Evidence for sulfur dioxide, sulfur monoxide, and hydrogen sulfide in the Io exosphere

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Abstract. Molecules in the Io exosphere are ionized and accelerated in the Jovian magnetospheric electric field creating a distribution in velocity space that is unstable to the generation of magnetic fluctuations at the frequency of the gyrating ion. On the inbound portion of first pass by Io, Galileo detected strong waves centered on the SO$_2^+$ gyrofrequency, but on the outbound portion, waves near the SO$^+$ gyrofrequency were seen, as well as a weak burst near the H$_2$S$^+$ gyrofrequency. On passes I24 and I25, waves at both the SO$^+$ and SO$_2^+$ gyrofrequencies were present. On the I27 pass, additional components were also observed, close to mass 34, 35, and 37 amu, as would be expected if H$_2$S$^+$, $^{35}$Cl$^+$, and $^{37}$Cl$^+$ ions were present. These disparate observations on geometrically similar passes suggest that the atmosphere of Io is quite variable, possibly changing with solar zenith angle and perhaps changing in concert with the relative activity of different volcanic sources.

1. Introduction

The detection of waves, generated by ions produced in the interaction of Io with the rotating Jovian magnetosphere, was one of the original objectives of the magnetic fields investigation on the Galileo mission [Kivelson et al., 1992], but the amplitude of the waves detected as Galileo passed Io, reaching 100 nT in amplitude at the SO$_2^+$ gyrofrequency, was a surprise [Kivelson et al., 1996]. The mechanism that creates these waves is ion cyclotron resonance in which an electromagnetic wave resonates with a gyrating ion and, depending on the phase of the resonance, either takes energy from the ion or gives energy to it [Huddleston et al., 1997]. If the particle loses energy in this interaction, its motion becomes more aligned with the magnetic field. Thus the pitch angle, the angle between the ion's velocity and the magnetic field direction, decreases. Because the interaction of the corotating torus plasma with the Io atmosphere produces ions only at the largest angles to the field, the ions can only decrease in pitch angle, and the waves grow in this interaction. Thus the particle distributions newly created in the Io torus are generally unstable to the generation of waves. One exception to this statement is that the atomic ions in the background torus, principally S$^+$, S$^{2+}$, and O$^+$, can damp waves because they have a more evolved, isotropic distribution from which the free energy has been extracted. Thus a source of atomic pickup ions such as S$^+$ and O$^+$ would have to be strong to overcome the damping at the O$^+$ and S$^{2+}$ gyrofrequencies by the denser torus plasma. Molecular ions in the torus far from Io, such as SO$_2^+$, SO$^+$, and H$_2$S$^+$, are rare because they are dissociated by solar EUV and impact with energetic particles but could be plentiful close to Io where they are produced in the upper atmosphere of Io.

The prime mission of Galileo included only one pass by Io, an inbound crossing of the wake region. Remote sensing instruments obtained no data during this pass, but the particles and fields data were recorded at full temporal resolution for later playback. After the completion of the prime missions, two further years of operation were approved, called the Galileo Europa mission (GEM). This extended period of operations included two Io passes, I24 and I25, in October and November 1999, on which high-resolution fields and particle data were scheduled to be recorded. Pass I24 was successfully completed, and ion cyclotron waves were detected [Russell and Kivelson, 2000], but a spacecraft "safer" event on I25 delayed recording of the magnetometer data until after closest approach to Io. Fortunately, when the magnetometer was turned on, it was still in the region of ion cyclotron wave production.

When the Galileo Europa mission terminated, the project received tentative approval to continue with a new phase called the Galileo millennium mission that included another close pass by Io, I27. This flyby successfully recorded magnetometer data through the encounter period. It is the purpose of this note to examine the spectral content of the ion cyclotron waves seen on these four passes as an indication of what molecular ions are present in the vicinity of Io and how the composition of the Io exosphere varies with time.

2. Observations

The first pass, I0, moved radially inward through the wake region caused by the corotating torus plasma overtaking Io in its orbit. The other three passes, I24, I25, and I27, were outbound passes across the upstream side overtaking Io on the side away from Jupiter. The local times of Io on these four passes were 1150, 1042, 1045, and 0856 LT.

The trajectories of Galileo on I0, I24, and I27 are shown in Figure 1. Along each trajectory is a sine wave showing where waves were observed. To show the relationship between the frequency of the waves and the expected wave frequency of ion cyclotron waves, in Plate 1 we display dynamic spectra of the time derivative of the signals with a line drawn at a submultiple of the gyrofrequency of protons, which in Hz is 0.01525 B[nT]. This frequency is divided by 64 for SO$_2^+$, 48 for SO$^+$, and 34 for H$_2$S$^+$. In constructing these dynamic spectra we calculate fast Fourier transforms over 256 points, shifting by 32 points to
Ion Cyclotron Waves
Mirror Mode
× Closest Approach

Figure 1. Trajectories of the Galileo spacecraft past Io on the IO, 124, and 127 flybys on December 7, 1995; October 11, 1999; and February 22, 2000. The plane shown is perpendicular to the model magnetic field vector through the center of Io. The Y direction points toward Jupiter, and the X direction is in the direction of corotation. The sine waves show where ion cyclotron waves were observed.

Figure 2. Power spectral density of the waves seen on the Io pass from 1740 to 1743 UT. The solid line shows the transverse power calculated from the sum of the powers on the three sensors minus the power in the total magnetic field. The dashed line shows the compressional power that arises because these waves propagate at a slight angle to the magnetic field.

Figure 3. Power spectral density on the Io pass from 1737 to 1740 UT.

calculate the next spectrum. The time derivative is used in the analysis to enhance the higher frequencies so that the weaker signal levels at these higher frequencies can be readily detected with the color bar. This technique is not necessary for the display of the power spectral density versus frequency shown in the figures. Next we discuss each of the dynamic spectra and show selected plots of the power spectral density versus frequency to illustrate the relative strengths of the peaks seen on each pass.

2.1. December 7, 1995

The dynamic spectrum of the waves seen on this first pass by Io is shown in Plate la over the period 1723 to 1743 UT covering the radial range from 0.3 Jovian radii (R_J) outside Io's orbit to Io's wake. We see that the waves are centered close to the gyrofrequency of singly ionized sulfur dioxide ions. Figure 2 shows a cut through this spectrum, showing the transverse and compressional power spectral density averaged over the period 1740 to 1743 UT. The transverse power is the power in the waves at right angles to the background magnetic field direction. An ion cyclotron wave propagating parallel to the magnetic field would have only a transverse component. Since these waves are propagating at a small angle to the field a compressional component arises. The spectrum in Figure 2 is relatively broad with a strong peak just below the local SO_2^+ gyrofrequency. It is possible that this close to Io that the ions received some acceleration along the magnetic field and the resulting Doppler shift moved the resonance to lower frequencies. Although no strong peaks are observed at frequencies sufficiently far from the SO_2^+ gyrofrequency that they must be due to molecules other than SO_2^+, weak signals at other frequencies cannot be ruled out. Plate 1a shows that the waves reach their peak intensity near 1743 UT and apparently broaden. This apparent broadening occurs as the wave power increases and more and more frequencies exceed the threshold power on the color scale. To demonstrate that the shape of the spectrum remains approximately constant, in Figure 3 we plot the spectrum from the previous 3-min where the dynamic spectrum appears to be narrower. The spectrum is very similar to
Figure 4. Power spectral density on the Io pass from 1752 to 1755 UT.

That from 1740 to 1743 UT except that the power is about a factor of 10 lower and the power is centered nearer the SO$_2^+$ gyrofrequency.

Plate 1b shows the outbound portion of this orbit. The spectrum has clearly changed. Initially, the waves are strong at and below the SO$_2^+$ gyrofrequency. Then the peak of the spectrum clearly shifts to the SO$^+$ gyrofrequency. Finally, there is a brief burst of noise near the H$_2$S$^+$ gyrofrequency. Figure 4 shows the power spectrum from 1752 to 1755 UT, where the spectrum has evolved to being centered on the SO$^+$ gyrofrequency. We note that as shown in Figure 1, the outbound portion of the trajectory is above the nightside of Io after about 1748 UT and from 1752 to 1755 UT it is well into the nighttime region. Thus the changing spectrum may be associated with the local time of the spacecraft.

Figure 5. Power spectral density on the I24 pass from 0434 to 0439 UT.

2.2. October 11, 1999

The dynamic spectrum seen almost 4 years later near the end of the GEM mission and illustrated in Plate 1c is much different than that seen in December 7, 1995. On this pass waves are initially seen at the SO$^+$ gyrofrequency, although later on the pass waves also appear at the SO$_2^+$ gyrofrequency. Figure 5 shows the wave spectrum from 0434 to 0439 UT. The waves are clearly peaked at the SO$^+$ gyrofrequency with no power obvious at the SO$_2^+$ gyrofrequency. The difference in the I24 waves and those on the Io pass is not simply due to the different geometry of the two trajectories. Figure 6 shows the spectrum from 0443 to 0444 UT where the Io and I24 passes cross as projected in the XY plane. Here two narrow, almost equal-amplitude peaks are seen in stark contrast to the single broad peak shown in Figure 2. A weak peak at the S$^+$ gyrofrequency might also be present, but it is close to the statistical noise. Finally, in Figure 7 we show the...
Plate 1. Dynamic spectrum of the time-derivative of the transverse magnetic field for 20 min during the Io pass from 1723 to 1743 UT; (b) for 15 min during the Io pass from 1750 to 1805 UT; (c) during the 12A pass from 04:28 to 04:48 UT; and (d) during the 12B pass from 13:48 to 14:08 UT.
2.3. November 26, 1999

The first data obtained on this pass were at 0442:44 UT located 0.25 \( R_j \) outside of Io's orbit. These data show a double peak, but since only 48 s were obtained at this time, we chose to display the spectrum from 0448:30 to 0450:08 UT in Figure 8.

This longer period allows us to calculate the power in narrower spectral bands. There are two narrow peaks at the \( \text{SO}_2^+ \) and \( \text{SO}^+ \) spectra with the \( \text{SO}_2^+ \) slightly stronger. This differs from the spectrum shown in Figure 6 on the I24 pass where the \( \text{SO}^+ \) peak was the stronger. We do not show a dynamic spectrum for this pass such as those in Plate 1 due to the spotty nature of the coverage on this pass.

2.4. February 22, 2000

The most recent pass by Io is shown in the dynamic spectrum shown in Plate 1d. Clearly seen are waves at the \( \text{SO}_2^+ \) and \( \text{SO}^+ \) gyrofrequencies and a broad band centered on mass 34 that we interpret as \( \text{H}_2\text{S}^+ \). Figure 9 shows the power spectra at the crossing in the \( \text{XY} \) plane of the I0 trajectory by the I27 trajectory illustrating the spectral difference between the waves seen on this pass, and those seen on the I0 pass and illustrated in Figure 2. The waves appear to be due to \( \text{SO}^+ \) and not \( \text{SO}_2^+ \), and their spectral widths are much narrower than on the I0 pass. Figure 10 shows a spectrum further along the trajectory showing three wave bands. Here the frequency of the waves suggests the simultaneous presence of \( \text{SO}_2^+ \), \( \text{SO}^+ \), \( \text{H}_2\text{S}^+ \), \( ^{37}\text{Cl}^+ \), and \( ^{35}\text{Cl}^+ \) ions. There is no peak here at the \( \text{S}^+ \) gyrofrequency, but there is a peak between the \( \text{S}^+ \) and \( \text{H}_2\text{S}^+ \) gyro-frequencies.

3. Discussion and Conclusions

As evident in Figures 2 to 10, the peak wave powers occur close to but not necessarily right at the ion gyrofrequencies. There are two reasons for this offset. First, there are effects due to the component of the velocity of the particle moving parallel to the magnetic field. If the ion velocities are created perpendicular to the magnetic field forming a ring around the magnetic field in velocity space that particle distribution is unstable to the generation of waves right at the gyrofrequency corresponding to the mass and charge state of that ion and the strength of the magnetic field. A finite velocity of ions parallel to the magnetic field still allows instability but the resonant frequency is Doppler
shifted away from the gyrofrequency. The ions created at Io should be accelerated mainly perpendicular to the magnetic field. However, Doppler shifts can occur when the flow gets (slightly) deflected along the field direction in the interaction. To the extent that all species arise from the same source regions and are similarly accelerated and that the ion cyclotron waves propagate at the same velocities, all lines should be Doppler shifted by roughly the same amount.

The second cause of slight frequency shifts is that waves can be convected out of their source regions by the flowing torus plasma. Since the magnetic field strength around Io varies spatially, the waves may not appear precisely at the local gyrofrequency at the moment of detection if they are carried to the spacecraft from a region of higher or lower field strength. Despite these effects offsetting the wave frequencies from the precise value of the local ion gyrofrequency, we expect the observed frequencies to be close enough to the local gyrofrequencies of the source ions that we can use the frequencies of the peaks as a rough ion mass spectrometer. Moreover, the wave powers provide an indication of the strength of each ion source.

The spectra seen on the inbound Io pass suggest that SO$_2^+$ was by far the dominant ion on this pass. Assuming that the wave power in the waves is directly proportional to the mass loading rate, ions were produced at a rate close to 4 times that of those produced on I24 at the crossing point. The amplitudes of the waves on I24 were similar to those on I25 at the same distance from Io while the waves on I27 appeared to fall off in intensity more rapidly than on the earlier orbits. While this effect could be due to the time variability of the volcanoes producing Io's atmosphere, it is also consistent with variation in the production of ions with local time. This is expected as the dayside of Io varies its location with respect to the flowing plasma. Further evidence for a local time effect on the Io pass is the spectrum seen outbound over the night hemisphere of Io. The spectrum clearly shifts to be centered at the SO$^+$ gyrofrequency, and a burst centered at the H$_2$S$^+$ gyrofrequency is seen.

The spectra on I25 and I24 are much more similar to each other than to the Io spectrum. Clearly, both SO$_2^+$ and SO$^+$ are being produced in about equal amounts on these orbits, but it appears that on I24, SO$^+$ was dominant and on I25, SO$_2^+$ was dominant. SO$_2$ is expected to be the dominant molecule in Io's atmosphere [e.g., Trafton et al., 1996], but Io's volcanoes are also expected to produce SO [Zolotov and Fegley, 1998]. We also see on I24 evidence for atomic S$^+$ ions, although it is possible that this peak is due to SO$_3^{++}$ or O$^+$ that have the same gyrofrequency. Finally, on I27 we see SO$_2^+$, SO$^+$, and a broad enhancement around the H$_2$S$^+$ gyrofrequency that includes peaks at the $^{35}$Cl$^+$ and $^{37}$Cl$^+$ gyrofrequencies. The wave power is close to that seen on the I24 pass. Chlorine (mass 37 and 35) has been reported in the Io torus [Kuppers and Schneider, 2000]. On one orbit, I24, a sharp sulfur peak is seen, indicating that a strong enough atomic source can overcome the torus damping. In closing, it is clear that the wave spectra seen at Io are very variable. We interpret this variability as due to changes in both the number density and the composition of the exosphere from which the ions are derived. Some of this variability appears to be associated with the varying local time of the ion source region. Other variability may be associated with changes in the types of volcanic activity during the different encounters.

Acknowledgments. This work was supported by the National Aeronautics and Space Administration under research grant NAG5-8938.

References


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(Received August 1, 2000; revised March 6, 2001; accepted March 16, 2001.)