Table 1. Physical parameters used in our model. Values from (*1*, *15*).

Planet	a (10^7 m)	$2\pi/\Omega$ (hours)	g (m/s^2)	U (m/s)	H (10^3 m)
Jupiter	7.1	9.9	23	50	20
Saturn	6.0	10.7	9	300	40
Uranus	2.6	−17.2	9	300	35
Neptune	2.5	17.9	11	300	30

Alternating potential vorticity gradients (Fig. 1) indicate the presence of strong zonal jets, as in the observations: Jupiter and Saturn have multiple jets and a prograde (eastward) equatorial wind (Fig. 2A), whereas Uranus and Neptune have large retrograde (westward) equatorial winds (Fig. 2B). Our shallow-water computations (Fig. 2, C and D) capture the approximate number, width, and amplitude of the observed zonal winds for all four planets. Precise, quantitative agreement is neither sought nor expected, given the simplicity of this model. The important point is that the values in Table 1 alone are sufficient to determine the gross features of the zonal winds. One feature that the model seems unable to reproduce is the direction of the equatorial jets for Jupiter and Saturn, indicating that a more sophisticated model is necessary for those two planets. Furthermore, our model predicts that more anticyclones than cyclones (*13*) are to be found on all four planets. This asymmetry is depicted by the skewness of the vorticity field (Fig. 3). The negative bias is observationally well established for Jupiter (*14*) but is not as robustly determined for the other planets.

In conclusion, our study strongly suggests that, however different the Jovian planets may be, their characteristic banded appearance is a direct consequence of the intrinsic shallow-water dynamics they all share.

REFERENCES AND NOTES

1. A. P. Ingersoll, *Science* **248**, 308 (1990).
2. P. J. Gierasch, *J. Geophys. Res.* **98**, 5459 (1993).
3. P. S. Laplace, *Mem. l'Acad. R. Sci. Paris* **88**, 75 (1775); H. Lamb, *Hydrodynamics*, (Dover, New York, 1932); J. Pedlosky, *Geophysical Fluid Dynamics* (Springer-Verlag, New York, 1979).
4. J. Y-K. Cho and L. M. Polvani, *Phys. Fluids* **8**, 1531 (1996).
5. P. S. Marcus, *Nature* **331**, 693 (1988); T. E. Dowling and A. P. Ingersoll, *J. Atmos. Sci.* **46**, 3256 (1989).
6. P. B. Rhines, *J. Fluid Mech.* **69**, 417 (1975).
7. The values of $L_D \equiv \sqrt{gH}/2\Omega$ are the least reliable of the parameters in Table 1, because of the poor knowledge of the vertical structure of the atmospheres of these planets. However, the number of bands in our computations is insensitive to the precise value of L_D; the number is controlled by $L_\beta \equiv \sqrt{Ua/\Omega}$.
8. G. P. Williams, *J. Atmos. Sci.* **35**, 1399 (1978).
9. M. E. Maltrud and G. K. Vallis, *J. Fluid Mech.* **228**, 321 (1991).
10. S. Yoden and M. Yamada, *J. Atmos. Sci.* **50**, 631 (1993).
11. The potential vorticity $q \equiv (\zeta + f)/h$ is conserved following the motion of each fluid element, thus serving as a tracer for the flow, and is the dynamically significant quantity to view. See, for instance, B. J. Hoskins, M. E. McIntyre, A. W. Robertson, *Q. J. R. Meteorol. Soc.* **111**, 877 (1985).
12. B. A. Smith *et al.*, *Science* **246**, 1422 (1989); L. M. Polvani, J. Wisdom, E. DeJong, A. P. Ingersoll, *ibid.* **249**, 1393 (1990); M. Allison and J. T. Lumetta, *Geophys. Res. Lett.* **17**, 2269 (1990).
13. Anticyclones are eddies with negative vorticity in the northern hemisphere and positive vorticity in the southern hemisphere. Cyclones are the converse.
14. M.-M. McLow and A. P. Ingersoll, *Icarus* **65**, 353 (1986).
15. R. Beebe, *Chaos* **4**, 113 (1994).

16. This work is supported by NSF. The computations were performed on the Cray C90 at the Pittsburgh Supercomputing Center. We are grateful to M. Allison for thoughtful suggestions on the manuscript and to A. Simon and R. Beebe for the zonal wind data in Fig. 2.

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A Magnetic Signature at Io: Initial Report from the Galileo Magnetometer

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During the inbound pass of the Galileo spacecraft, the magnetometer acquired 1 minute averaged measurements of the magnetic field along the trajectory as the spacecraft flew by Io. A field decrease, of nearly 40 percent of the background jovian field at closest approach to Io, was recorded. Plasma sources alone appear incapable of generating perturbations as large as those observed and an induced source for the observed moment implies an amount of free iron in the mantle much greater than expected. On the other hand, an intrinsic magnetic field of amplitude consistent with dynamo action at Io would explain the observations. It seems plausible that Io, like Earth and Mercury, is a magnetized solid planet.

Jupiter's moon Io has repeatedly surprised planetary scientists. First, Io's orbital position was unexpectedly found to control decametric radio emission from Jupiter's ionosphere (*1*). Early explanations suggested that the emissions were generated by magnetic field–aligned currents linking Io and Jupiter (*2*). These ideas were refined and linked to Alfvénic disturbances generated by the interaction of the flowing plasma of Jupiter's magnetosphere with an electrically conducting Io (*3*, *4*). After the discoveries of a large cloud of neutral sodium surrounding Io (*5*) and of a torus of ionized sulfur encircling Jupiter at the distance of Io's orbit (*6*), Voyager 1 found volcanic plumes distributed on the surface of the moon (*7*). The Voyager 1 magnetometer detected magnetic perturbations of ~5% of the ambient jovian magnetic field (~1900 nT) as it crossed Io's magnetic flux tube about 11 R_{Io} (radius of Io, 1821 km) below Io (*8*), thereby confirming the presence of a field-aligned current flowing several thousand kilometers away from the spacecraft and carrying more than 10^6 A into the jovian ionosphere.

The Galileo spacecraft flew by Io on 7 December 1995; its closest approach was at 17:45:58 UT (universal time) at an altitude of 898 km (*9*). Particles and fields data from the pass recorded on the spacecraft tape recorder will be analyzed in the early summer of 1996. However, survey data (*10*) read out directly from the magnetometer's (*11*) internal memory were returned in late December 1995. All three components of the background jovian field measured on Galileo's trajectory through the plasma torus followed predictions based on a recent extension (*12*) of Voyager-epoch magnetic field models (*13*) but in the wake of Io (that is downstream in the flow of torus plasma corotating with Jupiter), the field magnitude decreased by 695 nT in a background of 1835 nT (Fig. 1). Perturbations of the field along the spacecraft's trajectory were principally antiparallel to the model jovian field (Fig. 2). The field rotated slightly, but the bending was not what would be produced if the field had been pushed outward around Io but rather that caused by a field pulled inward toward Io. Indeed, the perturbations along the spacecraft trajectory are quite well represented by a model in which Jupiter's field is merely added to the field of an Io-centered dipole with moment aligned with the local field of Jupiter (hence antiparallel to Jupiter's dipole moment) (Fig. 3).

As the local corotation speed is greater than the Keplerian speed, the jovian plas-

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ma flows by Io at 57 km s^{-1}. If Io is sufficiently conducting, the interaction drives currents through the plasma. Following an earlier suggestion (*14*), Goldreich and Lynden-Bell (*2*) put forward a model of the interaction of Io with the jovian magnetosphere that formed the basis for subsequent ideas. They assumed that Io's conductivity was so large that the material on the entire magnetic flux tube that threaded Io was frozen in and was dragged not only through the magnetosphere but also through the conducting ionosphere of Jupiter at the northern and southern feet of the tube. They also noted that the currents connecting to the ionosphere would be carried by Alfvén waves and that any internal Io resistivity would modify the picture. Later work by others (*3, 4, 15*) showed that a finite Io resistance meant that the field lines threading Io (and its immediate neighborhood) do not move precisely with Io. How effectively the field lines threading Io move with it depends on the degree of matching between the Io resistance and the net impedance of the current-carrying Alfvén waves. Normally impedances will not match and there will be slippage.

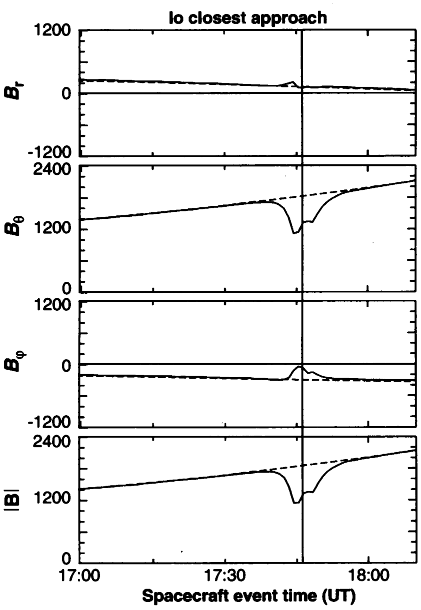

Fig. 1. Magnetic field components and total field (nT) measured by the Galileo Magnetometer on 7 December 1995 plotted versus spacecraft event time in UT. The data are shown in right-handed System III (epoch 1965) coordinates. The dashed curves are from the model of Khurana (*12*). Closest approach to Io is indicated by a vertical line.

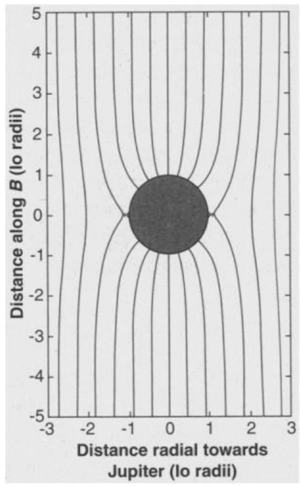

Fig. 3. Field lines for vacuum superposition of a uniform field ($\mathbf{B} = -\hat{\mathbf{z}}$ 1835 nT) and a dipole field ($\mathbf{B} = -\hat{\mathbf{r}}2B_o\cos\theta/R^3 \oplus \hat{\theta}B_o\sin\theta/R^3$) centered at Io. Here B_o is taken as 1835 nT and R is in R_{Io}. Note the bend in the field lines in the sense opposite draping around Io. Most of the flux originating within Io is directly linked to ambient flux as in a reconnection geometry.

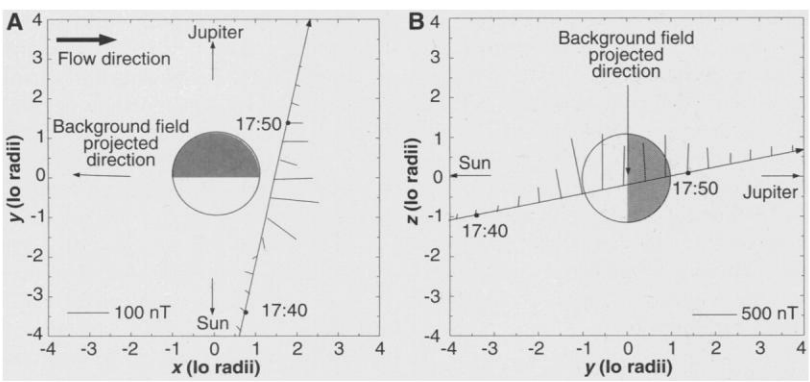

Fig. 2. Spacecraft trajectory inbound towards Jupiter in the region near Io (shaded region). The plots use a coordinate system referenced to the direction of corotation (along $\hat{\mathbf{x}}$). The unperturbed background field at the center of the wake lies in the *x*-*z* plane close to $-\hat{\mathbf{z}}$; $\hat{\mathbf{y}}$ is positive inward towards Jupiter. (**A**) shows the *x*-*y* projection and indicates the flow direction. The lines rooted along the trajectory are proportional to the projection of $\mathbf{B} - \mathbf{B}_{\mathbf{model}}$ of Fig. 1 and the scale for the field perturbations is indicated. Key times are given and the field data are separated by about one minute. The terminator is crossed close to the center of the wake, with the sunlit side corresponding to negative values of *y*. (**B**) shows the *y*-*z* projection of the trajectory and the perturbation field vectors. Note that the trajectory passes principally below Io's equator in this coordinate system.

Neubauer suggested that Io could be magnetized by an internal dynamo (*16*). Kivelson *et al.* (*17*) added the suggestion that there might be an Io magnetosphere. There are two important consequences of Io magnetization for the form of the Io plasma interaction. Firstly, when the dipole is anti-aligned with the dipole moment of Jupiter reconnection will link Io's internal field to the external jovian magnetic field. Slippage between Io and the flux tubes threading it is still possible. Secondly, the effective size of the Io flux tube is increased as flux is drawn into Io from the surrounding medium (Fig. 3).

The distinction between the "slipping Io flux tube" interaction and the frozen-in tube need not be great. In the slipping case, the Io-associated perturbations are guided by a pair of opposed currents tilted at angle $\alpha = \tan^{-1}(M_A)$, where M_A is the local Alfvén Mach number of the corotation flow (*18*). The frozen-in tube case corresponds to the limiting case where not only is the ambient flow stopped by the Alfvén wave perturbation but also the field attached to Io is tilted by precisely α. The attached tube is bent by the force associated with deflection of the corotating plasma around it. It is important to note that the angle between the current (which flows in the Alfvén wing) and the upstream field depends only on plasma properties and is independent of the strength of the interaction. The field perturbation and the current density can vary with the strength of the interaction, but the field cannot be tilted beyond alignment with the currents. Writing ΔB as the maximum transverse field perturbation in the Alfvén wing one can estimate (*16, 19*) I/d, the current per unit length flowing into the conductor from above or below Io, as

$$I/d = \frac{\Delta B}{\mu_0} = \frac{M_A}{\mu_0} B = 0.4 \text{ A m}^{-1}$$

As double this current flows radially outward, across an object of Io's diameter, one finds the maximum current is $\sim 3 \times 10^6$ A (*20*). A current of the magnitude inferred from the Voyager observations would give only ~30% of the 695 nT perturbation observed by Galileo (Fig. 1). We find (*21*) that a current of $\sim 12 \times 10^6$ A is needed to produce a perturbation at Galileo's orbit of the order detected.

A magnetohydrodynamic (MHD) simulation (*22, 23*) of the current-carrying region as a conducting, spherically symmetric body of Io's dimensions produced a field depression similar to the actual data, but its magnitude was too small (Fig. 4). Larger perturbations are obtained if currents flow not through Io or a near-surface ionosphere but through an extended, gravitationally bound Io ionosphere that closely approaches the Galileo orbit. We examined a range of MHD simulations (*22*) of an unmagnetized, conducting Io and can reproduce the observed signature only if Io has a radius of 1.4 R_{Io} (*24*). There is, however, reason to doubt that a conducting ionosphere, gravitationally or collisionally bound to Io, exists at high altitude. Currents flow where ion-neutral collisions satisfy $\Omega_i \approx \nu_c = n_n\sigma\nu$ with Ω_i, the ion gyrofrequency and ν_c, the ion-neutral collision frequency expressed in terms of n_n, the neutral density, σ, the collision cross section and ν, the relative ion-neutral speed. Near Io, $\Omega_i \approx 2\pi$ s^{-1}. With $\sigma \approx 4 \times 10^{-20}$ m^2 and $\nu < 100$ km s^{-1}, $n_n > 2 \times 10^{15}$ m^{-3}, which is improbably large at 900 km altitude. Such densities are present only below ~100 km in atmospheric models (*25, 26*). Although Io's ionosphere does not seem capable of producing the entire perturbation, it may contribute to the asymmetry in the geometric wake.

Many theories (*2, 3, 15, 27*) of the Io interaction have focused on an ionospheric closure path for currents generated in the magnetospheric plasma, but newly ionized ions can also produce currents called pickup currents (*28, 29*). Our MHD simulations with an ionization rate of 10^{27} ions s^{-1} falling with distance as $r^{-3.5}$ (and no charge exchange) show little change in the signature from the case with a conductor alone because the pickup currents are dwarfed by the ionospheric currents. Estimates suggest that charge exchange currents are not negligible but that they will not dominate unless the process occurs in localized regions. These charge exchange currents augment the Alfvén wing currents flowing towards the jovian ionosphere. Thus, the signature recorded by Voyager 1 as it crossed the Io flux tube would have included their contribution. As argued above, the inferred total current was insufficient to produce the perturbation detected by Galileo (*30*).

The effects of larger ionization and charge-exchange rates on the perturbation remain to be evaluated fully. The process is self-limiting as pickup and charge exchange extract energy from the flow. In the unperturbed torus plasma, the thermal energy is smaller than the flow kinetic energy, but when the flow slows, new ions may acquire thermal energy below the ambient temperature and cool the plasma. Thus pickup current density and the plasma pressure can either increase or decrease as the response is nonlinear and, therefore, hard to predict.

Finally, we consider an internally-generated magnetic field as the source of the perturbation. An internally generated field is expected to align closely with the local field of Jupiter whether the source is induced magnetization or an intrinsic field due to remanence or a self-sustained dynamo field (*31*). Correspondingly, Io's magnetic moment should be anti-aligned with Jupiter's (*32*). The fact that we do not see a change in the sign of the dominant component of the field places an upper limit of 4×10^{20} A m^2 on the magnitude of the dipole moment and this is an unambiguous overestimate. Our MHD simulation of the interaction of a flowing plasma with a magnetized Io (*33*) gives a perturbation of the required direction, size, and spatial scale near the wake center, along the Galileo orbit (Fig. 4). At 1.5 R_{Io} in the near-equatorial region, the field is significantly depressed. The perturbation is roughly double the drop that would be found in the absence of plasma effects, as the Alfvén wing current system and the internal magnetic field contribute in the same direction. The total current in the Alfvén wing is enhanced relative to the conducting case because the effective obstacle to the flow is larger than Io. The data depart from the model near closest approach; we suggest that local plasma structure introduces small-scale perturbations which account for the day-night asymmetry of the observations and that at less than 0.5 R_{Io} above the surface, conductivity irregularities and higher order multipoles may also be important.

The direction of the perturbation is also that expected from an induced magnetic field in a paramagnetic Io. Near the pole, the strength of Io's field is ~1.4 times the background jovian field. To achieve this enhancement of the field strength from a paramagnetic response would not be possible with the magnetic susceptibilities ($<10^{-3}$) of typical minerals (*34*). However, free iron, especially iron just below its Curie point (~1000 K), exhibits a strong paramagnetic response. Tidal forcing (*35*) is known to heat Io's interior. Assuming that the Curie isotherm is at 100 km depth a magnetic moment per unit volume μ ~40 A m^{-1} (*36*) is required to account for the observed perturbation. If iron, with a μ = 4000 A m^{-1} were the source, the crust would require a volume fraction of 10^{-2} of free iron, which is not consistent with the expected composition of Io (*37*).

The possibility of an internally generated field at Io has been considered by a number of authors. Levy (*31*) points out that the requirements on a self-sustained dynamo are not stringent when a constant seed field acts on the body. The seed field is in the sense required to account for the observations. More recent work (*38*) proposes that a dynamo can develop if the system is not in thermal balance or if heat

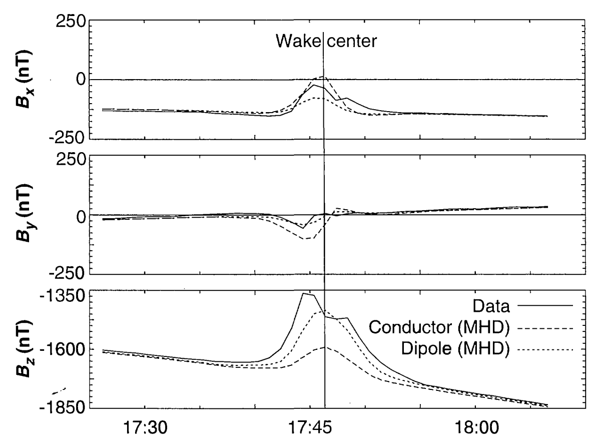

Fig. 4. The data in the coordinate system described in Figure 2 plotted versus UT (solid curves). Also shown are the results of two MHD models (*44*) along the spacecraft trajectory. The short dashed line shows the model with flow past a magnetized Io (magnetic moment corresponding to a surface equatorial field of 1300 nT). The dashed curves show the model with flow past a conducting Io.

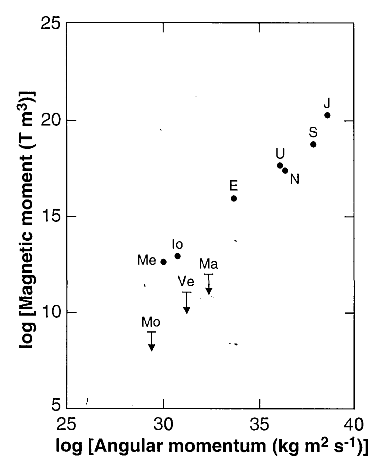

Fig. 5. The scaling relation, appropriately referred to as Blackett's law (*39*), between the magnetic dipole moment and the rotational angular momentum of the planets. The proposed magnetic moment of Io and the angular momentum (*43*) are plotted.

transfer in Io's mantle is chaotic with large fluctuations of heat flow in time. Nonlinear coupling between the orbital eccentricity and tidal heating can lead to an oscillatory solution with a dynamo switching on and off every few hundred million years and present roughly half the time. The magnetic moment inferred in our analysis is of the order expected from dimensional arguments and fits into a Blackett's law (*39*) scaling of planetary magnetic moments (Fig. 5).

Thus, unless the free iron in the mantle of Io is much greater than we expect or the plasma conditions have changed since the Voyager epoch (*40*), an intrinsic dynamo field of Io with a magnetic moment anti-aligned with Jupiter's moment and $\sim 10^{20}$ A m^2 in magnitude seems called for. This corresponds to a field strength of ~1300 nT at Io's equatorial surface in the absence of a background field. Reconnection links Io's field to Jupiter's and the foot of the Io flux tube is expected to be a distinct region in which much of the power generated by the Io interaction is dissipated in Jupiter's ionosphere, consistent with the evidence of isolated signatures at the foot of Io's flux tube (*41*). The interaction with a magnetized Io also perturbs the torus plasma, which means that models in which plasma currents generated near Io create the decametric arcs observed by the Voyager spacecraft (*42*) need not be significantly modified. The observed day-night asymmetry and the small-scale irregularities in the Io-related signature suggest that conductivity inhomogeneity, higher order magnetic multipoles, and pickup ions contribute to, without dominating, the observed magnetic perturbations. The recent evidence that Io has a large, molten iron–iron sulfide core (*43*) and that adequate heating to drive a dynamo field is present (*31, 38*) suggests that the inference of intrinsic dynamo action is physically reasonable. An intrinsic magnetic field would add Io to Earth and Mercury as the only solid planets with currently active internal dynamo fields.

REFERENCES AND NOTES

1. E. K. Bigg, *Nature* **203**, 1088 (1964).
2. P. Goldreich and D. Lynden-Bell, *Astrophys. J.* **156**, 59 (1969).
3. F. M. Neubauer, *J. Geophys. Res.* **85**, 1171 (1980).
4. D. J. Southwood, M. G. Kivelson, R. J. Walker, J. A. Slavin, *ibid.*, p. 5959.
5. R. A. Brown, in *Exploration of the Planetary System*, A. Woszczyk and C. C. Iwaniszewska, Eds. (Reidel, Dordrecht, Holland, 1974), pp. 527–531.
6. I. Kupo, Yu. Mekler, A. Eviatar, *Astrophys. J. Lett.* **205**, L51 (1976).
7. L. A. Morabito, S. P. Synott, P. M. Kupferman, S. A. Collins, *Science* **204**, 972 (1979).
8. N. F. Ness *et al.*, *ibid.* **204**, 982 (1979).
9. At closest approach, Galileo's System III (left-handed) location was $(r, \theta, \varphi) = (5.866, 90.047, 273.257)$. In a Jupiter-centered magnetic coordinate system with x sunward from Jupiter and the xz plane containing a centered dipole tilted 9.6° with north pole at 202° west longitude in left-handed System III, Io's position was $(x, y, z) = (5.856, -0.286, -0.186)$. All distances are in the radius of Jupiter, $R_J = 71{,}492$ km.
10. The magnetometer investigation provides averages over selected time intervals, which can range from 16 hours to 1 minute. For the Io flyby, the 1-min averaging interval was used.
11. M. G. Kivelson, K. K. Khurana, J. D. Means, C. T. Russell, R. C. Snare, *Space Sci. Rev.* **60**, 357 (1992).
12. K. K. Khurana, in preparation.
13. J. E. P. Connerney, *J. Geophys. Res.* **86**, 7679 (1981); J. E. P. Connerney, M. H. Acuna, N. F. Ness, *ibid.*, p. 8370.
14. J. H. Piddington and J. F. Drake, *Nature* **217**, 935 (1968).
15. D. A. Wolf-Gladrow, F. M. Neubauer, M. Lussem, *J. Geophys. Res.* **92**, 9949 (1987).
16. F. M. Neubauer, *Geophys. Res. Lett.* **5**, 905 (1978).
17. M. G. Kivelson, J. A. Slavin, D. J. Southwood, *Science* **205**, 491 (1979).
18. These currents close radially outward through Io or its gravitationally bound ionosphere and produce positive B_z perturbations along the spacecraft orbit through the wake.
19. Our calculations assume for plasma parameters: $n = 2000$ cm^{-3}, average ion mass = 20 m_p with m_p the proton mass, and a background field $B = 1835$ nT, which gives $v_A = 200$ km s^{-1} for the Alfvén speed and 0.28 for the Alfvén Mach number, M_A.
20. Neubauer (*3*) has pointed out that this implies that early estimates, 4.8×10^6 A (*8*) of the current, later, reduced to 2.8×10^6 A by M. H. Acuna, F. M. Neubauer, and N. F. Ness, *J. Geophys. Res.* **86**, 8513 (1981) were rather high; the estimates decrease if a small Mach number is assumed (*4*) or if the ionospheric conductivity is non-uniform (*27*).
21. We estimate the current closing through Io or its ionosphere and carried in wires separated by an Io diameter along the direction outward from Jupiter and swept back 15° with respect to the plasma flow.
22. J. A. Linker, M. G. Kivelson, and R. J. Walker, *Geophys. Res. Lett.* **15**, 1311 (1988); *ibid.* **16**, 763 (1989); *J. Geophys. Res.* **96**, 21037 (1991); J. A. Linker, *Eos* **76**, F343 (1995); J. A. Linker, *Adv. Space Res.*, in press.
23. The simulation uses resistive MHD equations given in previous publications (*22*) but improves the spatial resolution of earlier runs. The analysis adopts a spherical coordinate system with the pole along the corotational flow direction. The radial mesh size (71 cells) is 0.058 R_{Io} between 1-2 R_{Io}, expanding somewhat between 2-12 and then expanding more rapidly out to 25 R_{Io}, the location of the outer boundary. The theta mesh is 31 cells and the phi mesh is 32 cells. In different runs, Io is represented as a conducting sphere, and as a magnetized sphere with dipole moment either aligned with or anti-aligned with Jupiter's dipole moment. Plasma parameters are $M_A = 0.2$, $\beta = 0.3$. The latter value is unrealistically large but is needed for numerical stability and does fall in the $\beta < 1$ regime.
24. A similar idea was put forward by Neubauer (*3*) to explain the excessive current estimate derived from the Voyager measurements.
25. D. F. Strobel, X. Zhu, and M. E. Summers, *Icarus* **111**, 18 (1994).
26. Neutral densities $>10^{15}$ m^{-3} at 900 km would imply an exobase at higher altitude (1300 km for the scale heights obtained in (*25*) whereas observations of sodium in Io's exosphere imply a maximum exobase height of 800 km [N. M. Schneider, D. M. Hunten, W. K. Wells, A. B. Schultz, U. Fink, *Astrophys. J.* **368**, 298 (1991)]. Furthermore, if a very large ionosphere is the primary source of the currents it would be difficult to explain the approximate symmetry of the wings of the perturbation about the terminator. Atmospheric models predict strong asymmetries between day side and night side exobase heights, with an exobase at or below 100 km on the night side.
27. F. Herbert, *J. Geophys. Res.* **90**, 8241 (1985).
28. C. K. Goertz, *J. Geophys. Res.* **85**, 2949 (1980).
29. It is generally thought that new ions are added to the torus at a rate of 3×10^{28} ions s^{-1}, their source being neutrals sputtered from Io [T. W. Hill, A. J. Dessler, C. K. Goertz, *Physics of the Jovian Magnetosphere*, A. J. Dessler, Ed. (Cambridge Univ. Press, New York, 1983), p. 353], but the local source strength near Io is unclear. Charge exchange appears to be highly localized near Io with a source strength that has been estimated as 3×10^{28} ions s^{-1} falling as $r^{-3.5}$ with distance from Io [W. H. Smyth and M. R. Combi, *J. Geophys. Res.* **96**, 22711 (1991); W. H. Smyth, *Adv. Space Res.* **12**, 337 (1992)].
30. Another local current source of the field depression is the diamagnetic effect of newly created ions, including charge exchange ions, which can significantly increase the plasma density and its temperature (T). The perpendicular pressure required in the plasma to depress the field by the observed 38% is $\sim 8 \times 10^{-7}$ Pa. If the newly ionized ions have a thermal speed of half the corotation speed ($\sim 3 \times 10^4$ m s^{-1}) and the magnetic pressure deficit is $n_i kT$ (with n_i the ion density and k, Boltzmann's constant), then $n_i \gtrsim 6.4 \times 10^4$ cm^{-3} at the Galileo location for diamagnetism to be dominant. Near the center of the wake, higher densities would probably be required as our MHD computations show that new ions are picked up in the wake at speeds considerably below corotation. The range of estimated densities is substantially higher than densities inferred at this altitude from the Pioneer 10 occultations [A. Kliore, C. L. Cain, G. Fjelbo, B. L. Seidel, S. I. Rasool, *Science* **183**, 323 (1974)].
31. E. H. Levy, *Proc. Lunar Planet. Sci. Conf. 10*, 2335 (1979).
32. If it were aligned, it would produce an increase of field strength in the wake and would bend the field in a direction opposite to the observations.
33. The magnetic moment = 8×10^{19} A m^2 antiparallel to the jovian dipole moment corresponding to a surface equatorial field of ~1300 nT for an isolated Io.
34. See, for example, R. S. Carmichael, *Practical Handbook of Physical Properties of Rocks and Minerals* (CRC Press, Boca Raton, FL, 1989).
35. S. J. Peale, P. Cassen, R. T. Reynolds, *Science* **203**, 892 (1979).
36. μ is calculated from $B = (\mu_o/4\pi)(\mu V_S/r^3)$, where V_S is the volume of the magnetized shell.
37. G. J. Consolmagno, *Icarus* **47**, 36 (1981).
38. U. Wienbruch and T. Spohn, *Planet. Space Sci.* **43**, 1045 (1995).
39. P. M. S. Blackett, *Nature* **159**, 658 (1947); C. T. Russell, *ibid.* **272**, 147 (1978).
40. This seems unlikely as initial reports (I. Stewart, personal communication) from the ultraviolet spectrometer show no important changes in the torus emission spectrum.
41. J. E. P. Connerney, *Science* **262**, 1035 (1993); R. Prangé *et al.*, *Nature* **379**, 323 (1996).
42. T. D. Carr, M. D. Desch, J. K. Alexander, *Physics of the Jovian Magnetosphere*, A. J. Dessler, Ed. (Cambridge Univ. Press, New York, 1983), p. 226.
43. J. D. Anderson, W. L. Shogren, G. Schubert, *Science* **272**, 709 (1996).
44. The simulations (*22*) assume a constant background field as an initial condition. The simulation results were rescaled by the ratio of the model jovian field at the center of the Io wake (Fig. 1) to the background field of the simulation. The uniform background field was then subtracted, and the perturbations were added to the jovian field model.

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