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DETECTION OF THE IO PLASMA TORUS BY PIONEER 10

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Abstract. Evidence of corotating ions which appear to be primarily S^{++} and O^{++} has been discovered in data from the Pioneer 10 plasma analyzer, recorded as the spacecraft moved inward from 6.9 to 5.4 R_J during its encounter with Jupiter in 1973. H^+ or He^{++} ions or other light ions are also observed during this time. The Pioneer 10 plasma profile shows a relative variation with radial distance remarkably similar to the Voyager density profile. Both show a well-defined peak falling off steeply toward Jupiter and gradually decreasing away from Jupiter. The Pioneer 10 plasma data are also consistent with a constant temperature plasma for at least 0.5 R_J outside Io's orbit. A radially inward deflection from strict corotation is also evident in our data. Our detailed analysis of the Pioneer 10 plasma instrument's behavior and data in the inner Jovian magnetosphere indicates that the above results are not seriously distorted by radiation background. The previous study of Pioneer 10 data of the inner Jovian magnetosphere (Frank *et al.*, 1976) did not include the particular telemetered values from which our detection of these ions has been inferred.

Introduction

We have recently re-examined the data recorded by the Pioneer 10 plasma analyzers in the inner magnetosphere of Jupiter, and we have discovered a number of significant characteristics which are evidence for a variety of plasma phenomena not reported to date. This note will concentrate on the most spectacular of these new Jovian plasma results, the *in-situ* detection of the Io plasma torus in December 1973. The basis of these results involves analyzing the data from the outer collectors of the plasma analyzer. These collectors view the direction of corotation.

The fact that the Jovian system is variable has been well established on the basis of remote observations of radio, optical and ultra-violet emissions from the inner magnetosphere and Io torus region. However, the only spacecraft to traverse the torus were Pioneer 10 and Voyager 1. Comparison of the Pioneer and Voyager *in-situ* observations can provide very significant insights since the Voyager observations in 1979 were obtained during a period of apparently more activity in the inner magnetosphere (perhaps in association with more volcanic activity on Io) than during the time of the 1973 *in-situ* Pioneer 10 observations. The Pioneer observations were also obtained over a wider range of latitudes in the Jovian magnetosphere.

Observations

The first analysis of the Pioneer 10 plasma probe observations near the Io orbit focused attention on the data from the central sun-oriented collector. Here we study the data from the outer collectors (which could sample corotating plasma), and we show that as Pioneer 10 moved inward past the orbit of Io, plasma currents which were far enhanced over any background were alternately detected on the outermost collectors (collectors 1 and 5) of the medium resolution analyzer as the spacecraft rotated. Figure 1 shows the inbound Pioneer 10 trajectory and indicates the fields of view of the five current collectors in the medium resolution detector (Detector B) of the Pioneer 10 Ames Research Center plasma analyzer. As explained in more detail in Frank *et al.*, 1976, the Pioneer 10 plasma analyzer's five current collectors cover an angular range of ±70° from the centerline of the instrument, the centerline being parallel to the spacecraft's axis of rotation. Figure 1 shows how the trajectory on the inbound pass and the orientation of the spacecraft axis toward the earth combined to bring the corotation direction within the field of view of collectors 1 and 5 by the time Pioneer 10 reached the vicinity of Io's orbit. As each half-spacecraft rotation is divided into 256 equal sectors, and only the readings from the sector with the highest single reading are transmitted, the azimuthal direction of the peak of a distribution that is quite deflected from the centerline is determined by the analyzer within about a degree.

Figure 2 shows a sequence of the ion energy per unit charge E/Q spectra that were obtained from the data on collectors 1 and 5 from 2208 UT (GRT — Ground Received Time) to 2330 UT on December 3, 1973. These spectra are similar to those published previously, for example in association with Pioneer 7 observations of the extended geomagnetic tail (Intriligator *et al.*, 1979). The data from 2208 UT, the first data cycle after an hour-long gap, clearly show a discernable spectrum. The enhanced currents shown in Figure 2 are precisely from the direction expected for corotating ions during the period from 2208 UT (GRT) to 2330 UT on December 3, 1973, over a radial range from 6.9 to 5.4 R_J. The energy spectra show a smooth Maxwellian-like distribution suggesting a single dominant ion species with a temperature of dozens of eV, or several hundred thousand degrees K.

Figure 3 shows two composite spectra near 6.1 R_J obtained by combining the spectra recorded at 2246 and 2251 UT. Curve #1 indicates the composite spectrum from collector 1 obtained by combining the spectra obtained at 2246 and 2251 UT shown in Figure 2. Curve #2 is a similar composite from collector 2 obtained at the same time as curve #1. The spectra obtained at the same time on collectors 5 and 4 are very similar to curves #1 and #2, respectively. Curve #2 shows evidence for another particle population. Comparison of curve #2 with curve #1 shows that the spectrum in curve #2 peaks at roughly half the energy associated with the peak in curve #1. Also, as indicated by the difference in the vertical scales for curves #1 and #2, the peak in curve #2 is much less intense than the peak of the spectrum in curve #1. Collectors 2 and 4 are inner collectors much farther from the expected corotation direction (see Figure 1). The difference in the energy associated with the peak current in the two spectra implies that the particles detected on the inner

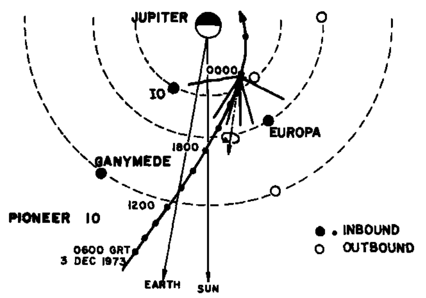

Fig. 1. Projections of the inbound trajectory of Pioneer 10 onto the ecliptic plane during Jupiter encounter in 1973. The projection of the five fans of acceptance of the five current collectors in the medium resolution plasma analyzer (Detector B) is shown. It is clear from this figure that the corotation direction is within the field of view of the outer collectors (collectors 1 and 5) by the time Pioneer 10 reached the orbit of Io inbound.

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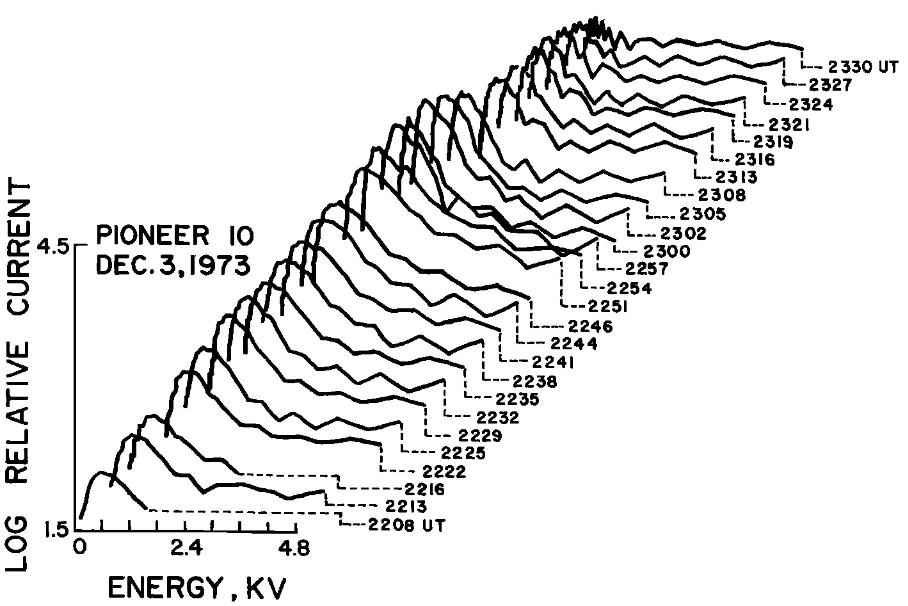

Fig. 2. Ion energy per unit charge (E/Q) spectra measured at Pioneer 10 in the vicinity of Io during the spacecraft's inbound trajectory on December 3, 1973. These spectra were measured on the outer collectors (collectors 1 and 5). These spectra are clear evidence for at least one particle population in this region.

collectors are not merely the outer fringe of the distribution detected on collectors 1 and 5, but a different population — different in mass, charge, temperature, or speed. It appears likely that this distribution is moving in approximately the same direction, but has a lower density than the main population seen on the outer collectors. Thus the main part of this second population probably impinges on collectors 1 and 5 but its signature is buried in the more intense current associated with the first population, and only the outer fringes of the second population appear on collectors 2 and 4. As discussed in the following section, we suggest that the spectrum in curve #1 is due to corotating S^{++} and the spectrum in curve #2 is due to corotating O^{++}.

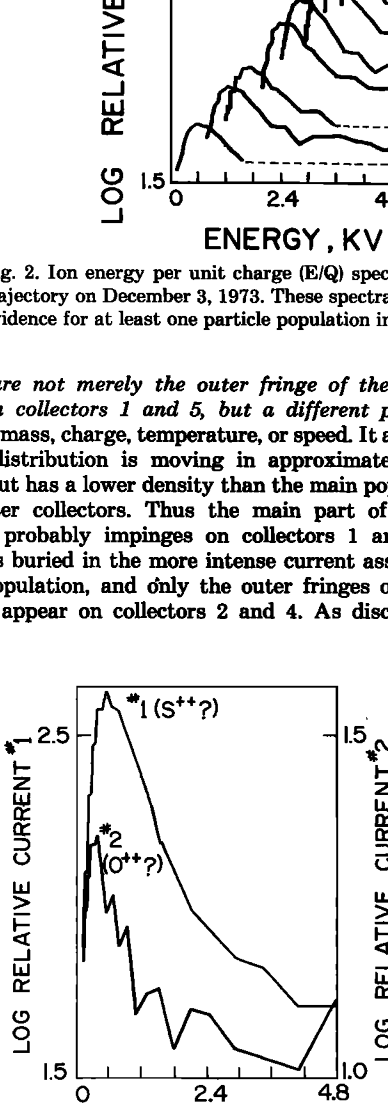

Fig. 3. Ion E/Q spectra obtained near 6.1R_J on December 3, 1973. Curve #1 shows the composite spectrum obtained from collector 1 (an outer collector) by combining the spectra obtained at 2246 and 2251 UT shown in Figure 2. Curve #2 shows the composite spectrum obtained at the same time from collector 2 (an inner collector), with an acceptance fan much farther from the expected corotation direction (see Figure 1). (The spectra obtained at the same time on collectors 5 (outer) and 4 (inner) are very similar to curves #1 and #2, respectively.) A comparison of the spectra in curves #1 and #2 indicates that the spectrum (curve #1) obtained on the outer collector is more intense and peaks at approximately twice the energy of the spectrum (curve #2) obtained on the inner collector. It appears likely that the more intense spectrum (curve #1) is associated with S^{++} and the other spectrum (curve #2) with O^{++} (see Discussion in text).

A close examination of the data provides some indications of additional ion detections. The upper edge of a sufficiently warm distribution of light ions would be above the instrument's energy threshold. There appears to be evidence in a few channels at the lowest energies of a few spectra for the intermittent presence of corotating hydrogen or helium ions or other light ions in the vicinity of the Io torus (e.g. at 5.4, 5.9, and 6.8 R_J). Similarly, some other ion spectra show high energy shoulders or peaks which suggest the presence of some corotating ion or ions with higher E/Q ratios than S^{++}. Finally, there are occasional hints in some spectra of a high energy tail extending to at least 4800 V, the upper limit of the instrument's energy scans. This tail could represent either a low density of even heavier ions or a tenuous hot population of one or more of the ions which we observe in the colder, higher density peaks (shown in the figures above). These more subtle detections appear in several spectra implying that they are not merely the result of random fluctuations in the intensities of the more obvious ions.

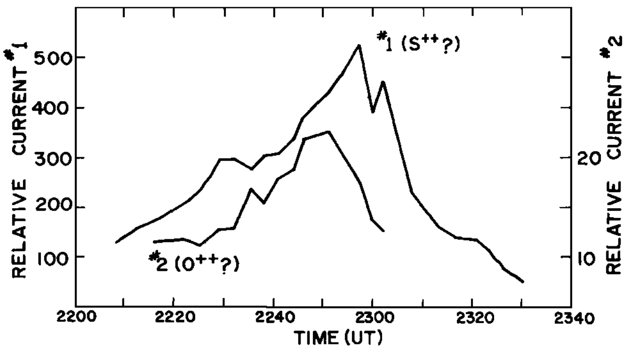

Fig. 4. Radial profiles of the peak ion currents associated with the ion spectra in the vicinity of Io during the Pioneer 10 passage in 1973. These peak ions currents provide a rough estimate of the relative variations of the associated ion densities. Curve #1, therefore, provides a rough estimate of the relative ion density measured on collector 1 which may be associated with M/Q = 16 and, similarly, curve #2 provides a rough indication of the relative ion density measured on collector 2 which may be associated with M/Q = 8. Curves #1 and #2 have linear scales.

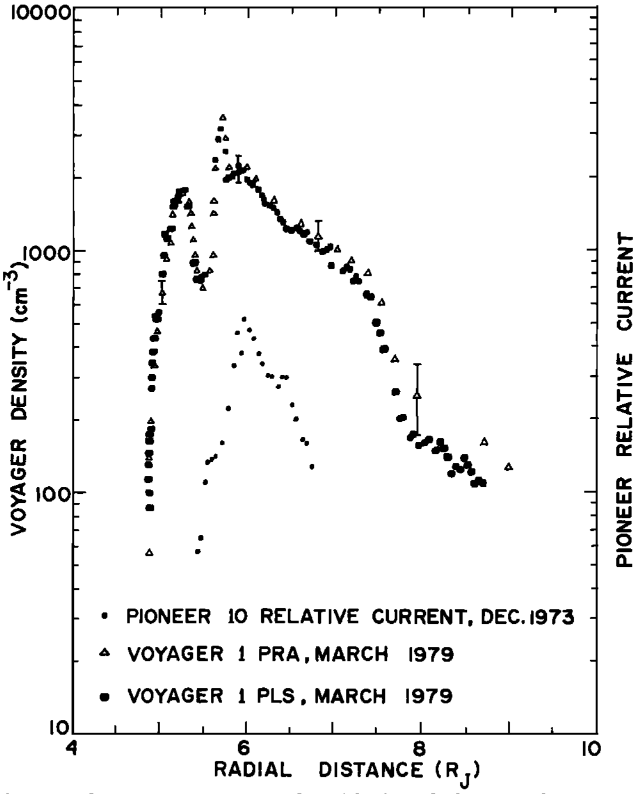

Fig. 5. Relative comparison (on a logarithmic scale) between the Pioneer 10 and Voyager 1 density results (Bagenal and Sullivan, 1981). The Pioneer 10 data are the peak currents shown in curve #1 in Figure 4. The PLS points show the derived ion charge density and the PRA data show the electron density. For clarity we have chosen to vertically separate the Pioneer 10 points from the Voyager points. The exact density values have not yet been determined.

In Figure 4 curves #1 and #2 show the peak current as a function of time of the two particle populations, collector 1 (S^{++}?) and collector 2 (O^{++}?), respectively. These estimates are based on the peak current in each energy cycle when each population is detected unambiguously. These peak currents provide a measure of the relative variations in ion density as a function of time. A comparison of Figures 2 and curve #1 in Figure 4, shows the qualitative effectiveness of this method of obtaining relative ion density estimates.

In Figure 5, we compare the Pioneer 10 peak currents shown in curve #1 in Figure 4, with the Voyager densities derived from the PRA and PLS instruments (Bagenal and Sullivan, 1981) where the PRA densities are electron densities and the PLS densities are their revised ion densities. Figure 5 shows a remarkable resemblance between the Pioneer 10 and the Voyager profiles, with a well-defined peak falling off steeply with decreasing radial distance inside of ~5.7 R_J and dropping off gradually with increasing radial distance outward from this peak. With respect to more quantitative comparisons, we must caution that we do not yet know the exact normalization of the Pioneer 10 data. Since the shape similarity is so great we chose not to draw them superimposed in Figure 5.

Discussion

A. Ion Identification

The energy of the peak currents in these spectra is near the sum of the bulk kinetic energy and the mean thermal energy, so assuming corotation, the spectra in curves #1 and #2 of Figure 3 are consistent with E/Q ratios of 16 and 8, respectively. The plasma analyzer separates particles only by energy-to-charge ratios (E/Q), so that it is not possible to separate particles with the same mass-charge ratio and the same speed, such as corotating S^{++} and O^{+}. Furthermore, the instrument's ability to separate different ion populations closely spaced in E/Q is limited by a combination of instrument resolution, the temperatures of the populations, and the relative abundances of the populations. In view of the Voyager UV reports (Broadfoot *et al.*, 1979; Sandel *et al.*, 1979) of the Io torus, the plausible identifications are S^{++} and O^{+} for E/Q = 16 and O^{++} for E/Q = 8. The lower apparent density of O^{++} relative to S^{++} or O^{+} is consistent with the Voyager (Broadfoot *et al.*, 1979 and Sandel *et al.*, 1979) and ground-based (Brown, 1976, 1978) estimates of the temperature of the Io torus combined with the high (35 eV) ionization energy needed to convert O^{+} to O^{++} (Leighton, 1959).

It is possible, of course, that these peaks represent higher ionization states of heavier elements or molecules. Neither our spectra nor the available Voyager data provide a basis for inferring that large quantities of elements heavier than oxygen and sulfur are present, and the available UV, ion, and electron spectra do not indicate the solar corona-like conditions that would be needed to produce very high states of ionization. Thus it is possible to restrict consideration to a small range of ion species. The following considerations suggest that S^{++} is the dominant ion in these observations.

In polar velocity space coordinates (the natural system for our instrument, which measures flux as a function of energy and two angles) a convected Maxwellian distribution is described by

$$B(v,p,a) = N\left(\frac{m}{2\pi kT}\right)^{3/2} e^{-\frac{m}{2kT}\left[v^2 - 2sv\cos(a + a_0)\cos(p + p_0) + s^2\right]} v^2\cos a \, dv\, dp\, da$$

where B(v,p,a) is the differential flux as a function of particle speed v, and the azimuthal (a) and polar (p) angles of particle motion. Here s is the speed, and a_0, p_0 the direction angles of convection. Evaluating this function gives the width of the distribution at any value below the maximum, in electron volts for the width in energy or in degrees for the angular width. These widths vary inversely with the mass of the particles, and the angular widths also decrease with increasing convection speed. However, as inspection of the formula shows, the angular width does not depend on charge. Therefore, O^{+} and O^{++} distributions of similar temperatures and flow directions would have similar angular extents, whereas an S^{++} distribution under the same conditions would be only about half as wide, measuring the width at, for example, 0.5 of the maximum. If we consider the actual widths of an S distribution and an O distribution at a temperature of 2 x 10^6 K, traveling at 57 km/sec (the speed of corotating ions near Io's L-shell near the magnetic equator relative to the tangential component of the spacecraft velocity) we find widths of 8° and 16°, respectively. Considering that the corotational direction is 12° from the outer edge of the field of view (FOV) and that the outermost detectors extend inward 7.5° from the outer edge of the FOV, it is clear that neither species in any charge state should have been detectable on an inner collector if the motion were strictly corotational. The boundary between the fields of view of the outermost collectors (collectors 1 and 5) and the inner collectors (collectors 2 and 4) for the distribution parameters given above is about 5 standard deviations from the center of a strictly corotating oxygen distribution and 10 standard deviations from the center of a strictly corotating sulfur distribution.

As described above, the actual distribution of the heavy ions is observed only on the outermost collectors, while the lighter ions are observed on the inner collectors. An approximate calculation of possible distributions indicates that, assuming masses of 32 and 16, the observed results can be produced by a ratio of light ions to heavy ones of 2:1, and deflection from corotation of 19° if both species have the same flow direction. Alternatively, a density ratio of 1:1, and a deflection from corotation of 22.5° could produce these results. Thus, the available information does not give a unique determination of the density ratio and deflection, but does indicate that plausible values are consistent with the data.

Our analyses indicate that the departure from corotation results primarily from a radially inward component of motion. The polar component is very slight.

Summarizing the species identification considerations, while the ions with M/Q = 16 could be either S^{++} or O^{+}, the difference in width of the two particle distributions detected indicates that the ions on the outer collectors are genuinely heavier than the ones with M/Q = 8 on the inner collectors. Thus, if the ions on the inner collectors are O^{++}, the ones on the outer collectors are predominately S^{++}. Presumably some O^{+} is present, as implied by the O^{++} ions.

We also note that the region of highest O^{++} density coincides with the region of highest S^{++} density, and both are near the time of crossing of the Io L-shell as calculated from the D3 model of the Jovian magnetosphere (Smith *et al.*, 1975; Kivelson and Winge, 1976).

While we have not presented in detail our light ion detections which might be H^{+} or He^{++} or other ions, we note that they are present intermittently through the Io torus and do not strongly suggest emission from Io.

As illustrated in Figure 5, the radial profile of the estimated relative ion density from our Pioneer 10 plasma analyzer corresponds qualitatively with the densities from the Voyager results (Warwick *et al.*, 1979, Bagenal and Sullivan, 1981). Also, as illustrated in Figure 2 the Pioneer 10 ion spectra appear to be consistent with a relatively constant ion temperature through much of the outer torus at least from ~2222 UT (~6.6 R_J) to ~2251 UT (~6.1 R_J). The Voyager plasma experimenters (Bagenal and Sullivan, 1981) have reported a constant temperature in the outer torus.

B. Instrumental Effects

We have recently analyzed the instrument behavior in detail by careful comparison of the ion data obtained under the most intense radiation (summarized in plate 1 of Frank *et al.*, 1976), the simultaneous electron data (unpublished to date), and the manufacturer's circuit diagrams (also unpublished), so it is now possible to determine that the instrument was not severely affected by radiation in the Io torus.

The peak currents of our spectra detected in the Io torus are some 50 times the apparent background in the Io torus. They are, at least, five times the highest reading from the time of most intense radiation. Also, they are much larger than the currents detected near the orbit of Io on the outbound trajectory, when corotating ions are not in the field of view of the instrument. Currents in these spectra are highly dependent on the energy which the instrument is set to accept, as shown in Figures 2 and 3. This could only occur if a true plasma distribution were entering the instrument aperture. This is unlike the unquestionable radiation effects closer to Jupiter. Therefore, all of our analysis of the Pioneer data and instrumental effects, particularly in light of the subsequent observations of the inner Jovian magnetosphere (Kupo *et al.*, Broadfoot *et al.*, 1979, Bagenal and Sullivan, 1981) leave no doubt that the Pioneer 10 plasma analyzer detected genuine corotating ions.

Frank *et al.*, 1976 focused attention on the data from the center collector (collector 3). We see some evidence of light ions at the lowest energies on collector 3, but all the more obvious heavy ion detections appear on collectors 1,2,4, and 5, as illustrated in Figures 2 and 3. The ion currents we are analyzing are more than five times larger than the highest reading from the time of most intense radiation which was the time interval analyzed by Frank *et al.*

Conclusions

The Pioneer 10 observations presented above demonstrate that the instrumentation was actually surprisingly effective in obtaining information on the heavy ion population in the Jovian magnetosphere. We have shown that the Pioneer 10 plasma analyzer directly detected a broad region of significant plasma density surrounding the orbit of Io. Our analyses indicate that two corotating ion populations are clearly detected over a broad interval. These observations are consistent with identification as S^{++} and O^{++}. Our analyses also imply a raidally inward deflection from strict corotation of these ions. We have found evidence of a relatively constant temperature of the ions between ~6.1 R_J and ~6.6 R_J. We have also found intermittent evidence of corotating H^{+} or He^{++} or other light ions.

The 1973 Pioneer 10 ion observations presented above have numerous qualitative similarities to the Voyager observations in 1979. The shapes of the radial profiles are similar, as shown in Figure 5. The way they both show a rapid decrease toward Jupiter and a slower decrease away from Jupiter suggests that such a density profile may be a persistent feature of Io's plasma torus. However, the Voyager peak is at ~5.7 R_J and the Pioneer 10 peak is at ~6 R_J (2257 UT). The Pioneer 10 and Voyager observations both indicate that the temperature was approximately constant over a wide radial distance.

More quantitative analyses of the Pioneer 10 observations will be published in the future. Quantitative comparisons with the Voyager data should help us understand the differences between conditions in December, 1973 and March, 1979 and may provide increased insight into the large temporal variability (Mekler and Eviatar, 1980) of the plasma content of the Io torus.

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