

A MECHANISM FOR THE PRODUCTION OF A DISK-SHAPED NEUTRAL SOURCE CLOUD AT IO

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ABSTRACT

Io adds of the order of 1000 kg s^{-1} of ionized material to the jovian magnetosphere. Freshly produced molecular ions, such as SO^+ and SO_2^+ , lead to the growth of ion cyclotron waves at frequencies characteristic of their gyro frequencies. These waves are seen over a region about $0.5 R_J$ radially inward and outward from Io and of similar or greater extent in the down wake direction but not upstream of Io. We examine simplified numerical simulations of the massloading process that preserve the essential physics and demonstrate how this geometry of the massloading region can be created and what we might expect to see on future Galileo Io passes.

INTRODUCTION

That Io plays an important role in the energization of the jovian magnetosphere has been known since the discovery of its control of jovian radio emissions [Bigg, 1964]. Voyager observations have revealed many details of the massloading process at Io [e.g. Goertz, 1980] but still it was widely believed that the primary mechanism for generating the field-aligned currents was a unipolar induction mechanism in which the electric field of the corotating jovian magnetosphere applied a potential drop to a conducting Io. In fact Galileo shows [e.g. Russell *et al.*, 1997] that much of the flow is deflected around Io and therefore the currents in the Alfvén wing must close in the massloading region. This current closure provides the Lorentz force needed to bring the added plasma up to corotational velocities. The Galileo observation also revealed that the 1000 kg s^{-1} that seemed required to explain the various Voyager observations [Dessler, 1980] were not added close to Io where the torus interacted with the Io exosphere [Russell *et al.*, 1997; Bagenal, 1997]. Rather, the evidence from the Galileo wave observations was that SO_2 was being added over a very wide radial extent, perhaps a half jovian radius inward and outward from Io [Kivelson *et al.*, 1996; Huddleston *et al.*, 1998]. This distance is much greater than would be expected if SO_2 were ejected from Io at the speed of 2.6 km s^{-1} that has been taken to be characteristic of neutral sodium ejection [Smyth and Combi, 1988] because SO_2 dissociates on time scales of about 0.5h near Io. This large radial extent is in contrast to the absence of any local ion production on the Io flux tubes directly beneath Io, inferred from the absence of ion cyclotron waves as Voyager I passed Io, ten Io radii beneath it, in 1979 [Russell and Huddleston, 2000].

While the initial Galileo data provided a radial range over which the massloading occurred, it was not until the availability of new Io data in the Galileo Europa Mission phase that the extent along the wake became understood. As discussed in the companion paper [Russell and Kivelson, 2001] SO_2 and SO ion cyclotron waves were not seen upstream from Io but were observed downstream as far as Galileo returned data. The absence of ion cyclotron waves upstream of Io clearly indicate that the neutral cloud of SO_2 and SO is not the banana-shaped cloud postulated for Na that extends upstream and down from Io but rather the neutral cloud extends only downstream. It is possible to understand the creation of such a massloading region in much the same way as has been postulated for the production of the directional feature neutral sodium cloud at Io [e.g. Wilson and Schneider, 1999] with just one more step added. This mechanism relies on the electric field of the jovian magnetosphere to accelerate ions, charge exchange to produce fast neutrals from these accelerated ions, and then transport across the magnetic field as neutrals, followed by subsequent ionization. It is the purpose of this paper to show results of a computer

simulation of this model to demonstrate how it can produce the observed massloading region and the wave generation observed as well as populate the Io torus over a wide radial range in the absence of interchange of flux tubes or the diffusion of particles.

THE MECHANISM

There are five steps in our model of the mass addition process: the initial ionization, gyration around the magnetic field, neutralization, transport across the magnetic field as a neutral particle, and reionization at some distance from Io. This process is sketched in Figure 1 for an individual ion. There are two key times involved in this process: the time, τ_1 , that the initial ion spends in its gyration and the time, τ_2 , the neutral spends transiting the magnetospheric region.

The first time, τ_1 , controls how much energy the particle will pick up from the corotating magnetosphere plasma through the action of the electric field. It picks up its maximum energy after half a gyration. The direction of motion of the particle is also controlled by this time. It is important to note that the radial electric field can only accelerate particles outward, inward and downstream. This mechanism does not accelerate particles in the upstream direction. Finally, we note that τ_1 depends on the cross-section for charge exchange of the relevant species and the density of the neutrals where the charge exchange occurs. We do not explore these issues herein.

The second time, τ_2 , controls how far the neutral particle travels before it is reionized and joins the torus plasma. This time constant depends on the various processes that can ionize particles, such as UV and EUV fluxes, impact ionization and possibly charge exchange. Again we do not explore the expected values from first principles but rather vary τ_2 to determine how τ_2 affects the properties of the massloading region.

THE MODEL

Figure 2 illustrates how this multi-step process is incorporated into a more realistic simulation of the Io interaction with its torus. This model is similar to that proposed by *Wilson and Schneider [1999]* for the production directional feature of the sodium cloud. The dots surrounding Io are the atmospheric neutrals. The ionized atomic species of the torus plasma drift upward in this diagram in the combined magnetic and electric fields of the jovian magnetosphere. These particles can directly participate in the initial ionization process or just be vehicles for supporting the electric field and subsequent acceleration of the ions that may occur in the exosphere due to photoionization. Some of the ions produced are accelerated into Io. This could be a source of sputtering that produces more exosphere but our early examination of the data suggests that the location of the sunlit side of Io relative to the torus flow is an important controlling factor. If sputtering and not sunlight were the important factor

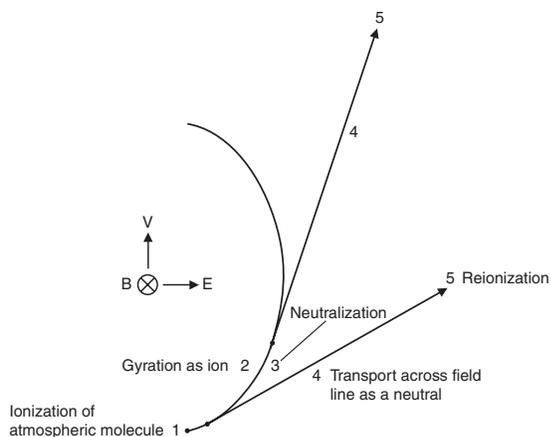


Fig. 1. Schematic of the mechanism used to produce the massloading disk. An atmospheric ion is produced. It gyrates part way around a cyclotron. It is reneutralized and moves in an approximately straight line in Jupiter's gravitational field for a distance determined by its lifetime and velocity. Then it is reionized.

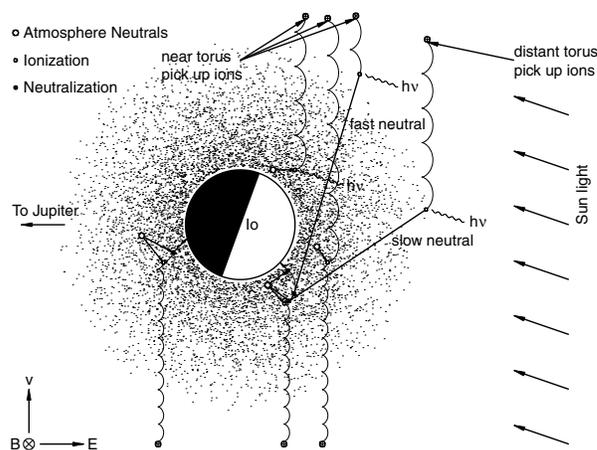


Fig. 2. Schematic of the model used. The Io exosphere, assumed here uniform, provides neutrals that are ionized in the flowing torus plasma. The newly made ions can escape into the torus flow, hit Io or become neutrals via charge exchange, thus making a fast particle that can travel far across the magnetic field. Eventually these fast neutral particles are reionized and join the torus.

in controlling the production of the exosphere, then the mass addition process would be more independent of the solar phase of Io. However, the power of SO₂ waves are very dependent on the phase of Io and the SO waves also, but less so [Russell et al., 2001].

The sketch in Figure 2 emphasizes the local frame of Io but particles move sufficient distances away from Io that we need to consider the motion of the particles in the combined gravity fields of Jupiter and Io as well as the magnetospheric electric field that we take to be that corresponding to strict corotation in a dipolar magnetic field. This geometry is sketched in Figure 3. We then integrate particle motion in this geometry varying only τ_1 , and τ_2 , in different runs, using a probabilistic formula to determine if any particular particle will be ionized or neutralized at a particular time in the simulation. Particles are traced from a uniform ring in Io's equator at an altitude of 300 km. If a particle moves below 280 km it is presumed to be lost to collisions.

APPLYING THE MODEL

We now examine the results of running the particle tracing model. Figure 4 shows the neutral particle cloud produced with a neutralization time, τ_1 , equal to the gyro period of the initial ion, and does so for 4 times 0.9h, 1.9h, 3.7h and 9.3h after the initiation of the simulation. The time for reionization of the fast neutrals is 1000 times this or about 2000s if the ion is SO₂⁺. This value is similar to the expected dissociation time for SO₂ [Summers and Strobel, 1996]. The model shows that after about 4 hours the neutral torus has achieved steady state. The neutral torus extends inward much less than it extends outward from Io.

The Io torus rotates much faster than Io orbits, 74 km s⁻¹ versus 17 km s⁻¹. Thus picked up ions move away from Io much more rapidly than the neutral cloud. This is illustrated in Figure 5 again for a τ_1 , equal to the gyro period of the ion at Io and a τ_2 , equal 1000 times τ_1 . After 9.3 hours the formation of the ion torus is almost complete. The radial extent of the newly born ions is of course the same as that of the neutral cloud. The only difference is that the ions form a complete torus while the neutral molecules that are being destroyed through ionization and dissociation, form only a cloud.

The strength of this source for the torus plasma depends on the exospheric density, torus electron density and temperature, solar UV flux and other details of the interaction, that we do not now explore, but we can construct normalized profiles that allow qualitative comparisons with the known torus properties. Figure 6 shows one such

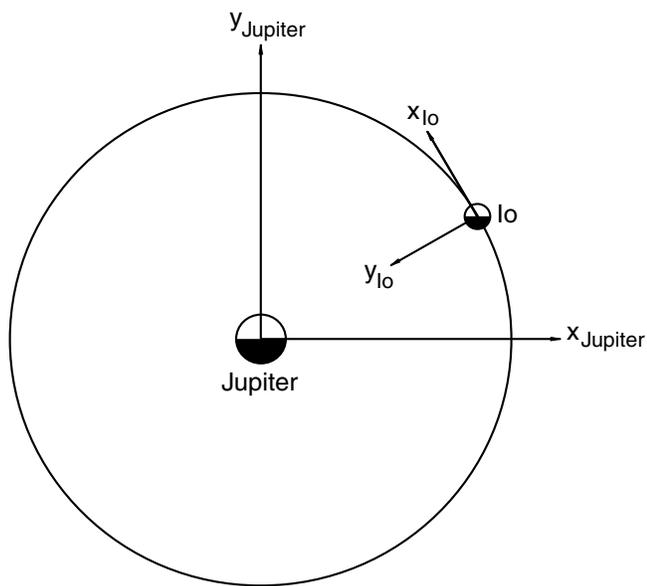


Fig. 3. Coordinate system used in the numerical calculations. The particles are traced in the combined gravity fields of Jupiter and Io as Io orbits Jupiter and the torus plasma corotates.

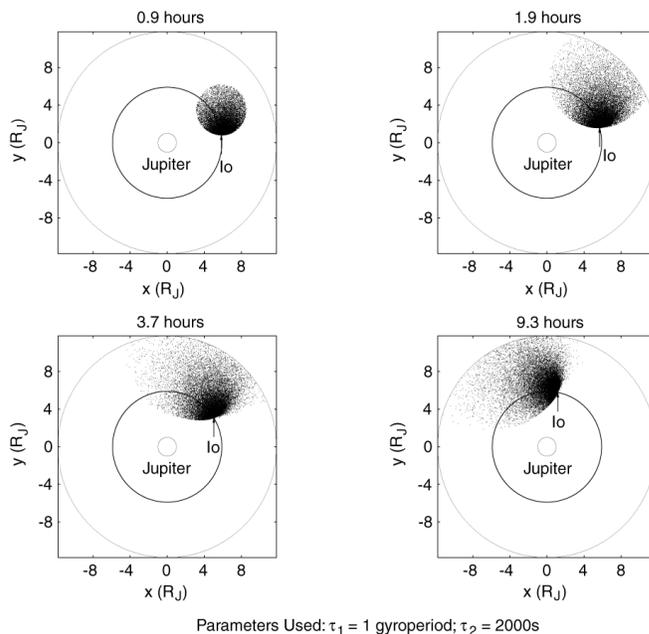


Fig. 4. The fast neutral particles produced for a run with τ_1 , equal the ion gyro period at Io and τ_2 equal 1000 times the gyro period. The neutral cloud shown at 0.9, 1.9, 3.7 and 9.3h after the initiation of the calculation. The Io exosphere is taken to be uniform in this run.

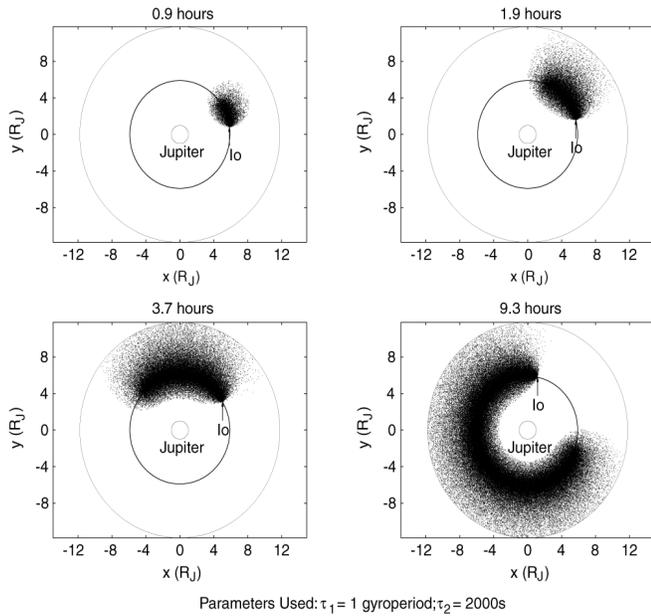


Fig. 5. The ions created in the simulation run from the neutrals shown in Figure 4.

profile again for τ_1 , equal to an ion gyro period and τ_2 equal to 1000 gyro periods or about 2000 s for SO_2^+ . For these parameters the torus is asymmetric about Io. The ion torus is denser and extends further in the outward direction.

Another important feature of the added ions is that they have much less energy inside of Io than on the anti-Jupiter side of the torus. Had the calculation been performed in a non-rotating geometry the neutral transport and reionization process principally provides just a translation of the particle's position but in the rotating gravitational setting the ions have a reduced gyro velocity in the inner torus region going to zero about $3.4 R_J$ as shown in Figure 7. While such reduced gyro velocities can help explain the cool temperatures in the inner Io torus, it is worth emphasizing how cold the inner torus is. At $L=5$ the ions being produced in our numerical simulation have a "temperature" upon pickup of 150 eV oxygen. This is to be compared to the actually observed temperatures of about 2 eV here [Bagenal, 1985]. Our model does not produce 2 eV until inside $3.5 R_J$. It is possible that reducing the flow velocity in the pickup region will produce cooler temperatures but we have not yet run such simulations. Thus while our model assists in the cooling of the inner torus, it may not be the entire story. Other cooling mechanisms could be present as discussed by Bagenal [1985].

DISCUSSION AND CONCLUSIONS

Models have been run varying the residence time of the ions in the initial cycloidal orbit, τ_1 , and the lifetime of the fast neutral, τ_2 , choosing different geographic sources and assuming that the exosphere exists only above the dayside of Io. Space does not permit us to review all of these runs herein but suffice it to say that varying τ_1 , varies the proportion of the material that enters the inner and outer tori. Varying τ_2 , varies the extent of the torus. Different geographic regions contribute to the torus at different radial distances as geographic regions have a fixed geometry

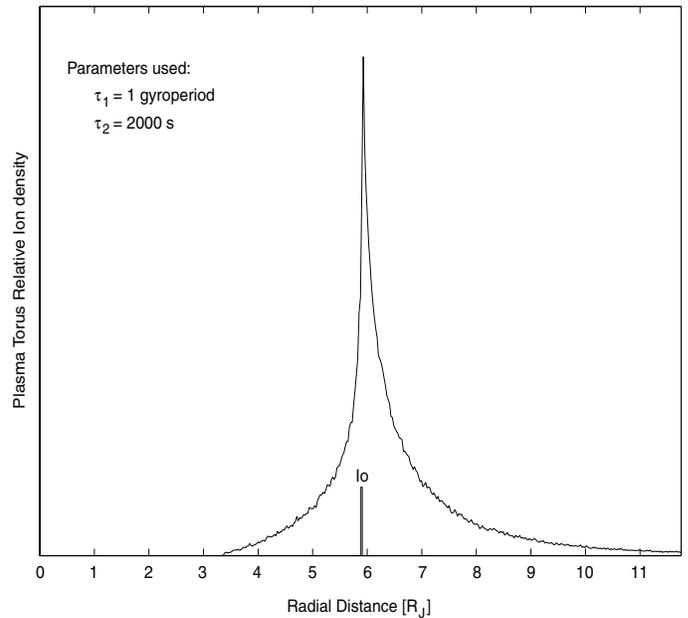


Fig. 6. The relative density of ions as a function of radius in the simulation illustrated in Figures 4 and 5.

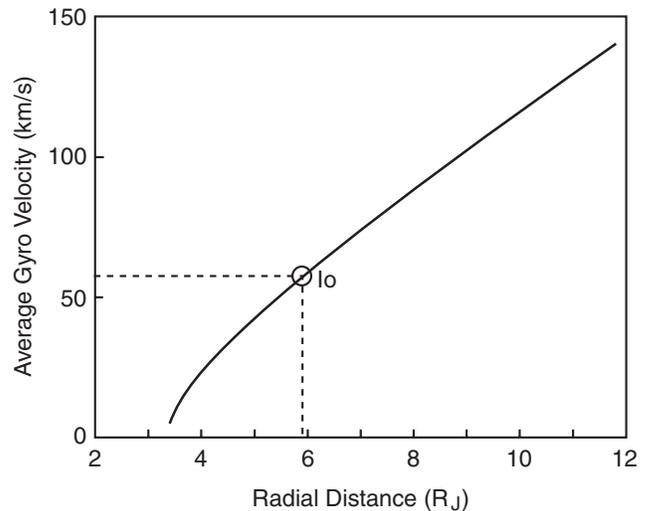


Fig. 7. The gyro velocity of the ions produced as a function of radius.

relative to the electric field of the corotating magnetosphere. Certain geographic regions have much better access to the magnetosphere than others. Fast particles produced on the jovian facing side of Io largely are accelerated toward Io's surface. Those on the anti-Jupiter side can move away from Io relatively unimpeded. Since the massloading region extends well downstream from Io, the estimates of newly created ions seen on the Galileo IO pass represent only a fraction of the mass added to the torus as a whole [Bagenal, 1997]. Paradoxically, in our model the momentum is added mainly at Io. Thus, most of the ionosphere-massloading region coupling should take place near the Io flux tube. Another important finding of these parametric studies is that, if as expected, the exosphere is strongly a function of where the sun is shining, then the ion production process will depend strongly on the solar phase angle of Io in its orbit. Such a solar zenith angle variation is expected for SO₂ [Spencer and Schneider, 1996]. Thus as the local time of Io relative to Jupiter changes from 9 AM on pass I27 to 5 AM and 1 AM on subsequent passes, we should expect the fast particle production region to move to the Jupiter facing side of Io and to weaken. Thus the waves seen on these later passes should be located differently than on the earlier passes and be weaker. These later passes provide a good test of the model.

ACKNOWLEDGMENTS

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