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THE ABUNDANCE OF O^{++} IN THE JOVIAN MAGNETOSPHERE

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Abstract. From a synthesis of data from the Plasma Science and Ultraviolet Science instruments on the Voyager 1 spacecraft we present a radial profile of O^{++} abundance between 4.9 and 42 R_J. We observe a sharp rise in O^{++} mixing ratio near 7.5 R_J, coincident with a sharp rise in effective electron temperature at the outer boundary of the Io plasma torus. Beyond 8.5 R_J the O^{++} mixing ratio is found to be roughly constant which indicates freezing of the ionization prevailing at the outer edge of the hot torus.

Introduction

The question of the ionization partitioning state of the plasma in the magnetosphere of Jupiter has not been resolved satisfactorily despite the Pioneer and Voyager flybys and intensive and extensive remote observations by means of telescopes at ground observatories, on board rockets and from Earth orbit. Peculiarities in the distribution of ions have raised basic issues for the mechanics of source processes, subsequent physical chemistry and mass transport. Of particular interest is the apparent discrepancy in the determination of the abundance of O^{++}. The presence of O^{++} ions in the cold torus with a mass to charge ratio of 8 was originally noted in the Voyager Plasma Science [PLS] data at the time of the Voyager 1 encounter by Bridge et al. [1979] (and further discussed by Bagenal and Sullivan [1981]; McNutt et al. [1981]; Bagenal [1985]; Bagenal [1989]). Although Voyager observations indicate the existence of significant quantities of O^{++} ions, ground-based spectroscopic observations by Brown et al. [1983] of the 5007Å line of OIII obtained negative results. They place a firm upper limit of less than 4 cm^{-3} on the O^{++} number density. More recently, Moos et al. [1991] report a low level detection of emission from OIII at 1661, 1666 Å by the Hopkins Ultraviolet Telescope in December 1990. They infer that O^{++} comprised about 2% of the torus ion density.

In this Letter, we shall present a radial profile of the O^{++} abundance that is the result of combining Voyager 1 PLS data from the inner torus (4.9-6 R_J) and the plasmasheet (11.7-42 R_J) with a recent analysis of spectra obtained by the Voyager 1 Ultraviolet Science [UVS] instrument between 5.75 and 8.25 R_J. Our aim is to test the hypothesis that the plasma in the sheet has diffused out from Io and represents a frozen-in picture of the composition and ionization state of the hot torus.

The PLS Observations

The Voyager PLS instrument consists of four modulated-grid Faraday cups which measure ion and electron currents in an energy-per-unit-charge range of 10 to 5950 V (Bridge et al. [1977]). When the plasma flow is of high sonic Mach number and directed into the sensors, the spectral peaks for the different ion species are well-resolved and the detector response is quite straight forward, allowing accurate determination of the density, temperature and flow velocity of each species in the cold region of the torus inside 5.6 R_J (Bagenal and Sullivan 1981; Bagenal 1985) and in regions of the plasma sheet in the middle magnetosphere (McNutt et al. 1981). Determination of the complex response of the detector to trans- or sub-sonic plasma flow has allowed analysis of suprathermal components of the ion spectra and spectra obtained in between these regions of cold plasma (Sands and McNutt, 1988).

Figure 1a shows a spectrum obtained at a distance of about 5.1 R_J from Jupiter exhibiting the 3 major spectral peaks for corotating ions with mass/charge ratios (A/Z) of 8, 16 and 32. The A/Z=8 ion is considered to be O^{++} rather than S^{4+} because of the absence of S^{3+} at A/Z=32/3. There is also a minor peak at A/Z=64 which is presumably due to either SO_2^+ or S_2^+. When the two outer major peaks of the spectrum, which correspond to O^{++} and S^+ respectively, were fitted independently, the two ionic species were found to have the same temperature (to within 1%). This is not surprising as the time scale for ion-ion thermal equilibration is only about an hour for these plasma conditions. The middle peak corresponds to ions with A/Z=16, presumably a combination of O^+ and S^{++} ions. If these ions with A/Z=16 are also in equilibrium and share the same temperature, then the S^{++} energy distribution would appear to have half the width of the O^+ distribution. If one assumes thermal equilibrium one can then estimate the relative contributions of S^{++} and O^+ ions to the A/Z=16 peak. The spectrum in Figure 1a illustrates that under this assumption, the spectrum can be fitted very closely with the A/Z=16 peak dominated by O^+ ions. At higher energies there appears to be a small suprathermal tail to the ion spectrum. Using the sub-sonic response of the detector, we fit this tail with a Maxwellian distribution of hot O^+ ions which have a temperature of about 100 eV but comprise only 2% of the total plasma density. The composition of the cold torus reported by Bagenal (1985) can be summarized as equal proportions of S^+ and O^+ with S^{++} and O^{++} each having mixing ratios of 5%.

Outside 5.6 R_J, where the plasma flow becomes trans-sonic, the spectral peaks of different ion species are generally not resolved by the PLS instrument. Thus the PLS insturment was not able to determine the composition in the warm region of

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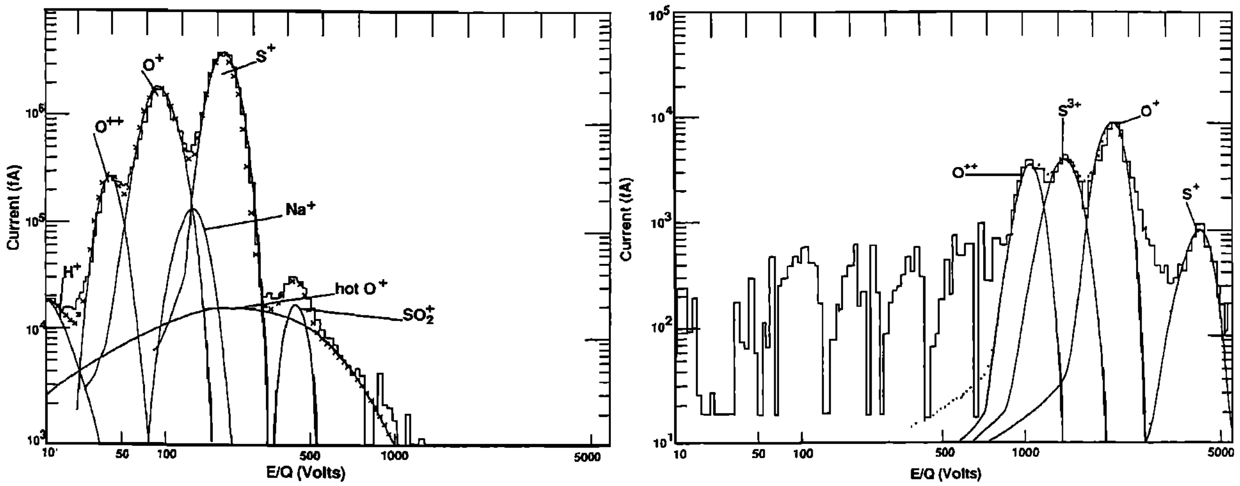

Figure 1. Voyager 1 PLS ion spectra at *(left)* 5.1 and *(right)* 27 R_J. The data (histogram) have been fitted with a convected Maxwellian function (smooth curve) for each ion species to produce a best fit the data (crosses).

the torus. Beyond 11.7 R_J, however, the Voyager spacecraft traversed regions of supersonic plasma where spectral peaks can be resolved. Since we cannot assume that conditions of thermal equilibrium prevail in the plasma sheet, we cannot determine the relative contributions of O^+ and S^{++} to the peak in the spectrum at mass/charge = 16 (McNutt et al., 1981). In Figure 1b, we show a spectrum of thermal plasma obtained at 27 R_J in which the presence of an ions of mass to charge ratios of 8, 32/3, 16 and 32 are apparent. Again, the peak at A/Z=8 could be due to a combination of O^{++} and S^{4+}. However, the unique identification of the peak at 32/3 with small amounts of S^{3+}, indicates that S^{4+} must have much lower abundance and that O^{++} is the dominant component at A/Z=8.

Ultraviolet Spectral Evidence

The Voyager 1 UVS instrument scanned the Jovian system for 30 days beginning March 15, 1979. These system scans have recently been reanalyzed with the aid of updated atomic data. In order to detect the weaker emission from the low density regions in the outer torus, the 30 days of data were binned in steps of 0.5 R_J, and the radial scale is, therefore, rather coarse. The spectra corresponding to 5.75 and 8.25 R_J are shown in Figure 2a.

The Voyager UVS spectra are blends of dense line spectra of sulfur and oxygen. The reduction of the data requires comparison to model calculations of the electron excitation process. The synthesis of the spectra to determine partitioning of species depends on electron temperature. Between 5.75 and 7.5 R_J the electron temperature is determined from analysis of the UVS spectra and is consistent with the in situ measurements [Sittler and Strobel,1987]. From 7.5 R_J outward the temperature profile derived from the PLS electron data by Sittler and Strobel [1987] was applied, because of loss of accuracy in the UVS temperature measurements at the higher temperatures (20 eV) of the outer torus.

The higher electron temperature of the outer regions of the torus is demonstrated by differences between the two spectra shown in Figure 2a. The emission lines toward shorter wavelengths have greater strength at 8.25 R_J, forced by the higher electron temperatures, producing significant differences in spectral shape. The actual differences in ion partitioning between these two locations is in fact greater than apparent from the two spectra because differences in the variation of

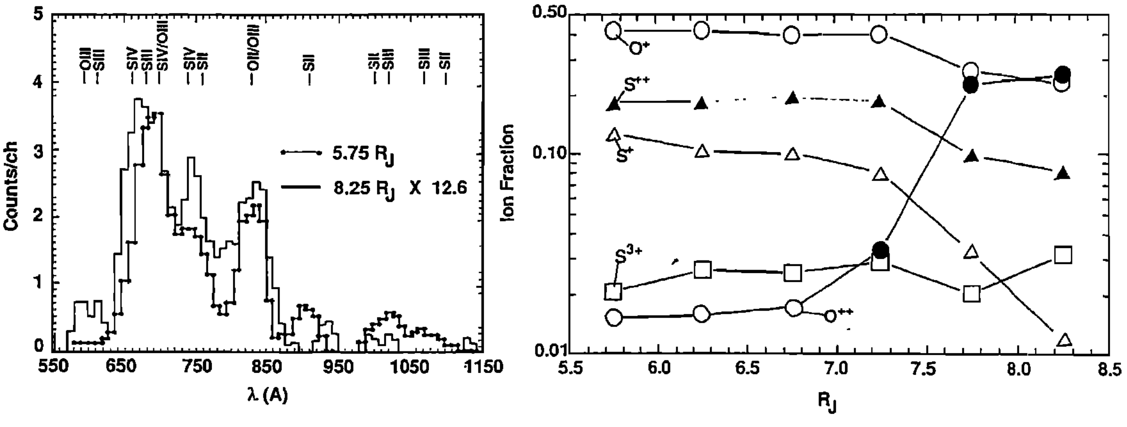

Figure 2. *(Left)* Spectra from Voyager 1 UVS at 5.75 and 8.25 R_J (normalized at 685Å). Modeled transitions are marked on the figure. *(Right)* The ion partitioning from fits to UVS spectra (except O^{++} open circles which are from model calculations).

collision strength with electron temperature affect the relative sulfur and oxygen excitation efficiencies. The feature near 600Å in the 8.25 R$_J$ spectrum is dominated by O^{++} and is measurable only in the spectra at 7.75 and 8.25 R$_J$, because of a combination of sufficiently high electron temperature and increased mixing ratio. In contrast the feature near 900Å is mainly due to S$^+$ and virtually absent at 8.25 R$_J$ principally because of reduced mixing ratio. The total oxygen ion abundance is accurately measured from the feature near 834Å. The separation of O^{++} and O$^+$ in the spectra, with the exception of the extreme conditions noted above, is difficult to determine from the UVS spectra, as discussed by Brown et al. [1983] and Shemansky [1987]. The actual amount of O^{++} between 5.75-6.75 R$_J$ at Voyager 1 encounter therefore remains uncertain because of the lack of definition in both of the Voyager instruments. The values indicated by the open circles in Figure 2b in this region are in fact model partitioning calculations rather than from reduction of the spectra. From 7.25 R$_J$ outward the higher electron temperatures and changes in spectral shape require the insertion of measurable O^{++} with a sharp rise in the mixing ratio [O^{++}] / [e] from values < 0.02 inside 7.0 R$_J$ to 0.2 at 7.75 R$_J$.

Radial Distribution of O^{++}

By combining these new UVS results with the O^{++} density determinations of McNutt et al. [1981] and Bagenal [1989] we are able to produce radial profiles of the O^{++} mixing ratio and density between 4.9 and 42 R$_J$ (Figure 3). At the outer boundary of the torus, where the total plasma density drops by an order of magnitude, the O^{++} mixing ratio increases by an order of magnitude. Farther out, in the plasma sheet, the O^{++} mixing ratio is fairly constant at about 10-20%.

While ion composition cannot be determined from the PLS ion spectra in the warm torus, fitting the spectra with a given composition puts constraints on the flow speed and temperature of the ions. For example, Bagenal [1989] found that the ion spectra at 6 R$_J$ could be modelled (using the supersonic response of the PLS detector) with a plasma having the UVS ion composition and moving within a few percent of rigid corotation. The spectrum required that in addition to a thermal population at 60 eV, the ions show a suprathermal tail (comprising up to 30% of the total charge density) with characteristic energies of 200 eV. When we tried to fit PLS ion spectra farther out in the torus with the same ion composition we found that a large (20%) reduction in flow speed from corotation was necessary to match the spectrum. On the other hand, if we assumed rigid corotation, we found that we required what seemed at the time to be an unreasonably large abundance of low mass-to-charge ions such as O^{++}. With the recent analysis of UVS spectra in the outer torus we returned to the PLS spectrum at 8 R$_J$ which we fit assuming rigid corotation. The resulting contribution of O^{++} to the spectrum (labeled PMODEL in Figure 3) is consistent with the current analysis of the UVS spectra in this region.

The radial profile of O^{++} abundance shown in Figure 3 raises three main issues: (a) the enhancement of O^{++} in the cold torus, which remains unresolved (Bagenal, 1989); (b) the abrupt increase in ionization at the outer boundary of the torus, presumably due to the presence of hot electrons; (c) the enhancement of the oxygen abundance between 7 and 8 R$_J$. The observed spatial distribution of O^{++} ions is consistent with electron impact ionization of O$^+$ being the main source of O^{++} rather than charge exchange (the rate of which decreases sharply outside the dense torus region). The number of targets available for impact ionization also decreases with radial distance, but this can be compensated for by local increases in electron temperature and in energetic electron fluxes. It is in the same region of the outer boundary of the torus that not only do Sittler and Strobel [1987] report an increase in the temperature of the cold electron population by about an order of magnitude, but McNutt et al.[1990] also note the very localized intensification of suprathermal electron fluxes. Whether these changes are linked to heavy ion precipitation and auroral activity as suggested by McNutt et al. [1990] remains an open question. Turning to the issue of the

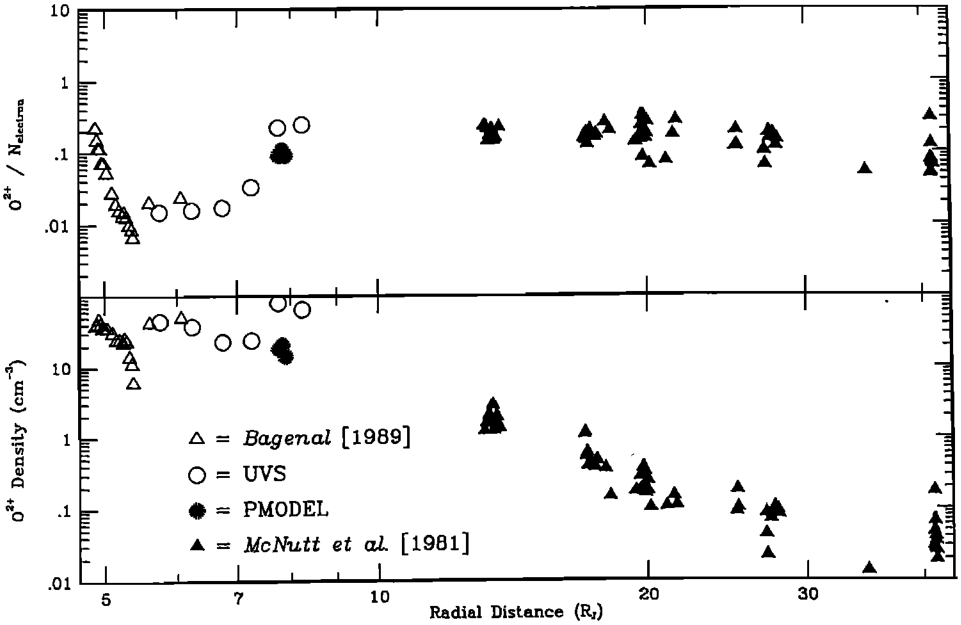

Figure 3. Profiles of *(above)* mixing ratios and *(below)* absolute values of O^{++} obtained from both PLS and UVS observations.

enhancement of oxygen between 7 and 8 R_J, we now face the possibility that there may be an additional, rather weak source of oxygen ions beyond 7.25 R_J. A candidate source is the icy satellite Europa as suggested by Bagenal [1989] and, on the basis of Pioneer 10 data, by Intriligator and Miller [1982].

The cold plasma in the mid-magnetosphere plasma sheet may be regarded as a 'frozen' image of the hot torus if, in the region outside the torus, the relevant reaction times are longer than the time of diffusive transport to regions of still lower density. Shemansky et al. [1985] have derived analytic expressions for the coefficients of excitation and ionization. Evaluation of the O^{++} creation rate coefficient as a function of electron energy shows that there is a broad maximum around 400eV of about $3x10^{-8}$ cm^3s^{-1}. Partitioning calculations with the diffusive tranport occuring on time scales of the order of 60-100 days and with the small fraction of suprathermal electrons in the dense part of the torus produce a mixing ratio of just a few percent for O^{++}. The existence of enhanced suprathermal electron fluxes outside the dense torus makes the creation of O^{++} ions by electron impact feasible out to about 8 R_J. At greater radial distance, in the tenuous plasma sheet, the mixing ratio of O^{++} can be expected to remain constant as the total density decreases.

In conclusion, it is apparent from the combination of the results described above that O^{++} was present throughout the Jovian magnetosphere at the time of the Voyager 1 encounter in early 1979. The obvious question which arises from the above concerns the non-observation of O^{++} by Brown et al. [1983] and the weak emissions reported by Moos et al. [1991]. Since the abundance of O^{++} in the dense region of the torus is extremely sensitive to the electron energy distribution [Shemansky, 1987] it has been suggested that the absence of O^{++} in the observations by Brown et al. [1983] could be explained by a depletion of hot electrons. It is also possible that the Earth-based observations were dominated by the high density region of the torus where the O^{++} abundance is very small. In fact, the 2% O^{++} mixing ratio reported by Moos et al. [1991] is consistent with partitioning calculations for the dense part of the torus. Analysis of the corresponding UVS data from the Voyager 2 encounter shows a lower effective temperature for the electrons and a significantly lower number density of O^{++} ions in the torus [Shemansky, 1987] consistent with time-variabilities reported by Mekler and Eviatar [1980] and Walker and Kivelson [1981]. The forthcoming encounter of the Ulysses spacecraft with Jupiter should provide additional information on the partitioning of the Io torus. We predict that if the level of activity is sufficiently high to maintain a torus of hot plasma containing enough suprathermal electrons, the plasma instumentation on Ulysses may observe a significant abundance of O^{++}.

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References

Bagenal, F., Plasma conditions inside Io's orbit, *J.Geophys. Res.*,*90*, 311-324, 1985.

Bagenal, F., Torus-magnetosphere coupling, in *Time-Variable Phenomena in the Jovian System* ed. Belton et al., pp. 196-210, NASA, SP-494, 1989.

Bagenal F. and J.D. Sullivan, Direct plasma measurements in the Io torus and inner magnetosphere of Jupiter, *J.Geophys. Res., 86,* 8447-8466, 1981.

Bridge, H.S., J.W. Belcher, R.J. Butler, A.J. Lazarus, A.M. Mavretic,J.D. Sullivan, G.L. Siscoe and V.M. Vasyliunas, The plasma experiment on the 1977 Voyager mission, *Space Sci. Rev., 21,* 259-287, 1977.

Bridge, H.S., J.W. Belcher, A.J. Lazarus, J.D. Sullivan, R.L. McNutt, F. Bagenal, J.D. Scudder, E.C. Sittler, G.L. Siscoe, V.M. Vasyliunas, C.K. Goertz and C.M. Yeates, Plasma observations near Jupiter: Initial results from Voyager 1, *Science, 204,* 987-991, 1979.

Brown, R.A., Shemansky, D.E. and R.E. Johnson, A deficiency of O^{++} in the Io plasma torus, *Astrophys. J., 264,* 309-323, 1983.

Intriligator, D.S. and W.D. Miller, First evidence for a Europa plasma torus, *J.Geophys. Res., 87,* 8081-8090, 1982.

McNutt, R.L., J.W. Belcher and H.S. Bridge, Positive ion observations in the middle magnetosphere of Jupiter, *J.Geophys. Res., 86,* 8319-8342, 1981.

McNutt, R.L., F. Bagenal and R.M. Thorne, Observations of auroral secondary electrons in the Jovian magnetosphere, *Geophys. Res. Lett., 17,* 291-294, 1990.

Mekler, Yu. and A. Eviatar, Time analysis of volcanic activity on Io by means of plasma observations, *J. Geophys. Res.,85,* 1307-1310, 1980.

Moos, H. W., Feldman, P. D., Durrance, S. T., Blair W. P., Bowers, C. W., Davidsen, A. F., Dixon, W. V., Ferguson, H. C., Henry, R. C., Kimble, R. A.,Kriss, G. A., Kruk, J. W., Long, K. S. and O. Vancura, Determination of ionic abundances in the Io torus using Hopkins Ultraviolet Telescope, *Astrophys. J., 382,* L105-L108, 1991.

Sands, M.R., and R.L. McNutt,Jr., Plasma flow in Jupiter's dayside middle magnetosphere, *J. Geophys. Res.,93,* 8502-8518, 1988.

Shemansky, D.E., Ratio of oxygen to sulfur in the Io plasma torus, *J. Geophys. Res.,92,* 6141-6146, 1987.

Shemansky, D.E., J.M. Ajello and D.T. Hall, Electron impact excitation of H_2: Rydberg band systems and the benchmark dissociative cross section for H Lyman-α, *Astrophys. J., 296,* 765-773, 1985.

Sittler, E.C., Jr. and D.F. Strobel, Io plasma torus electrons, *J. Geophys. Res.,92,* 5741-5762, 1987.

Walker, R., and M.G. Kivelson, Multiply reflected standing Alfven waves in the Io torus:Pioneer 10 observations, *Geophys. Res. Lett., 8,* 1281-1284, 1981.

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