Explanation of the inward displacement of Io's hot plasma torus and consequences for sputtering sources

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Radial profiles of the ion density and flux-tube content in the Io torus have peak values inside Io's orbit, even though Io is the effective source of these ions. Formation of an inward peak constrains either the velocity distributions or source regions of sputtered neutrals. A further constraint is that the ionization of neutrals on trapped trajectories that return to Io's surface must be limited. A dominant sulphur source is most easily reconciled with these constraints.

IO, the innermost of the four Galilean satellites, has a dense torus of plasma associated with it. This torus, perhaps the most intriguing feature of Jupiter's magnetosphere, has been the subject of intensive research and debate. Recent ground-based measurements of the torus[1], as well as measurements from the Voyager spacecraft[2,3], have shown that both the ion density (Fig. 1*a*, *b*) and NL^2, the flux-tube content (Fig. 1*c*), attain their maximum values as functions of radial distance from Jupiter well inward of Io's orbit, with NL^2 falling off sharply inside ~5.6 jovian radii (R_J).

Many features of the radial profiles can be understood in terms of radial diffusive transport[4-7]. Because diffusion driven by macroscopic processes in planetary magnetospheres is accomplished by the interchange of magnetic flux tubes, NL^2, proportional to the number of ions per unit magnetic flux, is the diffusing quantity[4]. (The parameter L labels a field line and, in a dipole field, L is the distance in planetary radii from the centre of the planet to the equatorial point on the field line. N is the number of ions per unit L.) The radial profile of NL^2 is consistent with diffusive transport of ions only if their source attains a maximum value near 5.6-5.7 R_J. Centrifugal forces drive rapid outward diffusion, consistent with the relatively slow outward decrease of NL^2 beyond 5.7 R_J. Slow inward diffusion driven by atmospheric winds explains the sharp decline inward from 5.6 R_J, but the heavy ions that form the torus must originate from matter on Io itself. The main purpose of this paper is to explain why, although Io is the actual source of particles, the peak in NL^2 occurs inside its orbit. Specifically, we have calculated the trajectories of neutral particles ejected from Io and have examined the conditions under which they tend to be ionized inside Io's orbit. We find that the requirement of a localized peak constrains either the spectrum of sputtered neutrals or their source locations on Io, or both. A further constraint is placed on the ionization of neutrals on trapped (non-escape) trajectories.

Calculations and modelling

It is generally agreed that the ions in the torus originally are ejected from Io as neutrals forming neutral clouds extending far from Io. These neutrals are ionized eventually to form the torus[8-10]. This sequence suggests a possible explanation for the peak in NL^2 inwards of Io's orbit; perhaps the trajectories of neutrals are such that they tend to be inward of Io's orbit at the time they are ionized[1]. We have investigated this possibility using simple models for the production of ions from the neutrals. We have assumed that neutral particles are ejected from Io's equator with initial positions spaced uniformly in longitude and separated by 5° (see Fig. 2*a*). At each initial position, 100 neutral particles are 'launched' radially, with specified initial velocities, each set of particles having a distribution of lifetimes of the form (Fig. 2*b*)

$$P(t)\,dt = (dt/\tau)\exp(-t/\tau) \qquad (1)$$

We ignore the consequences of misalignment of magnetic and rotational poles. Thus, the position of a neutral at the end of its life defines the radial coordinate of a newly created ion. To be physically meaningful, it is important that a distribution of lifetimes be used for the model, because if only the average lifetime were used there would be no way for the particles from a given source position with given velocity to spread in radial position.

At each initial position, trajectories were calculated for velocities in the range 1.0–4.0 km s^{-1} in increments of 0.1 km s^{-1}. We used an orbit calculation program (OBCAL) that integrates the equations of motion for the particles, taking into account the gravitational forces of Jupiter and Io, the other three Galilean satellites and the J_2 term in Jupiter's gravitational potential. (The Galilean satellite trajectories are modelled as slightly inclined ellipses.) Ephemeris data for the Galilean satellites were provided by the Jet Propulsion Laboratory (JPL). The program was tested by comparing calculations of the positions of both Io and the Galileo spacecraft with calculations performed by JPL; discrepancies were $<5\times10^{-3}$ R_J.

Sputtering, in which charged particles collide with neutral matter and neutral atoms and molecules are emitted, is believed to be the dominant process responsible for ejecting matter from Io[10]. To calculate the number of particles at a given velocity, we have assumed velocity distributions expected for sputtering. The particles are assumed to come from the surface of Io; however, this should not be construed as eliminating the possibility that the particles could originate from the atmosphere or exobase. As any assumed surface source distribution maps to a shifted velocity distribution at the atmosphere or exobase, our solutions also apply to the mapped sources at these altitudes. Note that all our sources are located at Io's equator and Io is assumed to lie in the magnetic equatorial plane; these assumptions serve to make the calculation manageable. High-latitude particles emitted radially would have similar trajectories except that their orbits would be inclined with respect to the spin equator. Because energy is used to incline the trajectory rather than to change the apsides of the trajectory, high-latitude particles in general need higher initial velocities to escape and to achieve the same eccentricity as equatorial particles. Therefore, the trajectories of high-latitude particles should be similar to those of equatorial particles, except that the orbits will be inclined and higher initial velocities will be necessary to achieve the same displacement from Io's orbit. By neglecting the tilt of Jupiter's dipole, we do not take into account that the L shell of

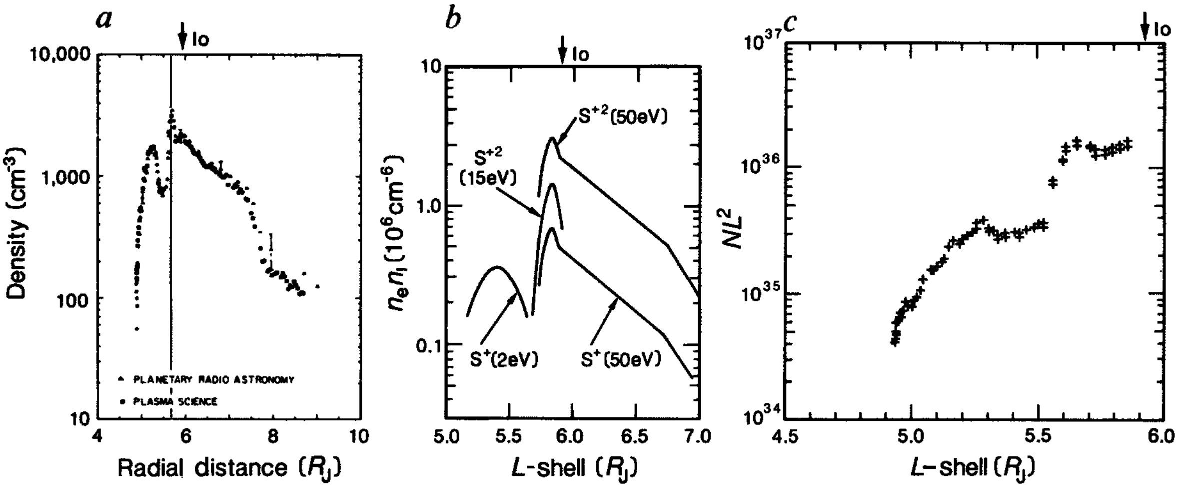

Fig. 1 *a*, Radial profile of *in situ* measurements from the Voyager spacecraft of charge density in the Io torus. The peak occurs well inside Io's orbit, at ~5.7 R_J (adapted from ref. 3). *b*, Radial profiles of ground-based measurements of sulphur-ion densities. Again the peak occurs inside of Io's orbit (adapted from ref. 1). *c*, Radial profile of NL^2, proportional to the total number of ions per unit magnetic flux, based on measurements from the Voyager spacecraft. This function, conserved in adiabatic transport, enters the canonical form of the equation for radial diffusion. The peak in NL^2 occurs at 5.6–5.7 R_J and thus requires a source of ions in this region. There also seems to be a 'plateau' at 5.2–5.3 R_J in the cold torus (this also appears as a small peak in *a* and *b*; adapted from ref. 2).

a newly created ion is necessarily the same or larger than the radial distance at which ionization occurs. However, because the electron density (and hence the ionization rate) is much higher in the centrifugal equator[11], neutrals will tend to be ionized when they are in the centrifugal equator. The change in L shell is then very slight (<0.02 R_J) and should not have any significant effect on the profiles shown here.

Results

Unless otherwise noted, our calculations assume a spatially uniform probability of ionization. First, we consider a mean lifetime of 40 h, appropriate for sulphur atoms being ionized by electron impact near Io. This is the lifetime that results if we use commonly accepted rate coefficients[12–14] and an electron density of ~2,000 cm^{-3}. Figure 3*a* shows the radial distribution of new ions from neutral particle sources distributed from 0 to 90° in longitude. Neutral velocities are assumed to obey what is called a thermal spike velocity distribution[15]

$$f(v)\,\mathrm{d}v \propto v^3 \exp(-mv^2/kT)\,\mathrm{d}v \qquad (2)$$

and only neutrals above the escape velocity ($v > 2.3$ km s^{-1}) are considered. (Here T, an arbitrary parameter characterizing the steepness of the distribution and not related directly to the actual temperature of the source, was chosen as 4,000 K. The thermal spike velocity distribution is only an approximation to observed sputtering spectra. For example, values of 2,000 3,600 and 5,200 K have been used to represent spectra for sputtering of various materials[16].) Note that a peak in density occurs between 5.6 and 5.7 R_J as required by the data. One should also recognize that the plotted profiles in Figs 3–5 are proportional to the source rate in a diffusion equation for NL^2.

Figure 3*a* shows that sputtered neutrals above the escape velocity with a plausible velocity distribution produce the spatial localization needed for a source of Io torus ions. The neutrals that tend to contribute most to the ionization peak between 5.6 and 5.7 R_J are those with a velocity slightly above the escape velocity (2.3–2.5 km s^{-1}). This can be understood as follows: particles that barely escape from Io, once away from Io, are on nearly circular trajectories around Jupiter and thus tend to be ionized at roughly the same distance independent of the lifetime of the neutral. Those neutrals that are injected inward thus tend to be ionized inwards of Io's orbit in a fairly narrow range of radial position. For higher injection velocities, neutrals tend to be on more elliptical trajectories and are thus ionized with a wider spread in radial position. As the thermal spike velocity distribution heavily favours injection of neutrals at lower velocities, neutrals with injection velocities favourable for formation of the inward peak tend to dominate the escaping particles. The 0–90° region of longitude is also favourable for formation of the desired peak because neutrals ejected from this region proceed on trajectories inwards of Io's orbit. However, as will be shown later, a source of neutral particles spread uniformly in longitude can also form the required inward peak. Our parameters are chosen to describe sulphur; however, because the results are relatively insensitive to lifetime they probably apply to oxygen as well.

Note that when all important gravitational forces are considered, particles with velocities as low as 2.3 km s^{-1} can escape Io even though the escape velocity from Io as an isolated body is almost 2.6 km s^{-1}. The number of neutrals ejected above the escape velocity gives the only constraint on the T parameter in the thermal spike velocity distribution. With $T = 4{,}000$ K, as in this calculation, ~4% of the neutrals escape. As will be shown below, this gives an adequate supply rate of neutrals.

Thus far, we have considered only neutral particles on trajectories that allow them to escape from Io. However, there is nothing in our model to prevent the ionization of neutrals on trapped trajectories (particles that, if not ionized, ultimately fall back to the surface of Io). Because the sputtering velocity distributions favour low velocities, a large fraction of neutrals will be on these non-escape trajectories. If we consider the same velocity distribution as in Fig. 3*a* with the same longitudinal region of sources, but include the ionization of neutral particles below the escape velocity, the radial distribution of newly created ions shown in Fig. 3*b* is formed. A small peak forms between 5.6 and 5.7 R_J, but contrary to the observations, a sharp peak forms at 5.9 R_J. This sharp peak forms because many more neutral particles are on trapped trajectories than on escape trajectories. Because of Jupiter's gravitational force, these low-velocity particles get much farther away from Io and take much longer to fall back to Io's surface than if only Io's gravitational force were considered. We are presently working on calculations of the neutral density near Io and find that the requirement of an adequate source rate of neutrals above the escape velocity implies that a dense neutral cloud (~10^5–10^6 cm^{-3}) forms within 3 Io radii of the surface of Io. For the case shown in Fig. 3*b*, a source rate of 3×10^{28} ions s^{-1} into the torus implies that $>10^{28}$ ionizations s^{-1} occur near Io, greater by an order of magnitude

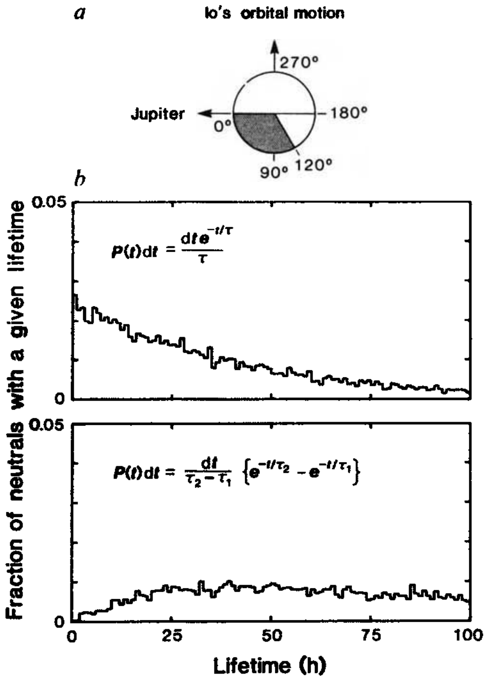

Fig. 2 *a*, Coordinate system for neutrals ejected from Io. The circle represents Io seen from above Io's orbit plane. For the calculations, particles were ejected uniformly in longitude with a separation of 5° between each position. The shaded area of the diagram shows the region where sulphur volcanoes are observed on Io[25]. Note that the coordinate system is right-handed, opposite to the one used by ref. 25. *b*, Histogram of a typical distribution of lifetimes, generated for a mean lifetime against ionization of 40 h for a spatially uniform probability of ionization. The distribution gives the probability that an atom survives a time t and is ionized between t and $t+dt$. The radial position of a neutral at the end of its life defines the radial coordinate of the newly created ion. *c*, As *b* for the case of a molecule that is first dissociated and the products subsequently ionized: τ_1, mean lifetime for dissociation of S_2, was assumed to be 46 h (see text); τ_2, the mean lifetime for ionization of S, is 40 h. A spatially uniform probability of electron impact is assumed. As the probability of ionization in the first few hours is small, the number of ions formed from neutrals on trapped trajectories is relatively insignificant. Because any S_2^+ ions formed are lost quickly by dissociative recombination, only S_2 molecules that are first dissociated contribute significant numbers of ions to the torus.

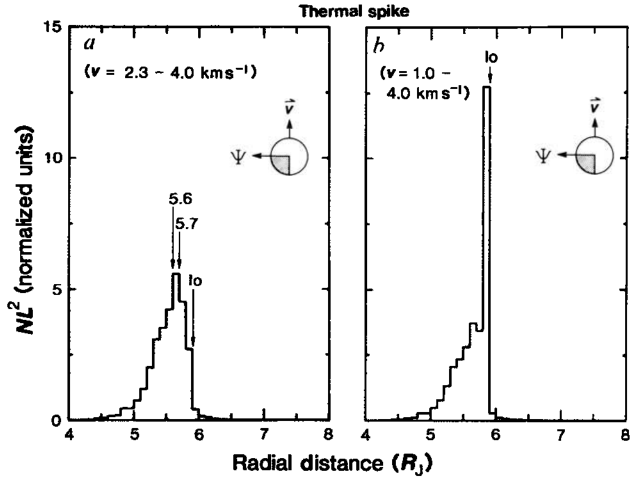

Fig. 3 *a*, Radial profile of NL^2 divided by the total number of particles, calculated for neutrals ejected from longitudes between 0 and 90° on the surface of Io with a thermal spike distribution of velocities, considering only velocities above the escape velocity. A distribution of lifetimes as shown in Fig. 2*b* with a mean lifetime of 40 h was used for the neutrals. The peak at 5.6-5.7 R_J is the major feature required of a source of Io torus ions. For neutrals above the escape velocity, any velocity distribution of ejected neutrals that falls off rapidly enough with increasing velocity will cause the inward peak in NL^2 to form. A rapid fall off with increasing velocity is in fact a characteristic of velocity distributions expected for sputtering. This figure and all succeeding figures show possible source profiles of Io torus ions. The profile of the total ion density would be modified by the effects of diffusive transport, but the peak would remain in the same location. *b*, As *a* except that neutrals with velocities below the escape velocity are included. A sharp peak forms at 5.9 R_J, in contrast with the observations. If we normalize the number of neutrals above the escape velocity to be $2\times10^{28}\ s^{-1}$, an adequate source rate[20] of 3×10^{28} ionizations s^{-1} in the torus is obtained, but the profile shown here would require 10^{28} ionizations s^{-1} within 3 Io radii of Io's surface. Observations place a limit of 10^{27} ionizations s^{-1} of sulphur and oxygen atoms near Io. Thus, for consistency with observations, some process must limit ionization of sulphur and oxygen atoms on trapped trajectories near Io. Injection of S_2 neutrals as the dominant source of torus ions is consistent with this requirement. The profiles shown can be regarded as the source rate in a diffusion equation governing NL^2.

than the limit placed on ionization of sulphur and oxygen atoms in the vicinity of Io by observation[17].

As the Io torus requires an injection rate of $2\text{-}7\times10^{28}$ ions s^{-1} (refs 18-20) and the sputtering velocity distributions greatly favour the production of particles on trapped trajectories, some process must limit the ionization of atoms on these non-escape trajectories. The ionization limit is required both to explain the formation of an inward peak and to be consistent with the observations of limited ionization near Io. One way that the ionization of atoms near Io could be limited is if the predominant sputtering products are molecules. If an electron impact is required to first dissociate the molecule, and the products are ionized by subsequent electron impacts, then neutrals on trapped trajectories would fall back to the surface of Io before they could become ionized.

For estimates of the importance of this two-step process we consider the sputtering of sulphur. Sulphur sputtered from the surface of Io has often been ignored as a source of torus particles because some estimates[10,15] indicated that sputtering yields for this element would be small compared with those for SO_2. These sputtering yield estimates were based on the assumption that the binding energy is much higher for sulphur than for SO_2 (ref. 10). However, recent experiments[21] have shown that sulphur gives anomalously high sputtering yields of the order of 10^4–10^6 per incident ion when bombarded with 30-300 keV He^+ ions, a yield as much as five orders of magnitude greater than estimates for the sputtering yield of SO_2 (ref. 10). The experiments indicate that the predominant product of sputtering of sulphur is S_2, with some larger sulphur molecules present as well. S_2 would dissociate and ionize as follows (the mean lifetime, τ, is shown for each process); because lifetimes for S_2 ionization and dissociation were not available, lifetimes for O_2 were substituted[22]

$$S_2+e^- \rightarrow S+S+e^- \quad (\tau_1=46\ h) \tag{3}$$

$$S+e^- \rightarrow S^+ +2e^- \quad (\tau_2=40\ h) \tag{4}$$

On the other hand, the S_2 molecule itself can be ionized

$$S_2+e^- \rightarrow S_2^+ +2e^- \quad (\tau_3=32\ h) \tag{5}$$

There is no observational limit on the ionization per second of S_2, as the observations near Io constrained only the ionization rates of atomic sulphur and oxygen. However, experiments with O_2^+ and NO^+ show that dissociative recombination occurs rapidly for these molecules for electron temperatures in the range 0.045-4 eV (ref. 23). Extrapolation of the dissociative recombination rates to 5 eV gives a lifetime in the range 4-9 h (for an electron density of 2,000 cm^{-3}), which is small compared with the ion diffusion time (30-100 days). Thus, the reaction

$$S_2^+ +e^- \rightarrow 2S \quad (\tau_4=4\text{-}9\ h) \tag{6}$$

proceeds sufficiently rapidly that any S_2^+ ions formed will be converted into neutrals. The neutrals will then have the corotation velocity and will quickly leave the torus. Therefore, S_2^+ ions

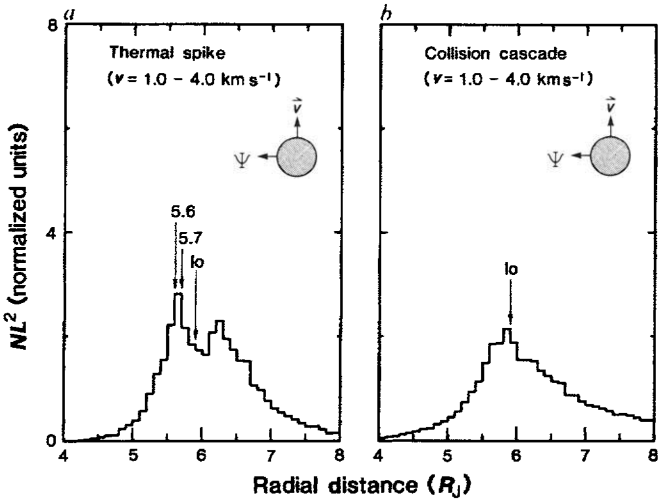

Fig. 4 *a*, Radial profile of NL^2 divided by the total number of particles. For this and all succeeding figures, the distribution of lifetimes described in Fig. 2*c* was used. Neutrals were ejected from all longitudes of Io, with a thermal spike distribution of velocities (see text). The range of velocities was 1.0–4.0 km s^{-1}. The required inward peak forms at 5.6–5.7 R_J. This is true for any velocity distribution that peaks below the escape velocity and falls off rapidly with increasing velocity. *b*, As *a* but for the limiting case of a collision cascade distribution (see text). A peak at Io is formed that is inconsistent with the required source. This velocity distribution does not fall off rapidly enough to form the inward peak, but does provide a direct source of neutrals over a broad radial range.

will not add significantly to the NL^2 profiles, and we need consider only those neutrals that are first dissociated and then ionized.

For a spatially uniform probability of electron impact, the probability of a neutral's being ionized between time t and $t+dt$ following an earlier dissociation is of the form:

$$P(t)\,dt = \frac{dt}{\tau_2 - \tau_1}\left(e^{-t/\tau_2} - e^{-t/\tau_1}\right) \quad (7)$$

If we generate neutral lifetimes using this probability distribution (Fig. 2*c*) and we use the thermal spike velocity distribution that we used in Fig. 3, but with neutral sources at all Io longitudes, we obtain the radial distribution of newly created ions shown in Fig. 4*a*. As the dissociation of the molecules must occur before the individual atoms are ionized, only a fraction of particles on trapped trajectories are ionized and the peak at 5.9 R_J is reduced. A clear peak of ion density forms at 5.6–5.7 R_J, as required by the data.

For the results shown in Fig. 4*a*, we have looked at a specific mechanism that can limit the ionization rate near Io if the source is rich in S_2. However, other processes can limit the ionization rate near Io independently of the neutral species. Because the neutral cloud within 3 Io radii of Io's surface has neutral densities orders of magnitude higher than the electron density, the physics must differ greatly in the neutral cloud from elsewhere in the torus. Other, possibly more important, mechanisms may limit ionization rates for neutrals in the dense cloud, and thus decrease the ionization probability for particles on trapped trajectories. Based on the spectroscopic observations, such a limitation certainly occurs. With a limitation on ionization near Io, any neutral species with a velocity distribution that peaks below the escape velocity and falls off rapidly enough with increasing velocity will form the inward peak.

Some workers[15,16] believe that the thermal spike distribution we have assumed is accurate only for high energy (keV–MeV) sputtering ions. If neutrals are sputtered by corotating ions, a collision cascade velocity distribution of the form

$$f(v)\,dv \propto v^3\,dv/(v^2+v_0^2)^3 \quad (8)$$

may give a better representation. Here v_0 is the velocity corresponding to the binding energy. A relatively flat velocity distribution for neutrals does not form an inward peak if sources are distributed uniformly around Io's equator. The steepest velocity profile allowed by equation (8) corresponds to $v_0 = 0$; in Fig. 4*b* we have plotted the ion distribution obtained for this limiting case. As can be seen in Fig. 4*b*, a small peak at Io is formed. Even in the limiting case, a collision cascade distribution does not fall off rapidly enough to produce the required inward peak.

The results shown in Fig. 4 were calculated for sources independent of Io longitude, but there are reasons why ejection of particles from Io may be asymmetrical in longitude. For example, the nature of the plasma flow around Io may lead to preferential regions of access for the sputtering ions[24]. This asymmetry would be highly dependent on the character of the interaction between Io and the torus plasma, which at this time is not well understood. An asymmetry in the source locations of sputtered particles could also occur if the dominant source of the neutrals on the surface were localized. SO_2 is found at roughly all longitudes; however, sulphur is confined to the region from 0 to 120° as illustrated in Fig. 2*a* (ref. 25). As mentioned previously, recent experiments[21] have shown that sulphur gives very high sputtering yields, orders of magnitude greater than the sputtering yields estimated for SO_2. Such large sputtering yields suggest that sulphur may be the dominant neutral injected into the torus. Furthermore, some calculations[26] suggest that a 4:1 injection ratio of sulphur to oxygen is consistent with the observed ion partitioning. If we consider sulphur neutrals with the thermal spike velocity distribution coming from the sulphur-rich regions on Io, a very sharp peak is formed (see Fig. 5*a*). Even for a collision cascade velocity distribution, the required peak is still formed if the sources are localized in the sulphur-rich regions (Fig. 5*b*).

Discussion

Our results show that the requirement that neutrals sputtered from Io must ultimately form a distribution of ions with a peak in NL^2 near 5.7 R_J, substantially constrains models of the source. Ionization of neutrals on trapped trajectories must not contribute significantly to the ion population. The velocity distribution of ejected neutrals must fall off sufficiently rapidly with increasing velocity so as to favour heavily those particles near the escape velocity, or the source must be localized in longitude, or both. These requirements are easily reconciled with sulphur being the dominant neutral injected into the torus. S_2 sputtered from the surface of Io must first be dissociated before it is ionized, limiting the ionization of atomic S near Io. S_2^+ ions that are formed will be lost rapidly by dissociative recombination. The sulphur-rich volcanoes are, in fact, confined to longitudes favourable for producing the observed peak[25].

The high sputtering yields for sulphur[21] allow a velocity distribution that falls off rapidly with increasing velocity and yet still gives an adequate source rate for maintaining the torus. For example, for a 3% escape fraction, 20% surface coverage and incident H^+ ions with energies >220 keV, it has been estimated previously[10] that a sputtering yield of one would give 10^{22} neutrals per second injected into the torus. A 4% escape fraction is obtained for the thermal spike velocity distribution of equation (2) with $T = 4,000$ K. The measured sputtering yield of 10^6 for sulphur would then imply an injection rate of $>10^{28}$ s^{-1}, approximately the rate required from other arguments[10,18,20]. This rate estimate may be low, as bombardment by heavier ions could lead to even higher sputtering yields, and lower energy ions (corotation energy to 220 keV) will undoubtedly contribute significant additional sputtering. Because flux-tube interchange diffusion produces strong outward mixing, the proposed sulphur source would produce a hot outer torus dominated by sulphur ions. It is not known whether sputtering of sulphur at Io will be as efficient as in the laboratory. In particular, the sputtering efficiency seems to increase with increasing source temperature[21]. In this regard, the 'hotspots' seen on Io[27] may be areas of more efficient sputtering. The

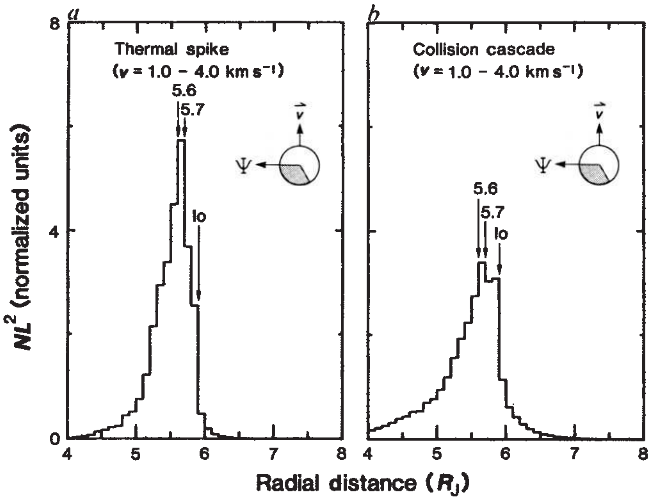

Fig. 5 *a*, As Fig. 4*a* except that the neutrals were ejected only from the sulphur-rich regions of Io[25] shown in Fig. 2*b*. A sharper inward peak is formed. As recent experiments[21] indicate that sulphur gives anomalously high sputtering yields, the sulphur-rich regions may be the predominant source of Io torus ions. Ionization occurring in a narrow range of radial location near 5.7 R_J as shown here could explain the narrow, 'ribbon-like' structure seen in ground-based observations of sulphur ions[1]. *b*, As *a*, except that a collision cascade velocity distribution with a binding energy of 0.1 eV was used. An adequate inward peak is still formed, even though the fall off of the velocity distribution is much more gradual. Recent experiments[21] on the sputtering of sulphur have shown that for sputtering by 3-9 keV Ar^+ ions, an effective surface binding energy of 0.1-0.3 eV is appropriate for sulphur.

longitudinal locations of the hotspots are also favourable for formation of the inward peak.

It is more difficult to reconcile our results with SO_2 as the dominant source. The requirement that the velocity distribution fall off rapidly with velocity, coupled with the much lower sputtering yields for SO_2, make it unlikely that a dominant SO_2 source on the surface of Io could provide the necessary escape rates to populate the torus. Although our results do not eliminate sputtering from a thick SO_2 (or sulphur) atmosphere as the dominant source, they do place constraints on this possibility. It has been noted[10,28] that sputtering from such an atmosphere can easily maintain the required total source rate of neutrals. However, the velocity distribution expected for this source[28] (similar to a collision cascade distribution) does not fall off rapidly enough for the neutrals to form the inward peak unless the source is longitudinally asymmetrical. The primary sputtering product from a thick SO_2 atmosphere (density of $\sim 10^{10}$ cm^{-3} at the surface) would be atomic oxygen[10,20], so again a mechanism that limits the ionization of neutrals near Io would be necessary. If the source is a thick SO_2 atmosphere, sputtering models predict more than adequate oxygen escape rates but they encounter problems in obtaining even the minimum required sulphur escape rates[10,20]. A thick atmosphere on the dayside of Io coupled with a thin atmosphere on the nightside that allows sputtering of sulphur from the surface of Io could resolve this dilemma.

In our calculations, assumptions regarding lifetimes for neutrals ignore any variation of ionization probability with position. Thus, we have effectively assumed a uniform electron density (n_e) and temperature (T_e) distribution throughout the torus. In actuality, n_e and T_e drop sharply inside 5.7 R_J, making ionization in the region of the observed peak more likely. By using a model with uniform n_e and T_e, we are able to investigate the question of whether or not the peak can form inward of Io solely because neutral particles tend to spend most of their time in this region. As our calculations have shown, there are physically plausible scenarios in which neutral particles will tend to be ionized to form a peak inwards of Io, even for uniform distributions of n_e and T_e. This then explains how the peak in the ion density could form inwards of Io in the first place. Heating of electrons by collisions with pickup ions would then, in turn, produce the observed radial variation of T_e (ref. 29). The T_e variation would increase the probability of ionization near the peaks of the derived profiles of newly ionized neutrals. Thus, in a self-consistent calculation, the locations of the peaks we have obtained would not change, but their steepness would be enhanced. We believe that 'the ribbon' of S(II) emission observed[1] near 5.7 R_J may be explained in this way. We have not taken into account the possible effects of collisions on the trajectories in our calculations. Although collisional processes could introduce some spread into the trajectories of the neutrals, our basic result, that the inward peak forms if the distribution of neutral velocities falls off rapidly with increasing velocity, should remain unaffected.

By assuming that the dominant neutral source of torus ions is S_2, we showed that only small numbers of ions are created near Io as necessary for consistency with observations. The limitation to the ionization rate near Io can be achieved in other ways. For example, the presence of the neutral cloud near Io can limit the amount of ionization. Within 3 Io radii of Io's surface, the density of sputtered neutrals will be much greater than the electron density, so it is possible that ionization near Io is limited by the availability of the electrons or by electron cooling resulting from interaction with the neutral cloud. A cooler electron temperature in the Io flux tube has in fact been observed[30]. If the presence of the neutral cloud does in fact limit ionization and other neutral species meet the constraints on the velocity distribution and/or source locations for formation of the inward peak, then S_2 need not be the dominant neutral injected into the torus.

Similar trajectory calculations have been performed previously for sodium[31,32] and a model, including the electron density and temperature profiles, has been published for oxygen[33]. The latter calculation provides useful insight into the supply of ions to the torus, but it does not explain why the radial profiles of ion density and NL^2 peak inwards of Io's orbit. In the cited calculation[33], the measured n_e and T_e profiles were assumed and then the position where the particles were ionized was determined. The calculated radial profile of newly created ions obtained in ref. 33 peaks roughly at Io's orbit (Figure 8 of ref. 33), farther out than the peak in the ion-density data. As electron and ion number densities must peak in the same location, the electron distribution assumed for the calculation in ref. 33 would not be maintained in a steady state. Furthermore, because the newly created pickup ions are responsible for the radial variations of n_e and T_e, a calculation that assumes observed radial profiles for these quantities does not demonstrate how the peaks developed inwards of Io in the first place. In addition, we note that the calculated[33] peak in the ion-creation rate was obtained for particles launched from the exobase (at 2,600 km) with a velocity of 2.6 km s^{-1}. This velocity maps roughly to a velocity of 3.0 km s^{-1} for a particle leaving the surface of Io. As seen in Fig. 4*b*, when velocities much larger than the escape velocity become important, the inward peak does not form for sources distributed uniformly in longitude. In fact, for a velocity of 3.0 km s^{-1}, even a source restricted in longitude will not form the inward peak. Thus it seems that the neutral velocity chosen for the calculations of ref. 33 is too high to form a peak much inside Io's orbit. Finally, we note that because neutrals with velocities below the escape velocity were not considered in ref. 33, the important effects of ionization of neutrals on trapped trajectories were ignored in their calculations.

Conclusions

We have investigated models for the formation of the peak in ion density and NL^2 inwards of Io's orbit. We summarize our findings as follows: (1) Neutral particles with velocities above the escape velocity sputtered from sources independent of Io longitude will form a peak inward of Io between 5.6 and 5.7

R_J, provided that the velocity distribution drops off sufficiently rapidly. We have shown that a thermal spike velocity distribution (equation (2)) produces such a peak whereas distributions that fall off as v^{-3} or less do not create the required peak. (2) If the sputtering sources are confined to longitudinal regions on Io where sulphur predominates[25], the inward peak is obtained even for less steeply decreasing velocity distributions (such as collision cascade). If a thermal spike velocity distribution is used, a sharper inward peak is formed. (3) Velocity distributions predicted for sputtering of neutrals place many more particles on trapped (non-escape) trajectories than on escape trajectories, so an adequate source rate[20] of ions in the torus ($2\text{-}7\times10^{28}\ s^{-1}$) implies that a dense neutral cloud ($10^5\text{-}10^6\ cm^{-3}$) will form within 3 Io radii of Io's surface. Ionization of atomic sulphur and oxygen in this cloud must be limited by some process to satisfy observational constraints on ionization[17] and for formation of the inward peak. (4) The above results are more readily reconciled with S_2 being the dominant neutral injected into the torus rather than SO_2 or O. In particular, the large sputtering yields recently demonstrated for sulphur[21] would allow sputtered sulphur to have a steeply decreasing velocity distribution and still give an adequate source rate of neutrals into the torus. In addition, the sulphur-rich volcanoes on Io are confined to a longitudinal region favourable for producing the inward peak[25]. A dominant SO_2 source on the surface is unlikely, because if SO_2 were sputtered with the required rapidly decreasing velocity distribution, the source rate of neutrals into the torus would seem to be inadequate. If the presence of the dense neutral cloud near Io limits ionization of all neutral species, a thick SO_2 atmosphere cannot be eliminated; however, velocity distributions previously estimated for this possibility[28] do not fall off rapidly enough with increasing velocity to produce the inward peak without invoking a source that is asymmetrical in longitude. (5) Although the above arguments suggest that the dominant source of ions in the hot torus is neutral sulphur, consistent with previous evidence from ion partitioning[26], an SO_2 or O source with a collision cascade velocity distribution would provide ions more widely distributed in radial distance and these ions may dominate the inner cool torus, whose composition need not be the same as that of the hot torus.

We thank F. Bagenal and J. T. Trauger for providing advance copies of their recent papers on the Io torus. We are grateful to P. R. Higbie for calling our attention to recent work on sputtering of sulphur and to W. H. Smyth for encouraging us to reconsider assumptions regarding the distribution of lifetimes. This work was partially supported by NASA under grant NSG-7295 and by the Jet Propulsion Laboratory under contract 955232.

Received 28 January; accepted 11 March 1985.

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Speed of sound in the solar interior

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Frequencies of solar 5-min oscillations can be used to determine directly the sound speed of the solar interior. The determination described here does not depend on a solar model, but relies only on a simple asymptotic description of the oscillations in terms of trapped acoustic waves.

SOLAR 5-min oscillations are acoustic waves that propagate in a waveguide beneath the surface of the Sun. For any particular wave, the guide is a spherical shell whose boundaries depend on the frequency and wavenumber of the wave. Upward directed waves are reflected just benath the photosphere, where the density scale height is comparable with the wavelength. Refraction of a wave initially propagating downwards deflects the path back towards the surface, at a point where the local horizontal component of the speed of the wave is equal to the sound speed.

The frequency of a wave that resonates in the waveguide depends on the variation of the sound speed with depth. The latter determines both the locations of the boundaries of the cavity within which the wave can propagate and the time it takes for the wave to traverse that cavity. By considering successively the frequencies of a sequence of modes that penetrate deeper and deeper, it is possible, at least in principle, to measure how the sound speed varies with depth.

Using an approximation to the observed dispersion relation presented in ref. 1 for modes with degrees in excess of 100, it has already been possible to estimate the sound speed in the upper half of the convection zone[2]. More recent observations[3,4] have isolated modes with degrees as low as unity, which sample almost the entire volume of the Sun. Therefore, we should now have sufficient data to infer the sound speed almost everywhere.