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Galileo evidence for rapid interchange transport in the Io torus

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Abstract. Anomalous plasma signatures were detected by the Galileo particles and fields instruments during the initial transit through the Io torus. These unusual events are characterized by abrupt changes in the magnetic field, enhanced levels of broadband low frequency electromagnetic waves and a pronounced change in both the flux and pitch angle anisotropy of energetic particles. Here we present a coordinated study of one of the events which occurred near $6.03R_J$ just after 17:34 UT on December 7, 1995. The available data are consistent with the concept of rapid inward transport, and this is interpreted as the first evidence for the predicted interchange motions in the region exterior to the orbit of Io. Theoretical arguments indicate that the interchanging flux tube is characterized by substantially reduced plasma density, a spatial scale comparable to 10^3 km, and an inward radial velocity comparable to 10^2 km/s.

Introduction

Rapid mass loading of plasma by ionization of neutral material emanating from Io can lead to the onset of unstable interchange motions (Hill et al., 1981; Siscoe et al., 1981). In the corotating frame, overdense flux tubes should be carried outwards, and these are replaced by the inward motion of depleted flux tubes. The decrease in centrifugal potential energy associated with the net outward transport of mass provides the energy source to drive the instability. However, due to the outward directed gradient in the pressure of energetic plasma (Armstrong et al., 1981), a portion of the potential energy released by the interchange motion must be used to adiabatically heat the energetic plasma during the net inward transport. Any residual energy is available to drive the interchange instability (Southwood and Kivelson, 1987) and overcome frictional dissipation at the foot of the flux tubes in the Jovian atmosphere. Enhanced pressure gradients in the energetic plasma can effectively quench or reduce rapid interchange motions in the outer torus (Summers et al., 1988). This leads to a ramp in the distribution of thermal plasma at a location colocated with the strong gradients in the phase space density of energetic plasma (Siscoe et al., 1981). There is a strong coupling between the energetic and thermal components of the plasma, and a thorough analysis of interchange motions requires detailed information on all components.

The most unstable interchange motions should be confined to the inner portions of the torus ($6<L<8$) where the modulating effects of energetic plasma pressure are not severe. There should also be a density differential between the inward and outward moving flux tubes. Richardson and McNutt (1987) established an upper limit of 10% for any density irregularities in the torus, based on the Voyager Plasma Science data. During the inbound passage of Galileo through the Io torus, anomalous regions were identified which are characterized by abrupt changes in magnetic field strength, strong enhancements in the intensity of low frequency plasma waves, and abrupt changes in the phase space density of energetic particles. Here we present a coordinated study of plasma changes during one event that occurred just after 17:34 UT on December 7, 1995 when Galileo was at L=6.03, immediately outside the location of Io. Although direct measurements from the Plasma Science Instrument are unavailable for this event, we demonstrate that the available data are consistent with a large density decrease indicative of an inward moving flux tube.

Coordinated observations during the anomalous 17:34 UT event

A summary of all the anomalous plasma events identified by the Magnetometer is given by Kivelson et al. (1997). Associated low frequency enhancements in the PWS detector are described by Bolton et al. (1997). The Energetic Particle Detector was operating in a limited protective mode (Williams et al., 1996) during passage through the high radiation environment in outer Io torus; full coverage was only initiated inside L=6.5. Four anomalous magnetometer events were identified for this inner region of the torus.

An overview of the observational data taken during a three minute period spanning one event at 17:34 UT is shown in Figure 1. The event itself lasted for 10 s. During this short interval, the magnetic field underwent an abrupt increase in magnitude (δB=22nT; 1.3% increase) with little change in direction (top four panels). Simultaneously, the Plasma Wave Subsystem (bottom) observed an enhancement of broadband low frequency waves (below 10 kHz). The upper hybrid line, near 550 kHz both prior to and after the event, dropped out during the interval of magnetic field enhancement and was replaced by a strong line near 100 kHz. This emission does not appear to be associated with the electron gyrofrequency, f_c=48.2 kHz, or electrostatic waves at $(n+1/2)f_c$. One possible interpretation of the 100 kHz signal is a change in the upper hybrid frequency, but this would imply a density during the event of only 95/cc, compared to 3700/cc in the background

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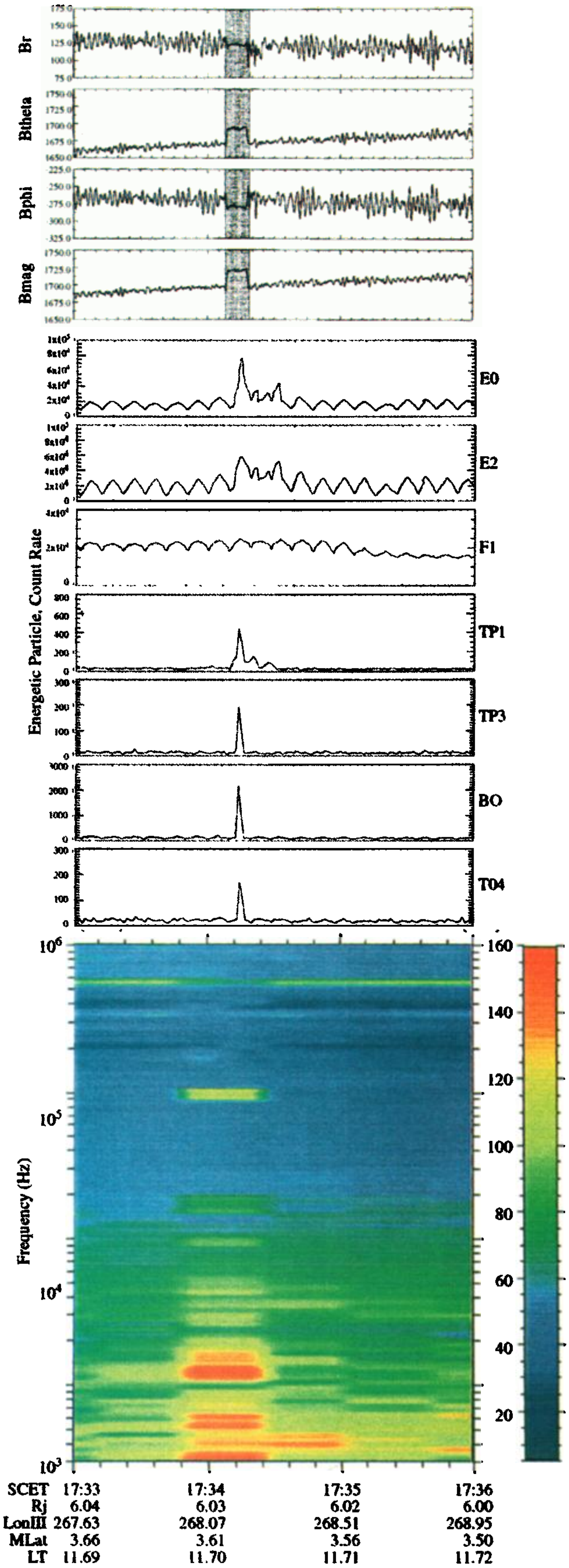

Figure 1. Plasma signatures in MAG (top panels), EPD (middle), and PWS (lower) during the 17.34 UT event.

Table 1. Energetic Particle Properties near L=6.03

Channel	Species	Energy (MeV)	ρ_L (km)	v_{gc} (km/s)	τ_B (s)
E0	electron	0.015-0.029	0.2	0.06	17
E2	electron	0.042-0.055	0.4	0.17	10
F1	electron	0.174-0.304	1.0	0.73	5
TP1	proton	0.8-0.22	23.3	0.34	313
TP3	proton	0.54-1.25	60.4	2.3	120
B0	proton	3.2-10.1	147	13.4	50
TO4	oxygen	1.8-9.0	440	7.5	260

plasma! Such a large density differential would make the flux tube extremely buoyant leading to rapid inward transport.

Changes in the count rate of energetic ions and electrons during the event are illustrated in the center panels of Figure 1. These selected particle channels span a broad energy range from 15 keV to 10 MeV. The energy for each channel, estimates of the typical bounce time, Larmor radius, and gradient drift speed associated with the Jovian magnetic field at 6.03 R_J are listed in Table 1. All particles exhibit a characteristic loss cone distribution with modest depletion along the direction of the ambient magnetic field both before and after the event. During the event, most channels show a pronounced flux enhancement. This increase is most dramatic for the highest energy ions in a direction close to perpendicular to the field. Low energy ions and electrons also exhibit significant flux enhancements and residual effects persist for a brief period following the period of magnetic field enhancement. Notably, higher energy electrons (E > 300 keV) show little change.

Figure 2 shows the evolution of the pitch angle distribution of energetic ions during the event. Because the event observed by the magnetometer occurred entirely within one revolution of the orbiter, one must carefully separate temporal and angular variations. For the spin which began at 17:33:58 (middle column), only the second passage of the EPD sensors through 90 degrees of pitch angle (near 17:34:08) occurred during the 10 second interval that the magnetometer measured the

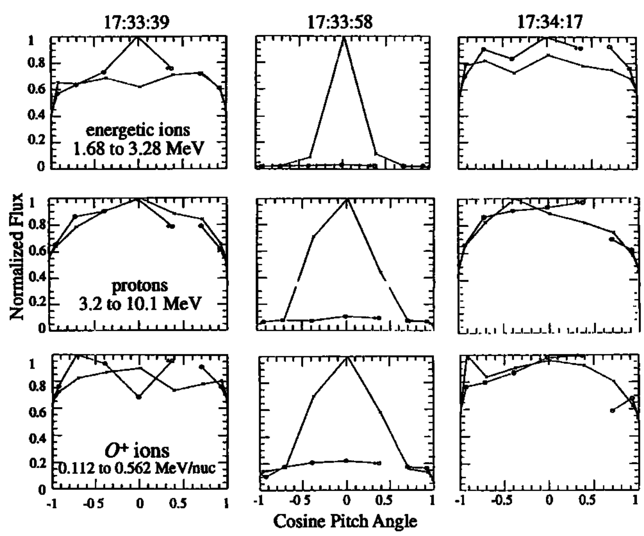

Figure 2. Ion pitch angle distributions over three successive spacecraft revolutions spanning the 17:34 UT event. The start times for each spin are 17:33:39, 17:33:58 and 17:34:17 SCET respectively. Shown from the top row to the bottom: 1.68 to 3.28 MeV ions (Z≥1); 3.2 to 10.1 MeV ions (Z≥1); 0.112 to 0.562 MeV/nuc O^+ ions.

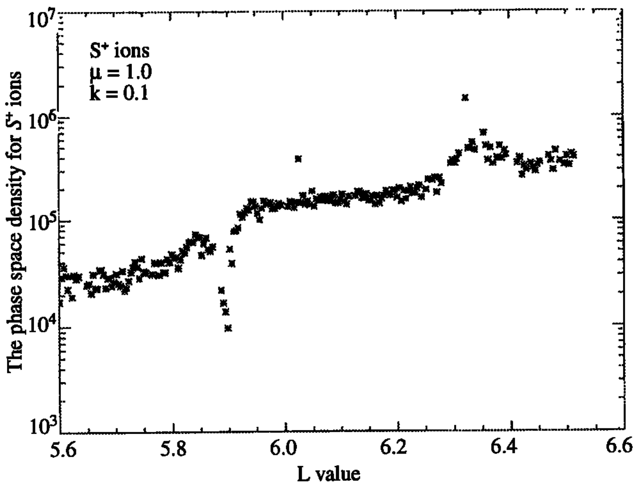

Figure 3. The radial profile of phase space density for energetic (1.0 MeV/nuc. G) S^+ in the torus. For the anomalous enhancement at L=6.03, the phase space density is comparable to that measured in the outer torus near L= 6.3.

anomalous field increase. The difference between the fluxes at 90 degrees is probably a temporal variation. These observations show that 90 degree pitch particles are significantly enhanced in this event. We cannot exclude the possibility that other pitch angles are also changed, but an explanation of this event must account for large and brief changes in the intensity of near equatorially mirroring energetic ions.

To understand the anomalous changes in the EPD data, we have compared the phase space densities of particles (with a fixed first and second invariant) during the event with those seen elsewhere in the Io torus. There is a large radial gradient in the phase space density of energetic ions in the Io torus. An illustration of this, for 1.0 MeV/nuc.G S^+ ions, is shown in Figure 3. The phase space density for S^+ ions observed during the anomalous event near L=6.03 is comparable to the average background values measured near L=6.3 as Galileo moved inward towards Io. (The sharp enhancement in phase space density of S^+ seen near L=6.32 is associated with a separate anomalous region which has also been identified by the magnetometer and PWS instruments.) A similar comparison has been made for other ion species and for different magnetic moments. Consistently, the observed flux enhancements at 17:34 UT can be explained in terms of an adiabatic transport from a "source" region in the outer torus. Source locations tend to be located further out in the torus for lower energy ions. The location of the entry point of energetic particles is well inside the L-shell estimated by Kivelson et al. (1997) as the source location for the buoyant flux tube. Flux enhancements are most pronounced for the highest energy ions, since these generally have a much steeper radial gradient in phase space density, presumably due to more rapid scattering loss (Thorne, 1982; Gehrels and Stone, 1983). The same concept can also account for the absence of any pronounced change in the energetic electron flux which does not exhibit a significant radial gradient in phase space density.

Theoretical Considerations

Our interpretation of the particle and field signatures during the anomalous 17:34 UT event is that Galileo encountered a flux tube with low mass content which was moving rapidly inward with velocity v_R from the outer torus. Energetic particles, which drifted azimuthally into the buoyant flux tube at a radial distance R = 6.03 + ΔR, were also transported inwards and arrived at Galileo after a time $\tau_T = \Delta R/v_R$ with little change in phase space density. The residence time $\tau_D = \Delta x/v_{gc}$ of energetic particles in the anomalous region is controlled by the gradient drift speed v_{gc} and the azimuthal dimension Δx of the flux tube. To reach Galileo we require $\tau_T \leq \tau_D$ which yields $v_R \geq v_{gc}\Delta R/\Delta x$.

Previous theoretical studies of small scale unstable interchange indicate that such transport may occur either in individual flux tubes with approximately the same dimension in the azimuthal and radial directions (Pontius et al., 1986; Southwood and Kivelson, 1989) or in finger-like structures with much larger radial extent (Yang et al., 1994). If the event at 17:34 UT had a finger-like structure which corotated past Galileo with $v_\phi \approx 60$ km/s in τ =10s, the azimuthal extent $\Delta x = \tau v_\phi \approx 600$ km. Using the estimate for the radial location of the source of S^+ ions shown in Figure 3 (ΔR =0.3 R_J) and assuming v_{gc} = 2.3 km/s consistent with the background Jovian field at L = 6.03, we obtain a lower limit on the inward transport speed $v_R \geq 83$ km/s. In order for the ions to remain within the inward moving flux tube, the Larmor radius must be smaller than the spatial scale of the flux tube. The above estimate for Δx is questionable, since the Larmor radius of the S^+ ions, $\rho_L \approx 300$ km. Larger azimuthal scales result if we adopt the alternative model of an isolated flux tube (Figure 4), and interpret the duration of the event in terms of the rate of inward convective transport. In this case $v_R = \Delta y/\tau$ where Δy is the radial extent of the structure. Then using the condition $\tau_T \leq \tau_D$ we obtain the relation $\Delta x \Delta y \geq \tau\, v_{gc}\, \Delta R = 5 \times 10^5$ km^2. With $\Delta x \approx \Delta y$ we obtain a minimal size for the structure $\geq$ 700 km and a minimum inward transport speed $v_R \geq 70$ km/s. A flux tube with spatial scale $\approx 10^3$ km is realistic, and this would require an inward convection speed $v_R \geq 100$ km/s. The inward transport time $\tau_T \approx$ 3 mins would then be less than the bounce time (τ_B = 11 min) and the strong diffusion scattering time (τ_{SD}) for the S^+ ions. Under such conditions, the second adiabatic invariant would not be conserved. However, since τ_T is much less than the strong diffusion scattering time $\tau_{SD} = 10^5$s (Thorne, 1983), particles with pitch angles near 90°, would reach Galileo with little change in phase space density.

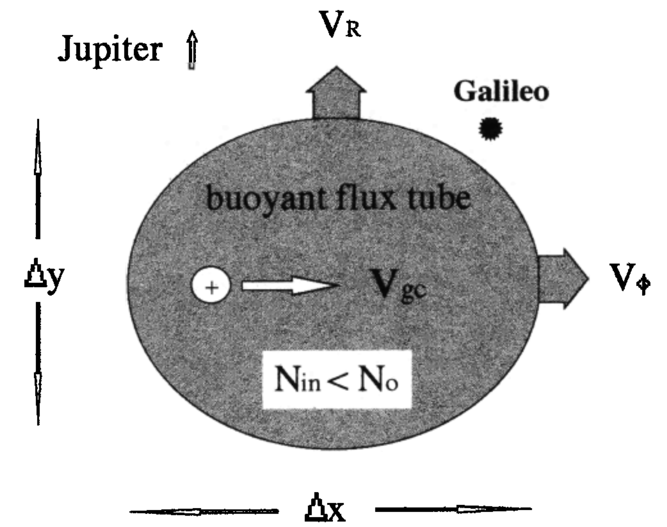

Figure 4. A schematic model for an isolated interchanging flux tube.

Conservation of total pressure ($p_{th}+ p_{hot} +B^2/8\pi$) across the boundary of the 17:34 UT event, where p_{th} and p_{hot} are the pressures of the thermal and energetic plasma, allows an estimate to be made of the thermal plasma density change

$$N_{in}/N_o = (T_o/T_{in})(1\text{-}2\ \delta B/\beta_o B_o - \delta p_{hot}/p_o)$$

Using measured values for the background plasma parameters; T_o=1.2 x $10^{6o}K$ (Frank et al., 1996), N_o =3700/cc, B_o =1700nT, $\beta_o = 8\pi p_o/B_0^2$ = 0.056, and the observed change in magnetic field δB=22nT, we obtain N_{in}/N_o = 0.53 under the assumption that $T_{in} = T_o$ and p_{hot}/p_o << 1. More realistically, one can expect $T_{in} > T_o$ due to adiabatic compression during the inward transport from a source region in the hot outer torus and this would enhance the density difference. Furthermore, the observed EPD flux increases suggest that the energetic plasma may contribute to the pressure balance. Consequently, a value $N_{in} \approx 95/cc$, consistent with the hypothesized change in upper hybrid frequency, is not totally unrealistic. Even the smaller anticipated density differential, δN = 0.47 N_o, should lead to rapid inward flow. Hill et al. (1981) provide an estimate of the inward flow speed $\upsilon_R \approx R\Omega^2\ \delta N/B\Sigma_p$ where Ω is the angular rotation rate, Σ_p is the Pederson conductivity at the foot of the field line in Jupiter's ionosphere, and δN is the change in flux tube content. For $\delta N \approx 0.47\ N \approx 10^3$ kg/W, a value for $\Sigma_p \approx 0.1$ mho is required to obtain the predicted inward transport rate $\upsilon_R \approx 10^2$ km/s. For a density as low as 95/cc the required conductivity is 0.2 mho. These values are within the accepted range (0.1-10 mho), but this restriction on Σ_p may not apply since the inward transport time for the flux tube is less than to the Alfvèn travel time between the torus and Jupiter.

Discussion

Anomalous plasma signatures identified during the Galileo transit through the Io torus have been identified as evidence for interchange instability. For one event near 17:34 UT we infer a density differential of at least a factor of 2 (and possibly much larger) for an isolated flux tube with a spatial scale comparable to 10^3 km. This is sufficient to induce rapid inward transport at a velocity comparable to υ_R=10^2 km/s. An independent argument for rapid inward radial speeds has been given by Russell et al., (1997), based on the absence of ion cyclotron waves within the anomalous flux tube. Preliminary analysis of selected EPD signatures suggests that the energetic particles are carried inward from a source region in the outer torus with little change in phase space density. This leads to the pronounced flux increases in high energy ions observed during the event. Further analysis of the entire spectrum of particles during this and other anomalous events are planned to test this interpretation.

Several important issues need to be resolved in future studies. These include the origin of depleted flux tubes in the outer torus, the role played by the energetic particle population in the pressure balance across the boundaries between inward and outward moving flux tubes, the complex trajectories of energetic particles (especially those with large ρ_L) though the interchanging flux tubes, the importance of this inward transport process as a source of energetic particles in the inner Jovian magnetosphere, and the mechanism for excitation of enhanced low frequency waves.

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References

Armstrong, T. P., et al., Low energy charged particle observations in the 5-20 R_J region of the Jovian magnetosphere, *J. Geophys. Res.*, **86**, 8343-8356, 1981.

Bolton, S. J., et al., Enhanced whistler-mode emissions: Signatures of interchange motion, *Geophys. Res. Lett.*, this issue, 1997.

Frank, L. A., et al., Plasma observations at Io with the Galileo spacecraft, *Science*, **274**, 394, 1996.

Gehrels, N., and E. C. Stone, Energetic oxygen and sulfur ions in the Jovian magnetosphere and their contribution to the auroral excitation, *J. Geophys. Res.*, **88**, 5537, 1983.

Hill, T.A., A. J. Dessler, and L. J. Maher, Corotating magnetospheric convection, *J. Geophys. Res.*, **86**, 9020, 1981.

Kivelson, M. G et al., Intermittent short-duration plasma-field anomalies in the Io plasma torus: Evidence for interchange in the Io plasma torus? *Geophys. Res. Lett.*, this issue, 1997.

Pontius, D. H., et al., Steady state plasma transport in a corotation-dominated magnetosphere, *Geophys. Res. Lett.*, **13**, 1097, 1986.

Richardson, J. D., and R. L. McNutt, Jr., Observational constraints on interchange models at Jupiter, *Geophys. Res. Lett.*, **14**, 64, 1987.

Russell, C. T., et al., Magnetic fluctuations in the Io torus: An overview, *Geophys. Res. Lett.*, this issue, 1997.

Siscoe, G. L., et al., Ring current impoundment of the Io plasma torus, *J. Geophys. Res.*, **86**, 8480, 1981.

Southwood, D. J., and M. G. Kivelson, Magnetospheric interchange instability, *J. Geophys. Res.*, **92**, 109, 1987.

Southwood, D. J., and M. G. Kivelson, Magnetospheric interchange motions, *J. Geophys. Res.*, **94**, 299, 1989.

Summers, D., R. M. Thorne, and Y. Mei, Theory of centrifugally-driven magnetospheric diffusion, *Astrophys. J.*, **328**, 358-372, 1988.

Thorne, R. M., Injection and loss mechanisms for energetic ions in the inner Jovian magnetosphere, *J. Geophys. Res.*, **87**, 8105, 1982.

Thorne, R. M., Microscopic plasma processes in the Jovian magnetosphere, in *Physics of the Jovian magnetosphere*, ed., A. J. Dessler, Cambridge University Press. p 454, 1983.

Williams, et al., Electron beams and ion composition measured at Io and in its torus. *Science*, **274**, 401, 1996.

Yang, Y. S., et al., Numerical simulation of plasma transport driven by the Io torus, *Geophys. Res. Lett.*, **19**, 957,1997.

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