IDENTIFICATION OF SULFUR COMPOUNDS IN IO’S EXOSPHERE

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ABSTRACT

Ion cyclotron waves have been identified in the vicinity of Io on each of the four Galileo passes, and on each pass there have been differences in the ion cyclotron waves observed suggestive of variations in the composition of Io’s exosphere. On the first flyby, IO, waves were seen centered on the SO$_2^+$ gyrofrequency and additionally at the SO$^+$ gyrofrequency outbound. On the next flyby, I24, first only waves associated with the SO$^+$ gyrofrequency were seen but later in the pass SO$_2^+$ waves appeared, and still later S$^+$ waves. On I25 the spectrum resembled that of I24 but the SO$_2^+$ waves were stronger, not the SO$^+$ waves. Finally on I27, SO$_2^+$ and SO$^+$ waves were seen as on the previous two passes but later in the pass a band of waves centered around the H$^+$ gyrofrequency was seen, including lines that could be due to Cl$^+$. Because each of these flybys occurred at a different orbital phase of Io, some of these differences may reflect the Io solar-zenith-angle variation of the atmosphere, but other changes may reflect variations in volcanic activity. © 2001 COSPAR. Published by Elsevier Science Ltd. All rights reserved.

INTRODUCTION

When ions are created in a flowing magnetized plasma, they are accelerated by the electric field in that plasma so that they drift with the plasma and gyrate around the magnetic field. The velocity of the drift and the cyclotron or gyro motion is equal to the relative velocity of the plasma and the neutral gas. Relative to the neutral gas the resulting trajectory of the ion is a cycloid, the path drawn out in space by a point on the rim of a rolling tire. In the frame of the moving plasma, the ions move in circles. In velocity space the charged particles are very inhomogeneous, lying on a ring at constant energy. Such a ring beam has much free energy and some of that energy can be given up to waves oscillating at the gyrofrequency of the ion. For singly ionized ions, the gyro-frequency is 0.01525 B/M, Hz, where B is the local magnetic field in nT and M is the ion mass in atomic mass units. The release of energy to the waves decreases the energy of the ion and causes it to move more parallel to the magnetic field. Eventually the ion could be made to move almost exactly along the magnetic field and the particle would follow the magnetic field into the atmosphere and be lost.

We do not expect to see waves associated with ions that have been in the torus plasma for some time because these ions have more isotropic distributions around the magnetic field that damp, at their gyrofrequencies, the waves whose growth is being fostered by the ring beams [Huddleston et al., 1997]. However, if the source of these generally monatomic ions is strong enough then an ion cyclotron wave could grow.

We expect to see waves near the ion cyclotron frequency with very little Doppler shift by the velocity of the plasma because the ions are cold and have only a small velocity component parallel to the magnetic field. The magnetic field would have to bend significantly so that the flow moved along the field for Doppler shifting to be noticeable.

Another way of seeing an apparent frequency shift is to measure waves generated elsewhere, in regions where the field strength is stronger or weaker than at the point of observation. At Io the field strength changes, but not greatly, so that this seldom presents a problem in wave identification. The wave generation process is treated in an accompanying paper by Blanco-Cano et al., [2001].

The waves are seen over an impressively large region, to almost 0.5 RJ away from Jupiter and almost as far downstream parallel to the corotation flow, but they are basically undetectable upstream and are much weaker on the jovian side of Io [Kivelson et al., 1996; Russell and Kivelson, 2000]. This behavior can be explained with a
three-step process involving two ionizations and a neutralization. When ions are produced in a flowing magnetized plasma they are accelerated but, if they are still in the presence of many neutrals, they may charge exchange with the neutrals while still moving rapidly. When neutral, the particles can move rapidly and far across magnetic field lines. Eventually they are reionized and remain as ions. These ions, now far from their source, form unstable ring beams, and generate waves extending far from Io. They extend in the downstream direction, out from Jupiter and to a lesser extent inward toward Jupiter, but not upstream from Io. This model is described in more detail in an accompanying paper [Russell et al., 2001].

The purpose of this paper is to review the frequency spectra of the ion cyclotron waves seen on the four encounters (to date) of Galileo with Io and infer the various heavy molecules that may be present in the exosphere of Io.

TRAJECTORIES

Io has been visited four times by Galileo: once on an inbound pass when Io’s solar phase angle was near noon; three times on outbound passes with Io near 11 hours solar phase angle (twice) and 9 hours (once). The four trajectories IO, I24, I25 and I27 are shown in Figure 1 in the plane perpendicular to the magnetic field vector, instantaneously through the center of Io. Positive Y values are toward Jupiter and positive X values are parallel to direction of the corotational flow. The segments on which high resolution data were obtained are shown by heavy lines. The IO pass went through Io’s wake region, while the other passes did not cross the wake.

THE IO PASS

Figures 2 and 3 show spectra obtained on the IO pass inbound toward Io at greater radial distances than Io’s orbit. The spectrum is broad but clearly centered close to the SO$_2^+$ gyrofrequency. There is some structure in the spectrum but there is not clear evidence of a second unstable gyrating ion. The waves encountered on this pass are the strongest seen on any of the four passes. If the atmosphere is the source of these ions then the positioning of the denser dayside atmosphere relative to the flow may be important. On this orbit the dayside Io atmosphere was positioned in the optimum location for ion escape by the three-step ionization-neutralization and reionization process. The ion-cyclotron waves seen on this pass have been discussed much more extensively by Kivelson et al.
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Fig. 3. The power spectrum of waves seen on the Io pass close to the crossing of the (later) I27 trajectory.

Fig. 4. The power spectrum of waves seen outbound from Io over the dark side of Io.

[1996], Warnecke et al. [1997], Huddleston et al. [1997] and Russell and Huddleston [2000]. The outbound pass after passage through the wake was above the nightside of Io. Here both $SO_2^+$ and $SO^+$ waves were seen as illustrated in Figure 4. The waves outbound were much weaker than inbound and decreased to background much more rapidly.

THE I24 PASS

The pass on October 11, 1999 cut across the upstream side of Io from the jovian side to the anti-jovian side. When directly upstream of Io Galileo saw a weak burst of waves centered on the $SO^+$ gyrofrequency that may have signaled ion production in the more symmetric exosphere itself but the rest of the waves seem to be associated with the production of a disk of fast neutrals that in turn creates ions over an extended region downstream of Io. Figure 5 shows the initial spectrum in this disk. The spectrum is sharply peaked at the $SO^+$ gyrofrequency. Figure 6 shows how the spectrum evolved a few minutes later. Both a narrow $SO_2^+$ and a narrow $SO^+$ peak are seen. Later on this same pass a further surprise presented itself. As shown in Figure 7 a third very narrow peak arose at the $S^+$ gyrofrequency. We did not expect a peak at the gyrofrequency of a component of the Io torus. More details on this pass have been given by Russell and Kivelson [2000].

Fig. 5. The initial power spectrum of waves seen on the I24 pass.

Fig. 6. The initial power spectrum of waves seen at the onset of the $SO_2^+$ waves. This should be compared with Figure 2.
THE I25 PASS

The next pass did not produce the expected data because a spacecraft safing event turned off the spacecraft before the encounter and the magnetometer was not properly configured to return data until just after the Io passage. However, sufficient data were obtained downstream of Io after closest approach to show that the waves were consistent with those on I24, but with the SO2+ waves being a little stronger than the SO+ waves.

THE I27 PASS

The last pass in our set occurred on the I27 orbit. This pass encountered Io at about 9 LT in the jovian magnetosphere and the waves were weaker than on the other three passes. As before both SO2+ and SO+ ion cyclotron waves were seen but as Figure 8 shows eventually a band of waves surrounding the H2S+ gyrofrequency was also found. Singly ionized Cl has been detected in the Io torus [Kuppers and Schneider, 2000] and it is possible that two of these peaks represent 35Cl+ and 37Cl+ associated waves. The highest peak in the spectrum is close to but below the mass 32 gyrofrequency and could be caused by S+ and/or O+.

DISCUSSION AND CONCLUSIONS

Io produces a disk of fast moving molecules that spread out downstream and both outward and inward from Jupiter. These neutrals are ionized and the ions promote the growth of ion cyclotron waves near the gyrofrequency of the ions. The strength of these waves varies with location in the massloading region and it varies with the location of Io relative to the Jupiter-Sun line. The lines in the frequency spectrum also vary. The first pass had lines solely due to SO2+ inbound and SO+ and SO+ outbound. The others included peaks at the gyrofrequencies of SO2+, SO+, as well as short bursts of S+ (on I24) and possibly H2S+, 35Cl+, and 37Cl+ (on I27). This suggests that the composition of the Io exosphere is variable, possibly signaling the activity of different volcanic sources. However, each of the encounters occurred at a different orbital phase angle of Io ranging from 9 LT for I27 to noon for I0. The atmosphere of Io is thought to vary with solar zenith angle so that SO2 is dominant at noon but freezes out at high solar zenith angles leaving SO to be more prominent [Wong and Smyth, 2000]. Since the main source region for massloading is on the anti Jupiter side of Io where the electric field accelerates ions away from Io, the ion composition can change with Io’s orbital phase. The observations suggest this is occurring.
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REFERENCES


