of plasma which have passed through the plasma-sheet boundary layer emerge into the central plasma sheet where the convection flow is directed azimuthally around the Earth, returning to the dayside to be recycled through the cusp and on again over the polar cap. Just what sort of terrestrial plasma distribution should be formed and coexist with the hot plasma sheet is difficult to say. Observationally, the result seems to be a region of warm anisotropic plasma having various combinations of field alignment, loss cones and transverse heating near the Equator. Certain transversely heated populations (tens of electronvolts) are quite well confined to the region close to the Equator (Olsen *et al.* 1987). The frequency of occurrence is comparable with unity at all local times with the exception of a region near dawn, where the probabilities are very low.

In the morning sector, this warm anisotropic 'cloak' appears to undergo an evolution from bidirectional field aligned to bidirectional 'conic' as it convects from night to day through dawn (Giles *et al.* 1988; Sagawa *et al.* 1987). This probably results from the formation of loss cones in what was initially a source cone. Simultaneously, the core distribution presumably builds to higher densities during the sunward convection, as the hot plasma gradually precipitates and is replaced by cooler plasma from the flux tube foot points (Horwitz *et al.* 1986).

Modelling of terrestrial plasma transport

We still seem to be far from a well-coupled description of both solar and terrestrial plasmas throughout the magnetosphere. Though great strides are being made in three-dimensional global magnetohydrodynamic (MHD) simulations, they do not typically include mass loading by terrestrial plasma. We do have more local models of quite a few bits and pieces of the puzzle. Several types of transport models are discussed below, which vary considerably in their degree of self-consistency and in the type of effects which are included.

Low-altitude collisional (classical) transport

The lowest-altitude parts of the F-region topside ionosphere are relatively immune to heating processes because of their strong collisional coupling with the neutral atmosphere, which represents an enormous heat sink in relation to the energy fluxes associated with polar wind or even auroral processes. If an upper boundary is chosen to correspond to the lowest altitude to which significant heating or acceleration extends, it is possible to formulate a hydrodynamic description of the topside ionosphere with which the consequences of the various collisional processes going on there may be described. The altitude at which the upper boundary conditions are imposed (flux, or density and velocity) may be treated as an additional free parameter of the system to crudely account for variations in the strength or effectiveness of the heating or acceleration processes occurring above the boundary.

This approach was used by Barakat *et al.* (1987) to explore the effects on plasma outflow owing to the ionospheric response to energetic processes occurring in the topside. An isothermal, collisional, chemically reacting plasma in steady subsonic flow, consisting of H^+, O^+, and e^- embedded in an MSIS neutral atmosphere, was explored. The basic free parameters of the problem were (1) the structure of the neutral atmosphere and strength of the ionospheric ionization source as driven by variations of the solar ultraviolet (UV) irradiance; (2) the demand placed upon the ionosphere by the energetic processes occuring in and above the topside, expressed as a flux boundary condition at the upper boundary; and (3) the altitude at which the demand is placed (i.e. the upper-boundary altitude), especially in the altitude region of ion–neutral charge-exchange chemistry from 600 to 1500 km altitude.

Here, we focus on the effects of these free parameters on the fractional O^+ composition of the total outflow. It was found that well-defined limiting fluxes existed for each species, but that these limits were interdependent. It was further found that the limiting flux of O^+ increased with solar UV flux due to the enhanced neutral atmosphere temperature. It was assumed for application to the polar regions that H^+ would be in limiting flow, whatever the flux of O^+ imposed at the upper boundary. Because of the charge-exchange chemistry coupling the two species, the limiting flow of H^+ is a decreasing function of the O^+ flux.

Figure 4 (solid curve) shows the results obtained for O^+ composition of the outflux as a function of a measure of the demand for total ion flux, for solar maximum winter UV conditions, low geomagnetic activity, and for an upper-boundary altitude of 1000 km. It is seen that the O^+ content of outflows is a strong function of the drift energy flux of the O^+, a measure of the energetics or demand for plasma flux. Plasma heating introduces a demand for ions due to enhanced escape, depressing densities near and below the heating region, while raising densities at higher altitudes. This effect is illustrated schematically in figure 5. An enhanced O^+ pressure gradient forms below the heating region and drives a flow of the F-region O^+ up to the heating region. As the flux demand is raised, O^+ participates. The result is that we fully expect the ionospheric source to vary in composition with total flux magnitude, so that regions of large (comparable with limiting fluxes) outflow driven by local heating are expected to be rich in O^+.

An enhanced neutral atmosphere temperature (solar maximum increases the O^+ fraction for

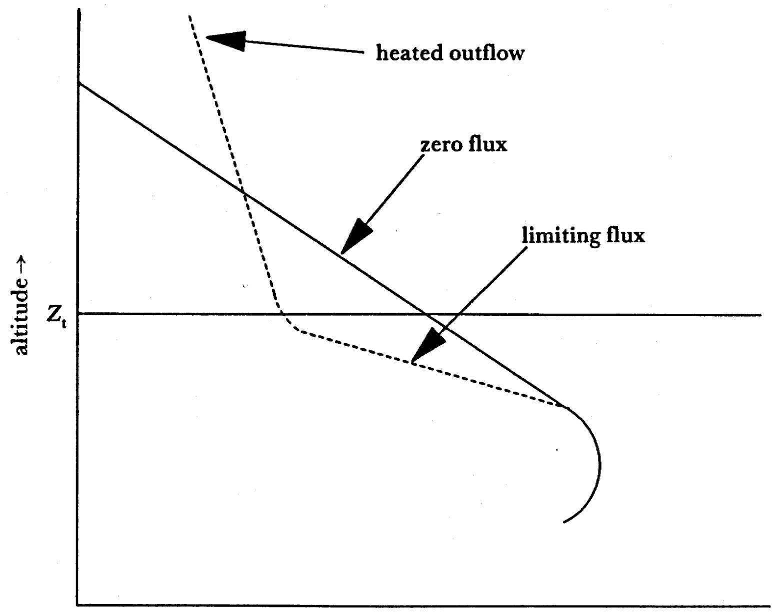

FIGURE 5. Plasma demand due to heating. Schematic diagram of the effect of plasma heating occuring above an altitude Z_t on the topside ionosphere. Owing to demand caused by escape of heated heavy ions which are ordinarily trapped, densities are reduced in the topside, but raised at altitudes above the heating region.

a given level of total ion flux demand (and constant upper-boundary altitude), sliding the solid curve to the left. This results from the induced changes in the neutral atmosphere, in particular the decrease in H densities coupled with the increase in O densities, which leads to charge-exchange chemistry that favours O^+ over H^+ in the region described. Similarly, for constant ion flux demand and solar UV conditions, the O^+ fraction increases with a decrease in the upper-boundary altitude. These effects result from relative motion between the acceleration region and the region of the neutral atmosphere in which O^+ is consumed to form H^+. A notable conclusion from this is that solar activity is expected to enhance the O^+ outflow content, other factors being constant.

Figure 4 also shows the results of a statistical survey of *DE*1 RIMS observations of the polar wind, including outflows which include substantial O^+. It may be seen that the general trends are qualitatively as described by the hydrodynamic model, though the fit is misleadingly good. Two parameters could be varied so as to move the model curve relative to the data. First, the neutral atmosphere temperature could be decreased, moving the model curve to the right into better agreement. However, this cannot be justified for the data-set presented, and in fact the neutral temperature should be increased to reflect the average conditions for the data. Secondly, the low-altitude boundary of plasma energization, or upper boundary of the calculation, could be moved upward from 1000 km, with the effect of moving the model curve to the right. It appears reasonable to conclude that ionospheric heating occurs typically above a higher-altitude boundary, consistent with the findings of Lockwood *et al.* (1985*a*) (heating above 2500 km), though additional modelling is needed to test this quantitatively.

Ambipolar kinetic transport

Above the artificially introduced boundary separating collisional and collisionless regions, we have available descriptions which are basically kinetic in nature, although the electrons are often treated as a massless fluid, in which case the approach is referred to as semikinetic. Barakat & Schunk (1983, 1984) have built on earlier efforts, by Lemaire & Scherrer (1973) and others, to show that electron heating can be very effective in lifting heavy ions out of the ionosphere, acting by means of the ambipolar potential which arises so as to maintain charge quasi-neutrality. The effect can be understood intuitively as the electrostatic coupling of electron thermal energy into the overall pressure equilibrium of the gas under gravitation. The most important aspect of this approach is the simplification of the electron parallel (to $\boldsymbol{B}$) momentum equation by neglect of inertial and gravitational terms, to a simple equilibrium between the electron pressure gradient and the local parallel electric field $\boldsymbol{E}_{\parallel}$. This approach to the electrons is equivalent to the assumption that they obey a Boltzmann distribution within the ambipolar potential.

Peng Li *et al.* (1988) have recently further developed this semikinetic approach to examine the effects of ion heating on outflows from the ionosphere. Hot plasma effects were not included, but lower-boundary ion distributions which have independent perpendicular and parallel temperatures (are bi-maxwellian) were included, and techniques were developed to eliminate the spurious 'double layers' (DLS) or abrupt potential jumps which have tended to occur in this type of calculation. Proper matching of ion and electron density at the lower boundary eliminates one source of spurious DLS. A DL will also occur if an ion species makes a subsonic–supersonic transition within the calculation space and the boundary conditions do not place this transition near the correct altitude. Such DLS are removed by adjusting the boundary conditions so as to move the transition height.

Peng Li *et al.* (1988) considered the range of parameters suggested by observations of upwelling ion events described above, and the relative contribution of ion and electron heating to the outflows calculated. Figure 6 summarizes their results with respect to the dependence of escape flux on ion and electron temperatures. Results are presented for simple thermal efflux, three values of electron temperature and for zero gravity thermal efflux. Note that for sufficiently high ion temperatures, the resultant outflow flux is relatively independent of electron temperature. This modelling technique thus leads to the conclusion that the observed levels of ion heating are sufficient to produce the observed ionospheric transport upward into the magnetosphere, independent of electron heating effects, assuming hot plasma effects are not important.

Space-dependent and time-dependent effects

It is clear from the observations that the convecting ionosphere is subject to very large variations in conditions, both at the top and bottom of its flux tube, particularly as it convects through the cusp/cleft region. There, a sudden opening up of the flux tube is accompanied by an intense heat input distributed at lower altitudes. The flux tube subsequently convects into the polar cap, whereupon the heat source is removed, and the plasma begins to adjust to the new conditions. We have been thinking of a rather uniform ionosphere which varies chiefly in density. In fact, we have localized regions of heating and acceleration through which the ionospheric plasma convects, responding in a fashion which is spatially two dimensional in the Earth frame, or time dependent in the plasma frame.

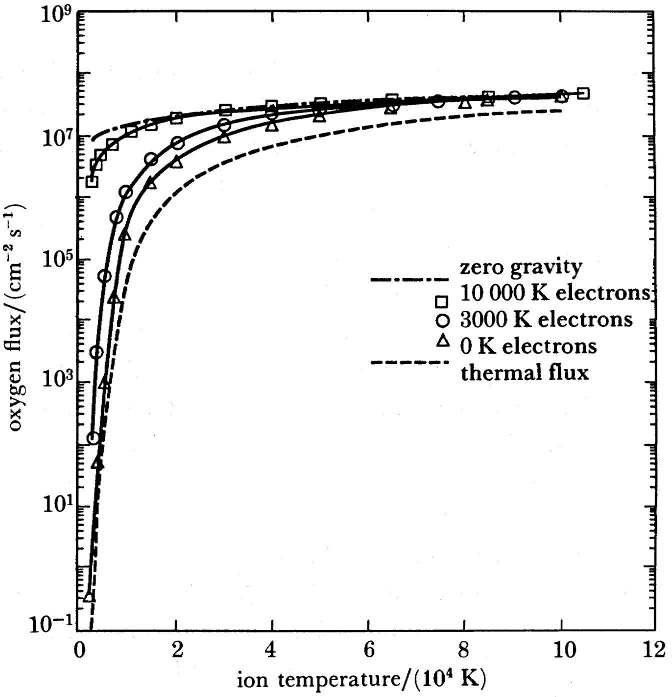

FIGURE 6. Oxygen ion escape flux against ion and electron temperatures in a semikinetic model of the high topside ionosphere, after Peng Li *et al.* (1988). The range of parameters is intended to apply to upwelling ion events, except that the low boundary density used limits the maximum flux well below observed values.

An approach which addresses these problems is exemplified by the work of Whitteker (1977) and more recently Gombosi *et al.* (1985), in which the plasma on a given flux tube is treated hydrodynamically and in a time-dependent fashion, so that the effects of heat inputs which are transient because of convection can be calculated. In Gombosi *et al.* this is done with a numerical technique based upon the behaviour of real gases at discontinuities, known as the Godunov scheme. This method permits a true time-dependent description retaining the inertial terms in the momentum equations, including energy equations with arbitrarily imposed heating-rate distributions (actually derived from cusp electron precipitation observations in Whitteker (1977)), and exhibiting acoustic waves including shocks. This technique permits a unified description of the low-altitude regions including the collisional and chemical processes and the ambipolar outflow effects, with a treatment of energetics which permits the inclusion of specified heating-rate profiles. However, it does not permit the calculation of global circulation within the magnetosphere, nor does it permit the inclusion of hot plasma effects.

Macroscopic fields and plasma transport

Having been heated and/or accelerated in the dissipative regions of the auroral zone, terrestrial plasma then participates in the macroscopic circulation of the magnetosphere. In the process it may experience further accelerations as a result of either the spatial structure of the fields or other high-altitude dissipation processes. None of the hydrodynamic or self-consistent kinetic models discussed above deal with such macroscopic effects. Thus, to track plasma from the ionosphere through the magnetosphere, one is obliged to argue that the ambipolar potential is a relatively weak influence on the plasma once it has been energized to tens of

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electronvolts, and proceed with single-particle trajectory tracing based upon models of the global magnetic and electric fields. This approach is the least self-consistent we have discussed, but is also unique in its ability to track the motions of individual ions deep into the distant magnetotail and back to the inner magnetosphere.

Regardless of point of origin, those ion components reaching high altitude are effectively 'picked up' to the convection velocities prevailing. Cladis (1986) has noted that ions leaving the cusp region with escape energy will reach the plasma sheet at distances where the neutral-sheet field-lines are tightly curved. When strong earthward convection prevails there, they will be accelerated to kiloelectronvolt energies on a single pass. They emerge along the opposite hemisphere's plasma-sheet boundary layer in a field-aligned earthward-travelling beam. This effect is implicit in the work of Speiser (1967) and Jaeger & Speiser (1974); it results from drift of the particles across equipotentials of the convection electric field. The types of trajectories found and the energy gains realized are illustrated in figure 7, from the work of Swinney *et al.* (1988). A noteworthy aspect of the four trajectories plotted (differing in convection speed) is that their energy gains reveal an optimum region in the magnetotail or set of conditions for maximal energy gain. The location of this maximum depends on the magnetic field structure of the plasma sheet, while the ion initial conditions and convection control the access of ions to it.

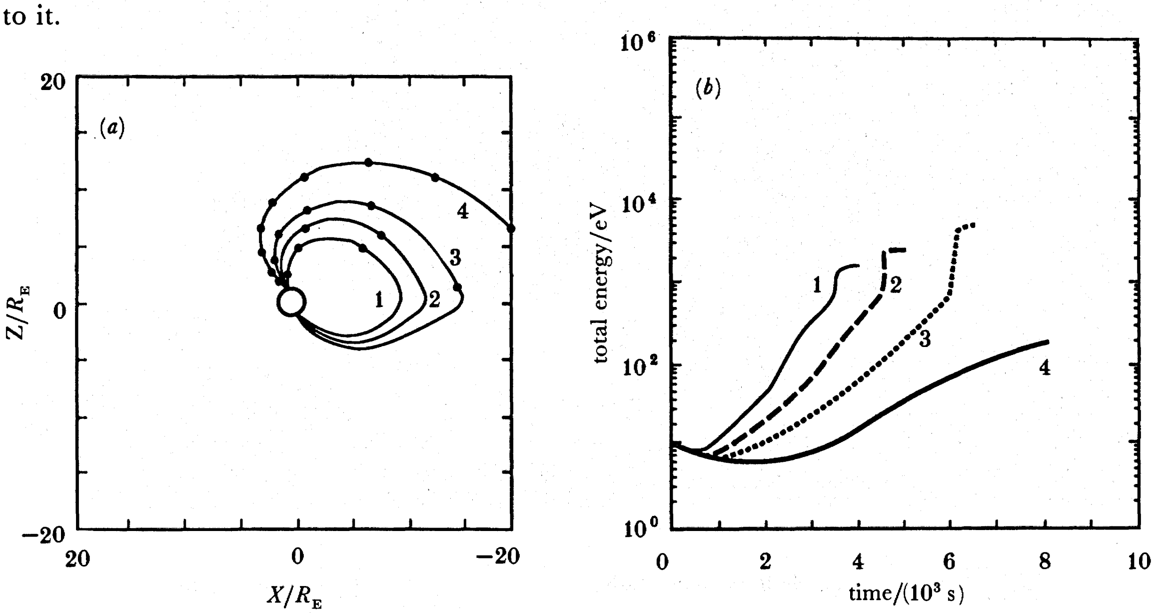

FIGURE 7. (*a*) Trajectories and (*b*) energy gains for typical upwelling O^+ ions emitted by the dayside cusp region, computed on the basis of single-particle motion in models of the magnetospheric fields, (after Swinney *et al.* (1988)). Curves 1–4 correspond to increasing convection electric field strength. Dots in (*a*) mark 1000 s intervals along each trajectory.

The important point to note is that, in addition to the nightside auroral ion outflows, both the polar wind light ions and the upwelling ions from the cusp/cleft region are convected into the near-Earth nightside plasma sheet for typical magnetospheric conditions. Several factors influence the distribution of this plasma entry into the plasma sheet. The strengh of the outflow at low altitudes influences how high the flow will go over the polar cap where it is accelerated by pickup into the antisunward flow there. Higher-altitude penetration here will produce convection further down the tail before entry into the plasma sheet. Stronger polar cap convection will tend to drive the plume to the plasma sheet closer to the Earth, but will also enhance the neutral sheet acceleration of the plasma, wherever it enters the plasma sheet.

It is possible to envisage a calculation in which the known plasma source within the ionosphere are tracked throughout the magnetosphere by using empirically determined fields. By using fluxes specified by low-altitude observations, it should then be possible to determine what terrestrial plasma distributions result, in much the same way that Jaeger & Speiser (1974) followed magnetosheath plasma from the cusp through the plasma sheet. It appears that the upwelling ion outflow from the cusp/cleft regions will produce in active periods a boundary layer of earthward streaming plasma at kiloelectronvolt energies on either side of the plasma sheet, as illustrated schematically in figure 8. This effect is remarkably similar to the observed behaviour of the plasma-sheet boundary-layer (Eastman *et al.* 1984). This type of modelling needs considerably more work to fully explore the global transport of both ionospheric and solar plasma within the magnetosphere. There is a need for improved models, empirical or theoretical, of the fields within the magnetosphere to support this.

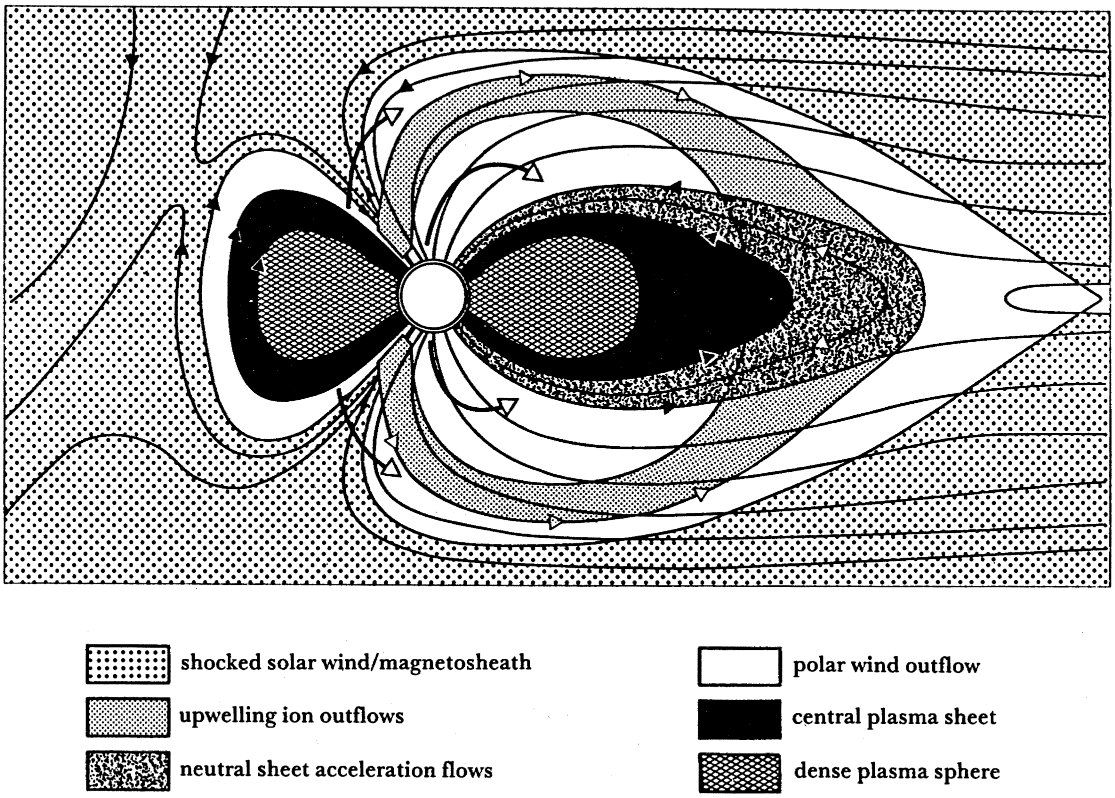

FIGURE 8. Schematic diagram of magnetospheric plasma transport, including upwelling ion/cleft ion fountain plume. The proportions of the diagram are exaggerated for clarity.

THE IONOSPHERIC CONTRIBUTION TO MAGNETOSPHERIC PLASMA

We can estimate that the magnetosphere contains 10^5 kg of low-energy plasma compared with about 10^3 kg of everything else above the 1 eV energy level. Many workers tend to think of magnetospheric plasma as that which makes up the plasma sheet and ring current, exclusive of the low-energy plasma. On the basis of energy density (pressure), this may be justified since

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the energetic plasma dominates the total kinetic energy by at least a factor of 10, and is certainly responsible for the geomagnetic perturbations in active times. Nevertheless, a strict accounting of the plasma must not exclude the core of the distribution function, because this core carries the bulk of the plasma mass density and is hence crucial to the dynamics of the magnetosphere by virtue of its control of the MHD wave speeds (Moore *et al.* 1987).

However, let us focus for the moment only on the energetic plasma sheet and ring-current particles. The question arises as to how the solar wind plasma and terrestrial plasma compete for entry into those regions. It is generally accepted that the magnetosheath plasma forms a magnetospheric mantle region which represents the boundary of solar plasma penetration into the magnetotail. As antisunward convection of the mantle proceeds downtail, it is thought that the north and south mantles approach each other, meeting at the neutral sheet at a distance of approximately 1000 R_E near the end of the closed terrestrial field lines, as shown in figure 8.

This view appears consistent with the scenario outlined here for terrestrial plasma transport into the near-Earth plasma sheet and, taken together with the operation of neutral sheet acceleration, is consistent with a terrestrial inner near-Earth plasma sheet and ring current. The situation is less clear when one considers the equatorial flanks of the magnetosphere where solar plasma also can presumably find itself on circulation paths which penetrate fairly deep within the magnetosphere (Eastman *et al.* 1984). However, the degree of actual penetration from the low-latitude boundary layers into the near-Earth plasma sheet is not at all well known, nor do we have an adequate understanding of how terrestrial and solar plasmas interact on closed field lines along the flanks of the magnetosphere.

Overall, it is possible to argue that the terrestrial plasma enjoys much better access to convection paths known to lead to the near-Earth plasma sheet than does the solar plasma. Moreover, the existence of a persistent polar wind, as well as the other more energetic ionospheric outflows, indicates that the terrestrial plasma is capable of competing successfully for dominance of high-latitude flux tubes, except in the cusp proper where the solar ram pressure is overwhelming.

Sharp *et al.* (1982) have pursued the question of the source of the plasma sheet by using *International Sun–Earth Explorer* (*ISEE*) data and have found evidence that the plasma sheet between 10 and 20 R_E is solar dominated in quiet times and ionospheric dominated in active times. Their results and the assumptions they identified in deriving them are shown in table 1.

TABLE 1. PLASMA SHEET COMPOSITION, 10–20R_E

(After Sharp *et al.* 1982.)

He^{2+} source specific?	ionospheric O^+/H^+ ratio	quiet composition (%) ionospheric	solar	active composition (%) ionospheric	solar
yes	fixed	5	95	60	40
yes	varies 0.05–0.5	36	64	73	27
no	varies 0.05–0.5	>36	<64	>73	<27

Sharp *et al.* (1982) examined the effect of the ionospheric source composition, finding that an ionospheric source which increases in O^+ content with activity would imply higher ionospheric contributions to the plasma sheet than would a fixed ionospheric composition, based upon the same *ISEE* data-set. The statistical work of Yau *et al.* (1985), and the modelling work of Barakat *et al.* (1987), give us good reason to believe that ionospheric outflow composition varies quite widely with geomagnetic activity, being H^+ dominated in quiet times, thus favouring the higher estimates of ionospheric contribution to this part of the plasma sheet.

What about the assumption of source specificity? Clearly if there were a terrestrial source of He^{2+}, our assessment of the solar contribution would drop again. There does appear to be a source of $m/q = 2$ ions in the low-energy plasma, and an outer plasma-sphere component of a few tenths of a percent is usually observed (Comfort *et al.* 1988). This apparently terrestrial source could contribute to some extent to the plasma sheet He^{2+} population.

Moving to the inner plasma-sheet and ring-current regions, the balance swings decisively toward a terrestrial origin for the hot plasma as well as the cooler plasmasphere. The evidence that solar plasma contributes to the plasma sheet and ring current lies mainly in the presence of observable quantities of multiple ionized He and O. Gloeckler *et al.* (1985) have recently shown that He^{2+} is indeed present in the ring current as well as high ionization states of O. The long term average He^{2+} ($m/q = 2$) contribution is found by Young *et al.* (1982) to be 0.8% in the synchronous orbit region. This deficit relative to the average abundance of the solar wind (4%, also the typical abundance observed in the distant plasma sheet) indicates that the ionosphere is contributing 80% of the plasma, if all the He^{2+} comes from the solar wind, and if H^+ and He^{2+} of solar origin have equal access. If He^{2+} is not transported earthward as effectively as solar H^+, then one would not need so large an ionospheric contribution. If He^{2+} is not entirely source specific, then a larger ionospheric contribution is implied.

Sharp *et al.* (1985) have shown that this sort of hot plasma composition is characteristic of the inner plasma sheet, that the mean composition evolves smoothly from solar dominated (in quiet times) to ionospheric dominated with decreasing radius, and that the effect of magnetic activity on the inferred origin of the plasma becomes statistically insignificant in the inner magnetosphere. These results, summarized in table 2, clearly imply that the inner plasma sheet and hence ring-current plasma, are basically terrestrial in origin.

TABLE 2. INNER PLASMA-SHEET OR RING-CURRENT COMPOSITION

(After Sharp *et al.* 1985.)

L shell	5–6	6–7	7–8	8–9	9–10	10–11	11–12
ionospheric contribution							
quiet	0.86	0.80	0.33	0.44	0.38	0.29	0.16
active	0.78	0.82	0.76	0.64	0.66	0.55	0.47

Our intent here has been to highlight some of the difficulties in determining the origins of the plasma sheet and the ring current. Chappell *et al.* (1987) have developed an argument, based upon recent ionospheric outflow observations, that the source strength of the ionosphere must be revised upward from earlier estimates, e.g. Hill (1974). Whereas estimates based solely on polar wind outflow implied an inadequate to barely adequate source for the amount of plasma required to supply the plasma sheet, the addition of the cleft ion fountain outflow leads to a source strength which is fully adequate to supply the magnetosphere with hot plasma even if some Maxwell demon were to prevent any flow of particles across the magnetopause. Of course, such a demon would have to allow energy flow, i.e. current flow, to power the magnetosphere and provide the energization necessary. Moreover, such a demon might be

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more preoccupied with preventing terrestrial plasma outflow than solar plasma inflow, since only the high-pressure plasma sheet stands a chance of inhibiting ionospheric outflow. The realization that terrestrial mass flow is outward on average represents a significant change in our perspective on solar terrestrial physics.

Conclusions

Significant progress in both observing and modelling terrestrial plasma has been achieved since Banks & Holzer (1969*a*) summarized the 'features of plasma transport in the upper atmosphere'. Figure 8 schematically summarizes our current understanding of terrestrial plasma transport into and through the magnetosphere. We have a polar wind driven by the relative vacuum of the solar plasma at high altitude. We also have heavy-ion-rich outflows driven by ionospheric heating. Most of the flux of ionospheric ions passes through the 1 R_E level at energies well below 1 keV. The plasma sheet is the downstream recipient of auroral and polar plasma outflows which vary greatly in composition with heat input to the cleft, neutral atmosphere structure (solar cycle), and convection strength across the polar cap. An important variable is the resulting location at which these flows are incident on the neutral sheet, since this controls the degree to which the flow is energized by its neutral sheet interaction. It appears that neutral sheet energization alone is adequate during active periods to generate the plasma sheet from this low-energy source. For quiet periods, some other energization mechanism seems to be required to account for the hot terrestrial plasma. The Earth appears to be the primary supplier of its own plasma environment within about 10 R_E geocentric, though a noticeable amount of solar plasma is also observed. The solar wind is increasingly important in the plasma sheet beyond 10 R_E particularly in magnetically quiet periods.

As regards hot plasma effects, there appears to be a discrepancy between the hydrodynamic and kinetic descriptions of hot/cold plasma equilibria along magnetic field lines. The hydrodynamic approach would seem to argue for a possible equilibrium with little ionospheric outflow in regions of large hot plasma pressure at high altitude (Banks & Holzer 1969*b*). In contrast, a kinetic description of this type of situation (Lemaire & Scherrer 1973) suggests that the hot plasma has little if any impact upon the cold plasma flow. This discrepancy lies at the heart of the difference between convection/loss and convection/hot plasma models of the plasma distribution in the magnetosphere, and is sorely in need of resolution.

We are indebted to the *DE*1 RIMS team at the Marshall Space Flight Center (MSFC) and the University of Texas at Dallas for the development of the RIMS instrument and to the staff of the Boeing Corporation for assistance with data reduction. This work has been supported by the NASA Dynamics Explorer Project, the NASA Space Plasma Physics Branch and the Data System Technology Program at MSFC. The efforts of C.J.P. have been supported by the National Research Council under its Resident Research Associate Program. Support for J.L.H. and G.R.W. was provided in part by NASA grant NAG8-058 to The University of Alabama in Huntsville.

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Discussion

S. Quegan (*University of Sheffield, U.K.*). An O^+ flux of 10^{13} m^{-2} s^{-1} would deplete the O^+ content of a flux tube in 15 min to 1 h. Therefore such fluxes cannot last long in the real ionosphere. How long, and more concisely what fraction of the O^+ is likely to be lost from a flux tube by these outflows, when convection is taken into account?

T. E. Moore. The observed fluxes from the dayside upwelling region are indeed exceedingly large, in some cases larger than the limiting steady-state outflow, *ca.* 10^{13} m^{-3} s^{-1}, a limit set primarily by friction between O^+ and O rather than by the ionization production rate. Therefore these fluxes could only barely be maintained in the steady state, even if the ionosphere were sunlit. If the ionosphere at the heating region is in darkness, depletion of the flux tube is indeed possible. However, the fluxes need only be maintained during the convection of the plasma through the heating region. Given the statistical size of this region (*ca.* 1000 km), and the rapid convection observed in the heating region (few kilometres per second), the typical duration of the upwelling in a given plasma flux tube column is several minutes. The statistical size of the upwelling region probably exceeds the instantaneous size, so that this is doubtless an upper limit, thus relieving the ionosphere of total depletion by these events. The source/loss balance as averaged over a convection circulation period is likely to fall well within the realm of possible steady state outflows.

A. S. Rodger (*British Antarctic Survey, Cambridge, U.K.*). Can Dr Moore give some indication of the timescales involved between heating of the ions in the vicinity of the cusp and their arrival in the noon–midnight plane (probably intended to be the equatorial plane) on the nightside?

T. E. Moore. Scaling from my figure 7, one finds that the time of flight to the neutral sheet is between one and two hours, depending upon the rate of convection over the polar cap, with the faster convection rates being those normally associated with geomagnetic activity. It is intriguing to speculate on the similarity of this timescale and that which Dave Southwood referred to in connection with substorm triggering. If the arrival of heavy-ion plasma in the magnetotail is causally related to the onset of substorms (as proposed by Baker *et al.* (1982)), this could represent an interesting link between dayside magnetospheric processes and nightside substorm activity.

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