Detection of SO in Io's Exosphere

C. T. Russell and M. G. Kivelson

The Galileo orbiter's close pass by Io in 1995 produced evidence for extensive mass loading of the plasma torus through the ionization of SO_2. On 11 October 1999, Galileo passed even closer to Io, this time across the upstream side relative to the flow of magnetospheric plasma that corotates with Jupiter. On the first flyby, ion cyclotron waves gave direct evidence for the production of SO_2^+ ions. On the second flyby, ion cyclotron waves associated with SO^+ were stronger and more persistent. Moreover, SO^+ emissions were seen closer to Io than SO_2^+ emissions, suggesting that the exosphere was spatially inhomogeneous. The location of the waves suggests a fan-shaped region of ion pickup extending in the anti-Jupiter direction. Because the wave spectra were different even where the 1995 and 1999 trajectories crossed, we infer that Io's exosphere is temporally variable.

After a lengthy interplanetary cruise, on 7 December 1995 the Galileo orbiter flew by Io and fired its engine to enter jovian orbit. One of the many discoveries (*1–4*) on this close flyby through the corotational wake of Io was the appearance in the magnetic field of intense ion cyclotron waves (*5*), predominantly at the ion cyclotron frequency of SO_2^+, close to 0.5 Hz at the orbit of Io. Cyclotron waves occur at the frequency of gyration about the magnetic field when the ions have no component of velocity parallel to the magnetic field. The pickup of newly created ions by the flowing magnetized plasma around Io produces ions whose velocity is predominantly transverse to the magnetic field, a distribution that has the necessary free energy to generate waves. The interpretation of the presence of only SO_2^+ ion cyclotron waves, and not those of the atomic ions identified in the Io torus by Voyager (*6*), was that, unlike the atomic ions, the molecular ion SO_2^+ is not present in the isotropic background torus plasma because it dissociates rapidly. The more isotropic torus ions damp the growth of waves at their ion gyro frequencies (*7*) and can prevent the growth of waves generated by the ring distribution of newly picked-up ions.

Because not all of the original objectives were achieved in the first Io encounter, and because many unexpected discoveries were made from the data that were returned, two additional Io encounters were incorporated into the extended mission, formally called the Galileo Europa Mission (GEM) (*8*). In order to complement the original encounter, the first of these latter two encounters passed on the upstream side of Io at an altitude of 617 km (Fig. 1). Galileo was 170 km above the plane at 0445 UT. The trajectory of the spacecraft on 7 December 1995 is shown for comparison. This first additional pass allowed us to test for spatial and temporal variations in Io's high upper atmosphere or exosphere but not for the presence of a weak intrinsic field (*9*).

Institute of Geophysics and Planetary Physics, 3845 Slichter Hall, University of California Los Angeles, Los Angeles, CA 90095–1567, USA.

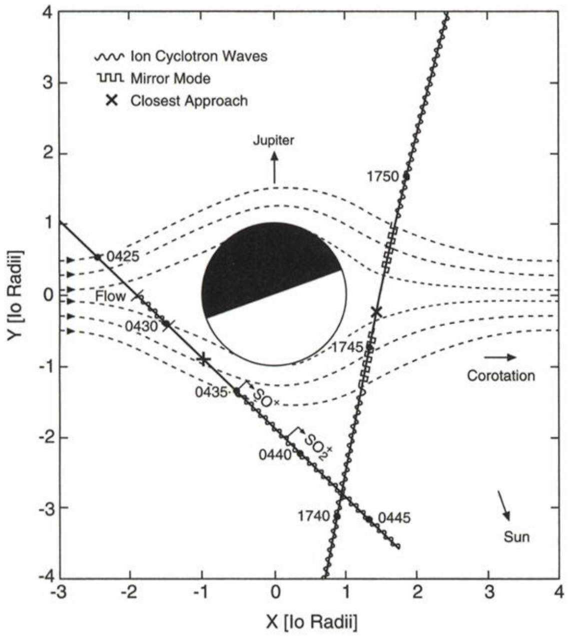
Before the closest approach, the dynamic spectrum of the signals seen at the spacecraft at frequencies from 0.01 to 1.5 Hz (Fig. 2) reveals low-power ion cyclotron waves between the local SO_2^+ and SO^+ gyrofrequencies. These waves may have been produced near the SO^+ gyrofrequency at a lower field strength upstream of Io and been carried to the spacecraft by the flowing plasma, or there may be a small component of flow parallel to the magnetic field in this region, shifting the resonance to a lower frequency. The waves disappeared just after 0429 UT and were absent when the spacecraft was closest to Io. Here we expect the plasma flow to be slower than at greater distances and the ion pickup velocity to be smaller, thus reducing the energy available for wave growth. When the waves returned at 0435 UT, they were centered on the local SO^+ gyro period. This is different from the 1995 encounter, in which the wave power clearly peaked at the SO_2^+ gyrofrequency. At 0439:30 UT, waves at the SO_2^+ gyro-frequency appeared and continued until the end of transmission at 0448 UT.

The spectra of magnetic fluctuations transverse to and along the magnetic field for the period from 0434 to 0439 UT (Fig. 3A) indicate that the waves are clearly centered on the SO^+ gyrofrequency, corresponding to the average magnetic field during the period over which the spectrum was calculated. The narrow peak at 0.05 Hz is the spin period of the spacecraft. The narrow peak at 0.2 Hz is an interference tone whose frequency remained constant during the flyby despite a significant change in the magnetic field strength. The SO_2^+ gyrofrequency was first seen at 0439 UT (Fig. 2). The spectrum of these waves from 0439 to 0440 UT shows that these peaks are due to SO_2^+ and SO^+ (Fig. 3B), and these are the ions we expect (*10, 11*). At 0443:30 UT, where the trajectories crossed, the amplitude of the waves integrated over both peaks is half that seen during the first flyby at 1741:30: 15 nT root mean squared versus 30 nT in 1995.

At 0444 UT, the strong higher frequency peak shifted to lower frequencies (Fig. 2). The power spectrum from 0440 to 0448 UT (Fig. 3C) indicates that the single SO^+ peak has become multiple. Although it is possible that other ion species might be present here that were previously absent, it is unlikely that SO^+ would disappear. Thus, it is most probable that the downward frequency shift is associated with a component of the flow along the magnetic field when the field and flow bend as the torus plasma moves past Io. The high-frequency peak could be due to waves convected from upstream, where the gyrofrequency is higher. The lack of a frequency shift of the SO_2^+ peak is consistent with upstream generation of these waves.

A clear peak at the S^+ gyrofrequency here does signal some changes in composition. Although the frequency of this peak is exactly twice that of the SO_2^+ peak, the temporal variation of the wave amplitudes at the two frequencies is different, indicating that the S^+ peak is not an artifact. Waves associated with atomic ions are normally damped by the background distribution of atomic ions in the torus, but a strong enough source can dominate over the damping, as seems to have happened here.

The regions of ion cyclotron wave generation seen on the 1995 and 1999 passes and the lack of report of this phenomenon on the Voyager flyby in 1979, which occurred 10 Io radii (R_{Io}) beneath Io, constrain the dimensions of the mass-loading region. On the 1995 pass, the region is asymmetric in the radial direction, extending 20 R_{Io} in the anti-Jupiter direction (sunward) and only 10 R_{Io} in the direction toward Jupiter. The October 1999 pass shows that in the upstream direction there is no wave generation beyond about 2 R_{Io}. A model that is consistent with these observations confines the primary neutral exosphere to a sphere of about 2 R_{Io} in radius. Exospheric particles become ionized and accelerated by the magnetospheric electric field that points radially outward from Jupiter perpendicular to the magnetic field. The gyrating ions then charge-exchange with neutrals and spread out in a fan perpendicular to the magnetic field. They are re-ionized, producing the waves observed by Galileo, principally in a region of about 20 R_{Io} outward from Io and in a smaller region inward, with a north-south thickness of about an Io radius near Io. The anti-Jupiter direction is favored because it was sunlit during these two passes, and because the electric field associated with the corotation of the torus plasma initially accelerates the ions away



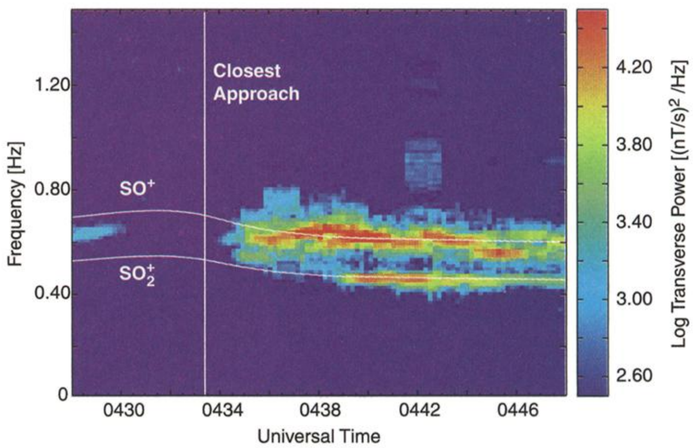


Fig. 1 (left). The trajectories of Galileo relative to Io and the inferred plasma flow on 7 December 1995 (labeled 1740 to 1750) and on 11 October 1999 (labeled 0425 to 0445). Sinusoids mark the presence of ion cyclotron waves, and square waves mark the presence of mirror mode waves (*14*). One Io radius is 1818 km. **Fig. 2 (right).** A dynamic spectrum showing the power spectral density of waves during the October 1999 Io flyby. Shown is the power in the derivative of the magnetic field in the direction transverse to the magnetic field. The analysis interval was 85.2 s in duration, and successive spectra are separated by 10.66 s. Spectral estimates have been averaged in bands of three frequencies to enhance statistical accuracy. The white lines are the gyrofrequencies of singly ionized SO and SO_2^+. The spectrum begins at the end of a 1-min data gap. There were no waves before this time.

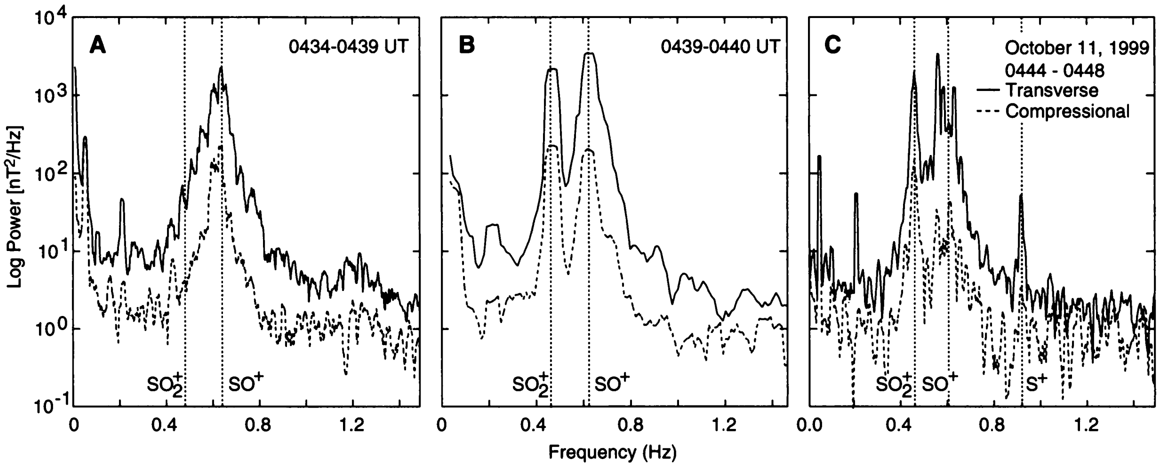


Fig. 3. The power spectral density of the magnetic field in the directions transverse to the magnetic field and along it. The time series was quadratically detrended before the power was calculated. Three spectral estimates have been averaged in the frequency domain to enhance statistical accuracy. The lines at 0.05 and 0.2 Hz are artifacts. **(A)** The period of initial SO^+ wave activity from 0434 to 0439 UT. **(B)** The period when the SO_2^+ waves appeared, from 0439 to 0440 UT. **(C)** The period when the waves at the SO^+ gyrofrequency disappeared, from 0444 to 0448 UT. The frequency resolution of these spectra is proportional to the duration of the time series from which they were calculated. It is 0.01 Hz in (A) and (C) and 0.05 Hz in (B).

from Jupiter. A confined mass-loading region can alter the direction of maximum growth rate of the ion cyclotron emission, because waves propagating along a slant path through the region of growth may gain more energy than those taking the shortest path. Consistent with this supposition, the waves on this pass generally propagated at angles from 10° to 30° to the magnetic field, not along the field.

We can only speculate on the reasons for the differences between the two passes. In 1999, Galileo passed over the active region of volcanism near Pele close to Pillan Patera, a volcano that has been active of late, as have other volcanoes such as Loki (*12*, *13*). The waves were seen downstream from the region in which the neutral atoms from Pillan Patera would be ionized and drift with the torus plasma in the corotation direction. The differences cannot be due to a different trajectory relative to the plasma flow past Io. Spectra at 1741 UT in 1995 and at 0443 UT in 1999, where the trajectories crossed, are very different. We are left with the speculation that the recent volcanic activity at Io produced an atmosphere with a different spatial structure and/or composition in October 1999 than in December 1995.

References and Notes

1. M. G. Kivelson *et al.*, *Science* **274**, 396 (1996).
2. L. A. Frank *et al.*, *Science* **274**, 394 (1996).
3. D. A. Gurnett *et al.*, *Science* **274**, 391 (1996).
4. D. J. Williams *et al.*, *Science* **274**, 401 (1996).
5. J. Warnecke *et al.*, *Geophys. Res. Lett.* **24**, 2139 (1997).
6. J. W. Belcher, in *Physics of the Jovian Magnetosphere*, A. J. Dessler, Ed. (Cambridge Univ. Press, New York, 1983), pp. 68–105.
7. D. E. Huddleston *et al.*, *Geophys. Res. Lett.* **24**, 2143 (1997).
8. The second of these encounters has now taken place, but because of a spacecraft safing event, the data close to Io were not obtained.
9. A summary of the magnetic field distortions observed during the pass and their possible bearing on the question of the intrinsic field of Io is available from the authors of this paper. A definitive answer to the existence of an intrinsic field is not available from this pass.
10. E. Lellouch, *Icarus* **124**, 1 (1996).
11. M. Yu. Zolotov and B. Fegley, *Icarus* **132**, 431 (1998).
12. A. S. McEwen *et al.*, *Icarus* **135**, 181 (1998).
13. R. Lopez-Gautier *et al.*, *Icarus* **140**, 243 (1999).
14. C. T. Russell *et al.*, *J. Geophys. Res.* **104**, 17471 (1999).

15. Supported by grants from the Jet Propulsion Laboratory from funds provided by NASA.

3 December 1999; accepted 7 February 2000