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Galileo measurements of plasma density in the Io torus

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Abstract. The measurements of electron density made by the Plasma Wave Subsystem instruments on Galileo during its pass through the torus on December 7th, 1995 are compared with a model based on Voyager 1 measurements made in March 1979. Outside Io's orbit, the plasma densities observed by Galileo are approximately a factor of two higher than the Voyager values. Shortly after crossing Io's orbit, the Galileo density profile dropped sharply and remained at low values for the rest of the inbound leg, suggesting that the 'ribbon' region was either absent or much farther from Jupiter than usual. The peak density on the outbound leg is consistent with Voyager-based predictions for the cold torus in both location (5.1 RJ) and magnitude (950 cm-3). Inside 5 RJ the density dropped sharply to less than 3 cm-3.

Introduction

Over the past 20 years the Io plasma torus has been observed remotely from the ground, Earth orbit and the Voyager spacecraft. Remote observations provide a measure of the 3-d structure as well as systematic and temporal variabilities (Thomas, 1993) but plasma parameters have to be deconvolved from emission intensities and spectral characteristics. No Earth-based data were obtained at the time of the Galileo encounter because Jupiter was close to solar conjunction. The two Voyager spacecraft measured EUV emissions from the torus for weeks around the Jupiter encounters in March and July of 1979 (Broadfoot et al., 1979). Voyager 1 made in situ plasma measurements when they flew through the Io torus (Bridge et al., 1979). In situ plasma measurements provide a wealth of detailed information about the velocity distributions of the ions and electrons measured along the spacecraft trajectory but cannot monitor the plasma conditions over space or time.

The net result of these different types of observations is that before Galileo the torus could be characterized as having strongest gradients in the radial direction, split into 3 main regions: the cold inner torus, the warm outer torus, a "ribbon" at the boundary between them, just inside Io's orbit. The cold torus has a peak density of ~1000 cm-3 at ~5.3 RJ, the dominant ion is S^+, the ion and electron temperatures are ~1eV and the emission is essentially all in the optical region of the spectrum. The warm torus has peak densities of ~2000 cm-3 at ~6 RJ, the dominant ions are O^+ and S^{++}, the ion and electron temperatures are ~60eV and ~5eV respectively. The ribbon, so-called because it forms a narrow (0.2 RJ wide), tall (0.5 RJ high) band around Jupiter, has peak densities of ~3000 cm-3 at a radial location which varies between 5.6 and 5.9 RJ. The ribbon straddles the sharp change in composition and plasma temperature between the outer and inner tori. Remote sensing observations of UV emissions suggest little longitudinal variations in the warm torus, but strong dawn-dusk asymmetries (Dessler and Sandel, 1992). Optical observations of the ribbon and cold torus emissions show both local time and longitudinal variations in intensity, radial location and vertical extent (Thomas, 1993; Schneider and Trauger, 1995; Schneider et al., 1997).

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Galileo flew through the Io torus on December 7, 1995. The torus plasma conditions were measured by the particles and fields detectors on the spacecraft (Frank et al., 1996; Garrard et al., 1996; Gurnett et al., 1996; Kivelson et al., 1996; Williams et al., 1996). To compare the electron densities measured by Galileo with those measured by Voyager 1, we first assume longitudinal symmetry and use a model of the torus based on Voyager measurements (Bagenal, 1994) to extrapolate from the Voyager trajectory to the location of Galileo.

Voyager 1 Model of the Io Plasma Torus

Both Galileo and Voyager 1 remained close to the equator and passed Jupiter on the dusk side (Figure 1). When Galileo crossed Io's orbit the spacecraft was close to noon local time while the Voyager 1 inbound crossing of Io's orbit was about 1645 hours local time. Figure 2 shows the Galileo trajectory in centrifugal co-ordinates. For a 9.6° tilted dipole magnetic field, the centrifugal equator is tilted 2/3 x 9.6° = 6.4° from Jupiter's (rotation) equator. Throughout this paper we have used the O4 and O6 magnetic field models (Acuna et al., 1976; Connerney, 1992) which include higher order multipoles. The difference between a tilted dipole and the O4/O6 magnetic field models barely changes the trajectory in Figure 2, but has important consequences for extrapolations in the cold inner region of the torus.

Figure 2 also shows contours of electron density from an empirical model of the torus plasma properties, based on Voyager 1 (Bagenal, 1994). The model combines in situ measurements made along the Voyager 1 trajectory through the torus (electron density and temperature, ion temperatures perpendicular to the magnetic field and composition inside Io's orbit) with EUV Spectrometer measurements in the warm torus. The velocity distributions are all assumed to be Maxwellian and isotropic in the case of electrons. The 'core', thermal ion population is also assumed to be isotropic, while the hot ion population (approximately 10% of the ions) is

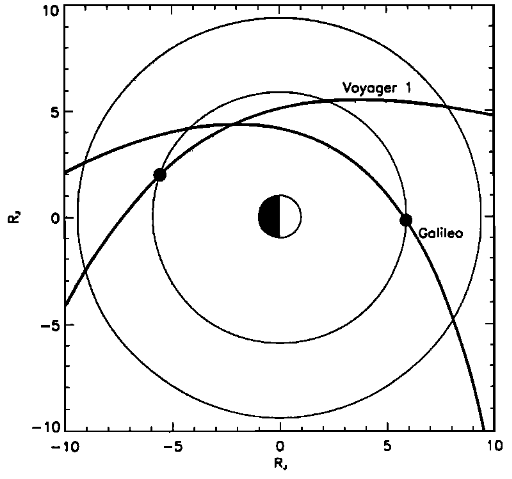

Figure 1. Trajectories of Galileo and Voyager 1 spacecraft through the Io plasma torus, projected onto the equatorial plane. The circles are the orbits of Io (mean distance 5.897 RJ) and Europa (9.4 RJ, where RJ =71492 km.)

assumed to have a thermal anisotropy (A=Tperp/Tpar=5). The plasma conditions at the location of the Voyager 1 spacecraft are extrapolated along magnetic field lines assuming diffusive equilibrium (Bagenal, 1994) that has been modified to allow for variations in the perpendicular temperature with latitude (Huang and Birmingham, 1992; Crary et al. 1996).

The closest approach of the Voyager 1 spacecraft was 4.88 RJ. To predict densities along the Galileo trajectory which reached 4.0 RJ, we have extrapolated the Voyager 1 density and temperature profiles inwards. Furthermore, the cold temperatures in the inner torus produce small scaleheights so that any extrapolations along the field are very sensitive to inaccuracies in the magnetic field models. Therefore, densities predicted from the model inside ~5 RJ are not reliable.

Local Electron Density Derived from PWS

The PWS instrument obtained data in the torus region from 7.7 to 5.4 RJ (1521 to 1825 hours) inbound and from 4.3 to 5.3 RJ (2322 to 0113) outbound on December 7/8, 1995 (Gurnett et al., 1996). The Galileo PWS observations obtained on the inbound trajectory show a distinct narrow band of emission at the local electron upper hybrid frequency, $F_{UH} = (F_p^2 + F_c^2)^{1/2}$, where the cyclotron frequency, F_c= 28 B (Hz), can be estimated from the local magnetic field (B in nanoteslas) and the plasma frequency, F_p=8980 $(N_e)^{1/2}$, allows a determination of the local density, N_e (in cm^{-3}). This is a commonly used diagnostic of electron density and the same method as used by Warwick et al. (1979) for the Voyager 1 passage through the torus and by Stone et al. (1992) along the Ulysses trajectory. Galileo PWS measurements are obtained every 18.67 seconds. The uncertainty in the location of the emission is governed by the 5% frequency resolution of the instrument. The step-like character of the data is due to quantization in frequency. On the outbound leg a distinct band of emission was only detected in the high density region of the cold torus. Elsewhere the densities are based on a low frequency cutoff of free space electromagnetic radiation and therefore allows only an upper limit to be placed on the local density. The cutoff is assumed to correspond to the plasma frequency either at the source or near the spacecraft.

Figure 3 shows the PWS and model electron densities plotted as a function of radial distance from Jupiter (where 1 RJ =71492 km). The sharp spike is the enhanced density detected when Galileo passed within 900 km of Io (Gurnett et al., 1996). Similar values were measured by the Galileo PLS instrument (Frank et al., 1996). Also shown in Figure 3 are densities predicted by extrapolating the Voyager-based model to the Galileo location different magnetic field models. Outside Io's orbit (5.876 RJ at the time of the Galileo flyby), the density is substantially enhanced above the values from the Voyager-based models. At 6 RJ the measured density is 3775 cm^{-3} compared with model values of ~2500 cm^{-3} (i.e. enhanced

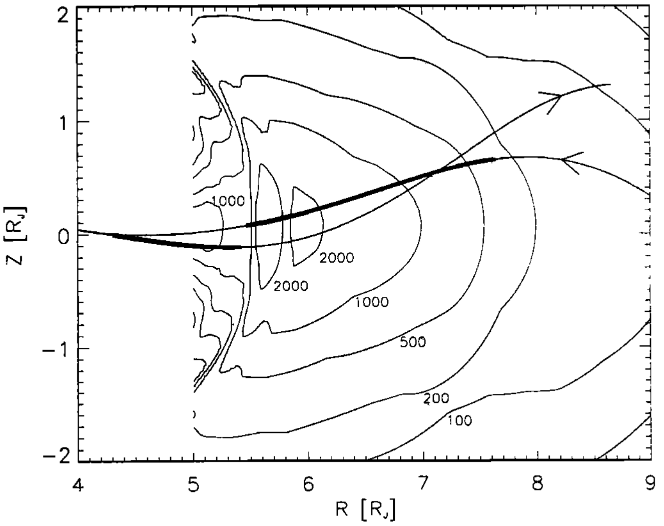

Figure 2. Electron density contours from the Voyager-based model (Bagenal, 1994) in centrifugal co-ordinates based on the O4 magnetic field model of Acuna et al., 1976. The trajectory of the Galileo spacecraft is shown, the thicker lines indicating the locations in which density measurements were obtained.

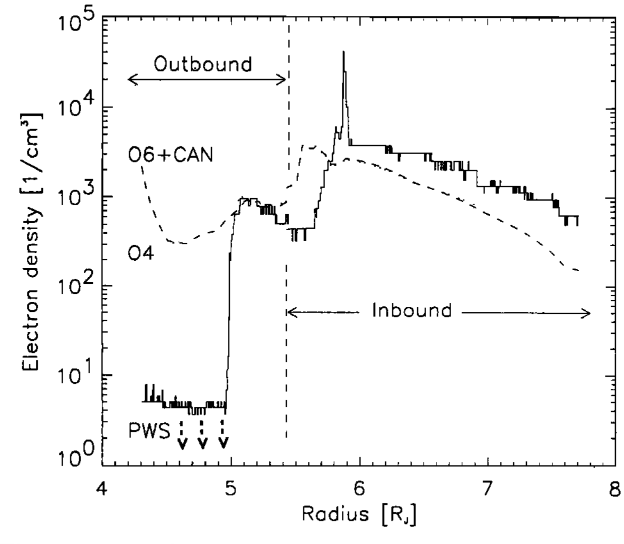

Figure 3. Radial profiles of the electron density measured by Galileo (solid) and predicted from the Voyager-based model using the O4 (dotted) and O6 plus current sheet (dashed) magnetic field models.

by a factor of 1.5). At 7.7. RJ the measured density was 628 cm^{-3} compared with predictions of 155-172 cm^{-3} (factor 3.6). The sharp spike in the density profile (40,766 cm^{-3}) is in Io wake. Inside Io's orbit there is a sharp drop in density by an order of magnitude from over 4000 cm to ~400 cm^{-3} in a distance of only 0.15 RJ. This is just where we would expect the highest densities of the ribbon region to be found, as shown by the models. The data from the outbound leg show a local density peak at 5.1 RJ in the cold torus which closely matches the model. Not expected is the very sharp drop to low densities of only 2-3 cm^{-3} inside 5 RJ. These deviations from the Voyager-based model are discussed below.

Discussion

If we first assume that the composition and temperature of the plasma in the torus remained the same as seen by Voyager, a factor of 2 increase in density of the outer torus should lead to a fourfold increase in EUV emissions. The Galileo EUV, however, measured emissions a few days before the first Ganymede encounter that were comparable to those seen by Voyager 1. Because these emissions are very sensitive to the electron temperature, the expected fourfold increase in emission could be offset by a 30% reduction in electron temperature from 5 eV (58,000 K) to about 3.5 eV (41,000 K). The spectral character of the EUV emissions seen by Galileo is consistent with such a decrease (Hord et al., 1995). Alternatively, the ions could be colder during the Galileo passage through the torus so that the vertical scaleheight would be reduced, increasing the density at the equator. However, the Galileo PLS measurement of ion temperature just outside Io's orbit was 101 eV, comparable to the Voyager value, indicating the scaleheight should be the same.

Figure 4 shows the radial profile close to Io's orbit to illustrate the missing ribbon region more clearly. At the time of the Galileo flyby Io was at a radial distance of 5.876 RJ. Because both Voyager and Galileo were close to the centrifugal equator, there is little difference between predictions using different magnetic field models. Even if the ribbon were much colder and the scaleheight reduced, it is unlikely that Galileo passed above or below the ribbon. Longitudinal variations in torus emission have been reported by many ground based observers. Most recently, Schneider et al. (1997) show (their Figure 2) the variations in intensity of emission from S$^+$ ions in the ribbon region with System III longitude. Assuming a constant mixing ratio of S$^+$ ions, the observed factor of 3 variation in intensity corresponds to a factor of 1.7 variation in density. Comparing the longitude of Galileo (270°) with that of Voyager 1 (200°), one would only expect a factor of 1.4 lower intensity and corresponding to a factor 1.2 lower density at Galileo. The density measured by Galileo was a factor of 8 lower than the Voyager predictions so that longitude alone cannot explain the difference.

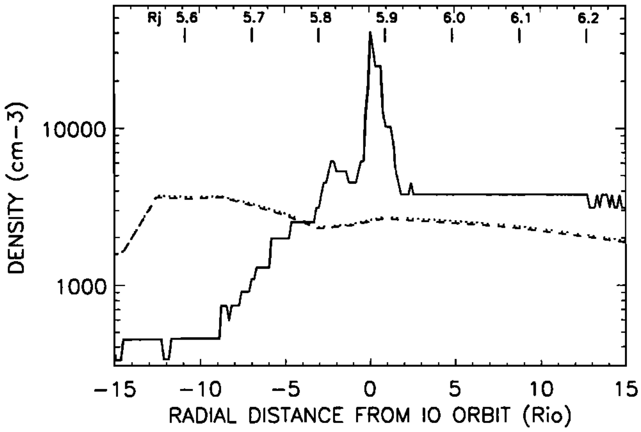

Figure 4. Density as a function of radial distance from the orbit of Io (5.897 RJ) in units of Io radii (1820 km).

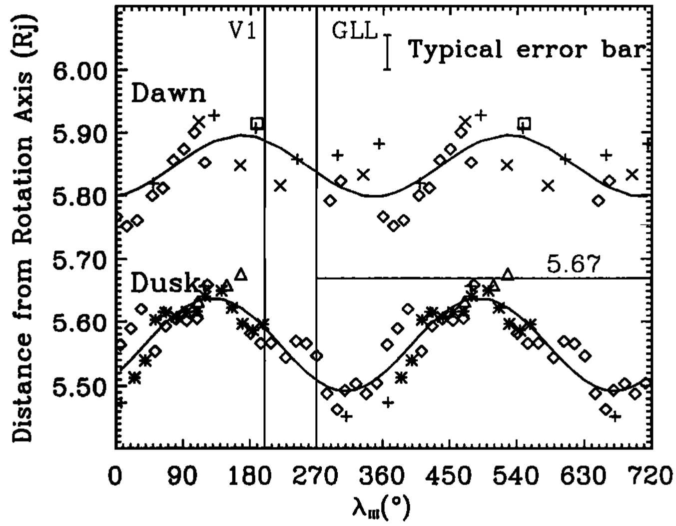

Figure 5. The expected radial distance of the ribbon region of the torus vs. longitude. The longitudes of Galileo and Voyager 1 when they crossed Io's orbit on their inbound trajectories are shown by vertical lines. Adapted from Schneider and Trauger (1995).

Local time variations in the location of the ribbon have been reported by Sandel and Dessler (1992) for UV emission and by Schneider and Trauger (1995) for optical emission from S$^+$ ions. The two papers report that the ribbon is farther from Jupiter on the dawn side of Jupiter than the dusk side and that there is a longitudinal modulation of the location. Sandel and Dessler (1992) report longitudinal variations a factor of 2 larger in amplitude. Figure 5 (adapted from Schneider and Trauger, 1995) shows how the radial distance of the ribbon varies with longitude for the dawn and dusk ansas. Voyager 1 was 1645 hours when it crossed Io's orbit while Galileo was close to noon. The Voyager 1 observation of the ribbon between 5.6 and 5.7 RJ matches the Schneider and Trauger (1995) prediction of the ribbon moving in towards 5.6 RJ on the dusk side of Jupiter. Assuming that the noon location of the ribbon should be roughly mid way between the dawn and dusk locations, Galileo should have crossed the ribbon at 5.67 RJ.

With the missing ribbon being inconsistent with known longitudinal and local time variations, there remain two possibilities: the ribbon was located closer to Io's orbit distance or was entirely absent at the time of the Galileo flyby. Figure 4 shows that while the secondary spike at 5.81 RJ is narrower than the usual 0.2 RJ width of the ribbon, it may in fact be the ribbon. At the same time, this density enhancement is only 2 RIO away from Io's orbit (3.3 RIO away from Io itself) and hence may be part of the Io wake.

Furthermore, if this is the 'usual' location of the ribbon, then the 0.14 RJ displacement towards noon is not consistent with the dawn-dusk electric field due to plasma flows down the magnetotail that has been invoked to explain asymmetries in the torus radiation. While we regard temporal variability as the explanation of last resort, it should be pointed out that if Herbert (1996) is correct in suggesting that the ribbon is caused by energetic particle impoundment of outward transport of the torus plasma, then the missing ribbon would imply that the radial gradients in particle pressure should have been considerably reduced during the Galileo flyby.

Figure 3 shows that while the model density was matched at 5.1 RJ, the density measured inside the cold density peak changed by a factor of 100 within 0.05 RJ. If this is a scaleheight effect, it means the spacecraft moved over 4 scaleheights. Since the cold temperatures (<1eV) in the inner torus result in very small scale heights (0.13 RJ), model predictions are very sensitive to knowledge of the location of the spacecraft relative to the centrifugal equator. This effect is illustrated by the differences between predictions based on different magnetic field models inside 5 RJ. Furthermore, Schneider and Trauger (1995) show significant deviations of the centrifugal equator (measured from images) from each of these magnetic field models and a vertical displacement of the cold torus with respect to the ribbon. Nevertheless, even if the centrifugal equator is more warped than suggested by the O4/O6 models, it is hard to see how such an abrupt change in density could be produced. We therefore conclude that Galileo observed a truncation of the cold torus inside 5 RJ.

Conclusions

From examination of the electron density measurements alone, the Io plasma torus observed by Galileo in December, 1995 appears to be very different from the torus observed by Voyager 1 in March 1979 and from ground based studies.

1. The densities observed by Galileo were enhanced by approximately a factor 2 between 7.8 and 5.9 RJ. For this higher density to produce similar UV emission intensities, the torus electrons must be cooler.

2. The densest part of the Io torus, the ribbon region, that normally separates the warm outer torus from the cold inner torus appears to be missing or displaced outwards to Io's orbit (where it would have been hidden in the Io wake signature). The missing ribbon cannot be explained by previously detected variations in latitude, longitude or local time.

3. The peak density in the cold torus was observed to be at the magnitude and location predicted by the Voyager based models. Inside the cold torus Galileo detected a factor 100 decrease in density within a radial distance of 0.05 RJ. While some of this change may be due to the spacecraft moving relative to a warped centrifugal equator, it is probable that the cold torus was truncated inside 5 RJ with densities dropping to less than 3 cm-3.

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