VOL. 7, NO. 1 GEOPHYSICAL RESEARCH LETTERS JANUARY 1980

SPATIAL DISTRIBUTION OF PLASMA IN THE IO TORUS

Fran Bagenal and James D. Sullivan

Center for Space Research, M.I.T., Cambridge, 02139

George L. Siscoe

Department of Atmospheric Sciences, University of California, Los Angeles, 90024

Abstract. In situ measurements of ion densities and temperatures have been analyzed to produce profiles of these plasma parameters along the Voyager 1 inbound trajectory between 7 and 5 R_J. The temperature profile shows a sharp decrease by a factor of $\sim$50 between 5.8 and 5.2R_J corresponding to a temperature gradient of $\sim$7 × 10^5 per R_J. The electron density profile, inferred from the ion density measurements, has two maxima at 5.7 and 5.3 R_J. A two-dimensional model of the spatial distribution of various ionic species in the Io plasma torus has been constructed. Using this model a contour map of electron density in a meridional plane has been made, it exhibits a well-defined inner edge to the torus at 5.6 R_J. The contour map of S^+ ion density indicates that most of the S^+ ions are concentrated close to the centrifugal symmetry surface and radially inward of the larger electron density maximum near 5.7 R_J.

Introduction

In situ measurements of ions in the plasma torus of Juipter's satellite Io were made with the plasma science instrument on board Voyager 1 (for initial Voyager results regarding the Io plasma torus see *Bridge et al. 1979; Broadfoot et al., 1979; Scarf et al., 1979; and Warwick et al., 1979). Warwick et al. (1979)* have constructed a two-dimensional model by extrapolating their smoothed electron measurements along the trajectory under assumptions of axial and mirror symmetry. Although such electron density models of the torus are invaluable, they provide little information about its ion properties, e.g., composition, densities and temperatures of the various ionic species. This paper presents profiles of positive ion temperature and densities along the inbound trajectory. These profiles are used, without smoothing, to construct contour maps of the plasma density in a meridional plane. The symmetry assumptions of *Warwick et al. (1979)* have been maintained with the additional assumptions that the ions are isothermal along a given magnetic field line and that their distribution along each magnetic field line is governed by a scale height.

In situ Measurement

The plasma instrument measures ions and electrons within an energy per charge range of 10 to 5950 volts (for detailed properties of the instrument, see *Bridge et al., 1977).* During the Voyager 1 inbound traversal of the torus, the main sensor was oriented toward the direction from which the torus plasma, corotating in Jupiter's magnetic field, appears to be flowing. On the outbound traversal of the torus the instrument orientation was less favourable and analysis of the data is more complex and as yet incomplete.

Near the orbit of Io corotating ions with mass to charge ratios, A/Z*, greater than $\sim$6 can be detected. At this distance the energy per charge range includes the ionic species which dominate the ultraviolet emissions *(Broadfoot et al., 1979).* Radially inward from the torus, there are well resolved peaks at A/Z* values of 8, 16, and 32 *(Bridge et al., 1979).* There is some ambiguity in the identification of the corresponding ionic species for each of these peaks. The peaks at A/Z* values of 8 and 32 are presumably dominated by O^{2+} and S^+though there could be contributions from S^{4+} and O^{2+}. Unfortunately, the common ratio of A/Z* = 16 for S^{2+} and O^+ results in the superposition of the spectral peaks of these two abundant ions. However, at the same temperature the oxygen ions have a larger thermal speed. Therefore, in regions where all the ionic species appear to have the same temperature, the proportions of O^+ and S^{2+} that are combined in the A/Z* = 16 peak can be determined using a fitting procedure with appropriate thermal widths for the different species. Although there are no resolved peaks of S^{3+} amd Na^+ in the cold region these ions could be present in the hot torus. Nevertheless, in the analysis presented here, S^+, O^+, S^{2+} and O^{2+} are taken to be the only species of significance. It has been shown that SO^{2+} (A/Z* = 64) and several heavier ions are also present *(Sullivan and Bagenal, 1979)* but they are minor contributors to the total ion density and are found outside the energy per charge range of this analysis.

The functional form of a sum of isotropic convected Maxwellian distributions is used to make a multidimensional parameter search for a least squares fit to the observed spectra. This produces in situ values of ion densities, the common temperature, and the common component of the bulk motion of the plasma into the detector for each high resolution spectrum, measured at 192 second intervals along the spacecraft trajectory. A few of the spectra have not been included in the present analysis because of missing points in the spectra (e.g., around 5.7 R_J). It is hoped that further work will include some of these missing spectra as well as data obtained at radial distances greater than $\sim$7 R_J.

Radial profiles of plasma

Figure 1 shows the radial profile of the temperature of the plasma derived from fits to the data assuming a common temperature for all species, i.e., the plasma is locally isothermal. There appear to be two very distinct regions; the hot torus where T $\sim$4 × 10^5K and a cold region closer to Jupiter where T $\sim$8 × 10^3K. This drop in temperature by a factor of $\sim$50 occurs within a very small radial distance (5.8 to 5.2 R_J), corresponding to a temperature gradient of $\sim$7 × 10^5K per R_J. In the cold region where the peaks in the energy per charge spectra corresponding to different ionic species are well resolved, independent fits for the temperatures of each species indicate that inward of $\sim$5.4 R_J, the assumption of an isothermal plasma is valid (for examples of spectra, *see Bridge et al., 1979,* and *Sullivan and Bagenal, 1979).* Within the torus, where the plasma appears to be much hotter, the individual ion peaks strongly overlap. By specifying which ionic species are present and by assuming that they all have the same temperature, individual ion densities can be determined. The value of common temperature derived from the fit is sensitive to the ratio of O^+ to S^{2+} for the A/Z* = 16 peak (located near the center of the broad distribution). Uncertainties in the density and temperature determinations can be found by investigating the two extreme cases by taking either S^{2+} or O^+ to be totally absent (see the discussion below). In the hot region close to Io, the apparent source of the ions, it seems unlikely that the plasma has had time to thermalize. In that case, a more realistic model for the hot region would assume a common gyrospeed at the point of ionization, i.e., temperatures proportional to the masses of the ions. Fits to the data under this assumption are not yet complete.

The values of the individual ion densities have been multiplied by their respective charge state and summed to produce the electron density that would balance the charge of all the ions detected. This measurement of electron density is independent of the identification of the ion species as the instrument measures the positive ion current. Figure 2a shows in the in situ electron densities as a function of

Paper 9L1664
0094-8276/80/009L-1664$01.00

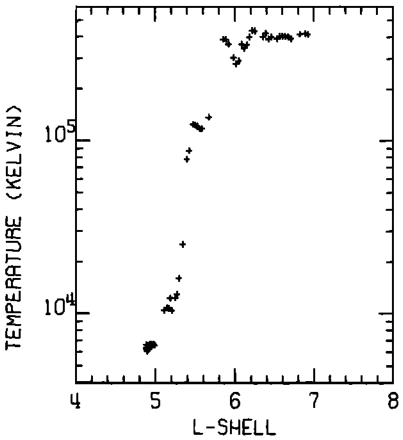

Fig. 1. The profile of ion temperature (versus magnetic L-shell) determined from multiple-ion energy per charge spectra, assuming the ions to be isothermal.

L-shell (assuming a dipole magnetic field). The profile shows two local density maxima at 5.7 and 5.3 R_J with a sharp drop in density by a factor of 3 to 5 between them. Radially inward of the maximum at 5.3 R_J, the density again drops rapidly, this time by more than an order of magnitude. Comparison of the electron density profile with the temperature profile (Figure 1) reveals that the second smaller electron density peak occurs inward of the sharp drop in temperature. The two-peak structure of the electron density profile was also shown in earlier papers of ***Bridge et al. (1979)*** and ***Warwick et al. (1979).*** Comparison of the electron density profile with the measurements of *Warwick et al. (1979)* suggests that in the cold region there are very few ions with $A/Z^* < 6$. In the torus (6 – 7 R_J) there are less than 200 electrons cm^{-3} unaccounted for by the measurements of ions with $8 \leqslant A/Z^* \leqslant 32$. In the hot region simultaneous fits for S^+, S^{2+}, O^+ and O^{2+} using the procedure outlined above, produces a ratio of total number of oxygen ions to sulphur ions

$$[n(O^{2+}) + n(O^+)]/[n(S^{2+}) + n(S^+)]$$

of around unity. This result is not consistent with a ratio of two which would be expected if the source of ions is complete dissociation and ionization of SO_2 ($SO_2 \rightarrow S^+ + 2O^+$) from an atmosphere of Io *(Pearl et al., 1979; Kumar, 1979).* Therefore, if the four species used in this model are in fact the major contributors in this region of the spectrum then a sulphur source in addition to SO_2 may be required to explain the ion measurements. On the other hand, the oxygen to sulphur ratio could be very different if there are substantial quantities of ionic species which have so far been assumed absent, e.g., O_2^+, Na^+, S^{3+} and S^{4+} or if there is significant loss of neutral atoms.

The S^+ density profile (Figure 2b) has a similar structure to that of the electron profile except that the inner S^+ density maximum has a value much larger than its density in the hot torus. Moving towards Jupiter from the location of this peak at $\sim$5.3 R_J the spacecraft measured a drop in the density of S^+ ions of nearly three orders of magnitude within a radial distance of 0.4 R_J. In the hot torus region the calculated S^+ density varies according to the assumed identification of the $A/Z^* = 16$ peak. The sensitivity of the S^+ density has been investigated by taking the extreme cases of $A/Z^* = 16$ corresponding to a single species of either S^{2+} or O^+, shown by vertical bars on Figure 2b. Similarly, if there is considerable O_2^+ or Na^+ present the S^+ density in the hot torus will have been over estimated in this analysis. However, the majority of the S^+ ions are found where the $A/Z^* = 32$ peak is well resolved.

The spacecraft took a little under half a rotation period of Jupiter (i.e., $\sim$5 hours) to traverse the region corresponding to the data shown here, so it is unlikely that these large density changes over a few minutes time scale could be due to azimuthal variations. Similarly, the latitude of the spacecraft remained small so that the structure shown must be in the radial direction. Therefore, the radial behavior of both the S^+ and electron density may be used to investigate the two-dimensional structure of the torus.

Two-dimensional Structure

The distribution of isotropic plasma along a magnetic field line can be found by balancing the forces acting on the plasma in the direction of the field. The centrifugal force tends to confine the ions to the centrifugal symmetry surface (equator) and the magnetic mirror force tends to confine them to the magnetic equator. The angular separation between these two surfaces for Jupiter is about 3° *(Hill, Dessler and Michel, 1974).* The ratio of the centrifugal to the mirror forces for equatorially confined particles is $2K_c/3K_\perp$ where K_c is the kinetic energy of the ion moving at corotational speed and $K_\perp$ is the gyro-kinetic energy *(Siscoe, 1977).* For the ions observed in the Io torus, this ratio is everywhere greater than 3, and in the cold inner region, greater than 60. Thus the magnetic mirror force may be neglected in deriving the off-equatorial density distribution, and the plane of mirror symmetry lies much closer to the centrifugal than the magnetic equatorial surface.

Coulomb collisions between heavy ions will tend to make them isotropic and isothermal along an individual magnetic field line. Similarly, the temperature of the electrons (T_e) will become the same as the ion temperature (T_i). Observations suggest the two temperatures are comparable *(Scudder, private communication; Broadfoot et al., 1979).* Balancing the centrifugal and pressure gradient forces for each ionic species separately produces a simple exponential variation of density, n_i, with distance from the centrifugal equator, z, namely

$$n = n_i \exp[-(z/H_i)^2]$$

where n_i is the equatorial density and the scale height $H_i = [2kT_i/3m_i\Omega^2]^{1/2}$ (k is Boltzmann's constant. Ω is the rotation rate of

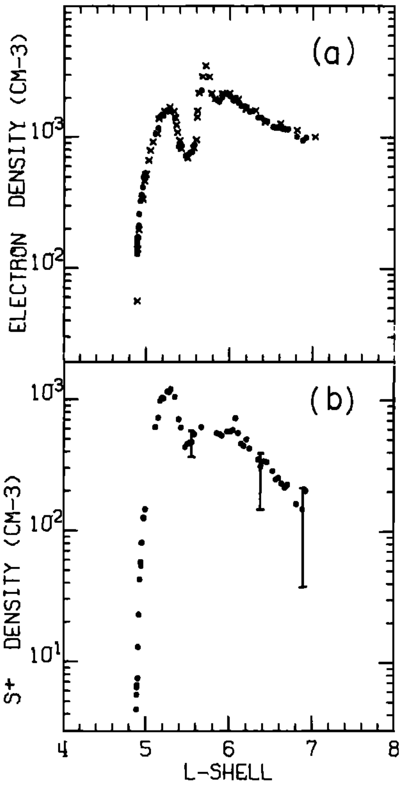

Fig. 2. In situ density measurements versus L-shell. Panel (a) electrons, (•). The measurements of Warwick et al., (1979) are shown by x. In panel (b) ions with $A/Z^* = 32$, assumed to be S^+ (o). The vertical bars show uncertainties in the density determination due to model dependence.

Jupiter). The effective ionic mass, m_i^*, *(Siscoe, 1977)* takes into account the consequence of including the electrons in the force balance by reducing the ion mass, in effect, by a factor of $(Z_i^* + 1)$ if $T_e = T_i$. This factor will be proportionally smaller if the electrons are colder.

The distribution of ions along a field line has been calculated including the electrostatic interactions between the different ionic species and their accompanying electrons. These calculations suggest that an independent scale height approximation is valid for the ionic species and limited spatial region considered in this analysis. However, there might be a significant effect on minor ionic species with low mass to charge ratios. These species would be drawn off the centrifugal equator by the electrostatic potential set up by the more dominant heavy ions.

The equation above has been used to determine for each ionic species off-equatorial densities which are then weighted by the corresponding charge states, linearly interpolated and summed up to give the electron density map shown in Figure 3. The cross-sectional shape of the torus shown is similar to that derived from the remote ultraviolet observations of ***Broadfoot et al. (1979).*** The electron densities shown here are underestimates because all of the ionic species are not included in this analysis.

The most striking feature of this density map is the sharp inner edge of the torus at the L-shell of L = 5.6. This is the location of the sharp drop in temperature (Figure 2) and the region in which *Scarf et al. (1979)* observed auroral hiss. Radially inwards from the torus the plasma appears to be closely confined to the centrifugal equator. Although the equatorial electron density has two maxima (1700 cm^{-3} at 5.3 R_J and 2100 cm^{-3} at 5.7 R_J), the total ion content per unit L-shell (NL^2) increases proportionally with L. In an accompany paper, *Richardson et al. (1980)* discuss the significance of this observation and show that the two density maxima do not necessarily imply an episodic source.

Figure 4 shows a contour map for S^+ ions alone made in the same way as Figure 3. The sharp inner edge of the torus remains but the majority of the S^+ ions form a triangular-shaped feature pointing towards Jupiter, situated entirely within the region where the $A/Z^* = 32$ spectral peak is well resolved. This shape is similar to the torus cross-section inferred from ground-based observations of S^+ optical emission (Nash, 1979; Pilcher, 1979; Trauger et al., 1979). These optical observations show agreement with the assumption that the $A/Z^* = 32$ peak is indeed dominated by S^+ ions. In the hot torus a comparison of the S^+ number densities derived from the ground-based and in situ measurements is not yet possible because of the model dependent uncertainties associated with composition.

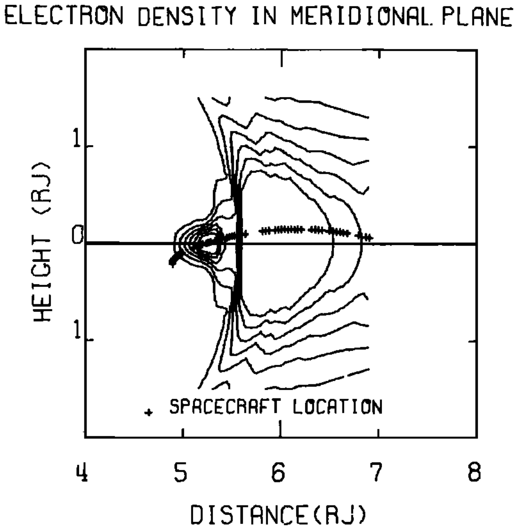

Fig. 3. Contours of equal density of electrons in a meridional plane (centered on the centrifugal symmetry surface). The location of the spacecraft at the time of each spectral measurement used is shown by +. Contour levels are in steps of 200 cm^{-3} (1 R_J = 71 398 km).

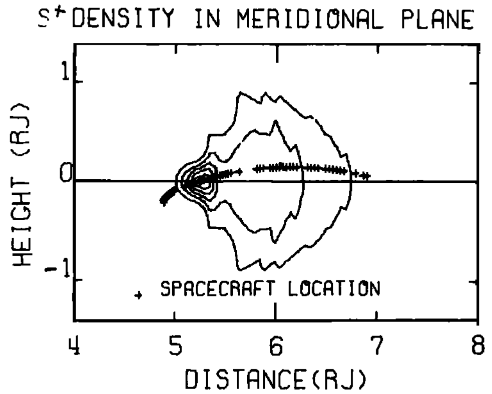

Fig. 4. Contours of equal density of ions with $A/Z^* = 32$ assumed to be S^+ in a meridional plane (centered on the centrifugal symmetry surface). The location of the spacecraft at the time of each spectral measurement used is shown by +. Contour levels are in steps of 200 cm^{-3} (1 R_J = 71 398 km).

Discussion

Plasma measurements made in the torus and therefore close to the apparent source, Io, indicate plasma temperatures close to 4 × 10^5K (35eV). The corresponding thermal (gyro) speeds of ~15 km s^{-1} for sulphur and ~20 km s^{-1} for oxygen are only a fraction of the corotation value of 57 km s^{-1} presumably because of the shielding of the corotational electric field by currents near Io *(Eviatar, Siscoe and Mekler, 1979; Goertz 1979)*. With the plasma source at Io, the density gradient is unstable at L-values greater than ~6 which results in enhanced outward diffusion *(Richardson et al., 1980);* thus the slowly decreasing density produces an indistinct outer edge to the torus.

Radially inward of Io's orbit the plasma diffuses slowly, remaining sufficiently dense for electron collisions to excite the ions and generate the considerable ultraviolet and optical emissions that first indicated the presence of the Io plasma torus *(Kupo, Mekler and Eviatar, 1976)*. The ions in this region are rapidly cooled by the radiation. The excitation mechanism is very dependent on the electron density and temperature so that as the plasma cools and collapses toward the centrifugal equator, the density is enhanced which further increases the cooling by radiation. Hence, there are cold isothermal ions inside a very sharp temperature gradient which forms a well-defined inner edge of the torus.

Recombination has a weaker dependence on temperature and density than the collisional excitation mechanism, but, eventually, as the ions diffuse towards Jupiter, they recombine to form neutrals which are slung off through the outer magnetosphere to be recycled as energetic heavy ions *(Eviatar et al., 1976; Krimigis et al., 1979; Vogt et al., 1979);* or to provide a source in the magnetosheath *(Broadfoot et al., 1979);* or to escape the Jovian system entirely.

Summary

1) In situ ion measurements show a sharp drop in temperature by a factor of 50 at about 5.6 R_J. corresponding to a temperature gradient of ~7 x 10^5K per R_J. The temperature drop occurs between two local maxima in the equatorial plasma electron density of at least 2100 and 1700 cm^{-3} at radial distances of 5.7 and 5.3 R_J, respectively.

2) The inner boundary of the Io plasma torus is very well defined by a steep electron density gradient at L ~5.6 R_J. The majority of the S^+ ions are found in a triangular-shaped region near 5.3 R_J and are confined to low centrifugal latitudes. It is proposed that as the plasma diffuses inward it is rapidly cooled by radiation and collapses toward the centrifugal equator.

3) The outer boundary of the torus is less distinct and is compatible with enhanced outward diffusion from a plasma source at Io.

Acknowledgements. The authors would like to thank H. S.

Bridge, J. W. Belcher and C. K. Goertz for helpful discussions and valuable assistance in preparing this paper. We would also like to thank D. Shemansky for useful comments as a referee. This work was funded in part by JPL Contract 953733 and NASA Grant NGL 22-009-015 (Wash).

References

Bridge, H. S., J. W. Belcher, R. J. Butler, A. J. Lazarus, A. M. Mavretic, J. D. Sullivan, G. L. Siscoe, V. M. Vasyliunas, "The Plasma Experiment on the 1977 Voyager Mission", *Space Sci. Rev. 21.* 259 (1977).

Bridge, H. S., J. W. Belcher, A. J. Lazarus, J. D. Sullivan, R. L. McNutt, Jr., F. Bagenal, J. D. Scudder, E. C. Sittler, G. L. Siscoe, V. M. Vasyliunas, C. K. Goertz, C. M. Yeates, "Plasma Observations Near Jupiter: Initial Results from Voyager 1". *Science 204.* 987 (1979).

Broadfoot, A. L., M. J. S. Belton, P. J. Takacs, B. R. Sandel, D. E. Shemansy, J. B. Holbert, J. M. Ajello, S. K. Atreya, T. M. Donahue, H. W. Moos, J. L. Bertaux, J. E. Blamont, D. F. Strobel, J. C. McConnell, A. Dalgarno, R. Goody, and M. B. McElroy, "Extreme Ultraviolet observations from Voyager 1 Encounter with Jupiter", *Science 204.* 979 (1979).

Eviatar, A., G. L. Siscoe and Yu Mekler, "Temperature Anistropy of the Jovian Sulphur Nebula", *Icarus, 139,* 450 (1979).

Eviatar, A., Yu Mekler, F. V. Coroniti, "Jovian Sodium Plasma", *Astrophys. J. 205.* 622 (1976).

Goertz, C. K. "Io's interaction with the plasma torus". submitted to *J. Geophys. Res. (1979)*

Hill, T. H., A. J. Dessler and F. C. Michel, "Configuration of the Jovian Magnetosphere," *G.R.L., 1,* 3. (1974).

Krimigis, S. M., R. P. Armstrong, W. I. Axford, C. O. Bostrom, C. Y. Fan, G. Gloeckler, L. J. Lanzerotti, E. P. Keath, R. D. Zwickl, J. F. Carbary, and D. C. Hamilton, "Low-Energy Charged Particle Environment at Jupiter: A First Look", *Science 204.*998 (1979).

Kumar, S., "The stability of an SO_2 atmosphere on Io", *Nature, 280,* 758, (1979).

Kupo, I., Yu. Mekler, and A. Eviator, Detection of ionized sulphur in the Jovian magnetosphere", Astrophys. J., *205.* L51, 1976.

Nash, D. B., "Jupiter Sulphur-Plasma Ring", *EOS. 60,* 307 (1979).

Pearl, J., R. Hanel, V. Kunde, W. Maguire, K. Fox, S. Gupta, C. Ponnamperuma, and F. Rantin, "Identification and gaseous SO_2 and new upper limits for other gases on Io", Nature, *280,* 755, 1979.

Pilcher, C. B., "Images of Jupiter's Sulfur Ring", submitted to *Science,* August, 1979.

Richardson, J., G. L. Siscoe, J. D. Sullivan, and F. Bagenal, "Time-Dependent Radial Diffusion in the Io Plasma Disk", *G.R.L.,* this issue, 1980.

Scarf, F. L., D. A. Gurnett, and W. S. Kurth, "Jupiter Plasma Wave Observations: An Initial Voyager 1 Overview," *Science, 204.* 991. 1979.

Siscoe, G. L., "On the equatorial confinement and velocity space distribution of satellite ions in Jupiter's magnetosphere", *J. Geophys. Res. 92.* 1641. 1977.

Sullivan, J. D., and F.Bagenal, "In situ identification of various ionic species in Jupiter's magnetosphere", *Nature, 280.* 798, 1979.

Trauger, J. T., C. Münch, F. L. Roesler, "A Study of the Jovian (SII) Nebula at High Spectral Resolution", *Astrophysical J.,* in press, 1980.

Vogt, R. E., W. R. Cook, A. C. Cummings, T. L. Garrard, N. Gehrels, E. C. Stone, J. H. Trainor, A. W. Schardt, T. Conlon, N. Lal, and G. B. McDonald, "Voyager 1: Energetic Ions and Electrons in the Jovian Magnetosphere", *Science, 204.* 1003, 1979.

Warwick, J. W., J. B. Pearce, A. C. Riddle, J. K. Alexander, M. D. Desch, M. L. Kaiser, J. R. Thieman, T. D. Carr, S. Gulkis, A. Boischot, C. C. Harvey, B. M. Pedersen, "Voyager 1 Planetary Radio Astronomy Observations Near Jupiter", *Science, 204,* 995, 1979.

(Received November 1, 1979;
accepted November 26, 1979)