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IO - JUPITER INTERACTION: WAVES GENERATED BY PICKUP IONS

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ABSTRACT

Ion pickup processes invariably produce anisotropic ion distributions and hence can give rise to wave generation. This paper discusses the waves due to the Io pickup source in Jupiter's magnetosphere. In the near-Io torus, the Galileo spacecraft observed ion cyclotron waves near the sulfur dioxide gyrofrequency, which grow due to the absence of a thermalized background component of these molecular ions in a torus plasma of predominantly dissociated species. These wave observations allow limits on pickup source rates to be estimated. On the edge of the Io wake, mirror mode waves were seen where the pickup ion contribution to the pressure anisotropy is sufficient to overcome the instability threshold. The mirror mode can dominate over the individual ion cyclotron modes in a multi-species plasma. The mass density in the torus cannot increase indefinitely and the plasma must be radially transported through the Jovian magnetosphere. Wave processes may be associated with any ion distribution anisotropies that arise during their radial transport, and with unsteady reconnection processes that may facilitate their eventual loss from the magnetotail.

INTRODUCTION

Jupiter's innermost Galilean moon, Io, is the major source of mass in the Jovian magnetosphere. The internal mass-loading and rapid Jovian rotation are responsible for the stretched magnetodisk shape of the middle magnetosphere, a feature unique to Jupiter in our solar system. Continual supply of volcanic gases from Io forms extended clouds of neutral particles, which become ionized on timescales of the order of hours (e.g. Brown *et al.*, 1983; Smyth and Marconi, 1998) to replenish the Io plasma torus. Newly ionized pickup ions are initially accelerated by the motional electric field due to the corotation (nominally $V_{CO} \sim 74$ km/s) of torus plasma and field lines past Io (orbital velocity $V_{IO} \sim 17$ km/s). A current is induced radially outward across Io and the torus, which is driven along field lines and closes in Jupiter's ionosphere. Ultimately, this coupling between Io and Jupiter acts to accelerate the torus plasma and slow down the rotation of Jupiter and its ionosphere; JxB forces re-accelerate the mass loaded plasma toward corotation downstream of Io. The torus is self-sustaining, but the mass density cannot build up indefinitely. The centrifugal force of the plasma corotation drives outward radial ion transport mechanisms to supply the Jovian magnetosphere, and ultimately plasma must be lost from the system along the magnetotail.

Wave instabilities are an integral part of ion pickup processes; wherever ion distribution anisotropies arise, so may waves be generated. These waves are a useful diagnostic for plasma conditions. In the near-Io torus, in common with comet/solar wind pickup environments, new pickup ions initially form anisotropic ring or ring-beam type velocity space distributions which are unstable to wave generation and hence scatter toward a more isotropic configuration. Eventually the ion distributions may become fully thermalized through collisional processes.

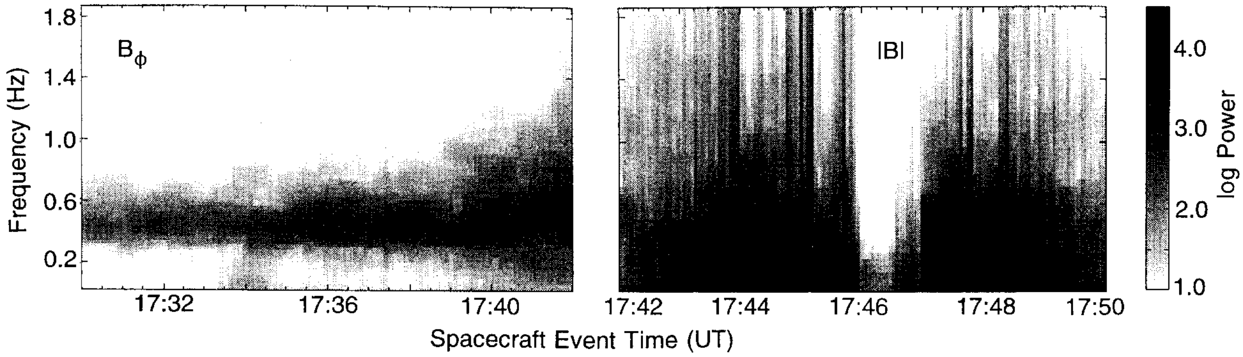

Fig. 1. Dynamic spectral analysis of magnetometer data during the Galileo-Io flyby. The left hand plot shows the power spectrum of the Bϕ azimuthal (transverse) component for the inbound pass 17:30 - 17:42 UT showing ion cyclotron waves in a band near 0.4 Hz . The right hand plot presents |B| compressional power in the mirror mode structures (nominally zero frequency) for 17:42 - 17:50 around closest approach.

OBSERVATIONS

During the Galileo-Io flyby ion cyclotron waves were observed near the sulfur dioxide gyrofrequency (Kivelson *et al.*, 1996, Warnecke *et al.*, 1997, Huddleston *et al.*, 1997, Russell *et al.*, 1999a) in extensive regions near Io (inbound, from ~20 R_{IO} to the edge of the Io wake, and outbound from the wake edge to ~7 R_{IO}). These waves were nearly circularly polarized, generally left-handed and nearly field aligned. Closer to Io, adjacent to the cold wake region, large amplitude mirror mode structures were seen. These were linearly polarized, highly compressional "dips" in the magnetic field. Figure 1 shows dynamic spectra of the B_ϕ (transverse) component of the field on Galileo's inbound pass, and of |B| for the time period centered on closest approach. The former shows a broad frequency band of ion cyclotron waves near 0.4 Hz (the SO_2^+ gyrofrequency) while the latter shows the compressional mirror mode (non-propagating, nominally zero frequency) on either side of the central wake. Two important questions arising from the observations are firstly, why do the waves appear near SO_2^+ frequencies when the torus composition is predominantly O^+ and S^+, and secondly, how does the mirror mode dominate near the wake edge. Ion cyclotron waves typically dominate in pickup ion mass-loading environments (notably at comets, e.g. Lee, 1992), while mirror mode structures are also seen under certain circumstances, at comet Halley (e.g. Russell *et al.*, 1991), occasionally in the solar wind (e.g. Winterhalter *et al.*, 1994), and in the magnetosheaths of the Earth (e.g. Tsurutani *et al.*, 1982), Saturn (e.g. Bavassano Cattaneo *et al.*, 1998), as well as Jupiter's magnetosheath (e.g. Balogh *et al.*, 1992).

ION CYCLOTRON WAVES IN THE NEAR-IO TORUS

Recent wave dispersion analysis (Warnecke *et al.*, 1997; Huddleston *et al.*, 1997) confirmed that it is in fact the thermalized background Maxwellian distributions of sulfur and oxygen ions in the torus that can quench the cyclotron instability for these species, by reducing the effective anisotropy of the combined pickup plus background distribution. That is, the background torus plasma will damp the ion cyclotron waves generated by the new pickup S^+ and O^+ near Io. However, for the small fraction of SO_2 that becomes ionized before dissociation, the unstable wave mode is not damped because the subsequent rapid destruction of SO_2^+ precludes a significant background population of thermalized SO_2^+ in the torus.

Limits on Pickup Ion Densities

Particle scattering to a more stable, isotropic distribution generates waves as these ions lose energy in the bulk plasma frame; the most likely asymptotic distribution is the "bispherical shell" (previously investigated at comets, see Galeev and Sagdeev (1988), and Huddleston and Johnstone (1992) for example). Free energy calculated as the energy difference between ring and bispherical shell geometries in velocity space leads to a simple relationship between the observed ion cyclotron wave amplitudes and the density of pickup ions required to generate these waves

Table 1. Io Source Rate Estimates

	average particle mass (amu)	source rate (/s)	mass addition (kg/s)	reference
Voyager "standard"	20	$\sim 3 \times 10^{28}$	1000	[*eg. Hill et al., 1983*]
SO_2 molecules	64	4×10^{27}	430	[*Smyth and Marconi, 1998*]
All new ions (dissociated)	21	$1.5\text{-}1.7 \times 10^{28}$	560	[*Bagenal, 1997*]
SO_2^+ ions	64	8×10^{26}	85	[*Huddleston et al., 1998*]
O^+ ions	16	$< 9 \times 10^{27}$	< 240	[*Crary, 1998*]

(Huddleston *et al.*, 1997). The resulting SO_2^+ pickup ion density profile inferred from the observed waves at Io is consistent with 5% of the total ion source estimated by Bagenal *et al.* (1997) in agreement with the Io wake composition reported by Frank *et al.* (1996) from the Galileo PLS instrument. Ion source rate estimates are calculated on the basis that the ion flux (N x V) passing Galileo per second is equivalent to the ion production rate per second along the flowlines upstream from Galileo. The estimates are compared in Table 1.

Based on the *lack* of cyclotron wave peaks at the gyrofrequencies of the dissociated torus species, Crary (1998) estimated an upper limit on O^+ ion production rate, 9×10^{27} /s, corresponding to a limit on effective anisotropy (ratio of ring to thermal background O^+) using wave dispersion to calculate a marginal stability criterion. Comparing the rates in Table 1, this O^+ rate is about 60% of the total ion source estimated by Bagenal (1997), which is a reasonable torus ratio. An upper limit for sulfur ions has not been calculated; using test particle simulations, Crary (1998) finds that S^+ ions are non-resonantly scattered on SO_2^+ cyclotron waves, while O^+ ions are not. Thus there is a competing process for the S^+ pickup ion scattering. The SO_2^+ cyclotron waves are damped in the non-resonant scattering process. We speculate that the damping of the waves may be one factor contributing to the absence of ion cyclotron waves during the Voyager 1 pass at a distance 11 Io radii south of Io (off the magnetic equator), while such waves were observed from as far as 20 R_{IO} on Galileo's inbound pass (in the ecliptic plane). Time variations, source region asymmetries, and Io's location with respect to the magnetic equator may also play significant roles (waves were seen only to ~7 R_{IO} on Galileo's outbound pass). However, even for a very localized source at Io, since the waves are mostly field-aligned we would have expected them to propagate north and south to distances beyond 10 R_{IO} along the field lines, had these waves remained largely undamped.

Io versus Comet Pickup Environments

The first major difference between typical solar wind pickup environments, e.g. at comets, and the pickup near Io within Jupiter's magnetosphere is that the new ions at Io are picked up into a same species torus plasma, while the heavy cometary ions are picked up into a proton/helium solar wind. Thus, at comets the new pickup ion distributions generate ion cyclotron waves at frequencies that are not readily absorbed by the background solar wind, while at Io as mentioned above, with the exception of SO_2^+, the background plasma quenches the cyclotron modes of the dissociated species. The other major difference at the Io - Jupiter interaction is the ratio V_{ph}/V_{inj} of the wave phase velocity to the pickup injection velocity. At comets, this ratio is small, $V_{ph}/V_{sw} \sim 0.1$. On the other hand, in the near-Io torus, the phase velocity of the SO_2^+ cyclotron mode was found from dispersion analysis to be ~55 km/s (Huddleston *et al.*, 1998) while the velocity of corotation relative to Io is ~57 km/s, giving a ratio of approximately unity. This ratio is important in determining the geometry of ion scattering in velocity space. Figure 2a shows the velocity space pickup geometry near Io with $V_{ph} \approx V_{inj}$. For V_{CO} nearly perpendicular to B, the ring injection point is the black dot on the $v_\perp$ axis, and the bispherical "shell" is comprised by the dashed line segments. The bispherical shell is a rather "squashed" sphere in Figure 2, indicating that considerable energy diffusion occurs with the pitch angle scattering. It is possible for ions to be considerably accelerated/decelerated by scattering successively on upstream and downstream propagating waves as shown in Figure 2b (see also Terasawa, 1989). In contrast, in Figure 2c, when $V_{ph} << V_{inj}$ the bispherical shell is not so different from a spherical shell and the ions scatter primarily in pitch angle with little change in energy. Note that at the resonance "gaps" at $\pm V_{ph}$, ions with a given $v_{//}$ velocity component cannot interact with purely parallel-propagating electromagnetic waves of the same velocity because those waves appear stationary in the ion frame. Here, ions must first scatter on the oppositely-propagating waves, e.g., on $-V_{ph}$ waves while in the vicinity of the $+V_{ph}$ gap. Alternatively, ions may perhaps scatter on obliquely-propagating waves, as discussed in the next section below. Note also that dispersion analysis (e.g., Warnecke *et al.*, 1997; Huddleston *et al.*, 1998) finds the wave phase velocity to be frequency-dependent, further complicating the simple scattering geometry.

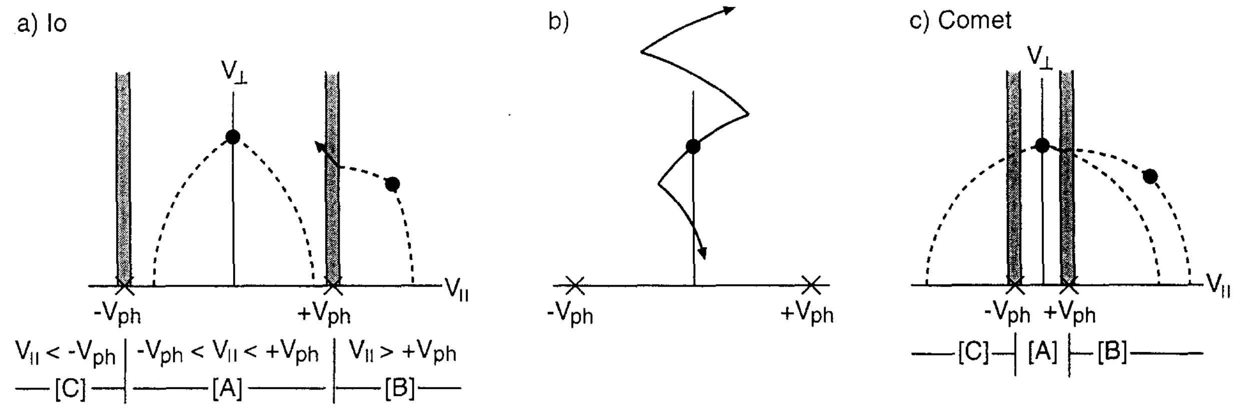

Fig. 2. Velocity space schematic diagrams showing ion injection, bispherical shell geometries (dashed lines) and possible scattering paths (arrows) for ions interacting with field-aligned ion cyclotron waves (velocities $\pm V_{ph}$) in cases of (a),(b) $V_{ph} \approx V_{inj}$ appropriate to the Io torus environment, and (c) $V_{ph} << V_{inj}$ as seen in typical comet/solar wind environments.

Cyclotron Wave Elipticity and Propagation Angle

Dynamic spectral analysis of the cyclotron wave properties in the near-Io torus is discussed in a companion paper (Russell and Huddleston, 1999). Elipticity spectrograms suggest the occasional presence of some right-handed (RH) polarized waves at certain frequencies typically a little above the gyrofrequency, and propagating obliquely to the field. This could either be a propagation effect, or a distinct branch mode of wave generation.

It makes sense for the RH waves to be oblique if they are generated directly by the pickup ions. For left-hand (LH) gyrating ions to be in resonance with purely parallel-propagating RH waves, the ions would need to be overtaking the waves to see the wave vector rotating "in reverse". For $V_{ph} / V_{inj} \sim 1$ and a perpendicular pickup geometry, this is difficult to achieve. It would require considerable energization of ions along $v_{//}$ to velocity magnitudes in excess of V_{ph} (regions labeled B and C in figure 2a). In region B(C) of velocity space, any scattering on $+V_{ph}$ ($-V_{ph}$) waves occurs through the anomalous Doppler resonance, interacting with RH waves. A greater likelihood of generating some RH waves results if the angle between the field and flow is reduced from the perpendicular such that ions are initially injected with $v_{//}$ near or in excess of V_{ph} as shown in the hypothetical case included in Figure 2a. However, at Io's orbit the ambient field is tilted only $\sim 10^{\circ}$ from north-south, and therefore the pickup geometry is nearly perpendicular for most of the torus. A possible exception to this is close to and ahead of Io where considerable north/south flow deflections might arise, and in combination with field distortions (including those caused by large amplitude waves and mirror mode structures) might lead to occurrences of a reduced angle between the field and flow. In such a case, ion scattering across the $+V_{ph}$ gap on purely parallel-propagating waves would still require energization of the ions, hence damping of $-V_{ph}$ waves which must therefore already be present at suitable frequency. The situation is different in the presence of obliquely-propagating waves. We recall here that the RH waves near Io were observed at oblique propagation angles in velocity space; such wave scattering centers are displaced from the $v_{//}$ axis. It is possible that this also represents a way of getting around the resonance gaps at such times when ions are injected with $v_{//}$ at or near V_{ph} of the parallel wave. An obliquely-propagating mode may perhaps have the dominant growth rate in such a situation. A preliminary dispersion parameter study confirms that oblique cyclotron modes are possible near Io (X. Blanco-Cano *et al.*, in preparation).

MIRROR MODE STRUCTURES AT THE IO WAKE EDGE

The observation of mirror mode structures in the ion source region on the flanks adjacent to the cold Io wake was not immediately expected because of the high ambient magnetic field (~1800 nT) and low β in the Io torus. Their presence tells us that the contribution of the highly anisotropic pickup ion pressure dominates the background plasma such that the pressure anisotropy $P_\perp >> P_{//}$ overcomes the mirror mode instability threshold there (Huddleston *et al.*, 1999). Dispersion analysis confirms that the multi-component plasma allows the mirror mode growth rate to dominate. Figure 3a (adapted from Huddleston *et al.*, 1999) shows the relative growth rates appropriate to the near-Io torus and outer wake edge where the torus background plasma still quenches the O^+ and S^+ ion cyclotron modes. Figure 3b illustrates the expected effect of increasing pickup ion densities and declining background contributions (encountered on moving in toward the cold wake where presumably the background torus plasma is excluded completely); in this case the mirror mode can dominate. The ion cyclotron growth is divided into several individual modes (each with different resonant frequencies) corresponding to the multiple species components, whereas the mirror mode instability is fed by the combined anisotropy of all species present.

WAVES IN THE JOVIAN MAGNETOSPHERE

The torus plasma density cannot continually increase with the continual addition of ions from Io, and the plasma is transported through the Jovian magnetosphere and must ultimately be lost along the magnetotail. Any anisotropies that develop in the distributions during their radial transport (e.g., through conservation of magnetic moment) can be a source of instability. We might also expect to find differences in the wave phenomena with local time. In the magnetotail there may be more wave phenomena associated with unsteady plasma transport and reconnection events. Recent Galileo observations (Russell *et al.*, 1999c) indicate that beyond $50R_J$ explosive reconnection occurs sporadically, releasing plasmoids down the tail as postulated by Vasyliunas (1983). Such events are thought to be internally driven, by the dynamics of the rapidly-rotating Jovian magnetodisk, rather than driven by the external influence of the solar wind as is often the case at Earth (i.e., magnetic storms).

The current sheet region of the stretched Jovian magnetodisk contains relatively intense fluctuations near ~23 R_J, while at magnetic equatorial latitudes in the quasi-dipolar region closer to Jupiter (~11 R_J) fluctuations are less intense (Russell *et al.*, 1999b). Fluctuations are largest where the field is weakest in the center of the current sheet, and appear to be mirror-mode like (Russell *et al.*, 1999b). The highest values of β (conducive to the mirror mode) are indeed expected in the current sheet where the plasma density is highest, but the source of anisotropy to generate these waves is not immediately clear. The atmospheric loss-cone is not expected to produce a very large anisotropy in the ion distributions, especially at distances far from Jupiter. Another possibility is that energetic neutral atoms (ENAs) produced by re-neutralization processes in the Io torus can subsequently be re-ionized elsewhere throughout the magnetosphere, providing a (perhaps weak) pickup source. Such a source of ions could in turn be a source of waves.

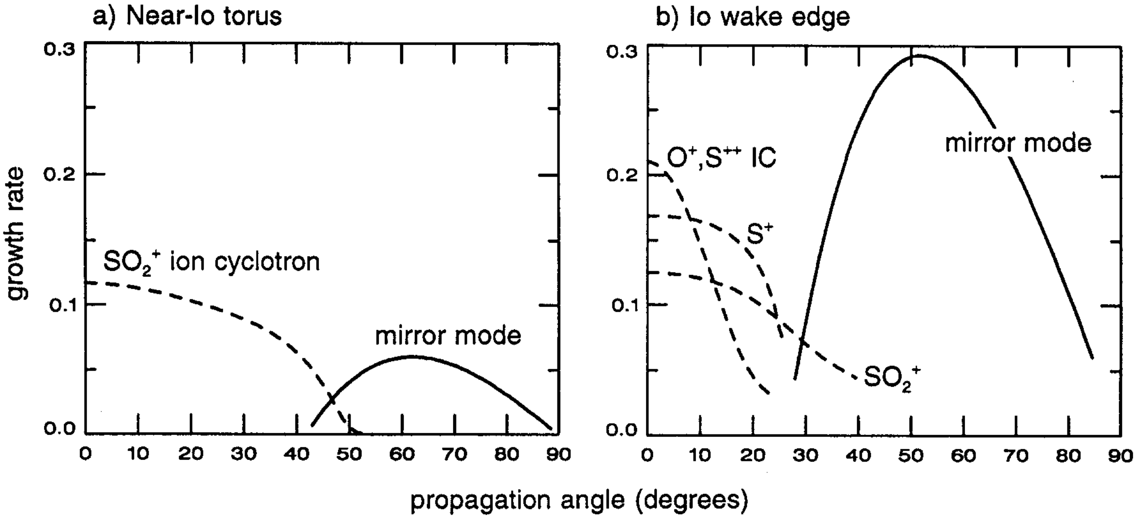

Fig. 3. Results from dispersion analysis (Huddleston *et al.*, 1999) for multi-species plasma conditions appropriate to the near-Io torus and the Io wake edge.

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