Revisiting the Inner Magnetospheric Oxygen Torus with DE 1 RIMS

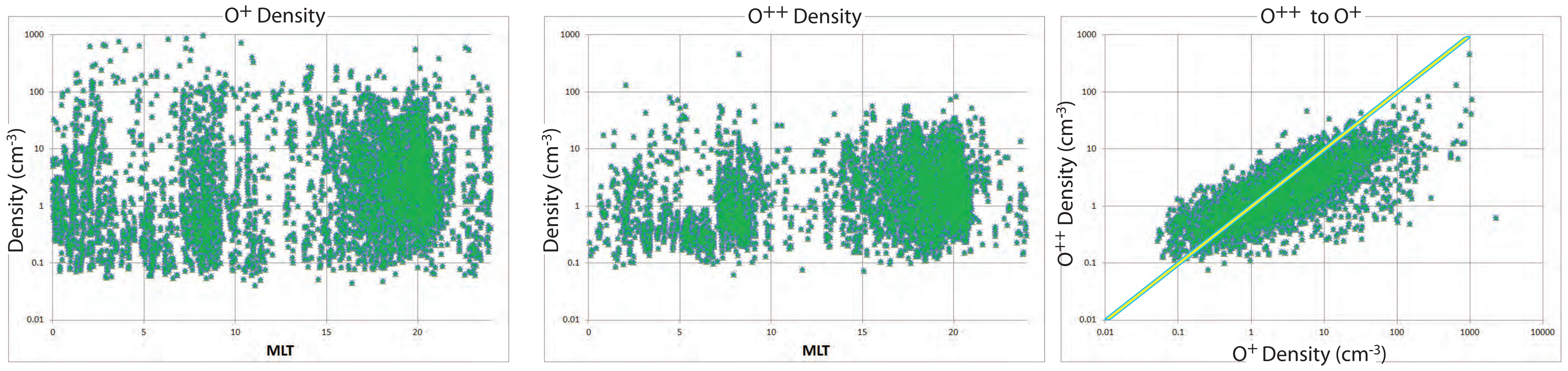
SM33C-2521

D.L. Gallagher NASA/MSFC, J. Goldstein SwRI, P. D. Craven NASA/MSFC, and R. H. Comfort UAH/Emeritus

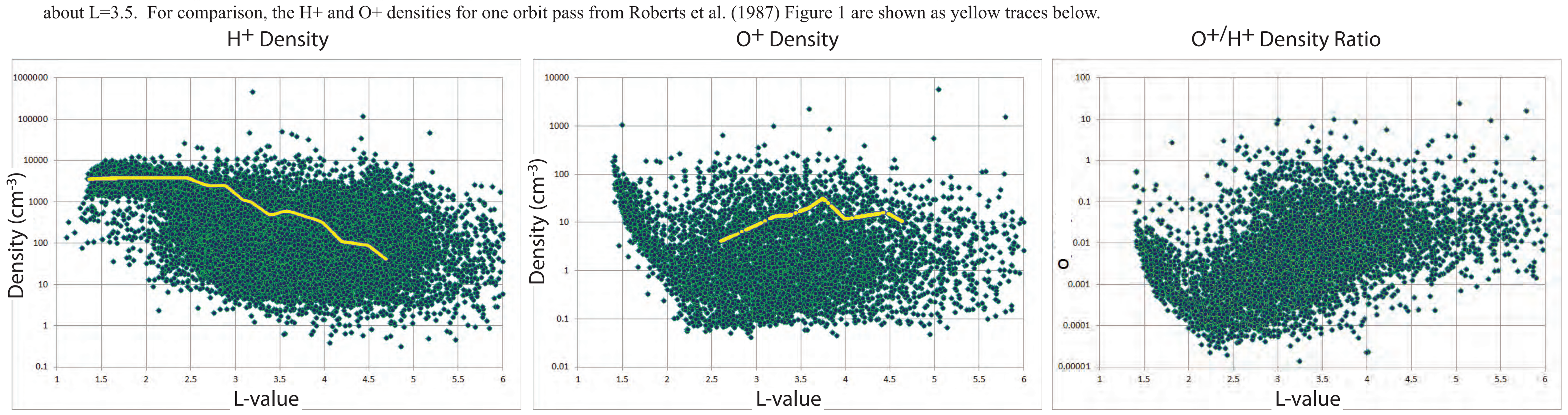
Nearly 35 years ago direct observations of cold plasmaspheric ions found enhanced O^+, O^{++}, and even N^+ densities in the outer plasmasphere, in particular during storm recovery conditions. Enhancements were seen inside or just outside of the plasmapause at all magnetic local times. Whereas nominal O^+ concentrations were found to be 1% or less inside the plasmasphere, enhanced O^+ in the vicinity of the plasmapause was found to reach densities comparable to H^+. Enhanced ion outflow (including oxygen) from high latitudes has also become part of our picture of storm-time phenomena. More recently it has become apparent that high latitude outflow is a source of inner magnetospheric warm ions that convect into morning and afternoon local times, to form what we now call the warm plasma cloak. Low to middle latitude ionospheric outflow and high latitude outflow are thought to result from very different processes and can be expected to contribute differently as a function of conditions and locations to the dynamic processes of energy and particle transport in the inner magnetosphere. Given the apparent proximity of their delivery to the vicinity of the plasmapause during plasmaspheric refilling conditions it becomes worthwhile to question the origin of the oxygen torus and its role in this region. While the observations do not yet exist to settle this question, there are measurements that contribute to the discussion in the new emerging context of cold plasma in the inner magnetosphere. In this paper we present and discuss DE 1 RIMS derived ion densities and temperatures that contribute to answering these outstanding questions about the origin and dynamics of the oxygen torus.

I. Plasmaspheric Heavy and Light Ion Densities

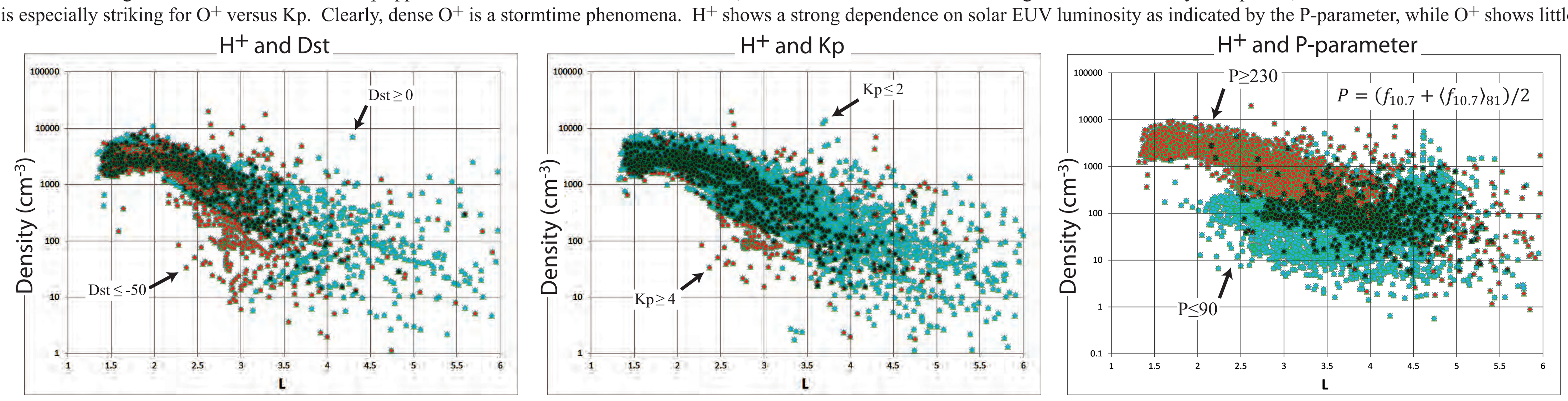
Roberts et al. (1987) provided a comprehensive analysis of heavy ion density enhancements in the outer plasmasphere. O^+ was most often found at morning local times, O^{++} in the late evening. The moment calculations of density and temperature presented here are a more conservative treatment of the RIMS analysis, therefore may show some differences with the previous study. In particular densities below about 0.1 cm-3 appear to show a threshold for the quality of fit required for inclusion. A predominance of evening values may bias observations to this magnetic local time region (left & center plot below). The significance of the difference with Roberts is not known. Curiously, these moment values show O^+ densities less than O^{++} at low densities and greater at high densities. The yellow line indicates where equal concentrations are located.



Enhanced heavy ions were found just inside the plasmapause, but could be seen at all local times. H^+ and O^+ ions are shown here so as to contrast their over all distribution with L-value. The plots below show a distinct change in behavior for both light and heavy ions below and above about L=2.2. While H^+ densities fall systematically at higher L-value, O^+ densities tend to rise relative to H^+ out to about L=3.5. For comparison, the H+ and O+ densities for one orbit pass from Roberts et al. (1987) Figure 1 are shown as yellow traces below.



Similar to the previous results, the following contrasts the light and heavy ion behavior with Dst, Kp, and the P-parameter (an averaged $f_{10.7}$ quantity, see Richards et al. (1994a, 1994b). H^+ (top row) and O^+ (bottom row) densities are plotted against L-value for extremes of environmental parameters. From left to right are plots for Dst, Kp, and P, respectively, where red (high activity) and blue (low activity) indicate the ranges of these values. The overlap appears as a third color. Above about L=2.2, H^+ shows reduced densities and higher levels of activity as expected, while O^+ shows increased densities. This is especially striking for O^+ versus Kp. Clearly, dense O^+ is a stormtime phenomena. H^+ shows a strong dependence on solar EUV luminosity as indicated by the P-parameter, while O^+ shows little correlation.



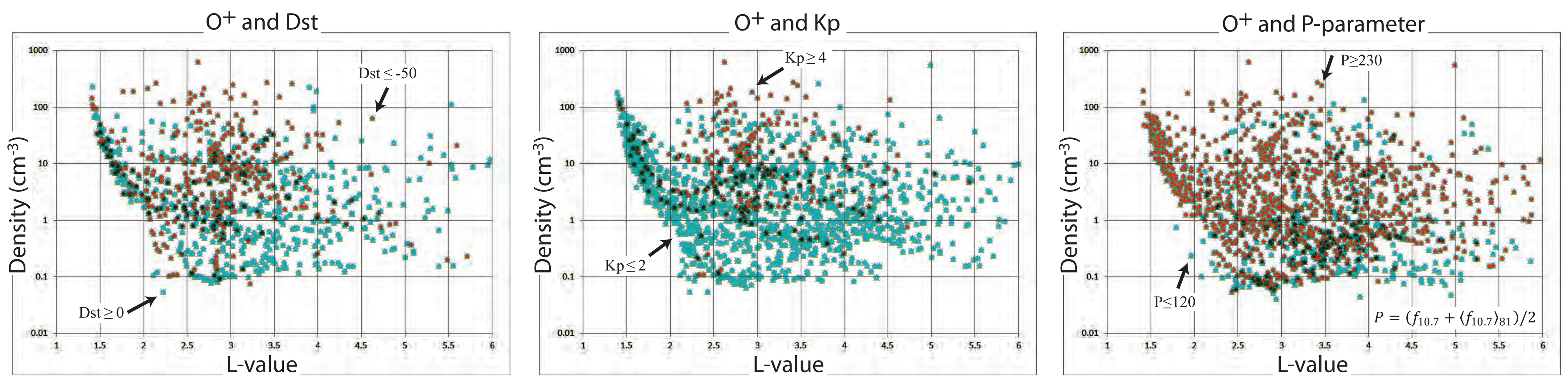


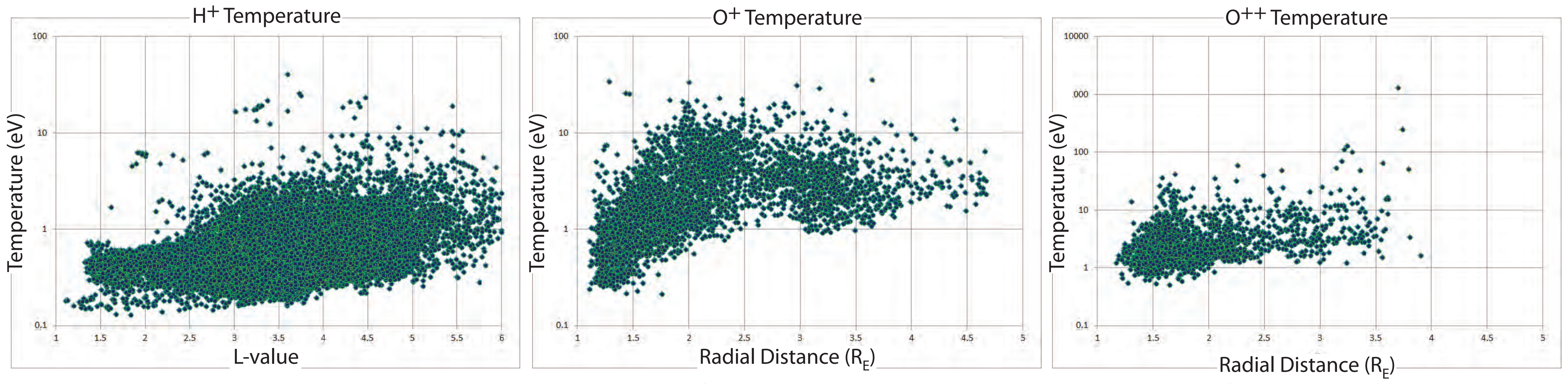
Table 1

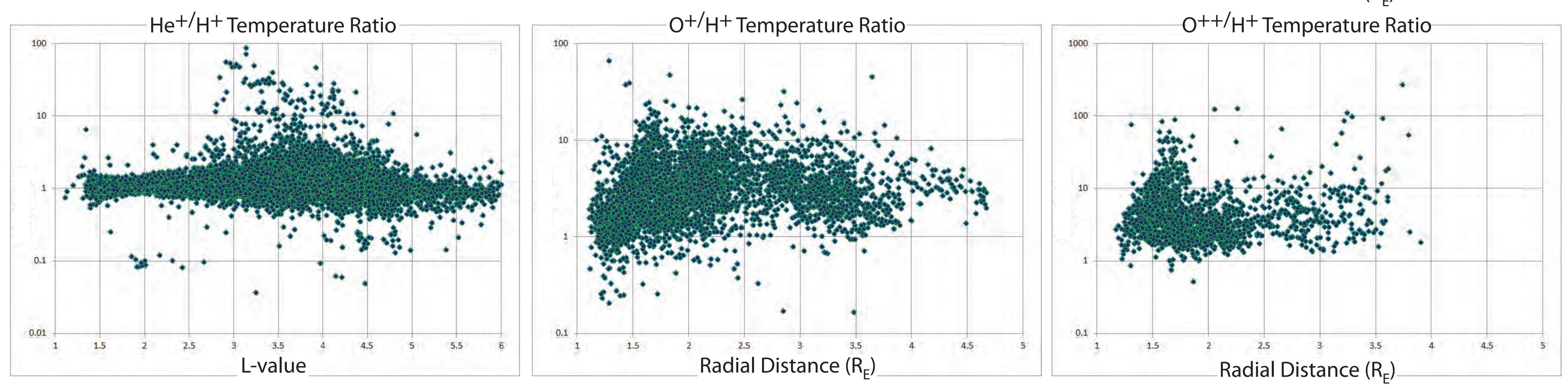
Density/Temperature	H+	He+	He++	O+	O++
H+	36,291/34,935				
He+	34,337/22,376	34,377/22,376			
He++	5,938/4,163	4,548/2,764	5,938/4,163		
O+	7,601/5,555			7,601/5,555	
O++	6,817/3,056			3,984/1,424	6,817/3.056

The numbers correspond to the number of densities and temperatures available for the different combinations of ions. Each value is associated with a time and the qualitative correlations shown require values for the same times. Read from the left column across the table to find the number of values available for each combination of ions. For example, reading across the O^{++} row to the O^+ column finds the number of O^{++} and O^+ density and temperaturey pairs that are available. Only those ion combinations shown are included in the table.

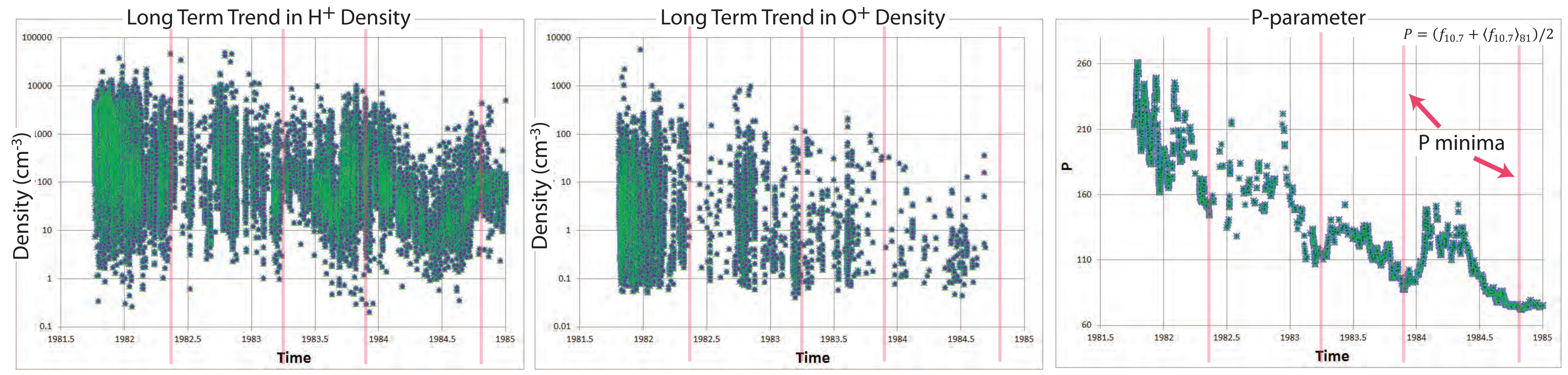
II. Plasmaspheric Heavy and Light Ion Temperatures

Along the top row below, the H^+ temperature is shown to rise systematically from low to high L-values. As with density, there is less scatter for L<2.2, roughly. At higher L-values the H^+ temperature scatter broadens generally to higher temperature, just as density falls with increased activity. O^+ temperatures show a distinctly different behavior, increasing with radial distance up to about r=2.2 and perhaps decreasing slowly further out. H^+ temperature is plotted versus L-value, rather than radial distance, because there is somewhat less scatter and the upward trend in temperature is greater . O^+ temperature is not well ordered at low values when plotted versus L-value, while it is when plotted versus radial distance. He^+, O^+, and O^{++} temperature ratios with H^+ are shown along the second row below. Quite unlike O^+ and O^{++}, the He^+ temperature ratio to H^+ is close to 1 with a slight rise with increasing L-value.





The long term, mostly solar cycle, trends in H^+ and O^+ are shown below. The rose colored vertical stripes correspond to minima in the P-parameter. They are shown at the same times in each of the three plots. The most striking apparent correspondence is between the maxima in H^+ density and minima in the P-parameter. What few values of O^+ density that are available do not show a similar trend. The second longer term trend is with the downward trend in the solar cycle across this time period. The H^+ density variation appears to narrow with falling P-parameter value. The high density profile in the O^+ scatter plot appears to show a falling trend as well. The lower density limit in O^+ is likely the result of the moment calculation being unable to perform a satisfactory fit for such low densities.



October 8, 1981 to December 31, 1984

III. Discussion and Summary

There are striking differences in the behavior between the light and heavy plasmaspheric ions. Differences in behavior are often distinct for L-values below versus above L=2.2. The number of moment values naturally weighs upon the ability to interpret the indications suggested in this presentation. For reference the number of density and temperature values for each ion available in this dataset are shown in Table 1. The consequence for heavy ions is that significant further filtering spatially or on environmental conditions will have quickly diminishingly returns.

Roberts et al. (1987) (and references therein) discuss two potential sources for enhanced, storm-time oxygen in the outer plasmasphere. One results from upwelling ions out of the region of the polar cleft that are swept by convection antisunward into the nightside polar cap and, for light ions, into the outer magnetosphere. Heavier ions with lower velocities would not be expected to go as far, perhaps being deposited in the nightside inner magnetosphere where they may be entrained in corotational drift. The second mechanism is enhanced, middle-latitude ionospheric outflow due to storm-related electron heating, perhaps resulting from interaction between the outer plasmasphere and the storm-time injected ring current. Nosé et al. (2011, 2015) provide supporting evidence for a direct mid-latitude ionospheric origin through observations and modeling. Chappell et al. (2008) have gone on to identify the high latitude outflow and subsequent trapped magnetospheric convection of a 10 eV to 3 keV ions as the warm plasma cloak. The lowest temperatures and observed locations are consistent with those associated with the plasmaspheric oxygen torus. Gallagher and Comfort (2016) have further suggested uncertainty remains in the source identification of what otherwise appears to be warmed plasmaspheric oxygen ions in the region of the plasmapause during active and recovery times.

Heavy ions in the outer plasmasphere, especially when found at densities comparable to the light ions and owing to its greater masses, will strongly influence the dynamic processes taking place in this region. What we know is that

1. light and heavy ions exhibit strikingly different properties, spatially and as correlated with environmental conditions
2. heavy ions resulting from storm-time enhanced mid-latitude ion outflow and antisunward convected high latitude outflow would have similar energies
3. enhanced heavy ions are found at active times between L=2.8 and 4 (and beyond)
4. L<2.2 and L>2.2 oxygen population densities behave very differently
5. oxygen temperatures r<2.2 and >2.2 behave very differently

Our ability to predict the loss, heating, and transport of particles and waves in this region requires that we understand the mechanisms that seed this plasma environment. A closer examination of the timing when dense oxygen is observed in these data may provide further evidence for their origin, however new, more direct tracking of high and middle latitude oxygen flows will likely be needed before this question is resolved.

IV. References

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