# The Response of Jupiter's Magnetosphere to an Outburst on Io

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## Abstract

Loss of material from the satellite Io provides the major source of material for Jupiter's magnetosphere; bombardment by particles in Jupiter's magnetosphere is the major cause of loss of material from Io. Though this basic outline is clear, the tightly coupled interaction between Io and Jupiter's magnetosphere has long resisted understanding. We have conducted a six-month-long campaign of intensive monitoring of the Io plasma torus and neutral sodium clouds to use the time-variable behavior of the system to determine the characteristics of the interaction. During the observations, a large outburst of material from Io – which we hypothesize to be caused by the eruption of a massive volcanic plume on the satellite – caused a transient increase in the neutral cloud and plasma torus masses. The response of the plasma torus to this outburst clearly shows that the interaction between Io and Jupiter's magnetosphere is stabilized by a feedback mechanism in which increases in the plasma torus mass cause a non-linear increase in loss from the plasma torus, limiting plasma buildup.

Jupiter's magnetosphere is filled with plasma mostly derived from Io, the innermost of the large satellites of Jupiter and the most volcanically active body in the solar system. The magnetospheric plasma and the volcanos on Io are coupled in a complex interaction: the volcanos feed material – primarily sulfur and oxygen atoms and compounds – to the atmosphere and surface frosts of Io [1]; bombardment by magnetospheric plasma removes the atmosphere and frosts into an extended cloud of gas surrounding the satellite [2]; this gas is ionized by collisions with the magnetospheric plasma, becomes incorporated into the Io plasma torus (the inner, dense, portion of the Jovian magnetosphere), and returns to further bombard Io, in a tightly coupled loop.

Although the situation as described above sounds inherently unstable, observations have shown that the plasma density in the Io plasma torus remained roughly constant over at least a 13 year period [3] even though volcanic activity on Io is presumably sporadic [4]. Stability of the system in the face of such varying volcanic input must be achieved through some feedback mechanism, either through the regulation of supply to the extended gas clouds surrounding Io or through regulation of loss from the plasma torus [5]. We will refer to these two types of feedback mechanisms as "supply-limited" and "loss-limited," respectively.

The type of stabilizing mechanism operating is determined by the detailed characteristics of the interaction between Io and the plasma torus and of the plasma transport processes in the Jovian magnetosphere; a knowledge of the stability mechanism thus provides insight into these two poorly understood phenomena. The system will be supply-limited if supply to the extended neutral gas clouds does not increase linearly with increasing plasma bombardment. Two atmospheric models which lead to supply-limitation include an ionospheric buffering model, where an increase in plasma bombardment increases Io's ionosphere, which then begins to deflect the plasma bombardment and reduce the supply of material to the neutral clouds [6], and a constant-source model, where supply to the neutral clouds is a characteristic solely of Io's atmosphere and does not change with changing plasma bombardment [7]. We currently lack sufficient knowledge of Io's atmosphere to be able to evaluate these models [8].

The system will be loss-limited if loss from the plasma torus depends nonlinearly on plasma mass, such that an increase in plasma mass causes an even larger increase in plasma loss. The only plasma transport model currently developed which would lead to loss-limitation hypothesize that depletion of the plasma torus is driven by centrifugally-driven diffusion, a non-linear diffusion caused by the fast rotation of the Jovian magnetosphere. In such a system, the diffusion rate is proportional to the square of the plasma density (rather than to the first power of the density for linear diffusion), so the diffusion rate and thus mass loss depend nonlinearly on mass [9]. Another possible loss-limiting mechanism could be plasma transport initiated by large-scale plasma instability [10], where the onset and growth of the instability would lead to a non-linear plasma loss. Currently, few observational constraints on the plasma transport mechanism are available.

The response of the system to variable volcanic input depends strongly on the type of feedback operating (Fig. 1), thus determination of the time-variable behavior of the system would provide significant insight into poorly understood aspects of Io, its atmosphere, the Jovian magnetosphere, and their interactions. To determine this time-variable behavior, we monitored emission from the Io plasma torus and from the extended neutral cloud of material surrounding Io for 6 months in 1991-1992. A major perturbation to the system occurred in March 1992. We report here on this perturbation, most likely due to a massive volcanic outburst on Io, and on the implications for Io's atmosphere and volcanos and for the interaction of Io with the Jovian magnetosphere.

**Observations.** We observed the Io plasma torus and the extended neutral cloud on 56 clear nights between 1 December 1991 and 1 June 1992 using the Lick Observatory 0.6-meter coudé auxiliary telescope connected to the Hamilton echelle spectrograph [11]. Light from a slit 6 arcminutes long by 10 arcseconds wide was passed through the spectrograph and dispersed to a resolution of $\lambda/\Delta\lambda$ of $\sim 40,000$, about 0.15Å. The slit was centered on the position of Jupiter and aligned with either the plasma torus plane, for observations of plasma torus ion emissions, or the Io orbital plane, for observations of the extended neutral cloud. The 6 arcminute extent of the slit gave a spatial resolution of about 0.1 $R_J$ for a distance of about 9 $R_J$ on the east (dawn) and 9 $R_J$ on the west (dusk) side of Jupiter (An $R_J$ is a Jovian radius, $7.14 \times 10^4$ km). Each of the almost 400 observations consisted of a 40 minute CCD integration centered at a wavelength of either 6725Å to record the plasma torus $S^+$ emission lines at 6717 and 6731Å, or 5890Å to record the extended neutral cloud Na lines at 5889 and 5896Å [12].

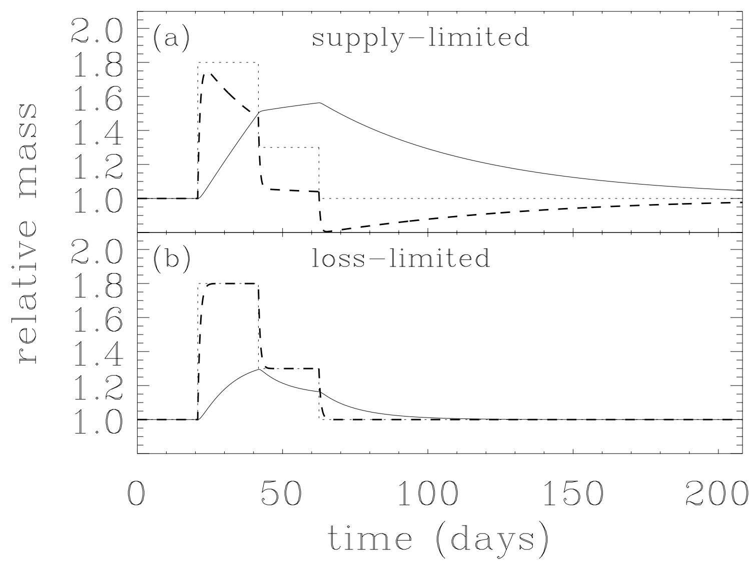


Figure 1: Models of the response of the extended neutral clouds of Io and the Io plasma torus to a volcanic outburst on Io [24]. The dotted line indicates the volcanic input, including a two-step 40 day outburst. The dashed line shows the neutral cloud mass, and the solid line shows the plasma torus mass. In both models, the neutral cloud mass responds quickly to the outburst because the lifetime in the neutral clouds is less than a day [26]. The plasma torus mass responds more slowly because the plasma lifetime is of the order of 50 days [27]. (a) The supply-limited case: In this model the stability of the interaction is maintained because an increase in the plasma density reduces the supply of material to the neutral clouds (by, for example, increasing the ionosphere on Io and deflecting the plasma [6]). After the volcanic outburst ends, the high plasma torus mass causes the supply rate to the neutral clouds to drop below its pre-outburst value. The decrease in supply to the plasma torus causes the magnetospheric mass to slowly decline until the equilibrium value is reached. Note that whenever the neutral cloud mass is greater than its equilibrium value, the mass of the plasma torus must increase. (b) The loss-limited case: In this model, stability is maintained because the plasma loss rate depends non-linearly on the plasma mass, as expected for centrifugally-driven diffusion [9], for example. Note the fast decay of the plasma torus perturbation, compared to the supply-limited case, which begins even as the volcanic input is above its pre-outburst value.

From these spectra, we extract emission intensity as a function of distance from Jupiter along the entire slit. These two species were chosen because they have the brightness emission intensities in the visible wavelength range for a plasma torus ion and neutral cloud atom, respectively. Sodium is approximately 100 times less abundant than sulfur or oxygen in the neutral clouds [2], but we will attempt to use it as a tracer of the major species, though its effectiveness as such a tracer has yet to be demonstrated.

The plasma torus spectra and neutral cloud spectra are analyzed separately. To examine the long-term behavior of the plasma torus intensities, we first remove short-term periodic modulations. The two observed modulations in the data occur at periods of 9.925 hours (the System III rotational period of Jupiter) and 10.214 hours (an unexplained modulation termed "System IV" [13]) [14]. The measured intensities are divided by the sliding-average of the modulation at these periods to remove the variations of about 30% and 40% for System III and IV, respectively. The corrected plasma torus intensity versus Julian date for a point 6 $R_J$ (the approximate orbital distance of Io) on the dawn side of Jupiter is plotted in Figure 2a. The long-term intensity behavior at other locations in the plasma torus is qualitatively similar. The emission intensity is proportional to the product of the electron and ionized sulfur densities, (approximately proportional to the square of the $S^+$ density), as the emission is due to the electron impact excitation of the sulfur.

Analysis of the emission intensities from the neutral sodium cloud suffers the complication that the emission seen is from the resonant scattering of sunlight; the emission intensity thus depends on the received solar flux at the wavelength of the atomic transition and therefore on the heliocentric velocity of the sodium atoms [15]. This effect is dependent mostly on Io phase, so we correct by removing the sliding-average modulation of the data at Io's orbital period. The total modulation by Io phase is 50%. No System III or System IV modulations are seen in the sodium data. The sodium intensities, summed along the entire slit and corrected for viewing at Io elongation, are shown in Figure 2b. The emission intensity is linearly proportional to the column density of sodium.

**An Io outburst.** The most striking feature of the data is a sudden increase in the brightness – and thus mass – of the neutral sodium cloud starting around Julian date 2448680 = 27 February 1992 (hereafter, only the last three digits of each Julian date will be given), followed by a more gradual increase in the plasma torus emission intensity. Figure 3 shows an expanded view of the period of the outburst, with both the neutral sodium and sulfur plasma torus emission intensities plotted relative to the medians of their values before day 670. The sodium cloud mass increases by an average of about a factor of two for at least 65 days, with transient increases of higher than a factor of 4. The plasma torus mass increases by almost 30% over this time period and drops back to its previous value after the sodium outburst has ended [16].

The timing of the neutral cloud and plasma torus perturbations is strong

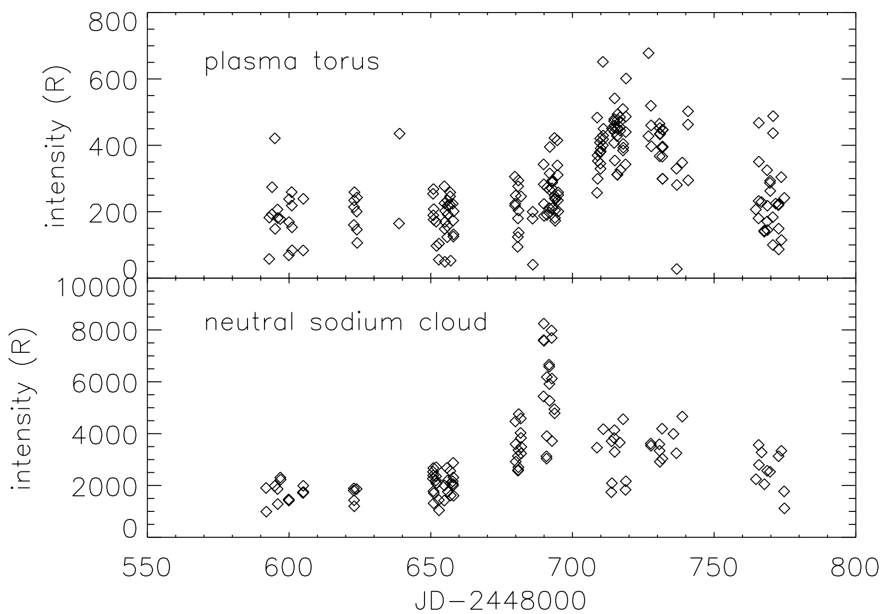


Figure 2: The intensity of 6731Å $S^+$ emission from the plasma torus and 5890Å sodium emission from the neutral clouds as a function of Julian date. The observations begin on 1 December 1991, which is JD 2448591. Intensities are in Rayleighs, defined as $1\text{R} = \frac{1}{4\pi} \times 10^6$ photons $\text{cm}^{-2}$ $\text{sec}^{-1}$ $\text{sterad}^{-1}$.

evidence that an increase in mass injection from Io causes the neutral cloud perturbation, which then causes the plasma torus perturbation. For example, on day 680, the sodium mass has already increased by a factor of 2, while all observations show that the plasma torus remains undisturbed. The simplest explanation for this observation is that the mass supply to the neutral clouds has suddenly doubled. The plasma torus intensity slowly begins increasing around this time, and a backwards linear extrapolation of the increasing phase of the plasma torus perturbation suggests a starting time around day 685. Such behavior is precisely that expected from an increase in injection of material from Io starting around day 680 [17]. The link between the neutral sodium and ionized sulfur perturbations suggests that sodium can be used to trace at least the basic behavior of the more abundant sulfur. We discuss this point further below.

The detailed response of the neutral clouds and plasma torus to this injection can be used to determine if the system is supply-limited or if it is loss-limited.

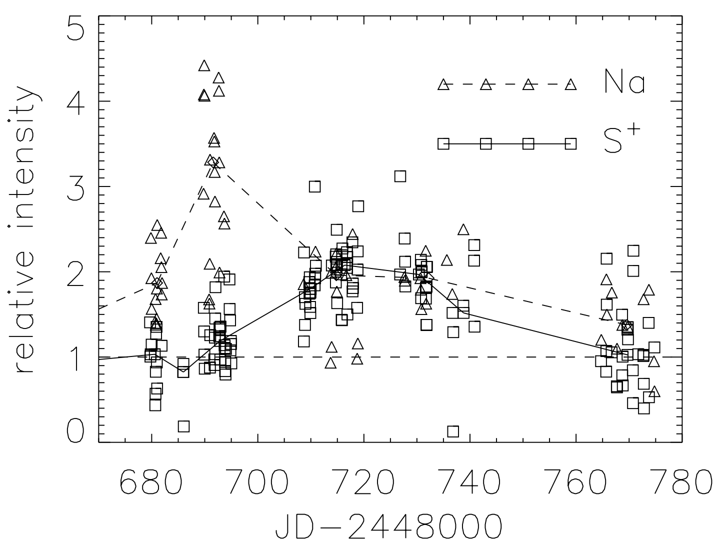


Figure 3: A direct comparison of the neutral sodium and ionized sulfur emission intensities. Both are plotted relative to the median of their pre-outburst values. The data are connected by lines going through the median values of the seven separate clusters of data. Note that between days 705 and 740 the plasma torus mass decreases slightly while the neutral cloud mass remains above its pre-outburst value. Such behavior can occur only in a loss-limited system.

One simple yet powerful diagnostic is that in a purely supply-limited system, the plasma torus mass must increase any time the neutral cloud mass is above its equilibrium value (see Fig. 1). This requirement results because supply to the plasma torus is proportional to the ionization and charge-exchange rates, which are proportional to the product of the plasma and neutral densities, while loss is proportional only to the plasma density. Figure 3 clearly shows that the system does not respond in this purely supply-limited manner; from day 705 until day 740, the neutral sodium cloud is about twice as massive as it was pre-outburst, but the plasma torus decreases in mass by 20% [16]. Such behavior can be achieved only in a loss-limited system.

This loss-limited behavior shows that the system maintains stability by a large increase in plasma loss as the plasma torus mass increases. This increased loss overcomes the supply rate increase caused by the higher plasma density,

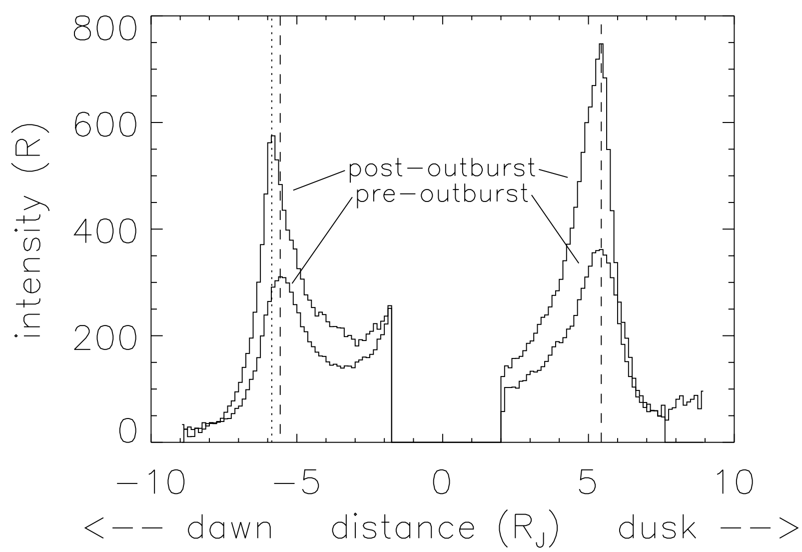


Figure 4: Spatial profiles of the line-of-sight emission intensity of the plasma torus before the start of the sodium outburst and after the start of the outburst. In addition to becoming brighter and more dense, the dawn side of the torus moved further out from Jupiter. The dusk side moved in towards Jupiter slightly. This shift likely results from an increase in the dawn-dusk electric field across the magnetosphere.

preventing a positive feedback which would make the system unstable.

**Magnetospheric response to an outburst.** Further evidence for a large increase in the plasma loss rate is found by examining the magnetospheric response to the outburst. Previous observations have noted that the plasma torus appears offset towards the dawn direction [18]. This effect is a predicted consequence of a large-scale electric field of about 4 mV $m^{-1}$ across the inner magnetosphere [19]. The field is thought to be due to the $\mathbf{v} \times \mathbf{B}$ electric field set up by the plasma flowing down to the magnetotail, with the field propagated to the inner magnetosphere in a manner analogous to terrestrial equatorial currents.

Our pre-outburst observations of the plasma torus show this expected dawn offset: the peak of emission intensity on the dusk side occurs at 5.4 $R_J$, while the dawn peak occurs at 5.6 $R_J$. During the outburst, the peaks of emission of the plasma torus shift even further dawnward (Figure 4). This shift is most prominent on the dawn side and only marginally visible on the dusk side. Figure 5(a) shows average intensity profiles for the dawn side for 4 different times: pre-outburst, the rising phase of the torus perturbation, the peak of the torus perturbation, and the declining phase of the torus perturbation. The dawnward shift of the plasma torus increases with each increase in the plasma mass. Figure 5(b) plots the fractional dawnward shift of the plasma torus versus the relative plasma torus mass for these time periods [20]. The plasma torus systematically shifts dawnward with increasing mass of plasma.

A dawnward shift in the plasma torus can be caused by an increase in the large-scale electric field across the inner magnetosphere. We show here a simplistic model that suggests that such an increase can be caused by an increase in the plasma outflow and thus by an increase in mass loss from the plasma torus [21]: the transition between where the magnetospheric motion is dominated by corotation and radial transport and where the tailward flow begins occurs around a characteristic distance, the Hill length $L_{\rm H}$, of [22]

$$L_{\rm H} = (\pi \Sigma R_{\rm J}^2 B_{\rm J}^2 / \dot{M})^{1/4}, \tag{1}$$

where $\Sigma$ is the Pederson conductivity of the Jovian ionosphere, $B_{\rm J}$ is the Jovian surface magnetic field strength, and $\dot{M}$ is the total rate of outward mass transport. As $\dot{M}$ increases, $L_{\rm H}$ decreases, and tailward flow begins closer to Jupiter. Closer to Jupiter the magnetic field strength, $B$, is higher, and for a simple dipole the strength goes as $B \propto 1/R_{\rm J}^3$. Thus the tailward plasma flow begins in a region of stronger magnetic field, and, assuming that the tailward flow velocity is controlled by the solar wind speed and remains constant, the electric field, $E$, which is proportional to $\mathbf{v} \times \mathbf{B}$, increases as

$$E \propto (\frac{\dot{M}}{\dot{M}_0})^{3/4}, \tag{2}$$

where $\dot{M}_0$ is the initial mass outflow rate. While this analysis is simplistic and cannot capture many of the complexities of the real magnetospheric interactions, it likely reproduces the basic behavior of the relationship between changing plasma outflow rates and the large-scale electric field: an increase in the mass outflow will cause an increase in the electric field, thus a dawnward shift in the Io plasma torus, as observed.

We see from the data (Fig. 5) that the dawnward shift and thus the plasma outflow rate increases precipitously as the mass of the plasma torus increases. This behavior is precisely that expected for a loss-limiting mechanism to stabilize the interaction between Io and the magnetosphere: an increase in the plasma mass causes an even larger increase in plasma loss, so the plasma mass decreases. From equation (2) and the measured shift in the plasma torus, we can attempt to estimate the plasma outflow rate as a function of the plasma mass. Figure 5(b) shows curves for the expected dawnward shift (assuming equation (2) is strictly correct) for two types of plasma transport postulated

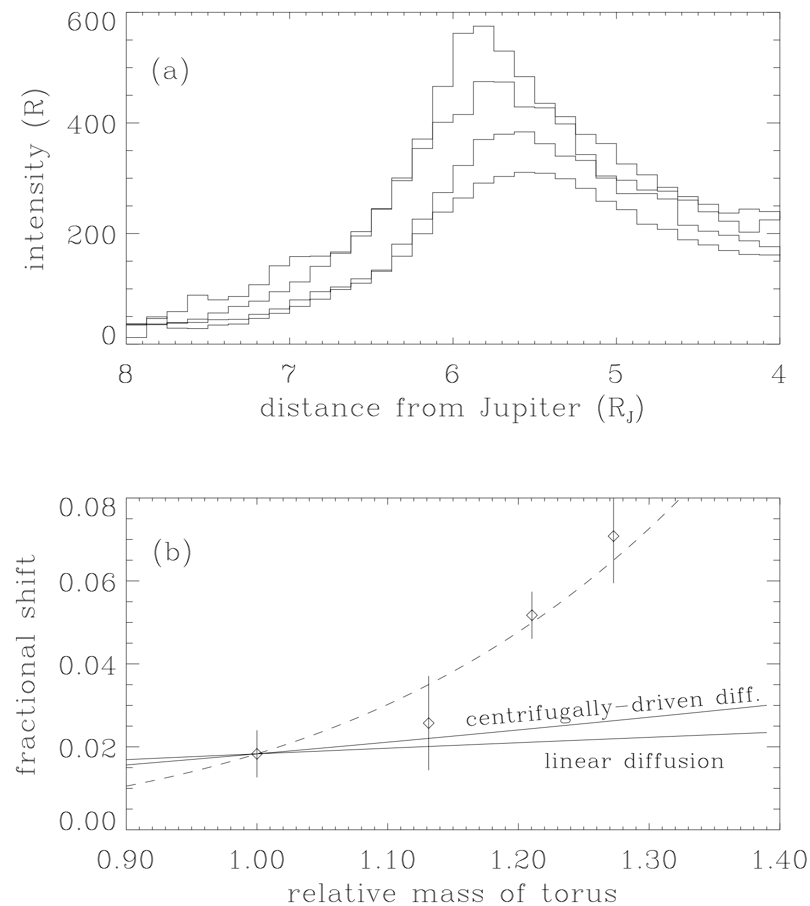


Figure 5: Shifts in the plasma torus. (a) The emission intensity profile at 4 time periods before and during the torus perturbation. The torus shifts systematically dawnward with the increase in mass. (b) The peak of torus emission as a function of relative torus mass for the four time periods above. Also plotted are the shifts expected for plasma transport by simple diffusion and by centrifugally-driven diffusion, using the model in equation (2). The shifts are best fit by a model where plasma outflow is proportional to the seventh power of the mass of the plasma torus, shown as a dashed line.

for the Jovian magnetosphere [23]: linear diffusion, where the plasma loss is directly proportional to the plasma density; and centrifugally driven diffusion [9] where the diffusion is proportional to the square of the density. The best polynomial fit to the data is given by a model where plasma outflow is proportional to the seventh power of the plasma mass. We place no significance on the specific polynomial fit; the critical characteristic suggested by these data is that plasma outflow increases quickly with increase in plasma mass. Even the non-linearity of centrifugally-driven diffusion cannot account for the large increase in plasma outflow with increasing plasma mass, if our simplistic model of the relationship between the plasma torus shift and the plasma outflow is approximately correct. Another – even more non-linear – mechanism, such as transport through large-scale plasma instability [10], is required in this case.

**Magnitude of the outburst.** Using our knowledge of the behavior of the system, we can now attempt to estimate the magnitude of the outburst from Io. In a purely loss-limited system, perturbations to the neutral cloud mass directly reflect perturbations to the source from Io. During the outburst, the neutral sodium cloud mass increases by about a factor of 2 for 60 days (and a factor of more than 3 for at least a 5 day period), thus the sodium supply from Io must have increased by at least that amount.

But is the mass increase in sodium, a minor species in the neutral clouds, indicative of the behavior of the dominant sulfur and oxygen? The subsequent increase in the sulfur plasma mass following the sodium outburst shows that atomic sulfur must have increased in mass at the same time as atomic sodium, but the total amount of the sulfur increase remains unknown. We can estimate the increase in atomic sulfur by the magnitude of the increase in sulfur plasma mass if we know the plasma outflow rate. We calculate a lower limit to the atomic sulfur increase by assuming the minimum plasma outflow consistent with the observed loss-limited behavior. This minimum outflow is given by centrifugally-driven diffusion, where plasma outflow increases with the square of the plasma mass. Using the simple model of the interaction between the neutral clouds and plasma torus described earlier [24], we find that small perturbations, such as that seen in the plasma torus, require a mass input increase of approximately the same amount as the perturbation. Thus, for the minimal plasma outflow, the 30% increase in plasma torus mass requires a 30% increase in neutral cloud mass. As the sodium mass increases by a factor of $\sim 2$, sodium would have to be $\sim 7$ times more abundant in the outburst than sulfur in this case.

Assuming, however, that the much larger increase in plasma outflow with increased plasma mass inferred from the plasma torus shift is correct, a much larger atomic sulfur increase is required to account for the increase in sulfur plasma mass. For this case, we find that the observed 30% increase in plasma torus mass requires a factor of $\sim 3$ increase in supply to the neutral clouds, in approximate agreement with the factor of $\sim 2$ increase in the neutral sodium cloud mass. Thus the data are consistent with the hypothesis that the mass of sodium is a direct tracer of the mass of the more dominant sulfur (and presumably oxygen) components.

The precise relationship between the mass in the sodium outburst and the mass in the sulfur and oxygen would be quickly determined by contemporaneous observations of neutral sulfur or oxygen during the sodium outburst. Unfortunately, no such observations were obtained during these observations. Future monitoring of the Io plasma torus system should put special emphasis on obtaining such observations.

**Cause of the outburst.** It is not possible to directly determine the cause of the increase in gas supply from Io, but with volcanic activity a know transient phenomenon on the satellite, the eruption of a volcanic plume on the satellite is a natural explanation. The only conclusive supporting evidence would be direct images of a new large plume on Io. Such images are currently possible only from remote observations taken by spacecraft in the Jovian system. No such spacecraft was inside the Jovian system during these observations. Groundbased infrared observations are able to monitor hotspot activity on Io [2], but we have no reason to expect that these are associated with plumes on Io, nor were any observations obtained during the outburst [25]. We therefore conclude that although no proof of the hypothesis will ever be possible, the eruption of a volcanic plume on Io is the most likely source of the sudden transient gas injection.

Voyagers 1 and 2 imaged 9 active plumes on Io [4], thus, even if the neutral clouds are supplied solely by an atmospheric component caused by active plumes, a typical plume should affect the supply rate by only a small amount. All plumes except one, however, were active during both Voyager encounters, 4 months apart, so short term variability is not necessarily expected for these plumes. Pele, the largest observed plume, was that only plume observed to have turned off between the Voyager 1 and 2 encounters. In addition, between the two encounters, a plume with dimensions similar to Pele resurfaced a large area around Surt. It thus appears that the largest plumes are the most variable, and that a plume with duration of only $\sim$ 60 days might be expected to be quite large. If the neutral clouds are fed by sputtering of atmospheres local to active plumes, we expect that the contribution of each individual plume should be roughly proportional to the surface area covered by the plume. Based on Voyager measurements of observed plume widths [4], we find that the surface area covered by Pele was almost 4 times greater than the surface area covered by all of the other plumes taken together. Thus the factor of 2 or more increase in the supply of sodium to the neutral clouds suggested by the data is reasonable for the largest observed plumes on Io.

**Implications for the system.** We propose the following scenario to explain the observations presented here. Starting on approximately day 680 a large plume, of dimensions similar to those of the Pele plume, began erupting.

This eruption greatly increased the surface area of plume material available to be sputtered into the neutral clouds, and the neutral cloud mass quickly adjusted to this increase in mass input. The plume remained active for about 60 days, and its output was highly variable during this time. The increase in mass of the neutral clouds caused an increase in the supply of ions to the plasma torus, so the mass of the plasma torus began to increase. The increase in mass of the plasma torus then led to a highly non-linear increase in plasma outflow, causing the plasma torus mass to fall to its equilibrium value quickly after the cessation of plume activity.

This scenario suggests the following implications for Io and the plasma torus: (1) The stability of the magnetosphere-Io interaction is controlled not by Io and the details of its atmosphere and mass pickup, but by the magnetosphere and the method of plasma transport. (2) An increase in plasma mass causes a very strong increase in plasma loss from the torus, as suggested by models where the plasma transport is driven by large-scale plasma instability. (3) Sodium is a good tracer of plume activity on Io, and the response of the sulfur plasma torus to the observed sodium outburst is consistent with that expected if sodium and sulfur are equally abundant in such outbursts. Observations of neutral oxygen or neutral sulfur during such an outburst are vital to confirm this suggestion. (4) The large response of the sodium neutral cloud, if it is representative of the sulfur and oxygen clouds, shows that the Io atmosphere is easily overwhelmed by the eruption of a single large plume, lending support to the idea that the atmosphere of Io is primarily due to plumes [8]. (5) Variable volcanic activity on Io affects plasma mass, plasma transport, and large-scale electric fields in the Jovian magnetosphere.

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[16] We estimate the total mass increase in the plasma torus by summing all emission along the slit and taking the square root, as the emission intensity is proportional to the product of the ion density and the electron density which we assume scale together. Figure 2 appears to imply an even larger change in mass only because of the structural changes that occur in the torus at the same time, discussed later.

[17] An alternative scenario might be envisioned where the increase in mass of the neutral sodium cloud is caused by an increase in the sodium lifetime caused, for example, by a decrease in the electron temperature. We reject this hypothesis for two reasons: (1) observations of the plasma torus, while not directly sensitive to electron temperature, show no change in the plasma torus mass, ion temperature, or rotation velocity at the start of the neutral sodium cloud perturbation and (2) the increase in mass of the plasma torus shows that for sulfur, at least, the supply increases precisely when the sodium mass increases, strongly suggesting that the sodium mass increase is caused by a sodium supply increase.

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[28] We have benefited greatly from conversations with A.J. Dessler, T.W. Hill, M.A. McGrath, E.J. Moyer, and D.H. Pontius. This research would not have been begun without a generous seed grant from the California Space Institute and would not have proceeded without the reliable help of Tony Misch and the other staff at Lick Observatory.