

PLASMA CONDITIONS INSIDE IO'S ORBIT: VOYAGER MEASUREMENTS

Fran Bagenal

The Blackett Laboratory, Imperial College of Science and Technology, London

Abstract. The Voyager 1 ion data that were obtained inside the orbit of Io allow accurate determination of convective velocity, temperature, and density of the major ionic species (S^+ , O^+ , S^{2+} and O^{2+} ions). The irregular radial profiles of ion temperature and flux tube content are not consistent with simple models of radial transport of plasma from a source near Io. The evidence of a source of ions well inside Io's orbit is provided by the detection of molecular (SO_2^+) ions at 5.3 R_J , the prevalence of non-Maxwellian tails to the ion distribution functions, the persistent presence of oxygen ions throughout the inner torus, and a 1-3% lag behind corotation outside 5.4 R_J .

Introduction

The preliminary presentation of the Plasma Science (PLS) ion data from the Voyager 1 traversal of the Io torus is given by Bridge et al. [1979], and subsequent papers have concentrated on deriving the basic characteristics of the plasma in order to describe the general shape and average properties of the torus [Bagenal et al., 1980; Bagenal and Sullivan, 1981; though see Bagenal et al., 1984]. These early descriptions, in conjunction with spectrophotometric studies of optical and ultraviolet emission from the torus [reviewed by Brown et al., 1983b] were taken as a basis for various theoretical studies of the processes governing the production, transport, and loss of plasma [Cheng, 1980; Goertz, 1980; Richardson and Siscoe, 1983a; Smyth and Shemansky, 1983; Johnson and Strobel, 1982]. These theoretical studies have now developed to the point of predicting details in the properties of the plasma, such as changes in ionic composition with radial distance, which can now be compared with experimental observations. It is with this objective in mind that we have returned to the PLS measurements obtained in the inner region of the Io torus where the data enable one to make a detailed comparison with theoretical expectations.

We have restricted the concerns of this paper to plasma that is confined by the magnetic L-shells located inside the orbit of Io at a radial distance of 5.91 R_J from Jupiter (1 R_J = 71,398 km). It is generally considered that the plasma in this region has slowly diffused inward from a source in the vicinity of Io [Richardson et al., 1980; Froidevaux, 1980] and has lost thermal energy via stimulated line-emission at ultraviolet and optical wavelengths [Brown et al., 1983b, and references therein]. The plasma inside Io's orbit is therefore cold, and its slow rate of transport implies it has had time to attain thermodynamic equilibrium. Voyager 1 took nearly 3 hours to

travel from Io's L-shell at 5.91 R_J to perijove at 4.89 R_J , and in this time the PLS instrument made 56 measurements of the ion distribution, from which it is possible to determine the densities of different ionic species, their temperatures, and bulk motion.

In contrast, the plasma in the region outside Io's orbit appears to be transported rapidly outward away from Io, taking 10-100 days to reach the outer boundary of the torus at $\sim 8 R_J$ [Richardson et al., 1980]. This traversal time is about the same as the time scale for Coulomb thermal equilibration [Book, 1980], so that the plasma in the warm torus, particularly that found closer to Io, may be far from thermodynamic equilibrium. In the PLS spectra obtained in outer torus the peaks corresponding to different ionic species are not resolved, and additional constraints will be required to extract further information about the plasma properties in this region.

Data Analysis

The Voyager Plasma Science experiment consists of four modulated-grid Faraday cups, three of which (A,B,C) are symmetrically positioned about an axis that generally points toward the Earth and a fourth (the side sensor, D) oriented at right angles to this direction. A full description of the experiment is given by Bridge et al. [1977].

Each of the 56 ion measurements obtained between 5.91 and 4.89 R_J consists of an energy-per-charge scan of the ions between 10 and 5950 eV from each Faraday cup. The scan in velocity space is integral in the directions perpendicular to the sensor normal and differential in the direction along the sensor normal. Thus the four energy-per-charge scans provide reduced (one-dimensional) ion distribution functions for four different directions in velocity space, convolved with the response functions of the sensors [see Appendix A of McNutt et al., 1981].

Barnett [1984] has shown that the response of each detector is a complicated function of the distribution of ions in velocity space. Fortunately, the response remains close to unity when the ions have a Maxwellian distribution, the plasma is cold, and the convective velocity is within the main field of view. During the Voyager 1 inbound traversal of the inner region of the torus, the symmetry axis of the main (A,B,C) sensors pointed (within 25°) into the corotating plasma flow. Since the normals to the three cup-apertures are inclined by 20° from the symmetry axis, the corotational flow remained within the main field of view of each sensor ($\sim 45^\circ$), and hence the approximation of unity response is valid.

At right angles to the main sensor symmetry axis, the side sensor pointed well away from the corotational flow throughout this period. Consequently, the fluxes in the D-cup were very small and have not been included in this analysis.

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Paper number 4A8054.
0148-0227/85/004A-8054\$05.00

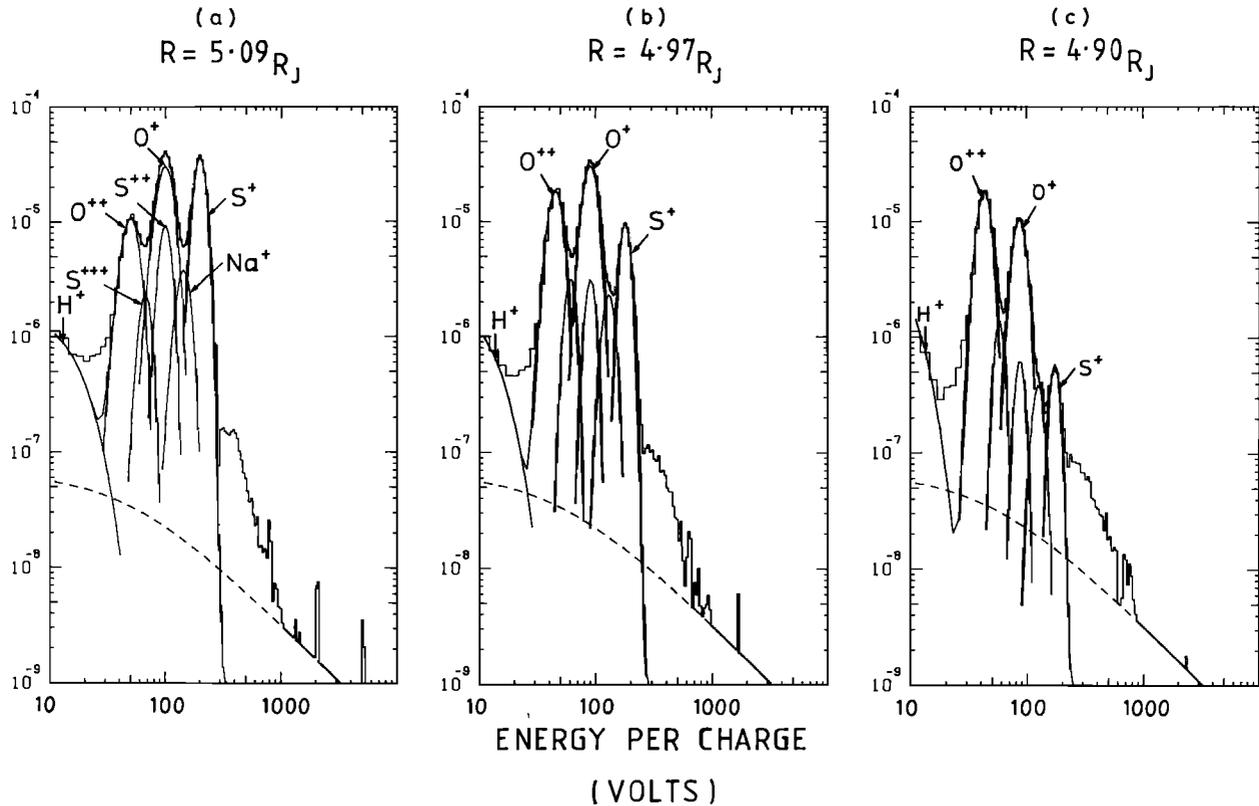


Fig. 1. Three ion spectra from the cold inner region of the torus. The histograms show the data. The Maxwellian functions for each species and the total fit to the data are given by smooth continuous lines. The dashed line shows the detector's measurement threshold.

Similarly, during the outbound traversal of the torus the corotational flow was at large angles to all the sensors, and therefore analysis of the outbound data will require the full response functions.

The energy-per-charge scans cover 10 to 5950 eV in 128 logarithmically spaced intervals. The first step to the discrimination of different ionic species is taken by making the reasonable assumption that all ions share the same bulk motion perpendicular to the magnetic field. The different ionic species are then separated according to the ratio of their mass number to charge state (A/Z). Thus the positions of the distinct peaks found in the energy-per-charge spectra (e.g., Figure 1) in the inner torus are consistent with ions having A/Z values of 8, 16, and 32, all corotating with Jupiter. The peaks corresponding to A/Z values of 8 and 32 are most likely due to O^{2+} and S^+ ions, while the peak for $A/Z = 16$ could be due to O^+ or S^{2+} ions or a combination of the two ionic species. In 8 of the 56 spectra there is also a well-resolved peak at $A/Z = 64$ corresponding to SO_2^+ or possibly S_2^+ . Enhanced fluxes in the lowest few energy channels indicate the presence of a small density of protons, while upper limits can also be placed on the densities of other minor species which would contribute to the spectrum in between the major peaks. Table 1 gives a list of ions and their corresponding values of A/Z .

In the inner region of the torus the time scale for Coulomb collisions between ions is only a few

hours, and one would expect the ion distributions to be isotropic Maxwellian functions. Indeed the individual spectral peaks can be fitted very closely with Maxwellian functions, not only near the center of the peak but also where the flux has dropped by 2 orders of magnitude or more (Figure 1a). With such confidence in the applicability of Maxwellian distributions, the density and temperature of an ionic species can be directly determined from the height and width of the spectral peaks. In addition, the position of the center of the peak determines the component of the ion's convective velocity of the ion population along the sensor normal. Thus with three sensors the three components of the convective velocity can be combined to provide the full velocity vector.

When the plasma is warmer and the spectral peaks merge, the plasma properties are not uniquely determined, but they remained quite well constrained by the data as long as the temperature stays below ~ 20 eV. Figure 2 shows examples of spectra which put quite stringent bounds on the ion bulk speed temperature and densities. By setting the bulk speed to decreasing fractions of the corotation speed, we investigated the range of parameters consistent with the data. Additional constraints placed on the fits to the data were that all the ions (except H^+) share the same temperature and that the data above the corotation energy of S^+ were not included. The energetic tail to the distribution was excluded because we were concerned with determining the properties of

TABLE 1. Positive ions in the Io torus

	Ion									
	H ⁺	O ⁺	O ²⁺ (a)	S ⁺ (b)	S ²⁺	S ³⁺	SO ⁺	SO ₂ ⁺ (c)	SO ₃ ⁺	Na ⁺
A	1	16	16	32	32	32	48	64	80	23
Z	1	1	2	1	2	3	1	1	1	1
A/Z	1	16	9	32	16	10 ^{2/3}	48	64	80	23

The following ions may also be present: (a) S⁴⁺. (b) O₂⁺, and (c) S₂⁺. Here, A is mass number and Z is charge number.

the thermal population, which comprise the bulk of the ions. With the inclusion of a small proportion of hot, nonthermal ions the average energy of the total ion population will be greater than the temperatures given here.

Due to a computational error, the ion temperatures from earlier analyses of PLS ion data [Bagenal and Sullivan, 1981] in the Io torus were quoted at half their correct values [Bagenal et al., 1984]. However, in these earlier analyses the tail was included in fits to the spectra and consequently the width of the distribution was overestimated. Thus the ion temperatures quoted by Bagenal et al. [1984] outside 5.7 R_J are larger

than those derived from the same data in this paper.

Results

Plasma Velocity

If the spacecraft was not electrically charged, the position of a spectral peak is a measure of the component of the ion's convective velocity along the sensor normal (which we shall call "ion bulk speed"). The net effect of a small, uniform spacecraft charge would be to introduce a small electrostatic potential difference between the plasma detector and background plasma and hence a

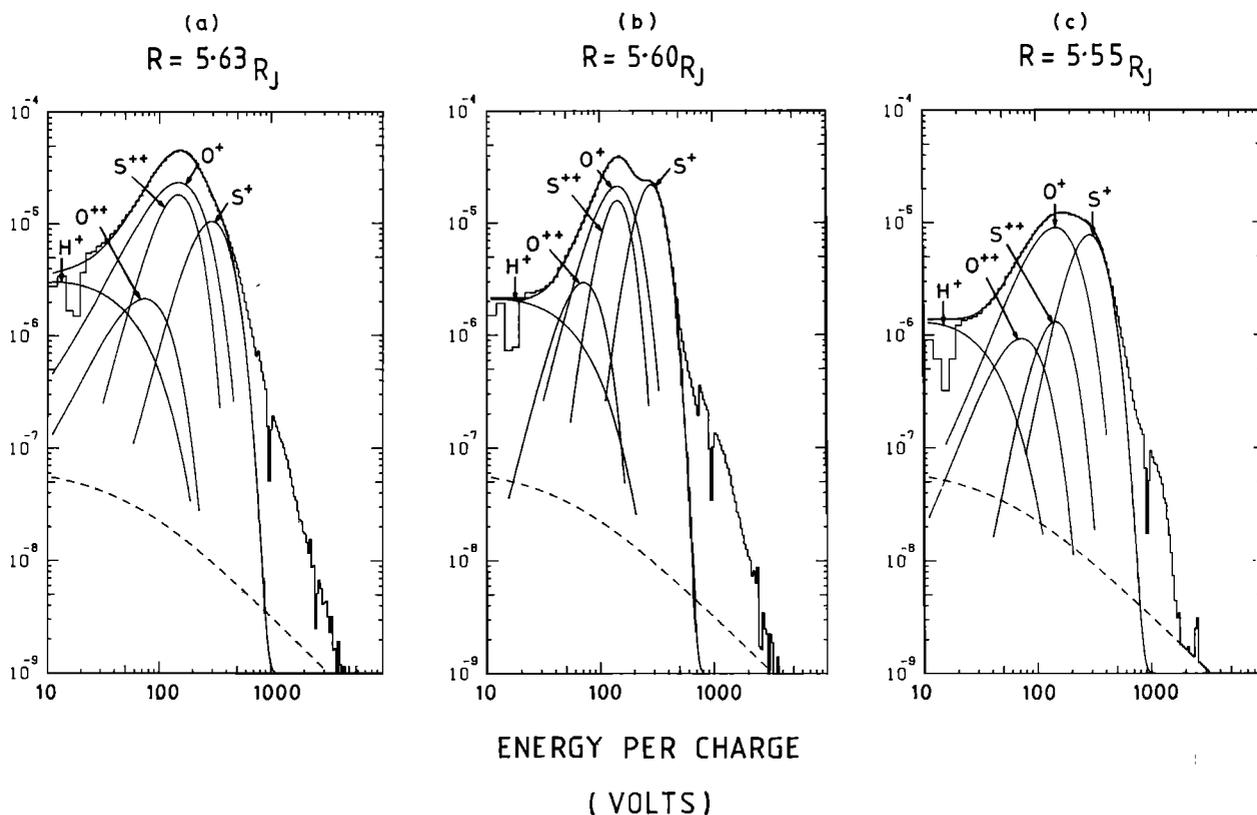


Fig. 2. Three ion spectra obtained within a period of 10 min in the vicinity of 5.6 R_J. The notches in the data (histogram) in the first few channels and again near 1000 V are due to interference, and the fluxes in these channels have not been included in the fitting procedure.

uniform displacement of the measured energy-per-charge spectrum. If the ion spectra are analyzed under the assumption that the spacecraft is not charged, the actual presence of a spacecraft charge is revealed as a systematic $(A/Z)^{-1/2}$ dependence of the derived bulk speeds for the different ionic species [Barnett and McNutt, 1983]. When we compared the positions of the three main peaks in a spectrum obtained at 5.1 R_J , we found a small systematic variation in bulk speeds in all three sensors which would imply the spacecraft had acquired a negative potential of 0.8 V, less than 0.5% of the corotational energy per charge of the $A/Z = 16$ peak.

Taking this small value for the spacecraft potential to be insignificant, we proceeded to analyze all spectra with well-resolved peaks (34 spectra between 4.9 and 5.3 R_J), assuming the ions were co-moving and in each case deriving a single value for the component of convective velocity along the normals of the A, B, and C cups. The three velocity components, V_A , V_B , V_C (which are not orthogonal) are measured in the frame of reference of the Voyager spacecraft. After transforming the measured components into the corotational frame, the residual velocity (\underline{V}) has been resolved in a coordinate system based on the unit vector \hat{b} , the local magnetic field direction as determined by the Voyager magnetometer [Ness et al., 1979] and a unit vector in the radial direction \hat{r} . As a result, the residual velocity can be considered to have three components: one parallel to the local magnetic field

$$V_b = \underline{v} \cdot \hat{b}$$

and two perpendicular to the field

$$V_r = \frac{\underline{V} \cdot (\hat{r} \times \hat{b})}{|\hat{r} \times \hat{b}|}$$

$$V_\Omega = \frac{\underline{V} \cdot (\hat{r} \times \hat{b})}{|\hat{r} \times \hat{b}|}$$

which are essentially in the radial and corotation directions, respectively.

Since the magnetic field and radial vectors always remained at large angles to the cup normals, uncertainties in cup response leave much doubt in the determination of the absolute values of V_b and V_r . Rather, the values obtained indicate the level of uncertainty in any residual parallel or radial motion. The derived values of V_b are systematically positive and lie between 1.5 and 2.0 km s^{-1} . The derived radial velocity, V_r , is directed toward Jupiter (except for one instance) and varies in magnitude between 0 and 1.3 km s^{-1} . Although understanding radial transport of material in the torus is of central interest, we are unwilling to draw any conclusions from the derived values of V_r . The levels of net radial motion expected in models of diffusion in the inner torus are orders of magnitude below figures derived here; for example, Richardson and Siscoe [1983a] quote $V_r \sim 10^{-4} \text{ km s}^{-1}$. On the other hand, transport models invoking a rotating convection system [Hill et al., 1981] suggest motion should be outward at the particular longitude that Voyager traversed the inner torus,

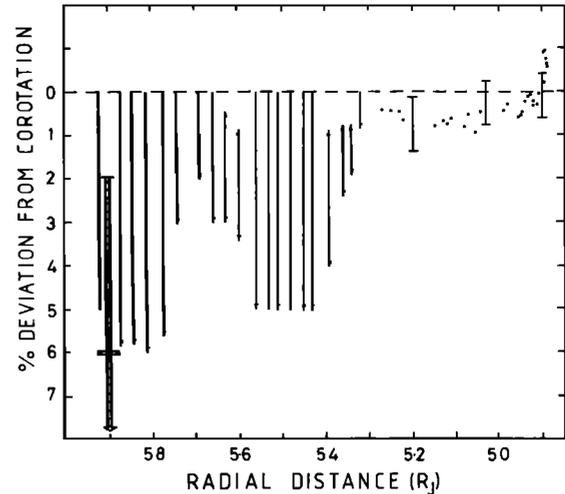


Fig. 3. The ion bulk speed in the corotation direction derived from fits to the Voyager ion data. The dots show cases where well-resolved spectra allowed the full velocity vector to be determined. V_Ω has been plotted as a percentage of the local corotation speed, and the error bars represent the total uncertainty in the measurement. Arrows indicate ranges in percentage deviation from corotation that allowed reasonable fits to the unresolved spectra. The hatched region at 5.9 R_J corresponds to the estimate of Brown [1983] of $6 \pm 4\%$.

while a systematic feature of our estimates of V_r is inward motion. It should also be noted that Voyager 1 traversed the inner torus close to dusk and hence any anti-sunward motion due to a dawn-dusk electric field [Barbosa and Kivelson, 1983; Goertz and Ip, 1984] would produce a perturbation in V_Ω (of $\sim 1\%$) rather than V_r .

In Figure 3, V_Ω has been plotted as a fraction of the local corotation speed:

$$\frac{(\underline{\Omega} \times \underline{r}) \cdot (\hat{r} \times \hat{b})}{|\hat{r} \times \hat{b}|}$$

The dots are the values obtained by fitting the data from three cups and determining the full velocity vector. The three error bars show typical errors based on the combined effect of the formal error in the fitting procedure and the instrumental error derived from the voltage characteristics of the instrument and digitization of the measurements. As such, these error bars should well describe the uncertainties in the measurement of V_Ω when the direction of the associated vector remained in the main field of view of all three cups. It is only inside 4.9 R_J , where the spacecraft orientation changed rapidly, that the measurements may be less accurate. Consequently, the trend toward supercorotation inside 4.9 R_J may disappear if a more accurate response function is used for each detector. Thus the firm conclusion from these results is that within a radial distance of 5.3 R_J , corotation is imposed to better than 1%.

Outside 5.3 R_J it is not possible to retrieve the full velocity vector because the spectral peaks are not sufficiently resolved to allow an

accurate determination of the ion bulk speed for each cup. To investigate the extent of any deviation of the plasma motion from corotation in the region between 5.3 and 5.9 R_J , we made the assumption that the plasma was moving in the local corotational direction but lagging behind rigid corotation. The magnitudes of the lag which allowed a reasonable fit to the 22 spectra between 5.9 and 5.3 R_J are indicated in Figure 3 by arrows. Deviation from corotation of up to 5% is allowed by the data, but some of the spectra with better resolution (e.g., the spectrum at 5.60 R_J shown in Figure 2) suggest a distinct lag of 1-3% behind rigid corotation. These values are consistent with the 6% (\pm 4%) lag deduced by Brown [1983] from optical emission from S^+ ions near 5.9 R_J .

Temperature

For Maxwellian distribution functions the temperature of each ionic species can be determined directly from the width of the spectral peaks. The spectra shown in Figure 1 are examples of the occasions when the three main spectral peaks, each consisting of eight or more data points, can be fitted very closely with Maxwellian functions to well over a thermal width away from the center of the peak. When the two outer peaks of the spectrum at 4.97 R_J (corresponding to O^{2+} and S^+ with A/Z equal to 8 and 32 respectively) were fitted independently, the two ionic species were found to have the same temperature (to 1%). This is not surprising as the time scale for ion-ion thermal equilibration is only about an hour for these plasma conditions [Book, 1980]. The middle peak corresponds to ions with A/Z equal to 16, presumably a combination of S^{2+} and O^+ ions. If these ions with $A/Z = 16$ are also in equilibrium and share the same temperature, then the S^{2+} energy distribution would appear to have half the width of the O^+ distribution. Therefore by assuming that the thermal equilibrium observed for S^+ and O^{2+} ions can be taken to encompass other ionic species, it is possible to estimate the relative contributions of S^{2+} and O^+ ions to the $A/Z = 16$ peak. The spectra in Figure 1 illustrate that, under the assumption that the ions are isothermal, the spectra can be fitted very closely and that the $A/Z = 16$ peak then appears to be dominated by O^+ ions.

The assumption that the main ionic species share the same temperature is valid inside 5.4 R_J . Further out, the extensive non-Maxwellian tails to the ion distributions suggest the ions are not so close to equilibrium. Moreover, observations of optical line-emissions indicate that at 5.9 R_J all S^+ ions do not share the same temperature [Brown, 1982] and that the average energy of S^+ ions is less than the S^{2+} ion temperature [Brown, 1981; Roesler et al., 1982]. Nevertheless, we would suggest that the majority (80-90%) of ions have come quite close to equilibrium and the temperatures of the various ionic species do not differ greatly, even near 5.9 R_J .

Where the temperature of the ions is greater than about 6 eV, the different distribution functions merge into a single spectral peak, but it is still possible to put quite stringent bounds on the ion temperature. Figure 2 shows

three spectra where the single merged peak is sufficiently narrow that the ion temperatures are quite tightly constrained, to 19.6 ± 5.0 , 9.3 ± 1.2 , and 14.1 ± 0.2 eV, respectively.

In Figure 7a we show the temperature profile derived from the 56 PLS ion spectra obtained on Voyager 1 inbound pass between radial distances of 5.91 and 4.89 R_J . It is clear that the ion temperature inside 5.9 R_J is irregular, falling in a series of steep drops to less than 0.7 eV by 4.9 R_J . The net effect is a decrease in temperature of nearly 2 orders of magnitude within a radial distance of 1 R_J . Most of the irregularities of the temperature profile are considerably larger than the uncertainties in the measurements and therefore must be considered as real features. An intriguing example is the dip in temperature near 5.5 R_J .

The temperature profile is hard to reconcile with any steady state structure. Any simple steady state model of the inner torus involves a constant source of particles near Io, steady inward diffusion of plasma, and continuous processes such as charge exchange adding energy while recombination and radiation cause the eventual loss of particles and energy from the system. In such a steady state situation the temperature profile would follow a smooth decrease away from the main plasma source, with decreasing radial distance from Jupiter, there being no obvious cause of strong radial variation in any process and the energy losses outweighing any heating. The irregularity of the temperature profile obtained by Voyager 1, in our view, implies there must be considerable time dependence plus additional sources and/or sinks. We will consider further evidence of deviation from a steady state later.

We next consider the temperatures of the minor species evident in the particularly well-resolved spectra. At the lowest energies of the spectra, enhanced fluxes form the shoulder of a spectral peak that is probably due to protons whose corotation energy is below the 10 V threshold of the instrument. An accurate determination of the proton density and temperature from such spectra will require a more detailed response function for the detector. Nevertheless, fitting these few points with a Maxwellian function centered on the corotation energy suggests that the protons have a temperature about 2-3 times the heavy ion temperature. The possibility that the protons are not in equilibrium with the bulk of the plasma population is perhaps not so surprising when one considers the obvious source of these protons is the ionosphere of Jupiter [Hill et al., 1974]. Protons which manage to escape from the gravitation of Jupiter will be accelerated by centrifugal forces as they move along the magnetic field away from Jupiter. These protons are initially very cold so that their gyromotion perpendicular to the field is small while their parallel motion increases to the local corotation speed ($\sim 70 \text{ km s}^{-1}$) as they reach the torus at the equator. These streaming protons would not be detected by the Voyager plasma instruments unless some fraction of them are scattered in pitch angle either by collisions (with heavy ions in the torus or counterstreaming protons) or possibly by wave-particle interactions. Protons suffering any

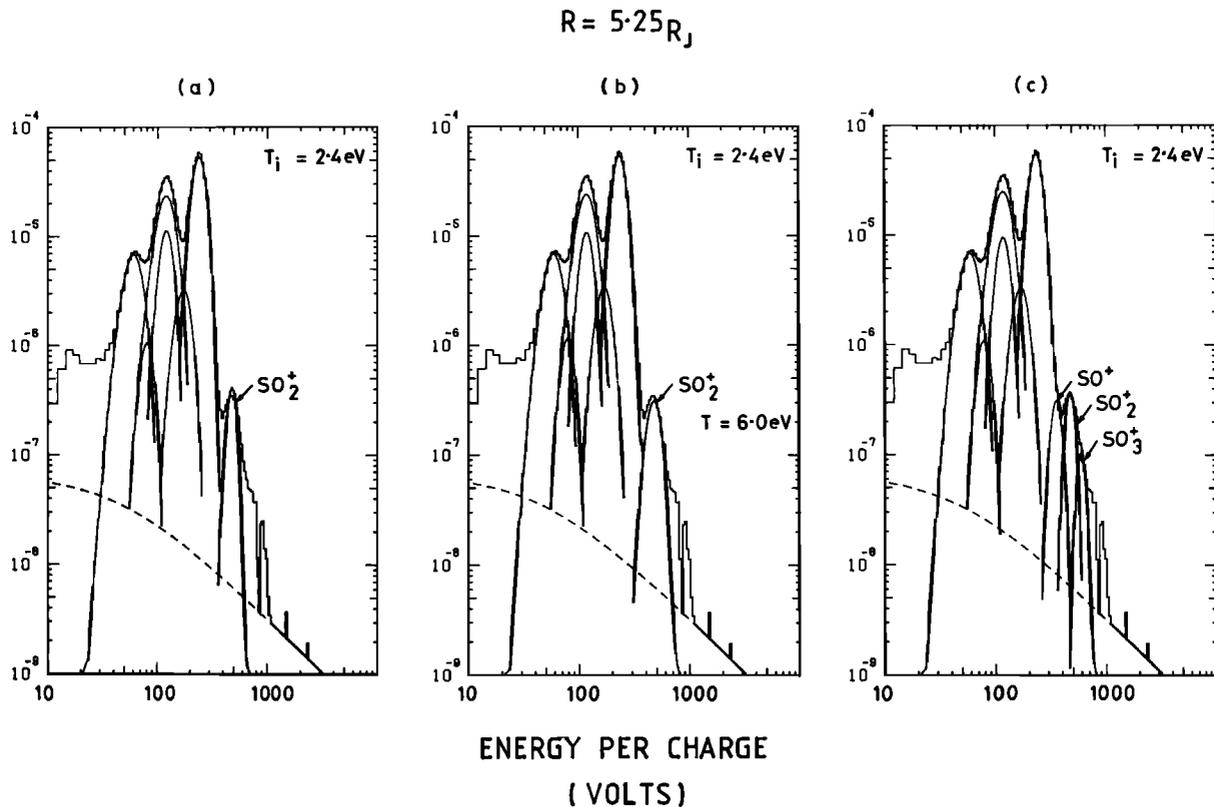


Fig. 4. An ion spectrum obtained at $5.25 R_J$ which has a distinct spectral peak corresponding to ions with $A/Z \sim 64$. The spectrum has been fitted under three different conditions. (a) The peak was assumed to be entirely due to the SO_2^+ ions at the same temperature as the other ionic species. (b) The temperature of the SO_2^+ ions was allowed to vary. (c) The SO_2^+ ions were accompanied by SO^+ and SO_3^+ ions, while all ions were assumed to have the same temperature.

changes in pitch angle would "mirror" before reaching the ionosphere in the opposite hemisphere and hence would be trapped by the magnetic field in the torus L-shells, and would pass repeatedly through the heavy ion plasma. Nevertheless, the fact that the protons detected by the Voyager instrument inside $5.4 R_J$ appear hotter than the heavy ions indicates that equilibration is incomplete.

Turning to energies above the main spectral peak, we next consider the temperature of ions with $A/Z = 64$ which produce a distinct spectral peak in eight of the spectra in the inner torus (e.g., Figure 4). Although McEwen and Soderblom [1983] have recently suggested that more sulphur than sulphur dioxide is ejected from volcanoes on Io, we follow previous authors [e.g., Cheng, 1982; Smyth and Shemansky, 1983] in preferring SO_2 as the source material for magnetospheric plasma. We therefore assume SO_2^+ rather than S_2^+ ions dominate the $A/Z = 64$ peak. On fitting the spectrum in Figure 4, we found the $A/Z = 64$ peak to be wider than would be expected if SO_2^+ ions were in thermal equilibrium with the background population. One possible explanation is that the SO_2^+ ions are indeed hotter than the main population because they have recently been ionized and have not had time to equilibrate. Fitting the SO_2^+ peak separately with a single Maxwellian function indicates a temperature of 6 eV for the SO_2^+ ions compared with 2.4 eV for the background

population (Figure 4b). A second explanation the wide peak could be that small quantities of SO^+ and SO_3^+ ions contribute to the SO_2^+ peak. Figure 4c shows a combination of SO_2^+ , SO^+ , and SO_3^+ and also produces a reasonable fit to the data. Laboratory studies of Johnson et al. [1984] show SO and SO_3 molecules are minor products of the sputtering of SO_2 frost, though their yields are at least an order of magnitude less than of SO_2 . Moreover, Becker et al. [1983] report SO^+ to be the dominant ion produced by electron impact dissociation of SO_2 . A major difficulty with both these explanations is that they require either neutral SO_2 or ionized SO^+ and SO_3^+ molecules to be present at $5.3 R_J$, a considerable distance away from Io, when their lifetimes for dissociation are quite short ($\sim 10^6$ s, Cheng [1980]).

In all the spectra obtained throughout the torus there are fluxes above the energies corresponding to corotating SO_2^+ ions. In the particularly cold region inside $5.3 R_J$ such fluxes are barely above the detection level of the instrument (Figure 1). Between 5.4 and $5.6 R_J$ the fluxes remain significant until about 1200 eV where there is a sharp cutoff (see spectra b and c of Figure 2). The ionization of any neutral material present at these radial distances would produce ions that pick up a gyro-energy equal to the local corotation energy [Siscoe, 1977]. At $5.6 R_J$ the energy associated with the convective

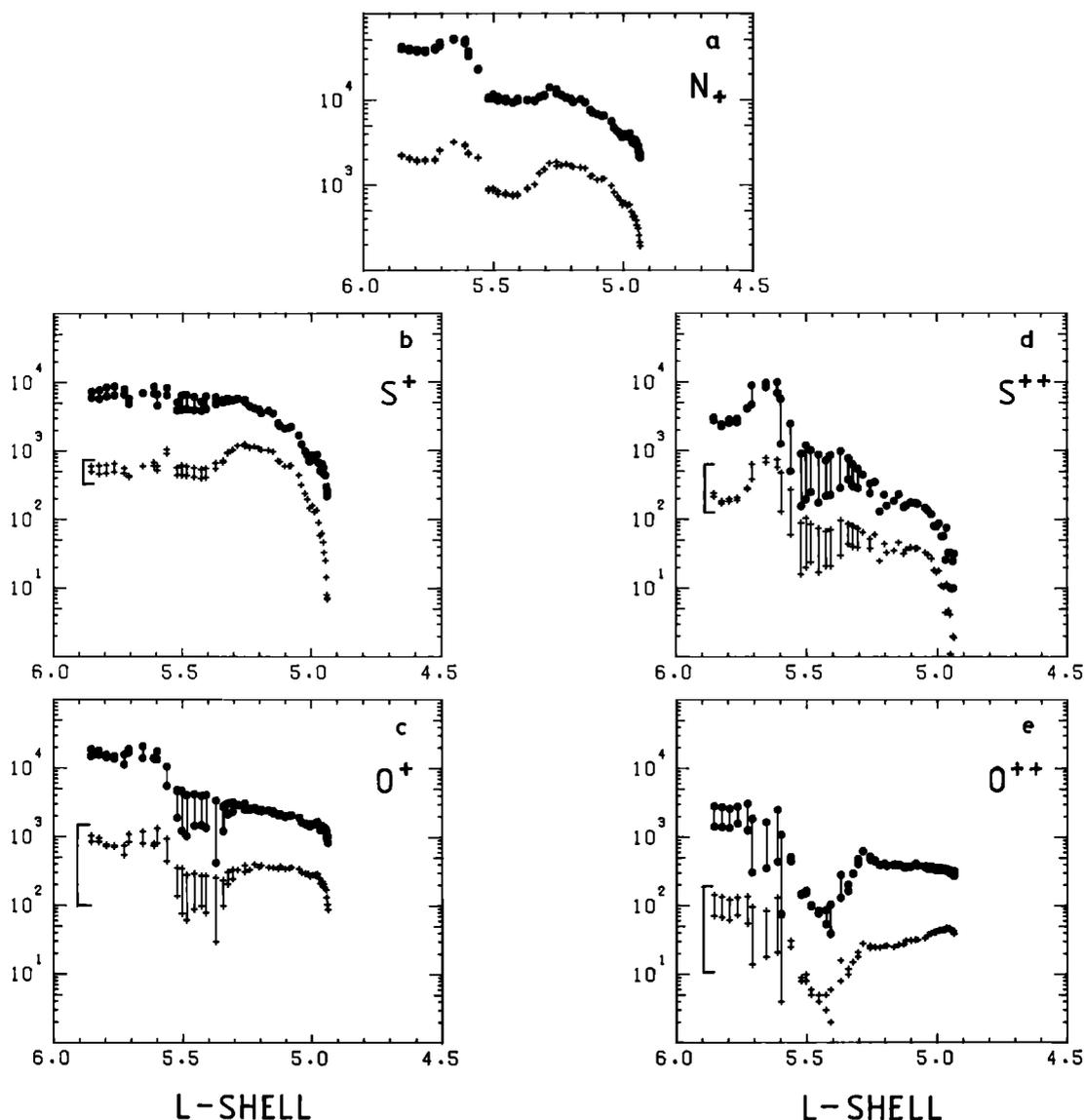


Fig. 5. Radial profiles of local density (crosses) and height-integrated density (dots) of the major ionic species derived from fits to the Voyager 1 ion spectra. The vertical lines indicate the ranges in values consistent with the data. The local density is in units of ions cm^{-3} . Square brackets illustrate the range in composition at 5.9 R_J reported by Bagenal and Sullivan [1981]. The height-integrated densities have been calculated by extrapolating the local measurements along the field lines (see appendix) and are given in units of $\text{ions cm}^{-3} \text{degrees}$ (which can be converted to a column density (ions cm^{-2}) by multiplying by $1.25 \times 10^8 R$, where R is in R_J).

motion of S^+ ions plus their gyromotion at the local corotation speed adds up to about 1200 eV, so that the ~ 1200 -eV cutoff could indicate a small fraction (about 10%) of newly ionized material with non-Maxwellian distribution functions.

The spectrum in Figure 2a does not have a sharp cutoff at ~ 1200 eV. The energetic tail to the spectrum merges with the Maxwellian component and extends all the way up to the highest energy channel at 5950 eV. Outside 5.63 R_J all the spectra have prominent energetic tails, while inside 5.63 R_J the tail is both reduced in magnitude and limited to energies less than ~ 1200 eV. The presence of a hot component to

the ion population is consistent with observations of S^+ line emission by Brown [1982] and the theoretical studies of Barbosa et al. [1983] and Richardson and Siscoe [1983b]. There are plenty of possible causes of the energetic tails exhibited outside 5.63 R_J (recent ionization of neutrals and recycling of torus material being just two), but why the tail should abruptly change at 5.63 R_J remains unexplained.

The ion temperatures given in this paper are those of the thermal (i.e., Maxwellian) component of the ion population. The fluxes in the non-Maxwellian tail (i.e., above ~ 500 eV for the spectra in Figure 2) have not been included in the fitting procedure. Therefore outside 5.6 R_J

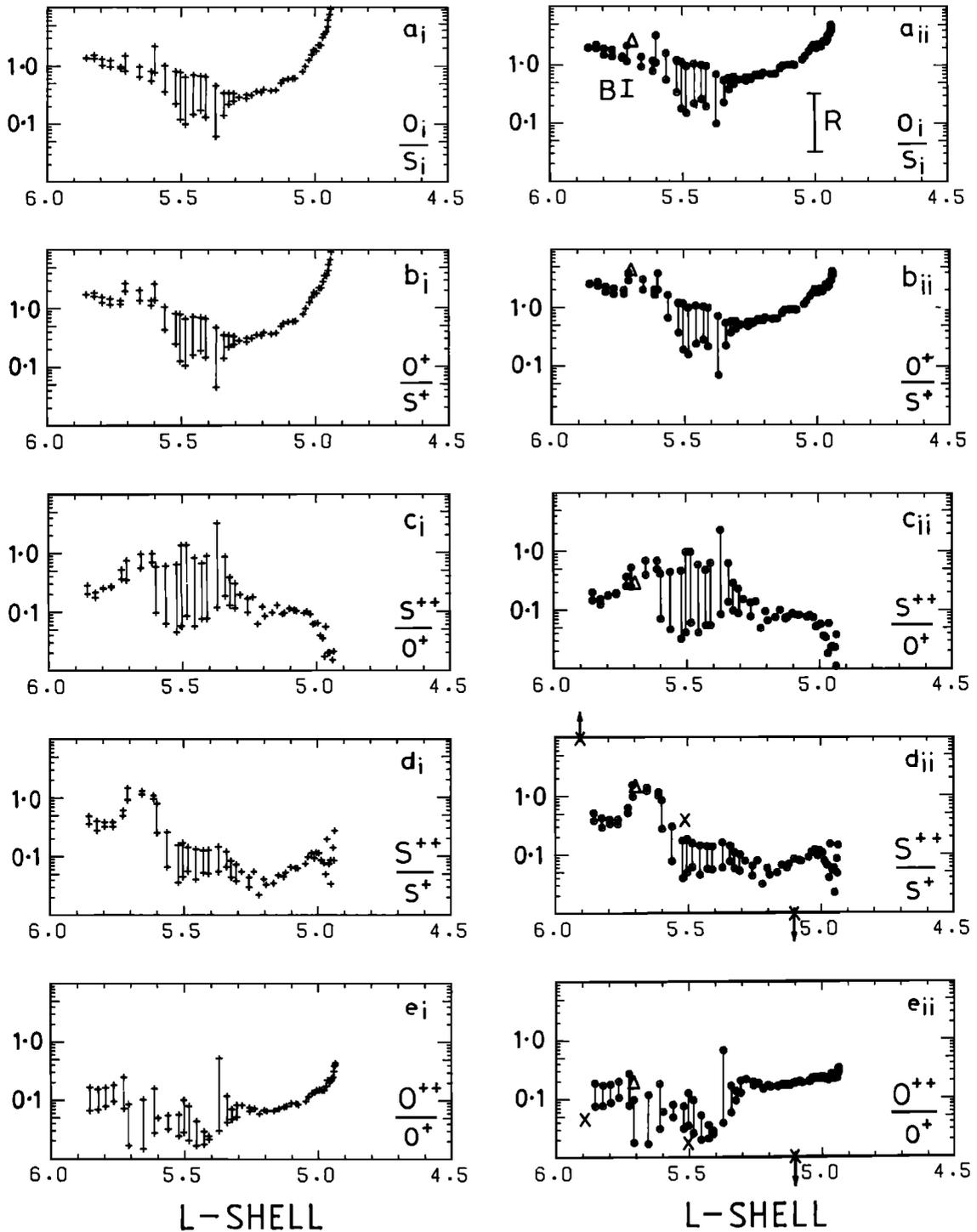


Fig. 6. Radial profiles of ratios of (i) local densities and (ii) height-integrated densities, for various combinations of ionic species. The vertical lines show the ranges in values consistent with the data. The additional symbols correspond to the following references: **B** Brown et al. [1983]; **R** Richardson and Siscoe [1983a]; **X** Johnson and Strobel [1982]; **Δ** Shemansky [private communication, 1984].

where there is a prominent tail to the distribution, the mean energy of the ions will be significantly higher than the temperatures derived in this analysis. For example, adding 10% (20%) more ions at 400 eV increases the average ion energy at 5.9 R_J from 35 to 75 (115) eV.

Composition

When the spectral peaks are well resolved the densities of the corresponding ions (O^+ , O^{2+} , S^+ , S^{2+} , and SO_2^+) can be directly determined, while upper limits can be placed on minor ions (e.g.,

H⁺, S³⁺, Na⁺) that might contribute fluxes in between the peaks. Measurements made at 5.2 R_J (when the spacecraft was close to the centrifugal equator) showed the plasma to be dominated by the singly ionized species, S⁺ (65%) and O⁺ (25%), while their corresponding double ionized species, S³⁺ and O²⁺, contributed about 2% each to the total ion population. The measurements require an upper limit of 5% for the local density of Na⁺ ions and require that the remaining minor species, S³⁺, H⁺ and any molecular ions, each comprise less than 1% of the ions at this location.

Note that inside 5.3 R_J the density of O²⁺ ions is accurately determined from the well-resolved spectral peak at A/Z = 8. The possibility that the A/Z = 8 peak corresponds to S⁴⁺ can be disregarded in this region because (1) to produce the observed spectral peak, the S⁴⁺ ions would need to have twice the temperature of the rest of the ions in a region where plasma conditions suggest complete thermodynamic equilibrium, and (2) it is hard to explain the presence of a significant density of S⁴⁺ ions in the absence of S³⁺ ions. On the other hand, outside 5.6 R_J the possibility that S³⁺ and S⁴⁺ ions could contribute to the lower end of the spectrum must be considered. Thus the measurement of ~ 40 O²⁺ ions cm⁻³ in the cold inner torus does not conflict with the observations of less than 4 O²⁺ ions cm⁻³ at 5.9 R_J by Brown et al. [1983a].

In Figure 5 the densities of the predominant ionic species are plotted (crosses) against radial distance. The densities of S⁺ and O²⁺ ions remain quite well determined as they contribute to the upper and lower shoulders of the merged peak. Unfortunately, the merging of spectral peaks increases the difficulty in distinguishing the contributions of S²⁺ and O⁺ ions to the middle of the merged peak, and the ratio of their densities [S²⁺/O⁺] is strongly affected by the value of the bulk speed; slower speeds generally suggest more S²⁺, less O⁺, and a slightly higher temperature. The effects of disregarding the tail to the distribution outside 5.6 R_J are found by comparing the densities derived in the present analysis with the range of values from previous studies (the range of ionic composition at 5.9 R_J reported by Bagenal and Sullivan [1981] is shown by square brackets in Figure 5). Because the ions with A/Z = 16 dominate the spectrum in this region (Figure 2a) the major effect of disregarding the tail is to limit the width of the ion distribution and hence limit both the ion temperature and the contribution of S²⁺ ions to the spectral peak.

The spectra in Figure 1 illustrate how the composition varied quite considerably along the spacecraft trajectory. However, in order to understand the causes of these changes it is necessary to separate variations attributable to the spacecraft's latitude from variations due to its decreasing radial distance. In the appendix we summarize how a plasma in diffusive equilibrium is distributed along magnetic field lines. Assuming the plasma to be so distributed, we extrapolated the measured ion densities along dipolar field lines in order to derive "height-integrated" densities by integrating the density of each ionic species over the latitudinal extent of the torus. These height-integrated densities are shown by data in Figure 5. (The height-

integrated densities have units of ions cm⁻³ degrees which can be converted to a column density (ions cm⁻²) by multiplying by 1.25 x 10⁸ R, where R is in R_J.)

The variation in composition introduced by the change in the spacecraft's latitude is illustrated by the difference between the local and integrated densities of S⁺ ions (Figure 5b). The S⁺ ions are confined to the equator, and as the spacecraft moved south of the equator inside 5.2 R_J, the measured S⁺ density rapidly dropped while the integrated S⁺ density retained a more gentle decline. Conversely, the density of O²⁺ ions, being relatively minor species of low A/Z, is expected to have a maximum density away from the equator [Angerami and Thomas, 1964]. Consequently, the local measurements of O²⁺ density (Figure 5e) increase inside 5.2 R_J, while the integrated density retains a decline.

The top panel in Figure 5 shows the total density of positive charge N₊, measured by the PLS detector. In the absence of negative ions or a substantial population of positive ions outside the 10 to 5950 eV range, N₊ must equal the electron density. Note that the maximum at 5.3 R_J in the local charge density profile is absent in the profile of integrated charge density which monotonically decreases inside 5.7 R_J. The integrated densities of each of the ionic species show similar trends, though there are some significant differences among species which are best illustrated by the ratios of their densities.

Figure 6 shows the radial profiles of five density ratios for both measured (left) and integrated (right) densities. As the local measurements are strongly dependent on latitude, it is the ratios of integrated densities shown on the right of Figure 6 that reveal the true radial variations in composition. The first thing to note about the right side of Figure 6 is that the ratio of oxygen to sulphur ions [O_i/S_i] rarely deviates outside a factor of 2 of unity. This is quite contrary to the expectation that charge-exchange reactions would preferentially remove oxygen ions [Johnson and Strobel, 1982]. The values of 1 to 2 for [O_i/S_i] in the outer region (5.6-5.9 R_J) are consistent with ultraviolet observations (D. Shemansky, private communication, 1984) and the conclusions of Brown et al. [1983]. The proportions of oxygen and sulphur ions in this region, close to the main source near Io, is presumably fixed by the main production mechanisms. If charge-exchange reactions then preferentially remove oxygen, the ratio [O_i/S_i] should rapidly decrease radially inward. Richardson and Siscoe [1983a] calculated values of 0.03 to 0.25 for [O_i/S_i] at 5.0 R_J. However, the Voyager 1 plasma data suggest that after decreasing from 2 at 5.9 R_J to about 0.5 at 5.4 R_J the value of [O_i/S_i] actually increased inside 5.4 R_J.

The second question to consider is whether the lower temperatures inside 5.4 R_J affect the average charge state. The ratios [S²⁺/S⁺] in panel (d_{ij}) and [O²⁺/O⁺] in panel (e_{ij}) show that the average charge does drop as the temperature decreases inside 5.6 R_J but the doubly charged ions maintain densities at one tenth of the integrated density of the singly ionized species. The theoretical calculations of Johnson and Strobel [1982], based on the dominance of charge-exchange reactions put the ratios [O²⁺/O⁺] and

$[S^{2+}/S^+]$ at least an order of magnitude lower than this, essentially ruling out anything other than singly ionized species.

Third, it must be noted that although the ratio $[S^{2+}/O^+]$ is probably the least constrained quantity in the inner torus, it is quite clear that inside $5.3 R_J$ there is considerably more O^+ than S^+ (by a factor of 8 to 10). Outside $5.4 R_J$ the ratio could be much larger, possibly of the order of unity, but our present analysis would indicate values of 0.2 to 0.5 for $[S^{2+}/O^+]$ in this region which is consistent with D. Shemansky's value of 0.35 from the UV observations at $5.7 R_J$.

Finally we conclude this section with some comments about the minor ion composition in the inner torus. When considering the height-integrated densities rather than local measurements, the total abundance is found to be greater for light ions such as O^{2+} and H^+ (which are not so closely confined to the equator as the more massive ions). Thus the abundance of O^{2+} ions increases from 2 to 5% on height integration, while the abundance of protons increases from less than 1% locally to 10-15% overall. The relative abundances of other minor ions do not change significantly on integration. The integrated density of Na^+ ions remains $\leq 5\%$ of the total, while the abundances of S^{3+} ions and SO_2^+ ions remain $\leq 1\%$.

L-Shell Density

In order to understand the processes governing radial transport of plasma it is necessary to obtain an estimate of the total number of ions per magnetic L-shell. Calculation of the total L-shell density from the local measurements requires knowledge of how the plasma is distributed both with latitude and in azimuth around Jupiter. We have taken a uniform distribution with longitude in our calculations because, although optical emission from S^+ ions shows a systematic variation with longitude, it is not clear whether the azimuthal asymmetry in emission intensity necessarily implies a substantial asymmetry in the total plasma density [see Brown et al., 1983]. The Voyager 1 measurements were made over a small range in longitude ($200-260^\circ$ System III longitude) so that the presence of a significant asymmetry in the azimuthal distribution would alter the absolute value of the L-shell density but not the shape of the radial profile.

Taking N to be the number of ions in a flux shell per unit L , the number of ions in a flux shell containing unit magnetic flux is directly proportional to NL^2 [Siscoe, 1978]. Earlier estimates of NL^2 in the torus region [Richardson et al., 1980; Bagenal and Sullivan, 1981] assumed the plasma to be distributed in latitude along dipolar field lines with an exponential scale height H (in units of R_J) so that

$$NL^2 = 2\pi^{3/2} R_J^3 L^3 \sum_i n_{0i} H_i$$

where n_{0i} is the density of the i th ionic species at the centrifugal equator.

Figure 7b shows the profile of NL^2 against L calculated assuming the plasma to be distributed uniformly with longitude and using a diffusive

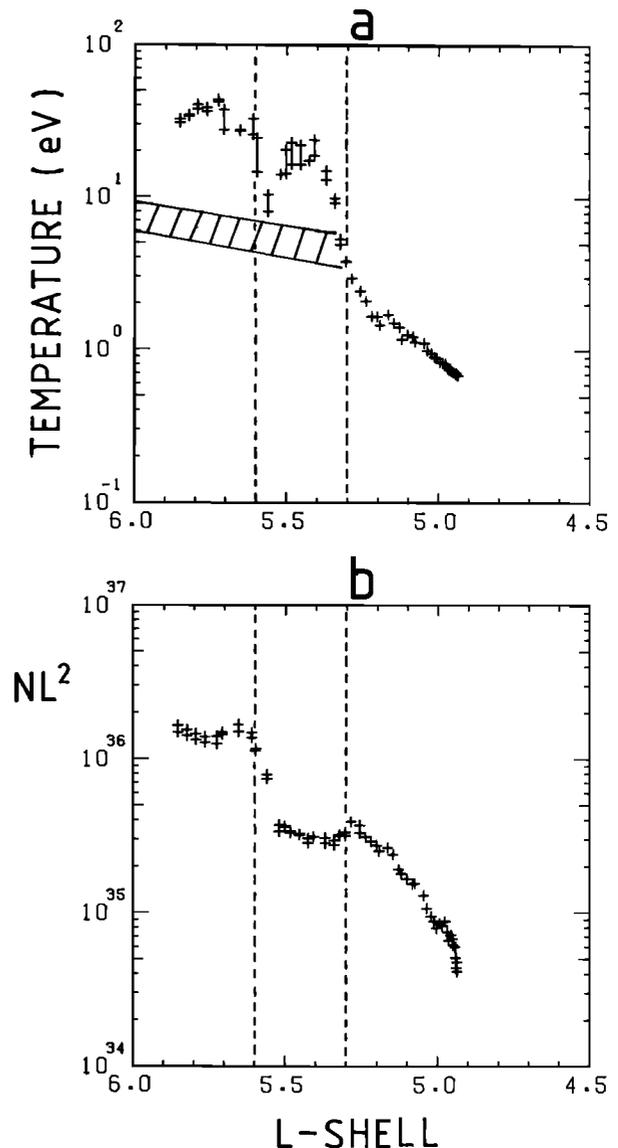


Fig. 7. Profiles of (a) temperature and (b) NL^2 against L-shell. The ion temperatures (crosses) in the top panel are from this study, while the electron temperature (hatched region) are from Voyager electron measurements [Scudder et al., 1981] and estimates from Voyager ultraviolet measurements [Snyth and Shemansky, 1983].

equilibrium model for the distribution of plasma with latitude, θ . Thus

$$NL^2 = 2\pi R_J^3 L^4 \int_i \sum n_i(\theta) \cos^4 \theta d\theta$$

The integral was computed numerically for latitudes containing torus plasma. In addition to the limitations of using a simple scale height distribution, the earlier estimates of NL^2 suffered from the computational errors discussed by Bagenal et al. [1984]. The net result is that the values of NL^2 used by various authors [Richardson et al., 1980; Richardson and Siscoe, 1981, 1983; Siscoe et al., 1981] to calculate diffusion rates inside Io's orbit were underestimated inside $5.6 R_J$ by a factor of $\sim 50\%$,

while the values between 5.6 and 5.9 R_J remain $\sim 1.5 - 2.0 \times 10^{36}$. Consequently, the profile is less steep inside 5.6 R_J , and the diffusion coefficient must be greater than the value estimated by Richardson and Siscoe [1983a]. However, their main conclusions (discussed below) remain unaffected.

Discussion

We must now consider whether there is a combination of source, transport, and loss processes that could produce the profiles of NL^2 and ion temperature shown in Figure 7. These same processes must also be consistent with (1) the observed electron temperatures, and (2) the radial variations in composition (shown in Figure 5). Electron temperatures derived from PLS electron measurements [Scudder et al., 1981] and from Voyager 1 [Smyth and Shemansky, 1983] are shown by the hatched region in Figure 7 between 5.3 and 5.9 R_J .

To account for the sharp decrease in NL^2 measured by Voyager in the inner torus, Richardson et al. [1980] proposed that the plasma source near Io had increased in strength by a factor of at least 20 within 100 days prior to the time of the Voyager 1 encounter. However, when Richardson and Siscoe [1983a] considered the radial transport of energy concomitant with particle diffusion, they were unable to reproduce the large drop in ion temperature by simply applying a time-dependent source. By introducing either considerable recombination or an outward convective flow, Richardson and Siscoe [1983a] could provide a decrease in temperature comparable with the observations but only if they used a diffusion rate at least 100 times slower than the rate that is generally accepted to account for Pioneer particle observations and to account for the power of the synchrotron emission. Richardson and Siscoe concluded that if plasma diffuses at a more reasonable rate, then the observed $\sim 5 \times 10^{10}$ W of optical emission from the inner torus [Morgan and Pilcher, 1982] is a factor of 20 too small to cool the ions to the observed temperatures and an additional $\sim 10^{12}$ W sink of ion energy is required.

In their theoretical study, Richardson and Siscoe chose an initial composition and temperature for the plasma at 5.9 R_J , and then calculated how these properties would vary due to ionization and pick-up of neutrals, radiation, charge exchange, recombination, and Coulomb interactions as the plasma diffused inward at varying rates. The composition that they started with consisted of equal quantities of S^+ and O^+ ions plus a factor of 4 less S^{2+} and O^{2+} ions. They also included some neutral oxygen and sulphur atoms in a proportion of 4:1. Their calculations concur with the expectations of Johnson and Strobel [1982] that charge exchange reactions will result in the preferential removal of oxygen ions. Richardson and Siscoe derived values for the ratio of sulphur to oxygen ions $[O_i/S_i]$ of 0.03 to 0.25 at 5 R_J , depending on the absolute densities of neutral atoms chosen for the initial conditions. In direct contrast to Richardson and Siscoe's results, we see no evidence in the Voyager 1 measurements of a preferential removal of oxygen,

and in fact, the ratio $[O_i/S_i]$ in Figure 6 (a_{ij}) shows the ratio to be greater than 1 at 5.0 R_J . In choosing the initial plasma composition at 5.9 R_J , Richardson and Siscoe have overestimated the relative amount of S^+ and underestimated the proportions of O^+ and S^{2+} ions. Nevertheless, we doubt that by only altering the starting conditions (or the diffusion coefficient) in Richardson and Siscoe's model one could (1) produce the observed composition, (2) remove sufficient thermal energy from the ions, and (3) account for the irregularities in the radial profiles of NL^2 and temperature.

Given the cross sections for charge exchange reactions of Johnson and Strobel [1982], we conclude the only way a substantial proportion of oxygen ions can be maintained in the inner torus is with an additional source located well inside the orbit of Io. The presence of molecular ions at 5.3 R_J indicates a local source because even the shortest estimates of diffusion time scales are much longer than the time scales for their dissociation. Therefore we suggest a cloud of SO_2 must extend inward from the orbit of Io to radial distances of at least 5.3 R_J . A cloud of SO_2 would also provide sufficient oxygen ions to balance their subsequent preferential removal via charge-exchange reactions, and hence the $[O_i/S_i]$ ratio for the plasma could remain near unity. Further indications of the presence of an ion source in the inner torus are the non-Maxwellian tails to the ion distributions and the deviation from strict corotation between 5.9 and 5.4 R_J . We do not imply by a "source" that the total ion density need change because each charge-exchange reaction replaces a cold ion with a new ion (having a gyromotion equal in magnitude to the local corotation speed). At the same time, charge-exchange reactions entail a torque being exerted on the ionosphere of Jupiter as the new ion is accelerated to corotation and hence provide an explanation of the lack of corotation [Pontius and Hill, 1983]. On the other hand, an enhanced level of charge-exchange reactions would exacerbate the problem of explaining the low ion temperatures in the inner torus because the total energy of the ions is increased in the process.

Finally, Richardson and Siscoe [1983a] suggested that the irregular profiles of NL^2 and ion temperature may have been caused by large temporal fluctuations in electron density and temperature on time scales short compared with diffusion times. Morgan and Pilcher [1982] have observed considerable fluctuations on a time scale of days in S^+ emission from the inner torus and report one occasion when they inferred an electron density greater than $\sim 3 \times 10^4$ cm^{-3} while T_e was less than 0.8 eV. Richardson and Siscoe [1983a] suggest that the Voyager 1 NL^2 and T_i profiles might be a result of a period of such conditions when the electrons rapidly removed the thermal energy of the ions via Coulomb collisions, followed by a return to "normal" plasma conditions just prior to the Voyager 1 encounter.

Many questions remain about the detailed nature of the plasma sources, sinks, and transport and the extent of their variability. The Voyager plasma data provide a basis for developing quantitative models of the plasma processes operating in the torus, but a better understanding

of the variability of plasma conditions will require careful monitoring of the optical and ultraviolet emissions from the plasma and neutral species.

Conclusions

In traversing the inner torus between a radial distance of $5.9 R_J$ and perijove at $4.9 R_J$, Voyager 1 observed a wide range of plasma conditions. We can summarize the Voyager 1 observations by describing three distinct regions with different plasma characteristics.

5.9-5.6 R_J . The plasma observed in this region immediately inward of Io's orbit is characterized by high L-shell densities of warm ions with extensive non-Maxwellian tails to their distribution functions. These non-Maxwellian tails imply the presence of a considerable number of hot ions which, we surmise, have been recently ionized and have not had time to equilibrate. The fact that estimates of plasma bulk speed in this region allow a lag of up to 5% behind rigid corotation is also consistent with considerable local ionization. Further evidence of deviations from thermodynamic equilibrium is the factor of 4-5 difference between the electron and ion temperatures.

5.6-5.3 R_J . At a radial distance of $5.6 R_J$, Voyager 1 moved into a different plasma environment. The sharp boundary is defined by a drop in NL^2 and the disappearance of flux at energy-per-charge greater than ~ 1200 V. The transition takes place between two spectral measurements and is accompanied by a factor of 2 dip in temperature.

Although there are few ions above 1200 V, the spectra have a distinct tail at energies between the main (thermal) population and the cutoff at 1200 V. These non-Maxwellian ion distributions suggest new material was still being ionized locally. Corroborative evidence of local ionization is provided by the 1-3% lag of the bulk speed behind corotation and the presence of molecular, probably SO_2^+ , ions in the vicinity of $5.3 R_J$.

5.3-4.9 R_J . Near $5.3 R_J$ the L-shell density profile steepened. The ion temperature dropped abruptly between 5.4 and $5.2 R_J$ and then continued to decrease until perijove. The plasma bulk velocity stayed close to corotation, and the non-Maxwellian tails of the ion distributions rapidly disappeared. These two facts suggest very little ionization of new material occurs radially inward of $5.3 R_J$. The ion distributions measured in this region are very close to Maxwellian functions and show that the different ionic species shared the same temperature. Such indications of thermodynamic equilibrium are not surprising in the light of the low ion temperatures. In fact, we expect that such a collisional regime would also allow equilibration between electrons and ions.

The differences in plasma conditions observed in these regions and the sharp boundaries between them suggest that the structure of the inner torus cannot be explained in terms of simple models of steady diffusion or steady radial convections. We support the conclusions of Richardson and Siscoe [1983a] that the inner torus must suffer

large temporal variations on a time scale of days and that the cold temperatures observed by Voyager 1 imply a considerable sink of ion energy. We further conclude that, in order to explain the observed molecular ions and the persistence of oxygen ions, there must be a cloud of SO_2 molecules extending radially inward to at least $5.3 R_J$.

Appendix

The diffusive equilibrium distribution of plasma along a magnetic field line is determined by the pressure gradient which balances the centrifugal forces and an ambipolar electric field [Angerami and Thomas, 1964; Hill and Michel, 1976; Bagenal and Sullivan, 1981]. The ambipolar electric field is due to the electrostatic coupling between the highly mobile electrons and the more massive ions which are strongly confined to the centrifugal equator. For small distances, $Z = r \sin \theta$, from the centrifugal equator, the distribution of a single ion species plasma along dipolar field lines can be simplified to an exponential scale height solution

$$n(Z) = n(Z = 0) \exp[-(Z/H)^2]$$

where the scale height (in units of R_J) is given by

$$H = \left[\frac{2 k T_i}{3 m_p \Omega^2} \frac{(1 + Z_i C)^{\frac{1}{2}}}{A_i} \right] \\ = 0.64 \left[\frac{T_i (1 + Z_i C)^{\frac{1}{2}}}{A_i} \right]$$

where k is the Boltzman constant, m_p is the proton mass, Ω is the angular velocity of Jupiter, $C = T_e/T_i$, T_e is the electron temperature, T_i , A_i , and Z_i are the ion temperature, ion mass number, and charge state, respectively.

Strictly, the above formulas are only valid when there is just a single ion species present. The diffusive equilibrium distribution of a multispecies plasma can be determined by solving

$$\frac{n_i(s)}{n_i(s_0)} = \exp - \frac{1}{kT_i} \{m_i[\psi(s) - \psi(s_0)] \\ - Z_i q[\varphi(s) - \varphi(s_0)]\}$$

under the constraint of local charge neutrality

$$\sum_i Z_i n_i = 0$$

where i includes all ionic species plus electrons and $\psi = \Omega^2 \rho^2 / 2$ is the centrifugal potential (ρ is the perpendicular distance from the rotation axis). There are $i + 1$ equations, while the unknowns are the i densities at position s along the field line, $n_i(s)$ plus the electrostatic potential $\varphi(s)$. These equations can be solved iteratively given a set of densities $n_i(s_0)$ temperatures T_i at a reference point, s_0 (e.g., the equator or the spacecraft location) where the electrostatic potential is set to zero.

Acknowledgments. The author would like to thank Ralph McNutt, Margaret Kivelson, David Southwood, Aharon Eviatar, and Stan Cowley for useful discussions and assistance with the manuscript. The work was supported by the U.K. Science and Engineering Research Council.

The editor thanks R. McNutt and another referee for their assistance in evaluating this paper.

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F. Bagenal, The Blackett Laboratory, Imperial College of Science and Technology, Prince Consort Road, London SW7 2BZ, United Kingdom.

(Received March 26, 1984;
revised August 28, 1984;
accepted September 19, 1984.)