Nonisotropic Coronal Atmosphere on Io

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A model is presented for calculating nonisotropic coronal atmospheres. This is tested by comparison with the analytic results for an isotropic atmosphere. It is then used to consider differences between sublimated and sputtered corona on Io with reference to the ion and electron bombardment of such corona when the exobase is at or near the surface.

Introduction

Io, Jupiter's innermost Galilean satellite, orbits in an environment rich in charged magnetospheric particles and shared by an extensive cloud of neutral sodium, potassium, oxygen, and probably sulfur [Pilcher and Strobel, 1982]. The presence of these neutrals is thought to result from the interaction of Io and its atmosphere with the heavy ions (mostly sulfur and oxygen) which dominate the Jovian plasma near Io. The torus ions are relatively cold (thermal energies of ~30 eV near Io) and overtake Io with a mean velocity of ~57 km/s [Belcher, 1983]. Since the nature of the atmosphere on Io has not been determined, the possibility remains that particles ejected (sputtered) from Io's surface by incident ions could be the dominant contribution to an atmospheric corona [Lanzerotti and Brown, 1983]. (We used the word corona as being equivalent to the exospheric part of an atmosphere in which collisions between molecules are unlikely.) Since subsequent removal of particles from this corona, through collisions with the plasma wind, may contribute significantly to the flux of neutrals escaping Io [Sieveka, 1983; Sieveka and Johnson, 1984], it is important to know the structure of such an exosphere.

If the flux of incident ions and the surface material to be sputtered are both isotropic, one can obtain coronal densities by a semi-analytical method [Watson, 1981]. If, however, the incident-ion flux is nonisotropic, as is the case for torus ions striking predominantly on the trailing hemisphere of Io, such a treatment is not possible. In this report a Monte Carlo calculation of coronal densities is presented for both an isotropic incident flux and a nonisotropic incident flux having one axis of symmetry. The accuracy of the Monte Carlo method is checked by comparing the calculation in which the bombardment is assumed to be isotropic with the semi-analytical result. After establishing the accuracy of the method, number density contours are given for the nonisotropic coronae, and the column densities are calculated along lines parallel to the symmetry axis. These latter quantities can be combined with appropriate collision cross sections to estimate the frequency of collisions between coronal particles and plasma ions as a possible source for the neutral torus [Sieveka and Johnson, 1984]. For comparison with the sputter-produced corona we also calculate the atmosphere generated by the sublimation of SO_2 frost from Io's dayside hemisphere. In all cases we assume full surface coverage of SO_2. Results can be scaled accordingly as more information on the surface is obtained, provided that the average SO_2 distribution remains roughly isotropic on a global scale.

Calculations

For a source uniformly distributed over the satellite's surface the angular position of the orbiting particle is not needed in determining the radial densities. A nonisotropic source, as produced by torus plasma bombardment, does, however, require angular as well as radial positions to describe the atmosphere. The Monte Carlo calculation used here is an extension of the one used by Sieveka and Johnson [1982] to calculate surface redistribution on icy satellites. In that paper, only the locations from which a particle left and at which it reimpacted the surface were required. In the present calculation a particle is followed throughout its trajectory to determine the mean time per unit distance, \( \Delta t/\Delta r \), it spends within the interval \( r \) to \( r + \Delta r \), while at the same time keeping track of its angular position. Each particle represents a fraction \( \Delta \Phi \) of the flux leaving the surface, and the contribution it makes to the number density \( n \) can be expressed as

\[
\Delta n(r, \Omega) = \Delta \Phi \Delta t/\Delta r
\]

(1)

All particles are assumed to stick upon reimpact with the surface.

If there is no axis of symmetry, three discrete variables are needed to describe \( \Delta n(r, \Omega) \). For the present calculation, however, the torus plasma is assumed to be symmetric about an axis aligned with the direction of flow, allowing the azimuthal variable \( \phi \) to be eliminated. This assumption should be valid, on the average, since the region of maximum plasma density is roughly centered at Io's orbit [Pilcher and Strobel, 1982; Sandel et al., 1979; Broadfoot et al., 1979; Brown et al., 1983].

The surface is divided into angular intervals \( \Delta \theta \), where \( \theta \) is the angle from the symmetry axis. Particles leave the surface from a given region \( (\theta, \phi) \) with initial velocity vectors distributed isotropically about the surface normal in the azimuth angle \( \phi \) and distributed as \( \cos \psi \) in the zenith angle \( \chi \). Their trajectories carry them around the satellite in both \( \theta \) and \( \phi \), but symmetry in \( \phi \) means that only values of \( \theta \) need to be recorded. Location in terms of \( \theta \) is approximated by \( \theta(r + \Delta r')/2 \) or if the particle's orbit reaches a maximum between \( r \) and \( r + \Delta r \), by an average of \( \theta(r) \) and \( \theta(r_{\max}) \). The mean time \( \Delta t/\Delta r \) needed to determine \( \Delta n \) is calculated in two ways. For particles passing entirely through the interval \( r \) to \( r + \Delta r \), \( \Delta t/\Delta r \) is simply approximated as \( r^{-1} \) evaluated at \( r + \Delta r/2 \). If, however, the orbit reaches a maximum in this interval, \( \Delta t/\Delta r \) is found by integrating \( \delta^{-1} \) from \( \delta(r) \) to \( \delta(r_{\max}) \) and dividing by \( \Delta r \). The angle \( \delta \) lies in the plane of the particles' orbit; hence \( \delta \) is given by the angular momentum, \( \delta = L/mr^2 \). The average density, obtained by summing the contribution \( \Delta n \) from all of the orbiting particles, is used to approximate \( n(r + \Delta r/2, \theta) \) (for more details, see Sieveka [1983]).

Densities were calculated up to 4.8 Io radii from the surface. This is approximately the location of the Lagrange sphere for
the Io-Jupiter system and defines a practical upper limit. Particles outside this sphere are considered to be part of the neutral cloud rather than Io's corona.

The energy distribution of sputtered particles has been discussed by several authors [Townsend et al., 1976; Johnson et al., 1984] and is still being investigated. Since the incident-ion energies at Io (∼280 eV for O⁺ and ∼560 eV for S⁺) are low and should result in limited electronic excitation, the energy distribution,

$$\Phi(E) = \left[ \frac{2E_b}{(E + E_b)^3} \right] \Phi$$

(2)

associated with collisional energy transfer is used in this paper. Φ is the total surface flux of sputtered molecules, and the quantity E_b is the binding energy of the material being sputtered. For comparison with Watson [1981] the value of E_b = 0.28 eV is used, although recent measurements on SO₂ ice have indicated a lower effective value of E_b, approximately ½ of the above value [Boring et al., 1984; Johnson et al., 1984]. These measurements were for ion energies greater than 10 keV, but as we expect they will also apply to the lower energies of the Io torus, an energy spectrum with the lower value of E_b is considered. A total surface flux Φ = 5 × 10¹¹ SO₂/cm² is used, based on an average sputter yield of ∼50 [Johnson et al., 1984] and an ion flux of ∼10¹⁰ ions cm⁻² s⁻¹.

We first compared typical Monte Carlo (MC) number densities to those obtained from the analytic expression [Watson, 1981] when the bombardment is isotropic. The values used for Δθ and Δr are 6° and 0.2 Io radii, respectively. Agreement between these calculations, when 2 × 10⁴ particles are used for the MC calculation, is about 2% or better. Integrated column densities agree to within 10% when the MC column density is calculated by a Simpson’s rule integration of the number density. Greater agreement with the semianalytical value can be obtained, if necessary, by decreasing Δr in the MC number density calculation. Finer resolution is costly in terms of computation time, however, and may not be warranted when other uncertainties involving incident flux, sputtered yield, and surface composition are considered.

RESULTS AND DISCUSSION

Figure 1 shows the radial column densities for nonisotropic coronae produced by a plasma impacting on the trailing side of Io and distributed as the cosine of the angle from the symmetry axis, θ. The values of U are 0.28 eV (curve 2) and 0.05 eV (curve 3). These are compared to Watson’s calculation for U = 0.28 eV (curve 1) with the yield given above. The importance of considering the nonisotropic result is apparent. Even at the point of maximum bombardment the column densities for curves 1 and 2 differ considerably [Sieveka, 1983]. The isotropic model for column densities, although straightforward to evaluate, in fact bears almost no relationship with the more realistic trailing hemisphere bombardment model. The differences between curves 2 and 3 in Figure 1 emphasize the importance of the parameter E_b even when the total sputter yield is held constant. The column densities are large for curve 3 as the escape flux is lower, but the particles are still energetic enough to travel considerable distances over the surface. The mean angular excursion across the surface of Io when E_b = 0.05 eV is of the order 1.2 rad [Johnson et al., 1984]. Curve 3 is the most realistic sputtered corona for full surface coverage of SO₂.

The number density contours associated with curve 3 are shown in Figure 2a. For comparison with the sputtered result we give in Figure 2b the result for a sublimated atmosphere calculated using a Δθ of 3°, Δr = 0.005 Io radii and T_max = 100 K. A maximum surface temperature of 100 K has been chosen for this comparison, as it has, roughly, the same maximum column density as our sputtered atmosphere. Also, 100 K corresponds to something of a dividing line for SO₂ sublimation on Io. For temperatures greater than 100 K the sublimated atmosphere cannot be considered collisionless and will have an exobase above the surface. Temperatures of ≤100 K should be typical of Io’s nightside. Implications of a higher surface temperature will be discussed shortly.

Whereas the sputtered atmosphere in Figure 2a occupies a large region of space about Io, the sublimated atmosphere in Figure 2b is very compressed because of the lower energies of the emitted SO₂ molecules. Of greater interest for studying the interaction of incident plasma with such coronae or for evaluating attempts by spacecraft to measure atmospheric density by stellar occultation is the column density N along directions other than radial. The solid curves in Figure 3 show column densities seen by particles traveling parallel to the symmetry axis. In this, we assume the subsolar point is centered on the trailing hemisphere to allow a direct comparison of the sublimated and sputtered corona. Although the maximum column density for a sublimated atmosphere with T_max ~ 100 K is approximately equal to that of the sputtered atmosphere.
Fig. 2a. MC calculated sputtered molecular densities (equivalent to those in Figure 1, curve 3).

Fig. 2b. MC calculated sublimated molecular densities corresponding to a maximum temperature at the subsolar point of 100 K. For a maximum temperature of 137 K the top contour corresponds to $\sim 1 \times 10^9$ mol/cm$^2$, which is the density we associate with the exobase.

Fig. 2. Density contours for sputtered and sublimated SO$_2$ on Io.

(curve 1), the sublimated atmosphere (curve 2) does not contribute outside of Io's disc.

The total number of particles available in such atmospheres for collisional ejection is determined by integrating $2\pi R \, dR$. Therefore, in Figure 3, curves for which the column densities are multiplied by $R$ are also shown (dashed curves) in order to compare contributions at each radius. It is seen that the sublimated atmospheric contribution falls off rapidly within the satellite disc, whereas the sputtered atmospheric column density decreases relatively slowly with distance from Io. This difference can be attributed to the large difference in the energy spectra of the ejected molecules [Sieveka and Johnson, 1982; Watson, 1981]. Therefore, although the maximum sublimated column density shown is about the same as the sputtered result, it is seen that bombarding ions are much more likely to experience collisions with the sputtered corona. We note that the sputtered column densities are not large enough to impede ion bombardment of the surface. (This requires densities of $>2 \times 10^{15}$ molecules/cm$^2$ [Lanzorotti et al., 1982].) However, low-energy-transfer collisions of the incident
ions with the SO$_2$ in the atmosphere leading to ejection of SO$_2$ are likely [Sieveka and Johnson, 1984]. In addition, for full surface coverage of SO$_2$ the sputtered atmosphere has of the order of an exospheric column density over the trailing hemisphere (Figure 2, curve 3, and Figure 3). At temperatures greater than 80 K the sputter yield increases with increasing temperature [Lanzerotti et al., 1982; Lanzerotti and Brown, 1983]. This increase, which we do not include here, would produce a corresponding increase in the sputtered atmospheric densities and is related to the production of new species (e.g., O$_2$, SO, SO$_2$) which are also sputtered energetically.

If sublimation is controlled by a maximum temperature of ~137 K, based on the observed albedo, the subsolar column density will be greater by a factor of ~10$^5$ [Matson and Nash, 1983]. The exobase now occurs above the surface. In the absence of any UV heating of the atmosphere the contour in Figure 2b would correspond to the exobase (~10$^9$ molecules/cm$^2$). Under this assumption the increased column densities in Figure 3 would still fall off rapidly so that the number of collisions with sublimated molecules outside the disc region remains small. However, incoming plasma ions impacting the dense regions of such an atmosphere would not, in general, penetrate to Io’s surface. Instead, when the atmosphere has an exobase, the bombarding ions will sputter molecules from the exobase (the new effective surface), thereby generating a sputtered corona superimposed on the thermal corona [Watson, 1981]. The sputtered molecule energy spectra used to generate such a corona are estimated by setting $E_a = 0$ in equation (2) and cutting the spectra off at the temperature of the exobase. Noting that the peak in the measured energy spectra of sputtered particles of 0.5E$_{th}$ (0.025 eV) corresponds to a temperature of ~300 K, a corona sputtered from an atmospheric exobase at 137 K should be reasonably well described by the sputtered corona shown in Figure 2a. This is particularly so as the exobase seen in Figure 2b for this atmosphere lies relatively close to the surface so that the gravitational effect is roughly the same. Under these assumptions therefore, Io would have a relatively stable SO$_2$ corona of considerable extent produced by the bombarding ions whether the SO$_2$ remains condensed on the surface of the trailing hemisphere (e.g., subsolar point on the leading hemisphere) or whether SO$_2$ is sublimated and forms an undissociated atmosphere. Such a stable corona would mean that the collisional ejection of coronal particles by plasma ions [Sieveka and Johnson, 1984] is a stable source of escaping neutrals independent of the orientation of the satellite to the bombarding flux and to the sun.

If UV heating of the atmosphere is considered and the chemical and transport processes are in equilibrium, Kumar [1984, 1985] has shown that the atmosphere can have an exobase at much higher altitudes. Such an exosphere is generally dominated by dissociated species (e.g., O [Kumar, 1984]) and may vary considerably with solar zenith angle. This will be treated in a subsequent paper. The observations established above, however, remain valid; the sputtered atoms/molecules will dominate the exosphere.

As the mean flight times $\tau_0$ for SO$_2$ sputtered from the surface [Johnson et al., 1984] are of the order of 10$^3$ s and the plasma ionization and charge exchange rate $\tau_1^{-1}$ is of the order of 6.1 $\times$ 10$^{-5}$ s$^{-1}$ [Kumar, 1984], only about 6% of the sputtered molecules are likely to be ionized in their ballistic orbits. Of the roughly 5 $\times$ 10$^{13}$ molecules which reside in the sputtered atmosphere at any time, of the order of 2 $\times$ 10$^{11}$ lie in the corona outside the disc. Ionizations produced within the disc region can contribute to an ionosphere [Kliore et al., 1974; Kumar, 1985] and will enhance the surface bombardment [Matson et al., 1974]. The atmospheric content of SO$_2$ and densities in Figures 2a and 3 should be increased because of this bombardment by a factor (1 - $Y_\text{Io}/Y_\text{sat}$) for ($Y_\text{Io}/Y_\text{sat}$) < 1 [Matson et al., 1974]. For a yield of about 50 we find ($Y_\text{Io}/Y_\text{sat}$) > 1. This implies that the maximum column density, limited only by ion penetration to the surface, is achievable on the trailing hemisphere even if there is not full surface coverage by SO$_2$. The maximum column density achievable on this trailing hemisphere by corotating ion bombardment is ~2 $\times$ 10$^{15}$ molecules/cm$^2$, the approximate penetration depth of the ions [Lanzerotti et al., 1982]. As this is much greater than an exospheric column density of SO$_2$, this sputter exobase also lies above the surface.

Ionizations (charge exchanges) produced outside the disc will result in the loss of SO$_2$ by sweeping. Combining this loss with collisional ejection (~1 $\times$ 10$^{13}$ s$^{-1}$ [Sieveka and Johnson, 1984]) and direct sputtering ejection (~3% [Johnson et al., 1984; Kumar, 1984]) gives a net loss of ~6 $\times$ 10$^{12}$ molecules/s (~1 $\times$ 10$^{28}$ amu/s). This rate is smaller than the estimated supply rate for the plasma [Cheng, 1984] even though we have assumed full surface coverage of SO$_2$. However, it does not include the enhancements discussed above. This estimate would also apply to sputtering from an undissociated atmosphere with an exobase near Io’s surface. A significant change in the loss rate therefore would require that the exobase be at a higher altitude than that assumed here [Watson, 1981; Lanzerotti and Brown, 1983; Kumar, 1984, Sieveka and Johnson, 1984] because of either UV absorption or enhanced sputtering or a higher component of energetic particles in the energy spectra.

In this note we have calculated the sputter corona produced by plasma ion bombardment of the surface of Io using laboratory data for the sputtering of SO$_2$. The atmospheric density profiles and column densities are therefore available for modeling the magnetospheric interaction with Io.

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Correction to "Nonisotropic Coronal Atmosphere on Io"
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In the paper "Nonisotropic Coronal Atmosphere on Io" by E. M. Siveka and R. E. Johnson (Journal of Geophysical Research, 90(A6), 5327-5331, 1985) there was an error of a factor of two in the numbers quoted for the corona on page 5330, column two. The figures are correct. The correct numbers are as follows: 10 × 10^{21} particles in the sputtered atmosphere; 4 × 10^{22} particles in the corona outside the disc; collisional ejection ~1 × 10^{-5} s^{-1}; net loss of material from Io ~6 × 10^{27} SO_2 molecules/s (~4 × 10^{27} amu/s). Using full surface coverage, these numbers are all lower limits as described in the text. Therefore, of the order of half to a fifth of the torus supply rates thought to be required can be achieved by sputtering from the surface and ejection from the corona produced by this sputtering. This estimate does not take into account either dissociation or the enhanced sputtering due to particles ionized in the disc region as discussed in the paper. The latter effect creates an exobase above the surface and increases the loss. Calculations for such exobases are in preparation.

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