Io's Interaction with the Plasma Torus: Galileo Magnetometer Report

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Galileo magnetometer data at 0.22-second resolution reveal a complex interaction between Io and the flowing plasma of the Io torus. The highly structured magnetic field depression across the downstream wake, although consistent with a magnetized Io, is modified by sources of currents within the plasma that introduce ambiguity into the interpretation of the signature. Highly monochromatic ion cyclotron waves appear to be correlated with the local neutral particle density. The power peaks in the range of molecular ion gyrofrequencies, suggesting that molecules from Io can remain undissociated over a region of more than 15 Io radii around Io.

On 7 December 1995, the Galileo orbiter passed within 0.5 R_{Io} (Io radii) above the surface of Jupiter's moon Io. The magnetometer (*1*) recorded magnetic field vectors with 0.22-s time resolution and stored them on the spacecraft tape recorder for transmission in mid-June 1996. The magnetic signature based on 1-min averages transmitted in late 1995 showed that the jovian field, whose magnitude was ~1835 nT near Io's location, decreased by ~40% near Io (*2*). In interpreting the signature, we considered plasma sources of field depression and contributions from an intrinsic field of Io. Our estimates of the contributions of various plasma currents to the field depression, based on Voyager 1 plasma measurements (*3*), suggested that plasma effects accounted for <30% of the signature. We argued that the observed field depression could be produced if Io had an intrinsic magnetic field with a magnetic moment on the order of 10^{20} A m^2 (10^{13} T m^3) anti-aligned with Jupiter's magnetic dipole. We concluded that an intrinsic dynamo provided a plausible explanation of the observations as it is consistent with some dynamo models and reasonable in a body with a differentiated core (*4*). This explanation remains viable in light of the full magnetometer results, but additional analysis incorporating data from other instruments is needed to evaluate alternative interpretations.

The data at higher time resolution provide insight into details of the interaction between Io and the plasma that flows by it. Before the encounter, the magnetic field **B** was predominantly in the θ direction with small B_r and B_ϕ components, and the magnitude was increasing, as expected for approach to Jupiter (Fig. 1). The Khurana-96 Jupiter magnetic field model (KK96) (*5*) represented the measurements quite well (magnitude errors <3%). Fluctuations, predominantly transverse to the background field, were observed at ~17:10 UT (universal time) and increased in amplitude as Galileo approached Io. The average field magnitude began to decrease monotonically 5 min before closest approach (17:45:58 UT, at an altitude of 898 km) and reached 610 nT within a background field of ~1000 nT at 17:44:50 UT. In this region, the KK96 model gives a field magnitude of about 1800 nT. The field signature became markedly different in the region immediately downstream of Io relative to the flow direction of torus plasma, a region that we refer to as the geometric wake of Io. The field magnitude leveled off, and its fluctuations became small. Near the outbound crossing of the geometric wake, the field again decreased, and its magnitude began to fluctuate much as it did during the inbound interval. The field returned to within 3% of model values at ~17:56 UT. Estimates of expected perturbations in a magnetohydrodynamic simulation (*2*, *6*–*8*) of a conducting Io are too small to account for the observations, whereas a magnetized Io model overestimates the field decrease in the geometric wake and underestimates it on both sides (Fig. 1). These localized departures correlate with properties of the local plasma (*9*).

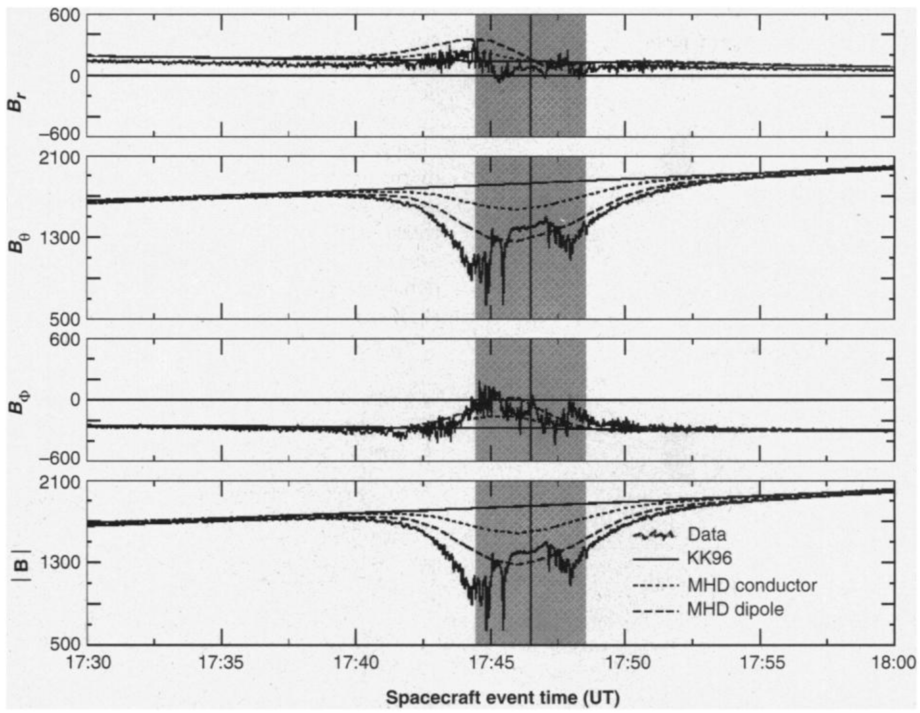

Fig. 1. Components and magnitude of **B** (in nanotesla) in right-handed System III (1995) coordinates (*27*) with θ positive southward, ϕ positive in the sense of rotational motion, and *r* radially outward from Jupiter. Solid lines are used to plot measurements from 17:30 to 18:00 UT spacecraft event time on day 341, 7 December 1995. The interval within the geometric wake is shaded, and a vertical line is shown at the wake center. Magnetohydrodynamic simulations (*6*) for a conducting Io (short dashes) and a magnetized Io (long dashes) have been scaled to the background field of Jupiter at the center of the geometric wake and added to the KK96 model (*5*) (solid curves) that represents the variations of the background field of Jupiter along Galileo's orbit.

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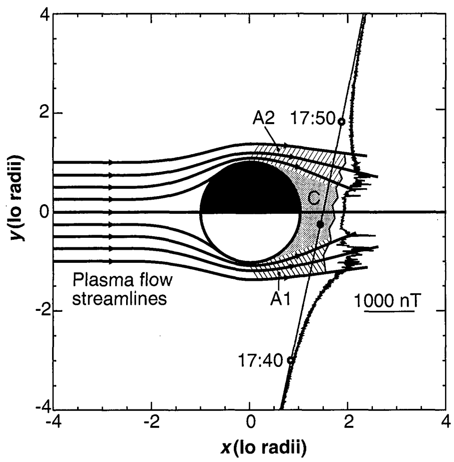
Incident torus plasma is modified by the presence of Io and by the addition of pickup ions (*10, 11*) from a population of neutrals originating from Io (*12*). Some incident plasma is likely to flow directly into Io or its atmosphere and ionosphere (Fig. 2). Some plasma is diverted to the sides, where it may be accelerated above co-rotation speed. Behind Io, in the geometric wake, there must be flux tubes that have been partially depleted of torus plasma by direct interaction with Io. These flux tubes slow as they pass over Io. They can be kept populated with torus plasma flowing along field lines and with newly picked up ions, which cause additional slowing (*6, 13, 14*). The downstream flanks of the geometric wake contain plasma that has flowed around Io. This plasma begins to fill in the wake as it moves on, but the full closure of the wake may occur several Io radii downstream of Io (*15*).

Along the Galileo trajectory, we distinguish among regions of different magnetic signatures on the basis of the flow pattern described above. Regions with plasma that has flowed past Io (A1 and A2 in Fig. 2) differ from regions in which Io blocks direct access to upstream plasma (C in Fig. 2). Photo-ionization and impact ionization increase the plasma density, especially along flow lines that pass close to Io and wherever flow is slowed, and flux tubes dwell in the source region. Pickup extracts momentum and slows the flow. Plasma heating (*16*) occurs in A1 and A2, where the flow speed may be above the thermal speed, but cooling occurs where the plasma is slowed below the thermal speed, as, for example, along the trajectories of flux tubes that are encountered in region C. Where plasma is heated, diamagnetic effects of enhanced plasma pressure (9) contribute to localized field depressions (A1 and A2). This interpretation is consistent with the wave perturbations that are normally found in regions of strong velocity-space anisotropy (such as that produced by pickup) and enhanced thermal pressure. The reduced level of fluctuations in region C suggests that it is dominated by plasma that was ionized in a region of slowed flow. Such ionization does not result in large velocity-space anisotropy, although it modifies the local field depression by a few percent (*9, 17*).

The magnetic fluctuations appear first >15 R_{Io} away from Io. Monochromatic, predominantly transverse waves with periods of 2 to 3 s, observed during the near-Io pass, are ion cyclotron waves (Fig. 3). The magnetic perturbations are largely transverse to the background field with almost circular left-hand polarization. A power spectrum of the interval reveals a peak near the gyrofrequency of SO_2^+ or an ion of the same mass per unit charge. The peak power typically falls between the gyrofrequencies of SO_2^+ and SO^+ throughout the pass (Fig. 4A), and no peaks in power are found near the gyrofrequencies of O^+ or S^+. The amplitude is largest near Io. The power varies as the cube of the inverse distance from Io on the inbound leg and as the inverse distance to the 3.5

Fig. 2. Galileo's trajectory past Io in the *xy* plane. The magnitude of the *z* component of the field is plotted toward positive *x* for each point on the trajectory. The Cartesian coordinate system has *z* along Jupiter's spin axis, *x* along the System III ϕ direction (parallel to the sense of co-rotation), and *y* radial and positive outward. Schematic flow streamlines illustrate that in regions A1 and A2, the plasma is likely to have flowed by Io from upstream and passed close to Io's surface, whereas the plasma in region C within the geometric wake has no direct upstream source in the equatorial plane. Closest approach at ~0.5 R_{Io} above Io's surface is indicated by a filled circle. Open circles indicate key times.



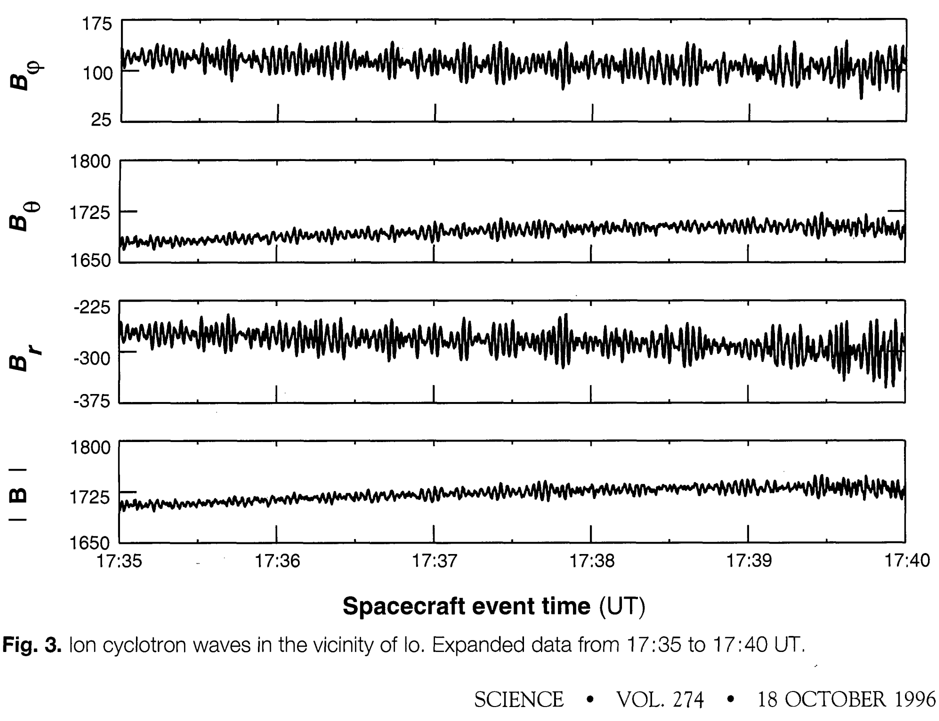


Fig. 3. Ion cyclotron waves in the vicinity of Io. Expanded data from 17:35 to 17:40 UT.

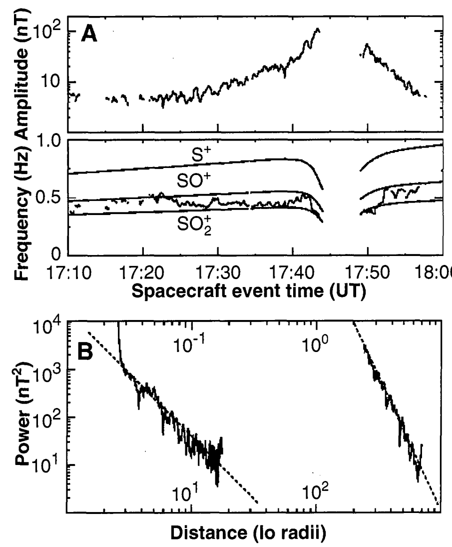


Fig. 4. Ion cyclotron waves in the vicinity of Io. (**A**) For frequencies above 0.3 Hz, the lower trace shows the frequency of the spectral peak of a dynamic power spectrum, plotted only where the fractional polarization of the signal exceeds 0.5. Reference lines are plotted at the gyrofrequencies of ions with mass per unit charge of 32, 48, and 64 (in units of proton mass per unit charge), corresponding, for example, to SO_2^+, SO^+, and S^+. The upper trace shows the amplitude near the peak frequency. (**B**) Power of the polarized signal versus distance in Io radii for the inbound (lower scale) and outbound (upper scale) portions of the flyby.

power on the outbound leg, roughly proportional to the expected variation of neutral particle density in Io's vicinity (*12*) (Fig. 4B). The wave amplitudes become as large as 250 nT peak to peak but are still small compared with the background field.

The dispersion relation for ion cyclotron waves in a cold multicomponent plasma shows that waves occur below the gyrofrequency of the heaviest ion in the distribution and for limited bands of higher frequencies (*18*). Finite temperature and anisotropy change the range of allowed frequencies, but only limited ranges of frequencies are favored for wave growth. In pickup plasmas near comets, wave power has been found to peak near the gyrofrequency of the heaviest ion in the distribution (*19*). Thus, the dominant power at the gyrofrequencies of SO_2^+ and SO^+ indicates that these ions are present in the pickup distribution, although they need not be the dominant species. Still, the evidence that ionization of molecules occurs as far as 15 R_{Io} away from Io lends support to dynamic atmospheric models (*20*) and to inferences from observations of the Na cloud around Io (*21*) that molecular ions are an important component of the near-Io plasma. Molecular pickup ions provide an additional energy source for the torus that has been ignored in calculations (*22*) of the energy input from neutrals generated by Io.

In regions A1 and A2, the nature of the waves changes. The fluctuations are no longer transverse but appear as dropouts in the field magnitude. If the perturbations are taken to be structures embedded in plasma nearly at rest with respect to Io, their duration of several seconds implies spatial scales on the order of $2\pi\rho_i$, where ρ_i is the gyroradius of a thermal ion. This scale is consistent with an interpretation of these fluctuations as mirror mode waves, which can also develop in the presence of velocity-space anisotropy. Details of the plasma distribution should enable us to understand why ion cyclotron waves grow in some regions and mirror mode waves in others and may provide further insight into the relation of the plasma to the sources of neutrals.

The large field depression centered at Io is plausibly dominated by an internal magnetic field of Io, but without further analysis, the data neither confirm nor rule out the existence of an internal field. Measurement of the plasma properties (*9*, *23*) constrain the interpretation but do not eliminate the ambiguity. In regions A1 and A2, a diamagnetic effect of the local plasma contributes ~200 nT to the ~400-nT field decrease (*24*). Positive perturbations in $|\mathbf{B}|$ are produced by the current flowing downstream of the spacecraft trajectory, accelerating the slowed plasma behind Io back to co-rotation speed (*25*). In region C, the pressure gradient exerts a force toward the center of the wake and increases the field magnitude there, opposing the decrease contributed by an internal dipole moment and by currents linking Io and its surroundings to Jupiter's ionosphere (the Alfvén wing currents) (*2*, *7*). If the latter currents close through a high-altitude current-carrying ionosphere of Io, the magnetic perturbation along Galileo's orbit could be as large as observed without contributions from an internal dipole. However, it is not clear whether the high-density plasma found near the center of the wake (9) is sufficiently collisional to have the properties required of a current-carrying ionosphere. The (unmeasured) neutral density would have to be large enough for the ionosphere to remain bound in the presence of electromagnetic forces ($\mathbf{j} \times \mathbf{B}$, where $\mathbf{j}$ is the current). A full analysis will require quantitative modeling (*26*). Although an unmagnetized Io with an extended (current-carrying) ionosphere must still be evaluated as the source of the magnetic signature, we believe that our original (*2*) estimate of the magnetic moment is a good upper limit to any intrinsic magnetic moment and is consistent with the high-resolution data when the additional contributions of local plasma effects are introduced.

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24. A particle pressure of ~250 nPa (*8*) at the inbound peak relative to a magnetic pressure decrease of ~900 nPa.
25. Momentum balance arguments suggest that near Galileo's orbit, positive perturbations in B_z of 100 to 200 nT are produced by reacceleration of the plasma in the wake.
26. It may be possible to determine if the cold plasma in the wake is an extended current-carrying ionosphere or a stagnant pickup plasma by estimating the heating that would be produced by currents flowing through the ionosphere and comparing the resulting temperature with the observed temperature (*9*) of $\sim 2 \times 10^5$ K.
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