Ion cyclotron waves at Io: implications for the temporal variation of Io’s atmosphere

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Abstract

When the flowing torus plasma encounters the upper atmosphere of Jupiter’s moon, Io, newly created ions are rapidly accelerated by the motional electric field. Many of these ions are resonant and form a spray of fast neutrals that travel far away from Io, before being eroded by photodissociation and impact. These ions, now far from Io, are unstable to the generation of ion cyclotron waves. These waves in turn act as a mass spectrometer allowing Galileo magnetic measurements to be used to probe the composition of the atmosphere of Io and how it varies in time and in space. We now have six Galileo passes by Io on which we have measurements with sufficient cadence to examine the ion cyclotron waves. One of these passes, on Galileo’s 53rd orbit, has not been discussed previously. These passes provide sufficient observations to begin to distinguish the sources of variability. We find that while the atmosphere of Io varies temporally throughout the mission, it also has a spatial variation in composition at any instant of time.

Keywords: Io torus, Io atmosphere, Ion cyclotron waves

1. Introduction

The Galileo spacecraft made seven close passes by Jupiter’s moon, Io. Of these, five returned a continuous swath of ≥ 3 Hz magnetic field measurements that were sufficiently rapid to resolve ion cyclotron waves up to approximately the oxygen gyro frequency (Kivelson et al., 1996; Russell et al., 1999; Russell and Kivelson, 2000). On an additional pass, 125, in November 1999, high-resolution data became available well after closest approach at which time weak but clearly resolvable ion waves were detected. On the remaining pass, 133, a spacecraft “saiving” event shut the spacecraft down for the entire period near Io. These encounters with Io each revealed strong ion cyclotron waves at the gyro frequency of one or more of SO2, SO3, and S+ ions. It was clear in the earlier data that the atmosphere under the track of the spacecraft was varying but the possible source of this variation, spatial or intrinsically temporal, was not unambiguous. It is the purpose of this paper to present the measurements obtained on the final complete passage, 132, on October 16, 2001, that have not previously been published, and to use these measurements, in conjunction with previous measurements, to examine the question of the spatial and/or temporal variability of the Io atmosphere.

Ion cyclotron waves are observed over a rather large distance on either side of Io in the radial direction from Jupiter, about 7RJ inward and about 20RJ outward (Kivelson et al., 1996; Russell et al., 1999). The electric field associated with the corotation of the Io torus plasma is in the outward direction. The Io torus is a collisionless plasma in which transport of ions across magnetic flux tubes is not expected. Only fast neutral particles should be able to travel far from Io. An important clue to the source mechanism is that the waves occur downstream of Io and not upstream. There is a mechanism that can produce fast neutral particles streaming away from Io in the half-space downstream from Io. This mechanism involves the production of fast neutrals in the Io exosphere.

As illustrated in Fig. 1, fast neutrals can be produced from the production of exospheric ions, followed by acceleration in the electric field, and then reneutralization, say by charge exchange (Russell et al., 2001; Wang et al., 2001).
The fast neutrals eventually are reionized by photoionization and impact, forming a "ring beam" of ions with a narrow gyro velocity spread and pitch angles close to 90° to the magnetic field. Such a ring beam is unstable to ion cyclotron wave generation at frequencies close to the local ion gyro frequency (Huddleston et al., 1997; Blanco-Cano et al., 2001). The fast neutral molecules and the molecular ions eventually dissociate so that the molecular species are removed from the system. Thus the torus is expected to be mainly composed of atomic ions. This lack of a background of torus molecular ions allows the ion cyclotron instability to grow at the cyclotron frequency of the molecular ions. If sufficient number of molecular ions with a Maxwellian distribution were present there would be wave damping. We note that waves at or near the atomic S⁺ gyro frequency do sometimes appear apparently overcoming any damping due to thermal S⁺ ions. We expect that S arises from the dissociation of SO₂ and SO molecules. Thus the appearance of these waves appears to signify a significant component of S⁺ in the ring beam even when the wave amplitude is small.

The Io atmosphere is at best poorly understood. If it consisted solely of SO₂ it might be only a daytime phenomenon and freeze out on the nightside (Spencer and Schröder, 1996). A recent model by Wong and Smyth (2000) has a spatially varying atmosphere that is downsized by SO₂ at low solar zenith angles and is downsized by SO at night when the SO₂ concentration falls below the more constant SO concentration. Thus we might expect a variation in the relative ion concentration when Galileo passes over regions of different solar illumination. However, we also know that Io is volcanically active and that different volcanoes have different styles of volcanism. Thus we might expect that the atmospheric composition is also varying temporally. It is possible that the data from the five Galileo passes can shed some light on which of these sources of variability is dominant.

2. Io encounter geometries

Fig. 2 shows the five complete passes: by Io in the plane perpendicular to the instantaneous model field through the center of Io with the corotating torus few moving from left to right. Schematic streamlines qualitatively replicating the post-Io flow observed by the Galileo plasma analyzer (Frank et al., 1996) are shown in both panels. The Io pass on December 7, 1995 in the left-hand panel passed directly behind Io. Ion cyclotron waves indicated by strioloidal lines along the trajectory, were observed inbound and outbound from Io (e.g. Russell et al., 1999). At either edge of the wake region mirror mode waves were observed. In the center of the wake a depressed field region of relatively low wave activity was observed. On October 11, 1999 Galileo flew by Io for the second time; on orbit 124, passing across the upstream nose of the interaction region. Here it encountered a weak burst of ion cyclotron waves that lasted only a couple of minutes. Later as Galileo moved to the downstream side of Io strong ion cyclotron waves arose. The next trajectory, 125, was similar to 124, but most of the data were lost due to a spacecraft icing event. When the magnetometer was turned on, the spacecraft was at \( \approx 7.2R_J \) and well out of the region shown in Fig. 3. Both SO⁺ and SO₂ ion
Fig. 2. The trajectory of Galileo in its passages by Io. Regions in which ion cyclotron waves were seen are illustrated. The coordinate system keeps the flow velocity to the right and the electric field due to corotation projected in the x-direction (outward from Jupiter) according to the instantaneous model field through Io.

cyclotron waves were observed until 11.5R_J downstream and 10R_J from the wake axis. Then on February 22, 2000 on pass 127, Galileo again moved from upstream to down, as it proceeded outward from Jupiter. This time the trajectory was at a smaller angle to the wake. Again the ion cyclotron wave amplitude increased rapidly as Galileo moved downstream "behind" Io. We note that the day-night terminator line on this panel is drawn for orbits 124 and 127. The terminator line for Io is nearly horizontal.

The next Io encounters were 131 and 132, drawn on the right-hand panel. Both trajectories crossed above or below the moon so that field lines connected Io and the spacecraft for part of the flyby. The 131 trajectory carried Galileo down the wake region almost parallel to the corotating flow. The field lines through Galileo connected it to the low field strength center of the wake. Somewhat behind the edge of Io ion cyclotron waves first appeared. The trajectory followed on 132 was similar to 124 and 127. On this pass waves also began well separated from the trailing edge of Io. The wave observations on this pass have not previously been described in the literature. They provide a very important contrast in amplitude and spectral content with those seen on the earlier encounters along similar trajectories and help us determine whether spatial or temporal variations are dominating the differences in the ion cyclotron spectra.

Fig. 3 shows where Io was in solar phase angle for each of these passes. For Io, Io was almost directly between Jupiter and the sun with its sunlit hemisphere in the direction of the corotational electric field of the torus. On 124 and 127 Io was on the morning side of Jupiter so that some of the outward side was dark. On 131 and 132 Io was on the predawn side of Jupiter with over half of the outward side in darkness. If, for example, the atmosphere were static and the ion production depended only on the amount of lit atmosphere providing
A source of ions on the outward side of Jupiter, we would expect the wave amplitude would drop from 10 to 12 at 137 to 131 and 132. Another change that might occur is in the frequency of the dominant spectral peaks. Wang and Smyth (2000) have predicted that the dominant molecule in the Io atmosphere would change from SO$_2$ on the dayside to SO on the nightside. Thus as the Galileo trajectory changes from crossing above the dayside at 124 and 127 to crossing principally over the nightside at 131 and 132, we might expect the ion cyclotron waves to change from SO$_2^+$ to SO$_2^{-}$ ion gyro frequencies.

3. Dynamic spectra

One of the most convenient methods of summarizing the behavior of the ion cyclotron waves on these passes is by their dynamic spectra in which the power of the transverse components of the oscillation is plotted versus time and frequency. This display is shown in Fig. 4 for passes 10 inbound and outbound, 124, 127, 131, and 132. The initial pass inbound on 10 was generally strongest at the SO$_2^+$ gyro frequency. The outbound pass had a stronger SO component and later a burst of what appears to be SO$^-$. Since the 10 inbound pass is over the daylit hemisphere and the outbound pass over the night hemisphere, this difference is suggestive of the day-night compositional difference found in the Wang and Smyth (2000) model.

The 124 pass has two major differences from the 10 pass. First the spectral lines are narrow. Second the waves are very much stronger at the SO$_2^+$ gyro frequency than the SO$_2^-$ gyro frequency. Moreover, their onset is much earlier than that of SO$_2^-$ waves. The 137 pass is different again. The waves are not as sharply contained in two narrow bands.

Fig. 4: Dynamic spectra of the transverse power in the oscillations seen on four Io encounters. The time derivative of the magnetic field was taken before the fast Fourier transform was calculated in order to filter the spectrum.
4. Power spectra

While dynamic spectra provide a convenient summary of the wave behavior, they do not present us quantitative assessment of the pass to pass differences as power spectra that are cut across the dynamic spectra for specified periods. Thus in this section we repeat our assessment of 10, 124, 131 and 132 differences using spectra. Fig. 5 shows the spectrum from 1740–1743 UT on IO inbound and from 1752–1755 UT on IO outbound. On the inbound pass there is a very strong narrow peak just below the SO$_2^+$ gyro frequency. (We note that we expect the waves to be slightly below the peak due to Doppler shifting by the particles parallel velocities.) There is also significant, albeit lower, power just below the SO$_2^+$ gyro frequency. Outbound the situation is reversed and the power near the SO$_2^+$ gyro frequency is stronger.

On 124, as illustrated in Fig. 6, the power is narrowly confined in bands surrounding the gyro frequencies of SO$_2^+$, SO$_2^-$, and S$^+$. The power in the SO$_2^-$ band is stronger than in the SO$_2^+$ band and much stronger than in the S$^+$ band. On 131 as illustrated in Fig. 7, the waves are generated in a low field region some distance from Galileo and the wave spectrum is both "shifted" to lower frequencies relative to the local gyro frequency and broader with no sharp peaks. This latter effect is presumably due to the distributed nature of wave growth over a range of field strengths. On 132 the wave spectrum most resembles that on IO inbound. Again it seems that we cannot explain these differences by the varying Galileo trajectories solar-zenith-angle controlled atmosphere but rather the differences reflect intrinsic temporal variations in the composition of the atmosphere from pass to pass.

5. Power versus cross flow distance

The wave power is proportional to the ion source rate (Huddleston et al., 1997) so that we can test the variability in the strength of the atmospheric source by comparing the

![Fig. 5. Power spectrum of the magnetic fluctuations transverse to the background magnetic field and along it on the IO pass inbound and outbound from 1740–1743 UT and 1752–1755 UT.](image-url)
wave power on the different trajectories. This comparison is shown in Fig. 8 where we show power versus cross-flow distance from the center of the wake. The T0 trajectory is almost orthogonal to the other trajectories but we can still compare its observations with those of the other passes at the crossing points. Doing this for T0 at 1740–1743 UT (see Fig. 5) and for T24 at 0443–0444 (see Fig. 6) we find that pass T0 had much stronger power (inbound) than the other passes. Since the solar EUV and energetic particle fluxes are not expected to be this variable, we conclude that the exospheric density must have changed by close to a factor of ten. The other passes are quite comparable and there is
no evidence for spatial ordering of the wave powers. For example, I32 is as strong as I24 and I27 despite Io being at earlier solar phase angles on I32. The temporal nature of the variation can also be seen by comparing passes at the same solar phase angle. There is a rather significant difference between the nearly parallel I25 and I27 passes at 7R_⊕, downstream (X = 7R_⊕) and near 5R_⊕ from the wake center and there is a large difference between passes I24 and I25. Again it is clear the atmosphere is varying, or at least it is clear that the density of the region that affects the acceleration of fast neutrals is changing.

6. Discussion

In our comparisons of the ion cyclotron waves on the Galileo passes by Io we have examined the possible effects of the local time of the fast neutral auroral region on Io, the solar phase angle of Io in its orbit and the intrinsic variability of the atmosphere. On the basis of Voyager observations it has also been proposed that the jovian magnetosphere has an active longitude, from 40° to 185°E (system III longitude (Hill et al., 1983). Io was inside this region on two of our six passes. The (East) system III longitudes at the time of the Io flybys were 87° (I0), 281° (I24), 192° (I25), 277° (I27), 201° (I31) and 97° (I32). Since the Io pass had much stronger waves than I32, a pass close in system III longitude to that of I0, and since both were well inside the active longitude range, the system III active region does not appear to be the reason for this difference. Also passes I24 and I27 are well outside the active system III longitudes but one is relatively quiet and one active. Again system III longitude does not appear to be the controlling factor.
We have ascribed much of this variability to the variability of the atmosphere due to volcanic activity. This variability can be seen from both Galileo images and ground-based telescopes, but we cannot monitor the volcanic activity on the side of Io that our cameras do not see. We also cannot monitor remotely the composition of the exosphere for a comparison with the observed spectra. The best we can achieve is to demonstrate that the amplitudes of the waves and their spectra do vary. Because we cannot predict many of these variations solely from the orbital positions of Galileo or Io, we infer that in fact the atmosphere is intrinsically time variable.

7. Summary and conclusions

Ion cyclotron waves are found to either side of Io but almost exclusively downstream from Io. The only mechanism known to create such a broad spatial distribution is ionization followed by pickup and then neutralization. Ion passes have occurred above a variety of solar zenith angles on Io and at a variety of solar phases of Io in its orbit about Jupiter. On these orbits spectral lines are present that are generated by $SO_2^+$, $SO$ and $S^+$ ions. The strength of these spectral lines varies from pass to pass both in absolute power and relatively to one another. The addition of measurements on passes 131 and 132 help us distinguish possible sources for this variability. Since the waves on 131 clearly demonstrated that the waves travel readily along the field lines from their source region, we need not be concerned with the variable distance of Galileo above the plume of Io's orbit in causing wave power variations. The large separation in solar phase angle between pass 132 and the earlier passes 124, 125 and 127 enable solar phase angle to be eliminated as a major factor. Furthermore, while there do appear to be changes as the spacecraft moves above different solar zenith angles on Io, mostly readily demonstrated on the 10 pass that made measurements over daylit and night regions, it is not possible to explain all variations due to these solar zenith angle dependencies. Finally, we see no evidence for system III longitude control of the waves. Thus, we conclude that Io's atmosphere is temporally varying possibly due to varying styles and amplitudes of volcanic activity.

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References


