

On the formation of Io's inner torus

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Abstract

In December 1995 and November 2002, the Galileo spacecraft traversed the inner Io plasma torus on the J0 and A34 passes, respectively. Observations of electron density showed a steep drop off at the inner boundary located between $4.5R_J$ and $5R_J$ on the two passes, and a much more gradual decrease in the outer torus. The [Wang, Y.-L., Russell, C.T., Raeder, J. The Io mass loading disk: model calculations. *Journal of Geophysical Research* 106, 26243–26260, 2001] model of torus formation considers multiple ionization and neutralization stages for the pickup ions, and predicts an inner torus boundary location which depends on the local plasma velocity at Io. For an inner torus boundary at $\sim 4.7R_J$, ions are picked up into a plasma flowing at ~ 37 km/s (74 km/s is the corotation velocity at $5.9R_J$). The steepness of the boundary and the double peaked density structure seen on the two Galileo passes is not reproduced by the [Wang, Y.-L., Russell, C.T., Raeder, J. The Io mass loading disk: model calculations. *Journal of Geophysical Research* 106, 26243–26260, 2001] model, which considers the source of mass loading at Io to be uniformly distributed around the moon and does not include outward radial convection. Adding this convection to the model, as would be required to maintain a steady state magnetodisk, steepens the inner torus boundary, but does so over very long timescales. The different inner torus density structure observed on the J0 and A34 passes is not reproduced by either the [Wang, Y.-L., Russell, C.T., Raeder, J. The Io mass loading disk: model calculations. *Journal of Geophysical Research* 106, 26243–26260, 2001] or outward radial convection models and indicates the possible occurrence of a large mass loading event in the 7 years between the passes or longitudinal asymmetry in the torus structure.

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1. Introduction

Observations of sulfur monoxide and sulfur dioxide ion cyclotron waves by the Galileo spacecraft at distances as far as $\sim 20R_{Io}$ from Io indicates that ions originating in Io's atmosphere are picked up and transported far from the moon. In order for the iogenic ions to attain such distances, Wang et al. (2001) considered a multistep acceleration and transport process. First, ions are picked up at Io and accelerated in the corotation electric field; second, they are neutralized

via charge exchange and travel across field lines; third, they are reionized and join the corotating plasma where they would then emit ion cyclotron waves as be detected by Galileo. The model produces the ion distribution shown in Fig. 1 with an inner torus boundary at $\sim 3.5R_J$. This inner boundary location is inconsistent with that seen on the Galileo J0 and A34 passes (Fig. 2), where it was observed between $4.5R_J$ and $5R_J$. In addition, the model does not reproduce the observed steepness of the boundary, nor the double peaked density structure.

Altering the pickup conditions in the Wang et al. (2001) model such that ions are initially picked up into local plasma flows moving at subcorotational speeds

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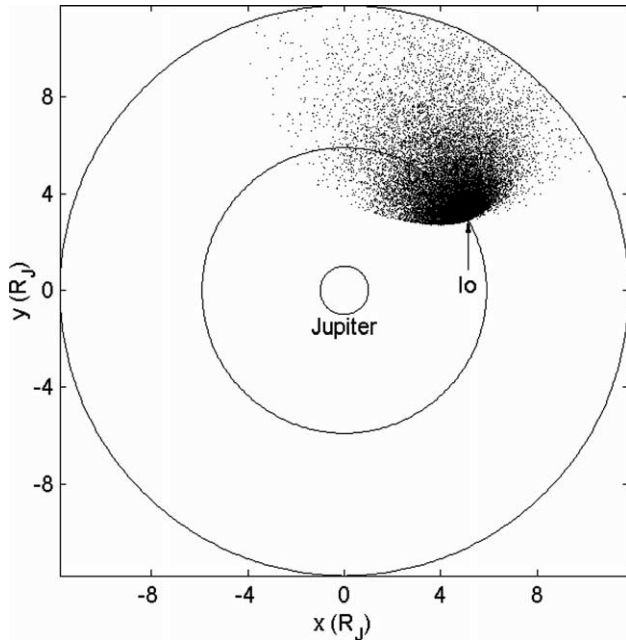


Fig. 1. Steady state ion distribution produced by the Wang et al. (2001) model, $t = 3.48$ h. The model uses sulfur monoxide ions launched from 300 km altitude above Io uniformly around the moon. Ions are permitted to travel 20 km back toward the moon (absorption region depth).

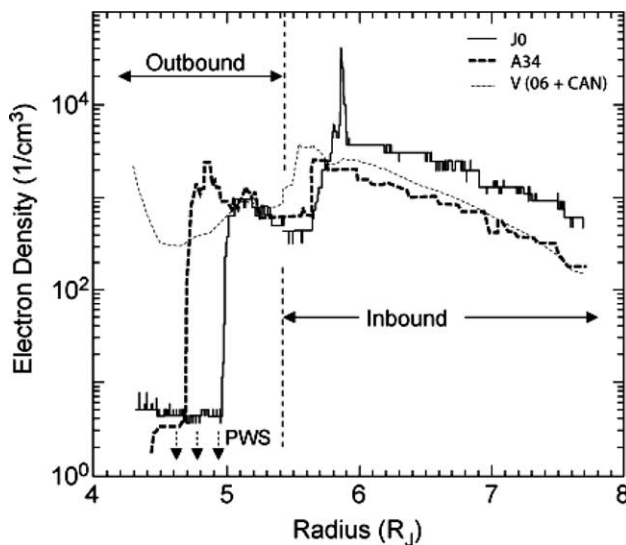


Fig. 2. Radial density profiles inferred from measurements taken by the Galileo (J0 and A34) and Voyager. Voyager measurements in the inner torus are unreliable due to low count rates. Adapted from Bagenal et al. (1997), A34 data courtesy D.A. Gurnett.

affects the location of the inner boundary (Cowee et al., *in press*). Ions picked up into decelerated flow fields will not be accelerated as much as if they had been picked up into a corotating flow. They will therefore have lower velocities when they become neutrals and will not move in as close to Jupiter. For inner torus boundaries located at $\sim 4.7R_J$ and $5R_J$, consistent with the A34 and J0

passes, the local plasma velocity is slowed from the corotational value of 74–37 and 12 km/s, respectively.

Including slow outward convection of ions is sufficient to steepen the inner torus boundary (Cowee et al., *in press*), however the convective velocities are so small that it requires thousands of years. The inward movement of the inner torus boundary from $\sim 5R_J$ to $\sim 4.7R_J$ in the 7 years between the J0 and A34 passes cannot be the result of outward convection. It is possible that a large mass loading event occurring in the 7 years between the two passes added a substantial amount of mass to the inner torus, filling in the region between $4.7R_J$ and $5R_J$. If the mass is added in the form consistent with the Wang et al. (2001) model, then boundary steepening would have to occur on a much shorter time-scale than thousands of years. Cataclysmic mass loading events would need to either add mass in such a way that ions stack up at the inner torus boundary, or there are other transport processes at work which act on much shorter timescales than the outward convection that maintains a steady-state magnetodisk. It is also possible that the inner torus is longitudinally asymmetric, such that the inner boundary and the density peaks lie at different radial distances in the different parts of the torus. In this paper we examine the possible causes for the apparent inward motion of the inner torus boundary observed during the Galileo mission.

2. Inner torus boundary location and gradient

Ion pickup into a decelerated local plasma flow at Io using the Wang et al. (2001) model produces torus distributions which peak at Io and decrease gradually away from the moon (Fig. 3). Using the steady state radial distributions for 20 km/s pickup velocity, we modeled the movement of ions due to outward radial convection. It is possible to reproduce a steep inner torus boundary as is consistent with the A34 pass in this way (Fig. 4). With small enough radial convection velocities in the inner torus, the ions build up sufficiently over time, however they neither reproduce the density peak seen at the inner boundary nor inward displacement of the peak near Io.

Is it possible for other variables used in the Wang et al. (2001) model to affect the radial distribution of the picked up ions? In the original paper, Wang et al. (2001) explored various lifetimes for each of the ionization and neutralization stages, showing the effects on the overall ion distribution. For long enough neutral lifetimes, the ions will build up at the inner boundary, as shown in Fig. 5. However, the radial profile of these long-lived ions still does not agree with the observed density profiles, since the buildup occurs relatively uniformly across the entire torus.

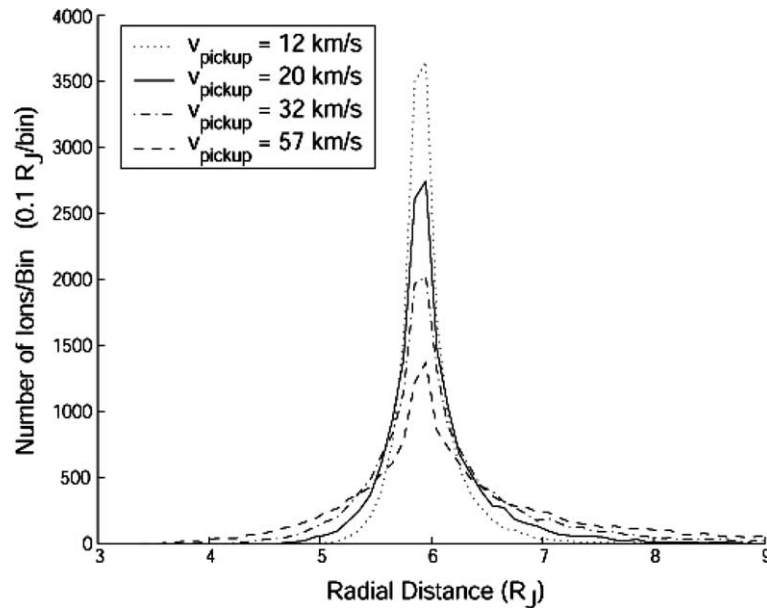


Fig. 3. Steady state radial densities produced by the Wang et al. (2001) model for various ion pickup velocities at Io. A pickup velocity is of 57 km/s means the ions are added into a local plasma flowing at the corotation speed at Io's orbital distance. Pickup velocities less than 57 km/s indicate the ion is picked up into a subcorotating plasma flow. As the pickup velocity decreases, ions will gain less energy and will not move as far away from Io.

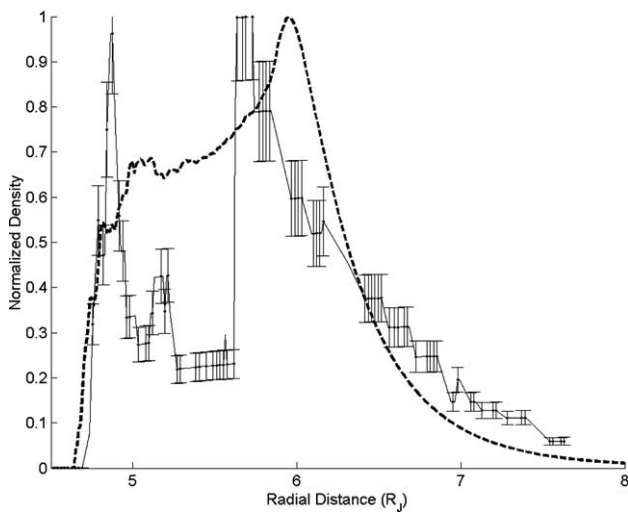


Fig. 4. Comparison of the model results for outward radial convection of ions in result F (thick dashed line) to the Galileo A34 pass inferred electron densities (thin solid line, with error bars). The convection model computes movement only in the radial direction, so results indicate radial sums of the ions in two-dimensions. Modeled densities must therefore be divided by the radial distance to reduce them to one dimension, for comparison with observations. This does not alter the modeled densities significantly, but it is a correction from Cowee et al. in submission JGR.

Cowee et al. (2003) considered the effect of single point sources of mass loading on Io, as would be consistent with a single volcano adding a substantial amount of mass to the torus. Because Io is tidally locked to Jupiter and therefore fixed in the electric and magnetic field geometry, ions released at certain longitudes on Io form distributions very different from that produced by uni-

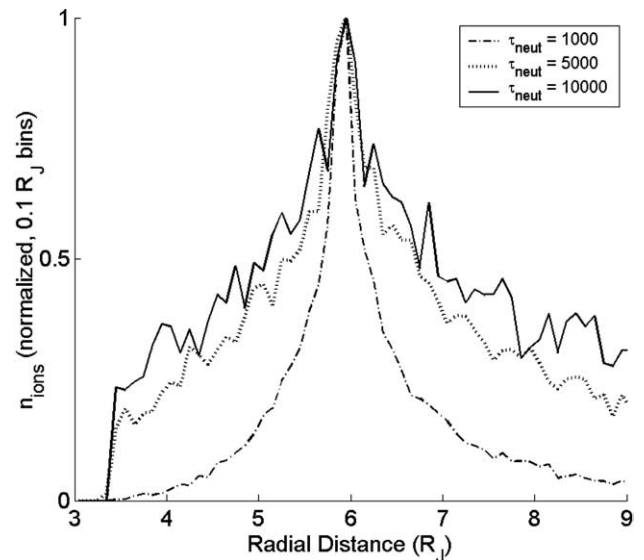


Fig. 5. Steady state radial density profiles of distributions produced by the Wang et al. (2001) model for varying neutral stage characteristic lifetimes (in units of SO^+ gyroperiod, 1.6 s) at $t = 3.48$ h. In the model, the ions have three stages: initial ion, neutral, and final ion. Each stage has a characteristic lifetime, τ , with $\tau_{\text{ion1}} = 20$ gyroperiods and $\tau_{\text{ion2}} = 500$ gyroperiods.

form mass loading at all longitudes. Fig. 6 shows the distribution and radial profile of ions released at 170° longitudes on Io. While the radial profile is clearly steep, it is very unlikely that, over the long term, a single volcano is responsible for mass loading the entire torus. Still, over the short term, single volcanoes could be responsible for directing material into either the inner or outer torus, or both. Fig. 7 shows how ions can be

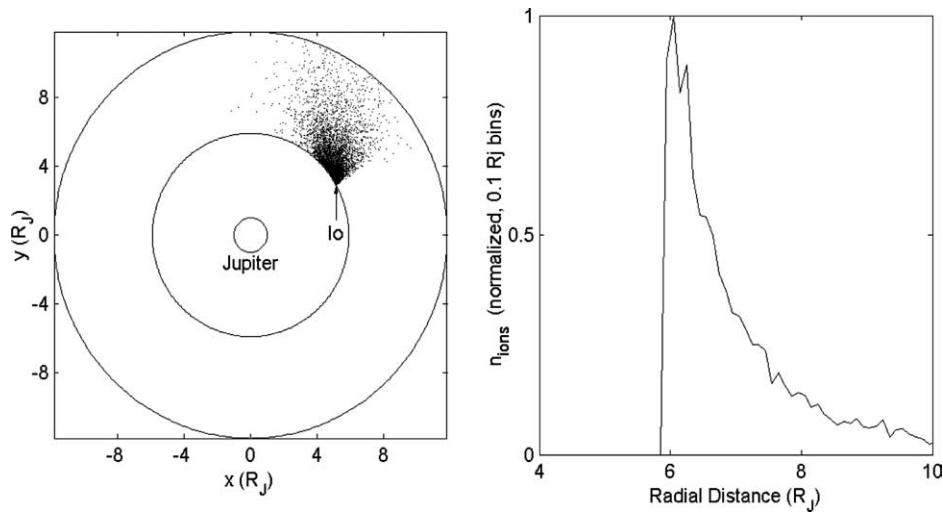


Fig. 6. Steady state ion distribution produced by the Wang et al. (2001) model for a single point source of mass loading at 170° longitude on Io (Cowee et al., 2003) and its radial density profile. Ions are launched from 300 km altitude, with a 20-km absorption region depth.

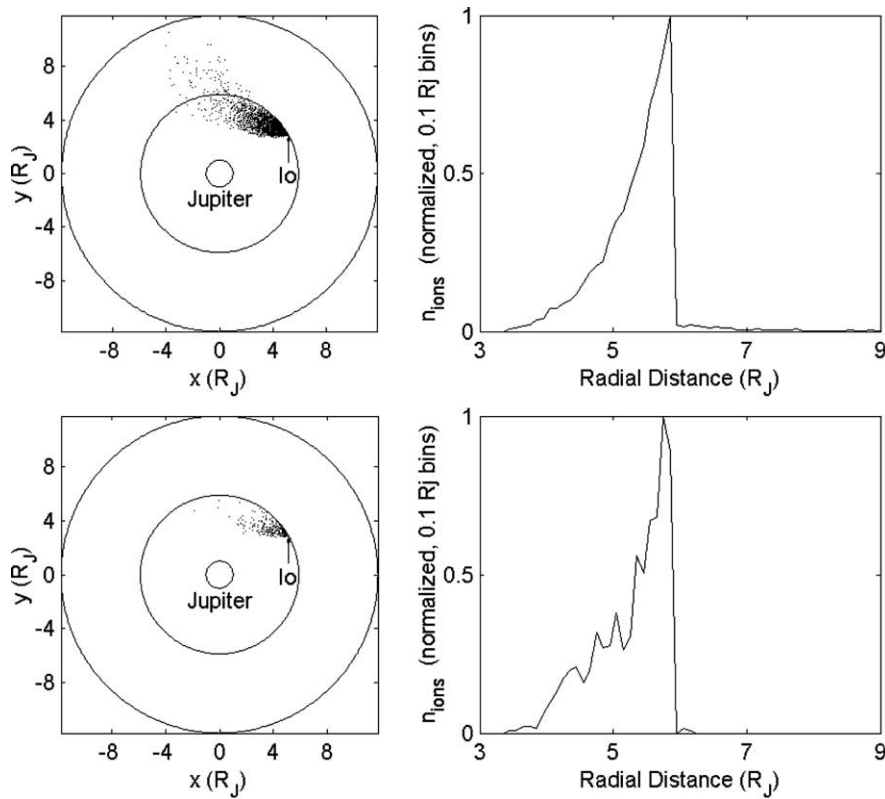


Fig. 7. Modeled steady state ion radial profiles for various point sources of mass loading on the upstream, Jupiter-facing side of Io. Sources are at 55° (top) and 65° (bottom) Io longitude. These point sources could represent single volcanoes whose eruptions add mass primarily to the inner torus. In the model, ions are launched from 600 km altitude, with a 300-km absorption region depth.

added primarily to the inner torus, with sources on the upstream, Jupiter-facing side of the moon. Thus, it is possible that over the short term the inner torus could have been favored over the outer torus.

Ions picked up from this region of the moon see an electric and magnetic field geometry which often causes

them to collide with the moon and be lost from the simulation. If they become neutrals when their current gyro-trajectory is directed back toward Io or will intersect the base of the absorption region defined in the model, the ion will be lost. As such, the height of the exobase where the ions are released and the depth of

the absorption region are important parameters which can determine how many ions will make it out into the torus. In addition, the lifetime of the initially picked up ion is important as well; if reneutralization occurs within the first half of a gyroperiod, all ions will be lost. In the model, the ions must live to at least this amount of time to have a chance of remaining in the torus.

3. Cataclysmic mass loading event

It is possible that the observed double peaked density structure at Io results from: (1) a constant source of mass added at Io, with ions remaining close to the moon and peaking just inside $5.9R_J$ and (2) a large mass loading event which fills the inner torus. If the ions fill the inner torus uniformly, then some transport mechanism must “scoop” them out to form the two peaks. The Wang et al. (2001) model cannot be modified to produce this double peaked density structure because modeled distributions are always peaked only at $5.9R_J$ and ions are added uniformly across the radial extent of the torus. While it can produce the constant near Io peak, it cannot produce a cataclysmic mass loading event which would add mass to the inner torus boundary area only.

Hypothetically, if mass loading sources could produce a density structure with a peak and steep inner boundary at Io and at $\sim 4.7R_J$ in the inner torus the overall structure would look like that in Fig. 8. To obtain the model results in this figure, the radial profile produced by the point source at 170° longitude on Io is used in the outward convection model. During the simulation, a similar radial

profile is added to the inner torus (at higher density) over a finite interval to simulate a significant mass loading event. The physical mechanism for the addition of mass in the inner torus that produces a strong peak at $\sim 4.7R_J$ is not modeled, and is specifically tailored by the authors; however a cataclysmic event is likely to occur due to the activity of an individual volcano on Io. Convection continues to act as the simulation progresses and will move ions out of the region between the two peaks. An already steep density profile in the inner torus is chosen because outward radial convection cannot steepen the boundary over small timescales.

4. Longitudinally asymmetric torus

Asymmetry in the Io plasma torus brightness was first identified by Sandel and Broadfoot (1982), and called the “east–west effect” because the dusk side of the torus is brighter (and hotter) than the dawn side. This is generally attributed to the effects of a dawn–dusk magnetospheric electric field. If the torus exhibits local time asymmetries, does it also exhibit longitudinal asymmetries which could explain the changing location of the inner torus boundary? Dessler and Sandel (1992) examined the location of the brightest regions of the torus in [SIII] 685 Å as a function of dawn–dusk location and system III longitude (λ_{III}) and Schneider and Trauger (1995) used observations [SII] 673.1 nm emissions with models to predict the location of the Io torus “ribbon,” a feature observed in both the density and temperature structure of the torus. Bagenal et al. (1997) compared the Voyager 1

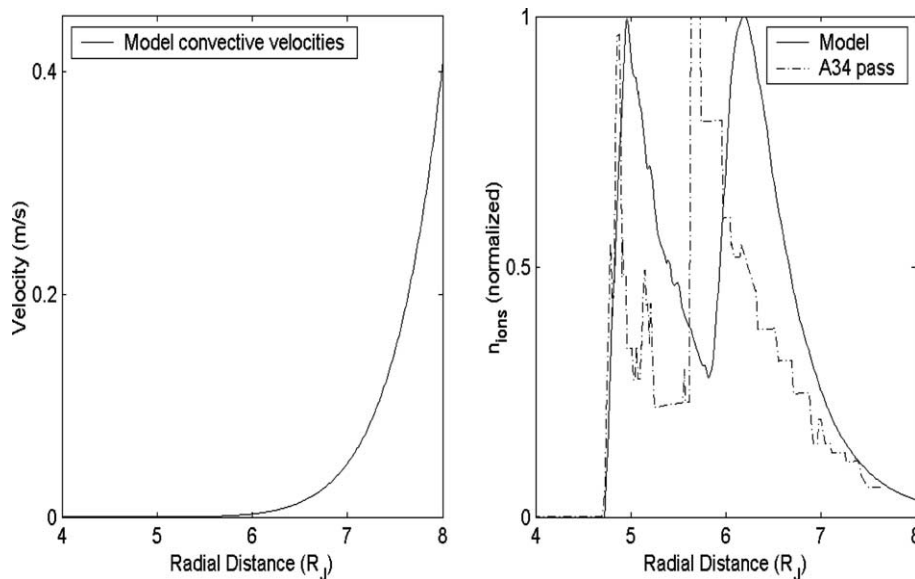


Fig. 8. Hypothetical double peaked density structure produced by a large mass loading event compared to the A34 pass (right). Here the model is tailored to include a constant source of mass loading at Io producing the near Io peak and a source which produces another peak at $4.7R_J$ over a short timescale. The mechanism which adds mass to the inner torus to produce a second peak is not specified in the model, and the radial profile from Fig. 6 is used. Outward convection acts in the model with the velocity profile shown (left). The modeled densities are displayed shortly after the transient mass loading event and will change over long time periods due to convection.

and Galileo J0 density observations to Schneider and Trauger's (1995) results and while they saw a correlation with Voyager results, the J0 (inbound) pass was not as easily interpretable. The "ribbon" was not detected where Schneider and Trauger (1995) predicted, and the authors proposed it was possible that it had either not been detected or was not in existence during the J0 pass.

Dessler and Sandel (1992) saw an average offset of $0.38R_J$ between the nearest and furthest torus ansae locations, with the ansa on the dusk side closer to Jupiter than on the dawn side, and closest at $\sim 300^\circ \lambda_{III}$. If the location of maximum brightness at 685 Å is a proxy of local density structure then could possibly indicate relative changes in the whole-torus density structure and inner torus boundary location, if they are all assumed to be connected. When Galileo passed the orbit of Io on the J0 (outbound) and A34 passes, it was located at approximately 1200 LT and $87^\circ \lambda_{III}$ and 1900 LT and $84^\circ \lambda_{III}$, respectively. Given these values, and assuming that at a given longitude at noon local time, the torus would be located midway between its predicted locations at dusk and dawn, the torus is further away from Jupiter on the J0 than the A34 pass (Figure 1 from Dessler and Sandel, 1992). Also, using the longitudes and local times of the inner torus boundary crossings rather than the Io orbit crossings for the two passes shows the same result. (During the J0 pass inner torus boundary crossing at $\sim 5R_J$ the spacecraft was outbound at approximately 1300 LT and $40^\circ \lambda_{III}$ and during the A34 pass at $\sim 4.7R_J$ the it was at approximately 1900 LT and $115^\circ \lambda_{III}$.) This is consistent with observations showing the inner torus boundary located closest to Jupiter on the A34 pass. It suggests that the density structure of the torus is approximately similarly shaped at all longitudes around Jupiter, but that particular density features can lie at different radial distances.

Nozawa et al. (2004) also looking at [SII] emissions over longer time periods saw a position difference of the ribbon between the dawn and dusk ansae of about $0.2R_J$. In addition, the authors identified system III periodicities (9.2 h rotation period) only over short periods of time; in the long term, they saw periodicities better correlated with the 10.2-h rotation period of system IV. They concluded that both long and short term variations are due to volcanic activity on Io and that in recent years (1997–2000) there has been a decrease in volcanism. Variations in the plasma torus structure were observed primarily in the ribbon region, and they suggest that an inner peak seen in the radial emission intensity profile could be due to a decrease in the density of the ribbon.

5. Conclusion

The density structure of the inner Io plasma torus shows a complexity not yet elucidated by models.

Although variations of the Wang et al. (2001) model show that the inner torus boundary location can be controlled by pickup conditions at Io, and that the steepness of the inner torus boundary can be reproduced by slow outward radial convection (Cowee et al., in press), the existence of a density peak at the inner boundary is unexplained. Indeed, the hypothetical construction of such a peak in the model indicates that if it is produced by a large mass loading event, then the inner boundary steepness is likely not due to outward convection which acts over too long of a timescale. Either ions mass load in such a way that steepness is naturally produced or that unknown transport processes act quickly at the inner boundary. A simpler explanation may be that the changes observed in the density structure between the J0 and A34 passes may be spatial rather than temporal. If the torus is closer to Jupiter at certain longitudes and local times or exhibits more complicated dynamic behavior, then the radial locations of the density features may not be direct indicators of changes in mass loading rates at Io.

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