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Effects of Plasmaspheric Ion Heating Due to Ionospheric and Magnetospheric Sources

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by

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In an initial study, we examined the He^+ observations from the Retarding Ion Mass Spectrometer on Dynamics Explorer 1 (DE1/RIMS), for more than 120 transits of the plasmasphere in the fall of 1981 [*Newberry et al.*, 1989]. We determined the He^+ to H^+ ratio as it varied spatially over portions of the DE 1 orbit, and its variation with solar and magnetic activities and with local time, focusing specifically on the inner plasmasphere. These variations were compared along the L = 2 field line with calculations made by the Field Line Interhemispheric Plasma (FLIP) code [*Richards and Torr*, 1988; *Torr et al.*, 1990; *Richards et al.*, 1994a,b]. We found that ion temperatures computed by FLIP were consistently lower than those observed. When a heat source was added, sufficient to bring the temperatures into agreement, the densities were also brought into good agreement. We suggested photoelectron trapping as a likely mechanism for providing energy to plasmaspheric ions from a readily available source. Recent calculations by *Khazanov et al.* [1992, 1994a] support the idea of more photoelectron energy being made available to the plasmasphere than previously calculated due to trapping through pitch angle scattering.

A more extensive statistical study of N^+ behavior using the DE1/RIMS data [*Craven*, 1993; *Craven et al.*, 1995a, 1996] suggests that the dynamics of N^+ are similar in most essential respects to the dynamics of O^+. However, the RIMS data indicate that the ratio of N^+ to O^+ densities decreases for increasing solar activity. Using FLIP we have found this appears to be related to a greater increase in O^+ density than in N^+ density which occurs at the F2 peak with increasing solar activity. Whether this has a dynamic origin or is rooted in temperature dependencies of source and loss processes is still to be determined. In general, the model shows that the N^+ to O^+ density ratio tends to increase with altitude above about 1000 km for all geophysical conditions, typically ranging from 0.1 to about 1.0, and decreases with increasing ion temperature. This increase with altitude is supported by RIMS observations. The ratio varies considerably below 1000 km altitude, depending on the solar activity, the geomagnetic activity, the local time, season, and other variables. One of the results of this study is that there appears to be much more N^+ in the magnetosphere, particularly above the topside ionosphere, than has generally been appreciated. Previous observations with insufficient mass resolution to distinguish N^+ from O^+ have typically attributed what was observed in this mass range to O^+. This difference could be significant for high precision resonant type processes (e.g. radiative emissions) or in quantitative comparisons of observations with detailed physical models which include realistic ion chemistry.

In a recently submitted paper [*Craven et al.*, 1995b], we examine the He^+ to H^+ density ratio for all the available data from 1981 through 1984 from the Retarding Ion Mass Spectrometer on the Dynamics Explorer 1. We find that there are two basic characteristics of the ratio of He^+ to H^+ densities in the plasmasphere. One is that the ratio decreases with radial distance r in the plasmasphere, and the other is the strong dependence of the density ratio on solar activity. The overall mean adjusted ratio for low activity is 0.1 and for high solar activity is 0.25. Previous studies, although with higher energy ions, have also seen a dependence of the density ratio on solar activity [*Young et al.*, 1982]. The model of the plasmasphere used by *Newberry et al.* [1989] shows a solar activity effect that is dominant over geomagnetic effects, but in either case the ratio increases with increasing activity. We are able to detrend the data in order to remove the decrease with r and with declining activity. The functions used for the detrending provide a basis for a first order model for the plasmaspheric He^+ to H^+ density ratio. *Farrugia et al.* [1989] using GEOS/ICE data, showed that the equatorial He^+ to H^+ ratio decreased by a factor of about 2 from 2 R_E to 6 R_E, a rate somewhat slower than that found by *Craven et al.* [1996], but still within the spread of the data. The behavior of the ratio in this study is qualitatively consistent with the results from FLIP.

We have recently been studying an interesting phenomenon in the topside ionosphere which relates to the thermal coupling of the ionosphere to the plasmasphere. A study of the Millstone Hill incoherent scatter data taken during the 1960s and 1970s often revealed anomalous electron temperature enhancements at night in the topside. We have performed a detailed statistical study of the occurrence characteristics of these events and found that it is mostly a winter phenomenon, occurring on 70% of the January nights, but rarely in summer. However, it also occurs, with lower frequency, in all other months from September through May. The events typically occur prior to midnight and last for 2-3 hours. There is little or no correlation with magnetic and solar activity.

In the past, these temperature enhancements were attributed to density decreases in the presence of a constant heat flux from conjugate photoelectrons [*Evans*, 1967; *Sanatani and Breig*, 1981]. However, the occurrence of these events at equinox, when conjugate photoelectron heating is non-existent, points to a more complex mechanism. Also, heating events do occur when the electron density is increasing rather than decreasing. And in those cases where the density decreases as the temperature rises, the subsequent temperature decrease usually occurs as the density continues to decrease. On the other hand, if the apparent ionospheric heating is a purely plasmaspheric phenomenon, totally independent of the conjugate photoelectron flux, it is difficult to understand why it does not occur in summer, when the ambient ionospheric temperatures are low and any heat source would be more noticeable. Results of this study have been published in the Journal of Geophysical Research [*Garner et al.*, 1994]. *Khazanov et al.* [1994b] have suggested that these heating events may be associated with the compression of convecting flux tubes on the night side.

Another study has been directed toward the relation of plasma properties to the density gradients forming the plasmapause. From a set of more than 150 plasmasphere transits made by DE 1 in late 1981, a subset of RIMS observations from 47 of these was selected, based on a drop in density exceeding an order of magnitude within a one half unit increase in L shell. It had been found previously in examining temperature and density gradients that the maximum temperature gradients tended to be co-located with the maximum (in magnitude) density gradients, suggesting that steep density gradients are places where the energetics of plasmasphere models should be tested. The study has followed a two pronged approach. First, the observations have been analyzed to determine what happens to the plasma properties across these boundary layers; this part is being concluded. Second, comparisons were made with FLIP model calculations to determine how well the model is able to treat these conditions.

An example of the transitions which occur near the plasmapause is shown in Figure 1. This figure, adapted from *Comfort et al.* [1996], shows the O^+ and He^+ concentrations averaged at specific locations relative to the plasmapause, with the corresponding average H^+ temperatures above. The '*L3*' data point occurs at the beginning of the plasmapause density gradient, the *L5* point denotes the bottom of the density gradient, and the *L4* point in between can be taken to represent the location of the plasmapause. The error bars indicate the scatter in the individual L values of these locations in the data set. A feature of primary interest is the minimum in O^+ concentration interior to the plasmapause and the large increase in concentration across this boundary. The variation in average ion temperature at these points is sufficiently similar to suggest a relationship. However, the temperature structure does not show the minimum at *L2*, and the temperature is that of H^+, which has been found to be generally in equilibrium with O^+ [*Comfort*, 1995]. The behavior of the O^+ concentration is in stark contrast with that of He^+, which is virtually unchanged across the plasmapause. Among other characteristics found in this study is a lack of strong correlation with magnetic activity, except for the location of the plasmapause.

In comparing these observations with simulations, we have used the FLIP model to evaluate plasma properties for several L-shells on selected days, and then compared these with DE 1/RIMS observations. As in the He^+ study [*Newberry et al.*, 1989], it was found that the observed ion temperatures are consistently higher than the FLIP calculations. However, we found that a photoelectron trapping factor similar to that found in the He^+ statistical study provides sufficient energy to increase the calculated ion temperatures to those observed, for the inner L shells. When this is done, it also increases the calculated He^+ and O^+ densities, resulting in good agreement with the observed densities. For the outer L shells, the situation is more complicated. Increasing the photoelectron trapping factor, even to 1.0, is insufficient to bring the computed temperatures up to those observed; and the corresponding He^+ and O^+ densities are also somewhat low. Where there is overlap with energetic ions from the ring current, the low energy part of which is observed by the Energetic Ion Composition Spectrometer (EICS) on DE 1, Coulomb collisions between heavy ring current ions and thermal H^+ and thermal electrons can also provide additional heat to the thermal ions. This has been computed, as described by *Kozyra et al. (1987)* and *Chandler et al. (1988)*, and this heat source has been included in the FLIP model.

An example is shown in Figure 2. The top panel presents H^+ temperatures, with filled circles showing DE1/RIMS observations. The open squares correspond to ion temperatures calculated normally with FLIP, while the open diamonds represent the same calculation, but with 50% photoelectron trapping, as described by *Newberry et al.* [1989]. For the outer L-shells (L > 2.7), the crosses denote ion temperatures computed by including both the additional photoelectron heating and the Coulomb collisional heating from ring current O^+. The bottom panel shows the corresponding densities for H^+, He^+ and O^+, with filled symbols representing the observations and open symbols the calculated densities; the progression of open symbols corresponds to the initial and final T_i, as described for the upper panel. For present purposes, the important points to note are that the introduction of the additional heating is generally adequate to raise temperatures to observed levels and when this is done, the densities correspondingly give good agreement between observations and calculation. The exception occurs at L = 2.98, where the density has dropped to a few hundred per cubic centimeter and the temperature has increased to ≥ 15,000 K; the calculated temperatures are far too low and the calculated He^+ and O^+ densities are also low.

We have recently studied this case in more detail [*Comfort et al.*, 1995a], examining the nature of heating mechanisms required to produce these high ion temperatures (1-2 eV). We found that heating the ions through the thermal electrons, as done by photoelectrons, could not transfer sufficient energy to produce the observed ion temperatures, due to decreasing collisional coupling between thermal ions and electrons with increasing temperatures. However, the observed temperature could be readily achieved if the heating mechanism operated directly on the ions (e.g. Coulomb collisions between thermal ions and ring current heavy ions [*Kozyra et al.*, 1987, *Fok et al.*, 1993] or wave-particle interactions [*Khazanov*, 1995]). But the resulting simulations also produced some effects which are not observed. In particular, ion temperatures in the topside ionosphere were up to 5000 K higher than observed, and heavy ion (O^+) concentrations at high altitudes were also much higher than observed. While these results are extreme examples, similar problems have been found in other case studies, e.g. *Horwitz et al.* [1990], *Craven et al.* [1995a]. We suggested that these inconsistencies between model results and observations could be diminished if the thermal conductivity were not so large, so that less thermal energy is transported to the topside ionosphere, where O^+ is the dominant ion.

To test this idea, in a subsequent study [*Comfort et al.*, 1995b], we postulated a reduced thermal conductivity coefficient in which only particles in the loss cone of a quasi-collisionless plasma contribute to the thermal conduction. Other particles are assumed to magnetically mirror before they reach the topside ionosphere and therefore not to remove thermal energy from the plasmasphere. This concept was used to formulate a mathematically simple, but physically limiting model for a modified thermal conductivity coefficient. When this modified coefficient was employed in the FLIP model in a case study, the inconsistencies between simulation results and observations were largely resolved. The high simulated ion temperatures were achieved with significantly less heat input, and resulted in substantially lower ion temperatures in the topside ionosphere, as seen in Figure 3a. The corresponding effect on densities and composition is shown in Figure 3b. We suggested that this mechanism might be operative under the limited low density, refilling conditions in which high ion temperatures are observed.

Among the significant lessons learned in these studies are two that bear directly on the direction of future investigations in this area. First, composition cannot be viewed independently of thermal structure. Even though other factors come into play, without accurate knowledge of the energetics, composition will not be understood on a quantitative basis. Second, solar and magnetic activity effects are real; but the causal relationship between activity and effects is frequently quite complicated because several different processes appear to be operating in different ways and on different time scales. Under these circumstances, large correlation coefficients should not be expected and are not generally found.

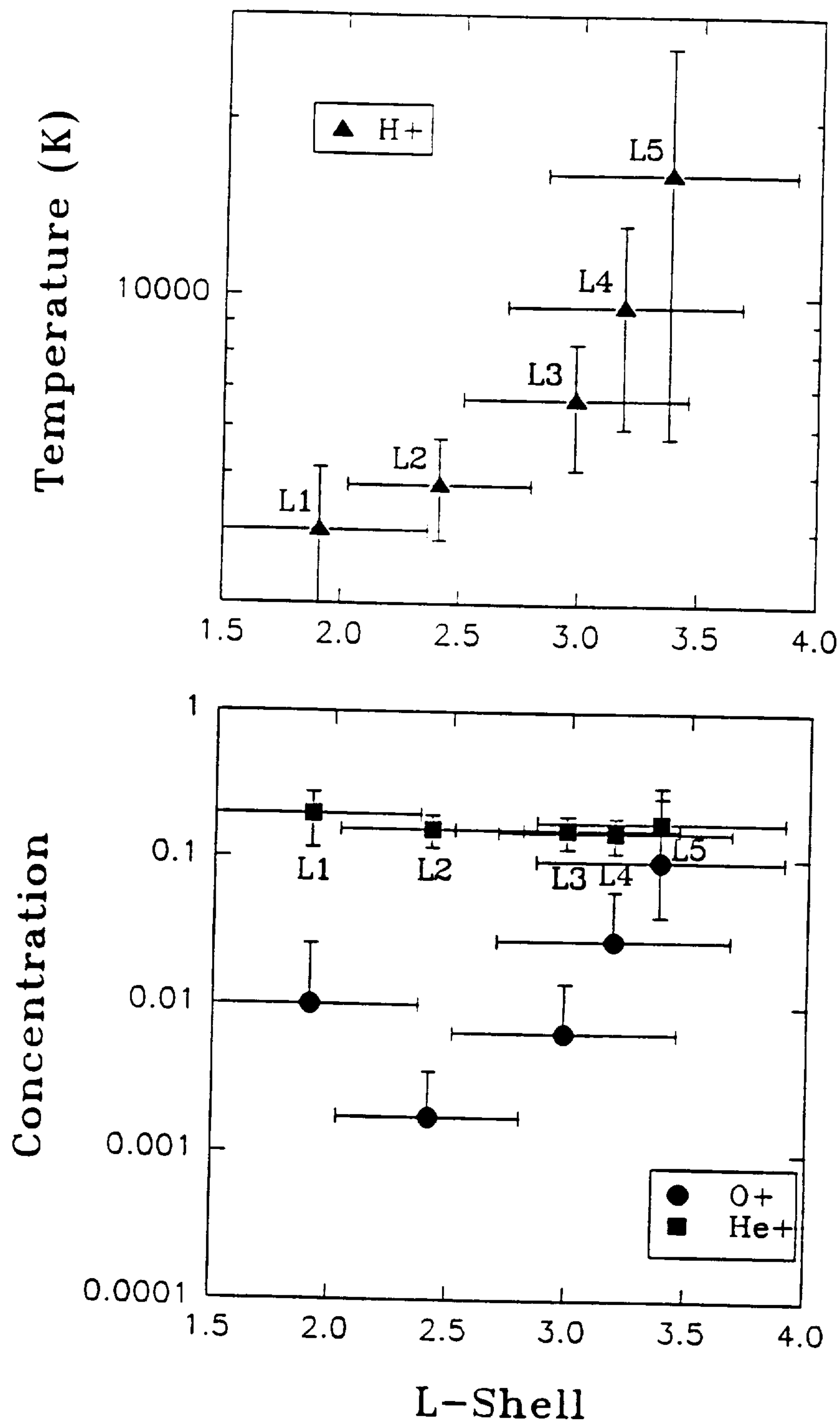

Figure 1. Average H^+ temperatures (upper panel) and He^+ and O^+ concentrations (lower panel) at L-shells specified relative to plasmapause location for a selected set of 44 steep plasmapause density gradients.

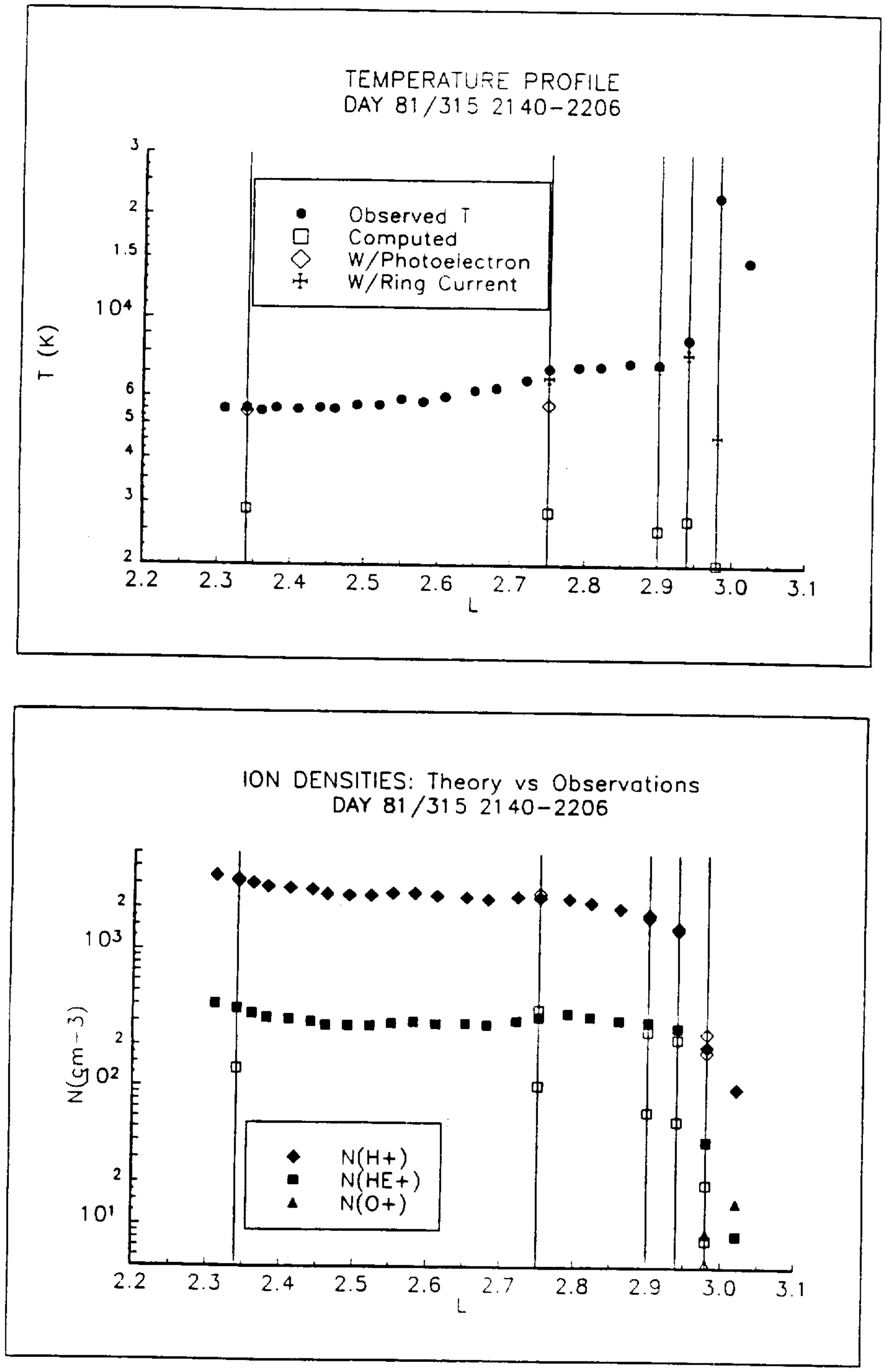

Figure 2. Case study comparisons of H^+ temperatures (upper panel) and ion densities (lower panel) observed by DE1/RIMS with those calculated by FLIP with different augmenting heat sources, as described in the text.

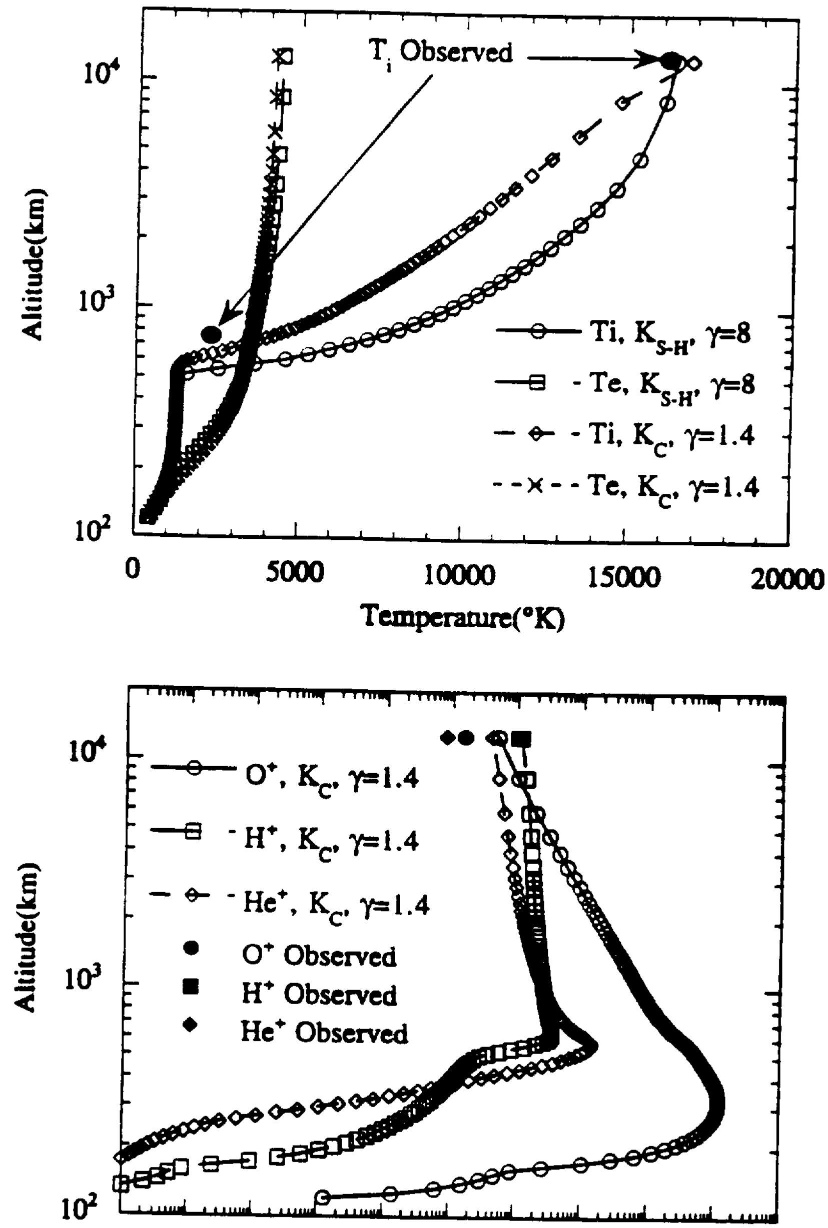

Figure 3. Comparisons of simulated profiles obtained from FLIP, using a modified (reduced) thermal conductivity for cases of direct ion heating, with observed temperatures at high altitudes. Upper panel shows temperatures profiles with and without the modified thermal conductivity. Lower panel show ion species densities with the modified thermal conductivity. Both show observed values.

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