ISEE 1 Observations of Thermal Plasma in the Vicinity of the Plasmasphere During Periods of Quieting Magnetic Activity

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Thermal (≤100 electron volts) ion observations made with the plasma composition experiment on ISEE 1 are combined with plasma density profiles obtained from plasma frequency measurements made with the plasma wave experiment to conduct an investigation of thermal plasma behavior in the vicinity of the plasmasphere during periods of quieting magnetic activity. Normally, the principal thermal ion population in the plasmasphere consists of cold \(kT \leq 1\ eV\), isotropic distributions with ion species in the order of dominance \(H^+ : He^+ : O^+\), while outside the plasmapause, the observed \(E \approx 100\ eV\) ion distributions usually are field-aligned in structure, have characteristic energies \(E \approx 10\ eV\) and \(H^+ : O^+ : He^+\) order of dominance in fluxes. During periods in which the magnetic activity quiets, the above two regions are separated by a new region in which, at times, low-energy (≈ 1–2 eV) \(H^+\) and \(He^+\) are found flowing along the magnetic field lines. On other occasions following quieting magnetic activity, pancake distributions (peak fluxes at 90° pitch angle) are observed in this region. Other complex distributions have been seen, and these complexities and the limitations of the data coverage preclude a satisfactory simple interpretation. It seems plausible to identify this region as the site of plasmasphere refilling. However, the data presumably also contain evidence of the quiet time rotation of the plasmasphere bulge region into the morning sector.

INTRODUCTION

One of the major unresolved problems in magnetospheric physics today is the question of how the plasmasphere fills. For several years there have existed theoretical models [e.g., Banks et al., 1971] that have made specific predictions on the temporal and spatial evolution of the plasma distributions along a magnetic flux tube during the filling process, but it has not been possible to test most of the predictions with appropriate experimental data. The most direct evidence of plasmasphere filling comes from sequential observations of plasma density profiles by ground-based whistler receivers and satellite-borne mass spectrometers, from which it has long been known that the plasmasphere contracts during periods of high-magnetic activity and expands during periods of magnetic quiet [e.g., Carpenter, 1967; Chappell, 1972]. An overall plasmasphere expansion occurs through the filling of those flux tubes that were depleted during a previous magnetically active period when their convection paths intersected the magnetopause, but which, during the quiet period, reside on convection paths that encircle the earth. Caution is appropriate in the interpretation of expanding plasmasphere as evidence for filling, however, since apparent expansion during quiet periods can also occur through the corotation of the plasmaspheric bulge region from dusk toward the morning sector [Carpenter, 1970]. In this case, of course, the expansion is more temporary and is restricted to the regions outside the dusk sector (where the plasmapause actually decreases in size).

In the theoretical model for refilling proposed by Banks et al. [1971], the filling process is initiated as an interaction near the magnetic equator between supersonic field-aligned plasma flows emerging from the two conjugate ionospheres at the feet of a flux tube depleted of plasma. The proposed filling model involves a shocklike interaction between the two flows, creating a high-density slab at the equator. The slab's edges are shock fronts that propagate down the magnetic field lines toward the topside ionosphere and where these shock fronts arrive at the topside ionosphere, the plasma flow character changes from supersonic to subsonic and proceeds until diffusive equilibrium is attained. Banks et al. [1971] estimated that for the \(L = 5\) field tube, the transition from supersonic to subsonic flow would take place about 22 hours after the filling process began, and that diffusive equilibrium is attained roughly 10 days after the initiation of filling. An alternative prospect is that there may be little or no interaction between such streams, and for solstice conditions, Bailey et al. [1978] have discussed the possibility of net plasma flow from the summer to the winter hemisphere. Even if the two streams should interact near the equator, Schulz and Koons [1972] have raised the question of whether the two streams really behave as colliding, collision-dominated plasma flows, or whether, for example, a collisionless thermalization driven by a two-stream instability is more appropriate.

The principal observations related to filling of the equatorial plasmasphere are from whistler observations of buildup in density profiles during periods of magnetic quiet. Park [1974] has found that the plasmasphere refilling time (attainment of diffusive equilibrium) increases with \(L\) shell from approximately 1 day at \(L = 2.5\) to 8 days at \(L = 4\). Because the filling times for the larger shells are long in comparison with the intervals between magnetospheric storms, these outer regions are rarely in diffusive equilibrium. Park [1974] has sug-
gested that the plasmasphere usually consists of two distinct regions: (1) an 'inner' plasmasphere, which is in equilibrium with its underlying ionosphere, and (2) an 'outer' plasmasphere, which is not in equilibrium but is still recovering from the previous magnetospheric disturbance. Typically, the boundary between the two regions lies in the range $L = 3-4$ [Park et al., 1978].

Possible evidence corroborating the Banks et al. [1971] prediction of 'filling from the top (equator) down' has been provided by Foster et al. [1978] in a comparison of densities in the equatorial plasmasphere and various signatures in the underlying topside ionosphere. They find that the lower altitude edges of the total density and the light ion troughs in the topside ionosphere (~ 1400 km) begin about $2^\circ-10^\circ$ equatorward of the plasmapause observed by the ground-based whistlers, a phenomenon also observed by Grebowsky et al. [1976]. These observations may imply that the flux tubes fill near the equator prior to the lower altitude parts. There is, however, also evidence from measurements of ion fluxes above Arecibo of interhemispheric plasma transport from summer to winter [Vickrey et al., 1979].

It would appear that direct measurements on the details of the plasma distribution functions along filling flux tubes are now required to make significant progress in our understanding of the plasmasphere filling process. The purpose of this report is to take a step in this direction by presenting measurements from ISEE 1 that provide, in addition to density profiles, new information on the changing energy, pitch angle, and compositional structure of the thermal ion distributions.

ISEE 1 was launched in October 1977 into a highly elliptical...
orbit with $\sim 22.5 \, R_E$ apogee and $30^\circ$ inclination. The data are primarily from the plasma composition experiment (PCE) when the instrument was in its thermal plasma mode, measuring ions in the energy per unit charge range of approximately 0–100 eV/e with a combination retarding potential analyzer (RPA), electrostatic analyzer (ESA), and ion mass spectrometer (IMS). Further details of the PCE are given by Shelley et al. [1978], and a brief description of the instrument’s thermal plasma mode is given by Baugher et al. [1980]. The PCE data are supplemented by density profiles derived from plasma frequency measurements made by the ISEE 1 plasma wave experiment [Gurnett et al., 1978, 1979].

**OBSERVATIONS**

The approach employed in this paper is to examine data taken on successive ISEE 1 passes during periods in which the magnetic activity decreased. Figure 1 shows density profiles versus $L$ for the outbound ISEE 1 passes on December 4 (day 338) and 7 (341), 1977. These densities were derived from measurements of the electron plasma frequency by the plasma wave experiment [see Gurnett et al., 1979; Carpenter et al., 1981]. As the $Kp$ history in the upper panel of Figure 1 shows, the pass on December 4 was taken when $Kp$ had the moderately high value of $\sim 3+$, while at the time of the December 7 pass, $Kp$ had been low ($\leq 1$) for about the previous 24 hours.

The density profiles for $L \approx 4.2$ for both days are similar in shape (although somewhat lower in density level) to the whistler measurements by Park et al. [1978]. They appear to be characteristic of the largely filled plasmasphere, although it is possible that the increase in density level in the range $L = 2.8$–3.5 could be due to either filling or corotation of a different portion of the plasmasphere into this local time sector.

To illustrate the characteristic features of the thermal ion distributions within this portion of the plasmasphere, Figures 2a and 2b show, respectively, the 0- to 100-eV fluxes of $H^+$, $He^+$, and $O^+$ and a contoured $He^+$ distribution function, taken just inside the plasmapause at $L = 3.99$ and 4.07, on December 4 (338), 1977. (The ion fluxes in Figure 2a are plotted versus spin angle about the ram direction, rather than pitch angle, because they show no modulation with pitch angle; see also Baugher et al. [1980].) The umbrella-like spin-modulated flux curves in Figure 2a are signatures of cold, essentially isotropic distributions moving relative to the spacecraft, owing primarily to the spacecraft orbital motion, with an offset from $0^\circ$ in the flux peak due to the corotational plasma motion. The contours of the $He^+$ distribution function in Figure 2b show more clearly the nearly circular contours of an isotropic, cold ($kT \sim 0.5$ eV) ion distribution function being translated in the spacecraft reference frame by the orbital motion and corotation. The $H^+:He^+:O^+$ order of ion dominance in Figure 2a is characteristic of the plasmasphere, although the peak ratios of about 1:0.37:0.1 for $H^+:He^+:O^+$ were somewhat higher than normal proportions of $He^+$ and $O^+$; for example, Young et al. [1977] find typical ratios from GEOS 1 to be 1:0.1:0.01. ISEE 1 also observes in lesser amounts $O^{++}$ and $M/Z = 2$ ions ($He^{++}$ and/or $D^+$) within the plasmasphere; these are not shown here.

The evolution of the ion distribution beyond $L \sim 4.2$, the approximate location of the December 4 plasmapause, is indicated in Figures 3a and 3b, which contrast the distributions at roughly the same $L$ shells on December 4 and 7. The $H^+$,
He⁺, and O⁺ 0–100 eV fluxes (at L = 4.6) on December 4 (338) and L = 5.05 on December 7 (341)) are plotted versus pitch angle in Figure 3a, since no ram angle anisotropies were evident (a reversal of the situation in Figure 2a). The fluxes for both days were field-aligned but with two important differences. The December 4 observation showed a compositional order of dominance H⁺:O⁺: He⁺, while the December 7 pass showed the H⁺:He⁺:O⁺ ordering characteristic of the plasmasphere. The other important difference seen in Figure 3a is that the hydrogen fluxes for the December 4 pass showed enhancement near both α = 0° and 180°, whereas the data of December 7 showed flux enhancement only for ions coming from the southern hemisphere (toward α = 0°). (It may be noted that the H⁺ detector swung closer to α = 0° than to α = 180° in its pitch angle sampling, while the reverse was true for He⁺ and O⁺.) The He⁺ also showed this trend, while O⁺ showed a stronger flux near 0° for the December 4 case. As will be discussed later, the stronger H⁺ and He⁺ fluxes from the southern hemisphere may be related to the differences in sunlight illumination of the two ionospheres at the base of the flux tube.

A further important difference seen was in the energy characteristics of these two flows, illustrated in Figure 3b. Figure 3b shows, for the two cases, the count rates for incoming ions with pitch angles near 30° plotted versus potential on the retarding potential analyzer. For the December 4 (day 338) case, little fall-off of count rate was seen until the potential reached 20 V, wherein the count rate decreased slowly with potential above this level. This situation is contrasted with the data of December 7 (day 341) in which a sharp fall-off in count rate was observed for potential ~1 V. Thus the observed ion flux in the December 4 case was carried by ions with characteristic energies of the order 20 eV, whereas the December 7 case ion flux was mainly carried by ions of energies ~1–2 eV. (The possible presence of ions with energies ≥20 eV on December 4 being excluded from detection by a positive vehicle may not be ruled out, however.)

This 1- to 2-eV flow of H⁺ and He⁺ ions was evident on the December 7 pass until about L = 7.6, at which point a H⁺:O⁺: He⁺ warm (~10–20 eV) ion flow was observed to be dominant, similar to the December 4 observations presented in Figure 3a and 3b.

A further example of these low energy H⁺ and He⁺ ion flows from the southern hemisphere observed during magnetic quieting is depicted in Figures 4 and 5. Figure 4 contains successive profiles of the maximum counts per spin detected in the 0- to 100-eV channel of the PCE (a rough indicator of the density variation, used here because the wave data were not available) for the ISEE 1 outbound passes on December 16 (day 350) and 19 (day 353), 1977. As can be seen from the Kp history in the upper panel of Figure 4, the pass of December 16 was taken during a period of moderate activity (Kp ~ 2) whereupon Kp increased for about 10 hours up to Kp ~ 5 and then declined to relatively low values prior to the December 19 observation. In particular, the Kp for December 18 (just prior to the second pass) was extremely quiet, with a ΣKp for December 18 (just prior to the second pass) was extremely quiet, with a ΣKp = 4°.

The steep decrease in count rate on December 16 starting at L ~ 4.8 was associated with a transition at L ~ 4.9 from cold, isotropic, H⁺:He⁺:O⁺ ordered plasma to warm, field-aligned H⁺:O⁺: He⁺ ordered plasma, and we may identify this transition with the plasmapause for this day. The ion characteristics for the region outside the December 16 plasmapause are indicated in Figures 5a and 5b. In these figures, these characteristics are contrasted with the observations at nearly the same L value on December 19, which showed an H⁺:He⁺:O⁺ ordered plasma with 1- to 2-eV ions flowing from the southern hemisphere. These features are quite similar to the observed thermal plasma characteristics observed during the December 4–7, 1977 interval discussed above.

Figures 6 and 7 illustrate a different feature, the appearance of warm H⁺ and He⁺ ions configured in trapped or pancake distributions [Horwitz et al., 1981], observed in the vicinity of the plasmasphere during magnetic quieting. Figure 6 shows density profiles taken on the ISEE 1 outbound passes of November 20 (day 324) and 25 (day 329), 1977, together with the Kp history throughout this interval (upper panel). The 3-day period prior to the November 25 pass was extremely quiet (Kp ≈ 1) whereas the activity was moderate (Kp ~ 2) just prior to the observation on November 20.

The density profiles up to about L = 4.2 on both days shown in Figure 6 were again characteristic of the plasmasphere.
sphere profiles reported by Park et al. [1978]. The plasmapause on November 20 was seen as a decrease in density at about $L = 4.3$, where a transition was seen from cold, isotropic ion distributions with $\text{H}^+ \cdot \text{He}^+ : \text{O}^+$ order of dominance to field-aligned distributions of 10- to 40-eV ions with $\text{H}^+ : \text{O}^+ : \text{He}^+$ order of dominance. This transition in ion distributions at the plasmapause is similar to that observed on the December 4 and 16 passes.

Figure 7a shows $\text{He}^+$ velocity distribution contours seen at $L = 7.27$ on the November 25 pass, beyond the $L = 4.3$ plasmapause of November 20. The upper panel of Figure 7a shows the $\text{He}^+$ velocity contours versus ram angle and indicates a mixture of cold, isotropic $\text{He}^+$ ions (the nearly circular contours at the core of the distribution) with a pancake distribution in the several volt ions (seen in the bulge in the contours toward the $\alpha = 90^\circ$ locations at the higher ion speeds; the pancake component is best illustrated in the pitch angle organized contours of the lower panel of Figure 7a). This type of distribution was also observed in $\text{H}^+$, while the 0- to 100-eV $\text{O}^+$ fluxes were very low. This mixture of cold, isotropic components with several electron volt pancake distributions in both $\text{H}^+$ and $\text{He}^+$ was seen on November 25 from $L = 4.3$ out to about $L \sim 9$, where the cold component decreased in intensity and the warm ion pancake distribution became dominant. Figure 7b shows the pancake distribution prominent in the 0- to 100-eV $\text{He}^+$ fluxes at $L = 10.40$ (just beyond the $L = 10$ cutoff in the plot of densities in Figure 6) while a field-aligned component is evident in $\text{H}^+$ and $\text{O}^+$ fluxes.

A final instance of thermal plasma behavior during quieting magnetic activity is presented in Figures 8 and 9, for the period January 18–21, 1978. Figure 8 shows again two successive
density profiles, for the inbound passes in the morning sector on January 18–19 and on January 21, 1978. In this period $K_p$ was high ($K_p \approx 5$) before the first pass and was moderate ($K_p \approx 1–2$) for about 1 1/2 days after the pass. The ~12 hour interval just prior to the second pass was very quiet ($K_p \approx 0^+$. The density profiles on both days up to $L \approx 4.8$ were similar to the plasmasphere profiles discussed previously, and examination of ion distributions shows that, as in the previous examples, the edge near $L = 4.8$ on the January 18–19 pass marked the transition from cold, isotropic $H^+:He^+:O^+$ ordered ions inside the ledge to warm, field-aligned $H^+:O^+:He^+$ ordered ions outside.

Considering now the region beyond $L = 4.8$ on January 21, 1978, a population of cold, isotropic $H^+:He^+:O^+$ ordered plasma was observed out to about $L = 7$ as indicated in the Figure 9a example of spin-modulated 0- to 100-eV ion fluxes at $L = 5.79$. At the higher energies, a warm ion pancake component in $H^+$ and $He^+$ was also observed. Beyond $L = 7$, a somewhat unusual mix of warm ions was seen illustrated by Figure 9b for $L = 7.43$, in which the 0–100 eV $H^+$ fluxes were in a pancake configuration, while $He^+$ and $O^+$ were field aligned.

**DISCUSSION**

To summarize briefly the data presented, the baseline or initial conditions involved were magnetically active conditions with the plasmapause at contracted distances. Here the plasmapause was observed to distinctly separate a region of cold, isotropic plasmaspheric plasma with an order of ion dominance $H^+:He^+:O^+$ from a region outside containing field-aligned flows of 10- to 40-eV ions with $H^+:O^+:He^+$ ion flux dominance. As magnetic activity became quiet, we observed one or more of the following types of ion distributions dominant in the region immediately outside the contracted active period plasmapause: (1) low-energy (1–2 eV) field-aligned flows of primarily $H^+$ and $He^+$ ion fluxes streaming from the sunlit hemisphere toward the dark hemisphere,
cold, isotropic plasmaspheric type distributions, and/or (3) pancake or trapped distributions of $\sim 10 \text{ eV} \ H^+$ and He$^+$ ions, with O$^+$ either field-aligned or isotropic. Beyond these regions, the ion distributions are typically of the same type as are observed outside the active period plasmapause, i.e., field-aligned flows of 10- to 40-eV ions with H$^+$:O$^+$:He$^+$ order.

Of the above, the most likely type of distribution to be associated directly with the refilling process is obviously the flow of 1-2 eV H$^+$ and He$^+$ along the magnetic field lines. These flows are probably related to upward flows at lower altitudes at the ionospheric feet of these flux tubes. Ordinarily, adiabatic conservation of the ion magnetic moments during the ions transport from the ionosphere to the magnetosphere would cause the ions to collimate within a pitch angle cone of $\approx 5^\circ$; thus, some pitch angle scattering has evidently taken place to provide fluxes observed at larger pitch angles as seen in Figures 3a and 5a.

Note that in both Figures 3a and 5a, the 1-2 eV H$^+$ and He$^+$ ion flows were observed emerging mainly from the southern hemisphere. These events occurred near winter solstice when the southern ionospheric feet of the filed lines were sunlit and the northern feet were in darkness. We have used a field line tracing program together with an Olson-Pfitzer magnetic field model to determine the shadow heights along the feet of these field lines for the cases of Figures 3 and 5. For the Figure 3 case on December 7, 1977 at 0202 UT, the northern ionospheric shadow height was 1130 km, while the southern hemispheric shadow was at ground level. For the Figure 5 case on December 19 at 0053 UT, the northern hemispheric shadow height was 2259 km and the southern hemispheric shadow was again at ground level.

Since these instances of the field-aligned flows involved flows from the southern (summer) hemisphere that were observed in the northern (winter) hemisphere, it appears that
these represent interhemispheric transport from the summer to winter hemisphere. Hence, if there is an interaction near the equator to start filling there, as proposed by Banks et al. [1971], it seems that at least some of the plasma flow is not blocked there, but is allowed to proceed into the opposite hemisphere.

We suspect that the distribution in the occurrence of these flows seen outside the active period plasmapause is related to the changing location of the inner boundary of the flux tubes threading the plasma sheet and the diffuse aurora. It is on the diffuse auroral flux tubes that we believe the energization of these ionspheric ions to 10 eV and higher is taking place. However, the relationship of the plasmapause to the plasmasheet is outside the intended scope of this paper and will be discussed in a separate report (J. L. Horwitz et al., manuscript in preparation, 1981). As depicted in Figure 10 (upper panel), it appears that during times of high magnetic activity the plasmapause and the inner boundary of the plasmasheet/diffuse auroral flux tubes are adjacent (J. L. Horwitz et al., in preparation, 1981). During periods of quieting this plasmasheet inner boundary recedes to greater geocentric distances, leaving a gap between it and the active period plasmapause (lower panel, Figure 10). It is suggested that it is within this gap, linked most likely to the mid-latitude light ion trough in the ionosphere, that the 1- to 2-eV H+ and He+ field-aligned flows occur.

The data presented here do not allow determination of the sequence of events which lead to the formation of the cold, isotropic plasmas and the pancake distributions beyond the plasmapause. We do not know the conditions determining when these distributions or the field-aligned flows would be observed, but we suspect that it may have to do with the differences in filling time interval and/or geomagnetic latitude. That is, it is possible that the rather extended quiet interval preceding the November 25 observations has allowed the evolution from the initial flows to the observed mixture of cold, isotropic plasma and several electron volt pancake distributions, while the low geomagnetic latitude of the January 21 observations may have permitted the observation of distributions forming initially only very close to the magnetic equator.

In any case, since a cold, isotropic component is evidently the end product of the filling process, it clearly plays a central role in the filling and it is certainly crucial to determine the processes that lead from the field-aligned flows to this stage.
Fig. 8. Similar to Figures 1, 3, and 6 for January 18 and 21, 1978.
Fig. 9. (a) Spin modulated 0–100 eV H⁺ He⁺, and O⁺ ion flux curves at $L = 5.79$ on January 21, 1978, similar to Figure 2a. (b) Similar to Figure 7b for January 21, 1978.
DIFFUSE AURORA
ACTIVE
PLASMASPHERE
PLASMA SHEET

SUNLIT IONOSPHERE
VERY LOW-ENERGY H+/HE+ FLOWS
(INNER) PLASMASPHERE
FILLING REGION

Fig. 10  Schematic presentation of the relative locations of the plasmapause and the inner boundary of the plasma sheet-diffuse auroral flux tube during active periods and when activity has quieted.
The role of the pancake distributions in the primary filling process is uncertain—they may, for example, be an interaction of cold ions with cyclotron waves [Gendrin and Roux, 1980].

Finally, it should be reiterated that there remains a degree of uncertainty regarding the effect of the possible rotation of the plasmaspheric bulge region during the observation intervals upon the interpretation of the increasing density levels and changing ion distributions. The bulge rotation concept is illustrated schematically in Figure 11. Here, we have shown the bulge rotating during a quiet period from dusk into the night sector, with some shape distortion owing to the rotation speeds varying with radial distance. In the morning sector, where we have shown the spacecraft trajectories, the plasmapause is near its minimum radial distance under normal conditions. Hence, the bulge rotation during quiet periods will, on the average, lead to some expansion in this sector. The filling region shown is the region outside the active period plasmapause where convection trajectories are newly encircling the earth and flux tubes are allowed to fill. As is indicated, it is quite possible that each pass contains both evidence of filling and the bulge rotation.

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