FeS cores are only possible for the $+1\sigma$ value of C_{22}.

Although a large suite of three-layer Europa models is possible depending on the actual value of C_{22}, the core density, and the densities of the water ice-liquid shell and rock mantle, the gross features of these models are all similar. In these models, Europa has a metallic core about 0.4 R_E in radius and a water ice-liquid shell about 150 km thick. Although Io is somewhat larger than Europa, a possible model of Europa is an Io-like interior surrounded by a shell of water ice-liquid. Europa could have a subsurface liquid water ocean; our determination of the low degree and order gravitational coefficients cannot distinguish if the water in the outer shell is solid or liquid. Instead of a metallic core, Europa could have a dense deep interior that is a mixture of metal and rock, but the presence of a europan magnetic field, as implied by the magnetometer data (*13*), would argue in favor of a metallic core in Europa as a necessary site for magnetic field generation.

REFERENCES AND NOTES

1. For results from the Pioneer 10 and 11 Mission, see G. W. Null, J. D. Anderson, and S. K. Wong [*Science* **188**, 476 (1975)] and G. W. Null [*Astron. J.* **81**, 1153 (1976)]. For results from a combination of radio Doppler data from the Pioneer 10 and 11 missions and from the Voyager 1 and 2 missions, see J. K. Campbell and S. P. Synnott [*Astron. J.* **90**, 364 (1985)].
2. G. Schubert, T. Spohn, R. T. Reynolds, in *Satellites*, J. A. Burns and M. S. Matthews, Eds. (Univ. of Arizona Press, Tucson, 1986), pp. 629-688.
3. J. D. Anderson, E. L. Lau, W. L. Sjogren, G. Schubert, W. B. Moore, *Nature* **384**, 541 (1996).
4. J. D. Anderson, W. L. Sjogren, G. Schubert, *Science* **272**, 709 (1996).
5. J. D. Anderson, E. L. Lau, W. L. Sjogren, G. Schubert, W. B. Moore, *Nature*, in press.
6. See, for example, T. D. Moyer, *Tech. Rep. No. TR 32-1527* (Jet Propulsion Laboratory, Pasadena, CA, 1971); B. D. Tapley, in *Recent Advances in Dynamical Astronomy*, B. D. Tapley and V. Szebehely, Eds. (Reidel, Dordrecht, Netherlands, and Boston, MA, 1973), pp. 396–425; J. D. Anderson, in *Experimental Gravitation*, B. Bertotti, Ed. (Academic Press, New York, 1974), pp. 163–199.
7. W. M. Kaula, *Theory of Satellite Geodesy* (Blaisdell, Waltham, MA, 1966).
8. In addition to the zero-degree parameter GM, where G is the gravitational constant and M is the total mass, the two non-zero coefficients (J_2 and C_{22}) measure the contributions to the gravitational potential of the spherical harmonics of degree l and order m for $l = 2, m = 0$ and $l = 2, m = 2$, respectively. In terms of spherical coordinates fixed in the body of Europa (radius r, latitude ϕ, and longitude λ), where r is the radial distance from the center of mass and longitude is measured from the Europa-Jupiter line in an equatorial system defined by Europa's spin axis, the gravitational potential V, complete through the second degree and order, is

$$V = \frac{GM}{r}\left[1 - \frac{1}{2}J_2\left(\frac{R}{r}\right)^2(3\sin^2\phi - 1) + 3C_{22}\left(\frac{R}{r}\right)^2\cos^2\phi\cos 2\lambda\right] \quad (2)$$

The reference radius for Europa is $R = 1560$ km.
9. The first encounter with Europa on 19 December 1996 occurred at 06:52:57.7 UTC (spacecraft time) at an altitude of 692 km (above the reference sphere), a latitude $\phi = -1.68°$ and a longitude $\lambda = 323.16°$ (east longitude). The second encounter on 20 February 1997 occurred at 17:06:10.2 UTC at an altitude of 586 km, a latitude $\phi = -17.01°$ and a longitude $\lambda = 35.31°$ (east longitude).
10. The value for Europa's GM reported by J. D. Anderson, W. L. Sjogren, and G. Schubert [*Science* **272**, 709 (1996)] is 3196.81 ± 0.69 km^3 s^{-2}. This differs by 8.6 standard deviations from the value reported here, which we adopt for future applications. The pre-Galileo value reported by J. K. Campbell and S. P. Synnott [*Astron. J.* **90**, 364 (1985)] is 3201 ± 10 km^3 s^{-2}, which is consistent with both reported values from the Galileo mission. The error in Europa's derived mean density is dominated by the error in the radius, so the relatively small inconsistencies in reported GM values are not important for the density determination. We adopt a mean density of 3018 ± 35 kg m^{-3}.
11. For example, W. M. Kaula, *An Introduction to Planetary Physics: The Terrestrial Planets* (Wiley, New York, 1968); W. B. Hubbard and J. D. Anderson, *Icarus* **33**, 336 (1978); S. F. Dermott, *ibid.* **37**, 310 (1979); V. N. Zharkov, V. V. Leontjev, A. V. Kozenko, *ibid.* **61**, 92 (1985).
12. H. Jeffreys, *The Earth* (Cambridge Univ. Press, London, 1962).
13. M. G. Kivelson *et al.*, *Science* **276**, 1239 (1997).

14. This experiment was coordinated at JPL by the Radio Science Systems Group under R. G. Herrera and S. Asmar. The radio Doppler data were generated with the support of the Telecommunications and Mission Operations Directorate and the Deep Space Network (DSN). The data analysis depended on the availability of software and personnel of the Galileo Project Navigation Team, W. E. Kirhofer, Team Leader. This work was sponsored by the Galileo Project and was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. G.S. and W.B.M. acknowledge support by grants from NASA through the Galileo Project at JPL and the Planetary Geology and Geophysics Program.

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Europa's Magnetic Signature: Report From Galileo's Pass on 19 December 1996

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On 19 December 1996 as Galileo passed close to Jupiter's moon, Europa, the magnetometer measured substantial departures from the slowly varying background field of Jupiter's magnetosphere. Currents coupling Europa to Jupiter's magnetospheric plasma could produce perturbations of the observed size. However, the trend of the field perturbations is here modeled as the signature of a Europa-centered dipole moment whose maximum surface magnitude is ~240 nanotesla, giving a rough upper limit to the internal field. The dipole orientation is oblique to Europa's spin axis. This orientation may not be probable for a field generated by a core dynamo, but higher order multipoles may be important as they are at Uranus and Neptune. Although the data can be modeled as contributions of an internal field of Europa, they do not confirm its existence. The dipole orientation is also oblique to the imposed field of Jupiter and thus not directly produced as a response to that field. Close to Europa, plasma currents appear to produce perturbations with scale sizes that are small compared with a Europa radius.

On 19 December 1996, the Galileo spacecraft completed the first stage of its reconnaissance of the Galilean satellites of Jupiter as it passed by Europa, the only large moon not previously encountered. Closest approach was at 06:52:58 universal time (UT) at the spacecraft at an altitude of 688 km. The radial distance from Jupiter to Europa's orbit is 9.38 R_J (radius of Jupiter = 71,492 km) and near Europa, Jupiter's magnetic field was ~450 nT. Data were acquired at 24 s per vector over large parts of the orbit, and for 51 min near the closest approach, the magnetometer (*1*) data were recorded on the tape recorder at a sampling rate of 0.33 s.

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Consistent with Galileo's motion outbound from Jupiter, the measured magnetic field magnitude (B) decreased from ~460 nT to ~325 nT during the 5 hours that included Galileo's closest approach to Europa (Fig. 1). Because Jupiter's dipole moment is tilted by 10° from its spin axis, the dipole equator moves back and forth across Galileo with the 10-hour periodicity of Jupiter's rotation. Galileo was below Jupiter's magnetic equator ($B_r < 0$) at 05:00 UT (Fig. 1), crossed the magnetic equator at ~05:30 UT, and reached maximum displacement above the equator shortly before 08:00 UT. Fluctuations of $B >$ 5 nT are commonly absent in the regions well above the magnetic equator where the Europa encounter occurred. At the time of closest approach, Galileo was approaching the northern boundary of the plasma sheet, and the background magnetic field of Jupiter ($\mathbf{B}_o$) was oriented predominantly southward and radially outward from Jupiter, with a small component along the sense of Europa's orbital motion.

In the 0.33-s time resolution data acquired near closest approach, the signature of the Europa interaction is evident as substantial field rotations that appeared rather abruptly in B_θ, but grew more slowly in B_r. A magnitude depression of ~50 nT occurred near closest approach; additional depressions of ~30 nT lasting for ~16 s near 07:01:45 UT and for ~6 s at 07:06:15 UT were recorded as Galileo crossed in front of Europa in the sense of its orbital motion.

Analysis of a measured magnetic perturbation that is neither large compared with the background field nor well ordered presents a challenge. Various processes produce currents that perturb the magnetic field. For example, because the speed of corotation is much larger than the speed of Europa's orbital motion, magnetospheric plasma which approximately corotates with Jupiter sweeps by Europa, approaching from the trailing hemisphere. Interaction with Europa or its ionosphere drives currents that slow the flowing plasma and divert it so that it will flow around the obstacle where it may be accelerated before it converges downstream of the moon on the leading hemisphere in what is referred to as the wake. Plasma currents are also generated where neutral atoms or molecules from Europa are ionized by electron impact or other processes. The currents arising from the interaction between Europa and the flowing plasma must produce some and could produce all of the magnetic perturbations observed. The largest perturbations are transverse to the background field $\mathbf{B}_o$. Such perturbations can be carried by Alfvén waves for which the field change $\delta\mathbf{B}_{\perp A}$ is related to the velocity change $\delta\mathbf{u}$ by $\delta\mathbf{B}_\perp = \pm B_o \delta\mathbf{u}/V_A$ where $v_A = B_o/(\mu_o\rho)^{1/2}$ is the Alfvén speed in terms of ρ, the mass density, and μ_o, the permeability of vacuum. If the flow is stopped, $\delta\mathbf{u} = \mathbf{u}$ where $\mathbf{u}$ is the incident flow velocity, giving a maximum field perturbation of $\delta B_\perp = \pm B_o u/v_A = \pm M_A B_o$, where M_A is the Alfvén Mach number. Near Europa, M_A is ~1/5 to 1/3 and magnetic perturbations amplitudes could become as large as those observed (~100 nT) whether or not there is an internal field. Any pickup of newly ionized neutral atoms would enhance the perturbation. However, because Ganymede (*2*) and possibly Io (*3*) have internal fields, there is interest in investigating what limits could be put on an internal field of Europa. Here we investigate whether the magnetic perturbations could be produced by an internal field of Europa or as a paramagnetic response to the imposed field of Jupiter by fitting a Europa-centered magnetic dipole to the perturbations of the background field. The orientation of a centered dipole moment is an important element in the interpretation of the perturbation. A paramagnetic response would be oriented along $\mathbf{B}_o$, and the symmetry of plasma responses would be governed by $\mathbf{B}_o$ and the flow direction.

The small changes of field magnitude and orientation near Europa are small (Fig. 2, A and B), so it is useful to examine the departure of the measured field from the trend of the background field. We represent the background field using a small offset to a model of the magnetospheric field of Jupiter (*4*). The perturbation field obtained as the difference between the measured field and the background field (Fig. 2, C and D) is largest near closest approach, which occurred on the side facing Jupiter; another significant magnetic perturbation was localized at the center of the wake (07:01:44 UT) (Fig. 2, C and D).

In fitting the data to a centered dipole, we assumed that plasma perturbations contribute significantly to the signature only in localized regions such as the center of the wake and that Europa is the dominant source of the magnetic field variations on the scale of its radius. The perturbation field is fit by a centered dipole pointing at an angle of 135° from the spin axis in the meridian 20° west of the Jupiter-facing meridian plane. This fit assumes that vacuum superposition of the background field and the dipole field is justified as a first approximation. At the surface, the magnitude of this dipole field ranges from 240 nT near the magnetic poles to 120 nT near the equator. Although the model (Fig. 2, E and F) does not fit all of the observed signal, it does reflect many features of the measured perturbations such as the field rotation in the vicinity of

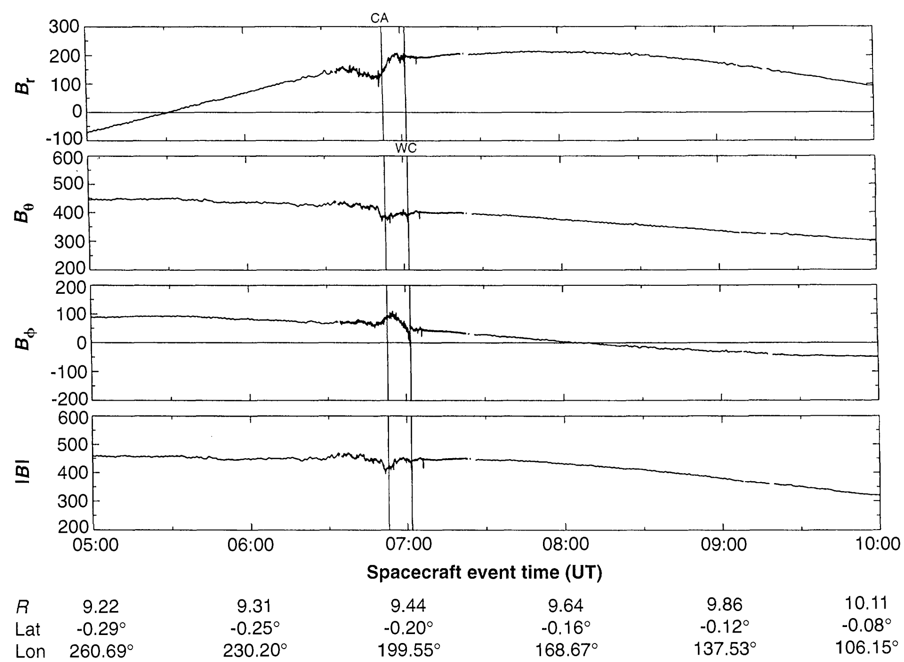

Fig. 1. The three components of the magnetic field B_r, B_θ, B_ϕ, and its magnitude B in right-handed System III (1995) coordinates (*11*) from 05:00 UT to 10:00 UT on 19 December 1996. Trajectory information (radial distance, R, in R_J, latitude, longitude) is given beneath the panels. Data are 48-s averages on 24-s centers except for 06:33-07:24 UT near the closest approach, where 2-s averages of the high-resolution data are plotted on 1-s centers. Closest approach to Europa occurred at a radial distance = 1.43 R_{Eu} (Europa radii), 1.65° south of Europa's spin equator and 47.6° west of the Jupiter-facing meridian plane. Closest approach (CA) and the center of the wake (WC) relative to the flow of corotating plasma are marked.

Table 1. Estimated maximum surface field magnitudes (near the magnetic poles) compared with the local background field and angles between fitted dipole moments $\hat{\mathbf{M}} = \mathbf{M}/M$ and the spin axis direction (unit vector $\hat{\Omega}$) and the background magnetic field direction ($\hat{\mathbf{b}} = \mathbf{B}_o/B_o$) for the Galilean moons of Jupiter. Data for Io, Ganymede, and Callisto were taken from (*3*), (*2*), and (*10*), respectively.

Moon	B_{surf}/B_o	$\cos^{1}(\hat{\mathbf{M}} \cdot \hat{\Omega})$	$\cos^{-1}(\hat{\mathbf{M}} \cdot \hat{\mathbf{b}})$
Io	~2600/1800	~180°	5°
Europa	240/420	135°	65°
Ganymede	1500/120	170°	34°
Callisto	<30/35	~80°	37°

closest approach and the location of the maximum perturbation. If an internal field is the dominant source of the perturbation, the poor quality of the fit requires higher order multipoles in addition to the dipole moment. If higher order multipoles are important, then the range of surface field strengths will increase. The relative amplitudes of the different multipole moments give clues to the probable source of an internal field. Large quadrupole moments as observed at Neptune (5) and Uranus (6) are thought to indicate that the field is generated in a shell at intermediate depth in the planetary interior, not in the core. The possibility of a source outside of the core would be of special interest for Europa which may have a liquid ocean in a shell beneath the surface (7) where convection could in principle drive a dynamo. However, the likelihood of dynamo action in such a shell is quantitatively improbable because it requires unreasonably large convective flow speeds (8).

We now consider what can be inferred about the source of the magnetic perturbation from the magnitude of the surface field and the inclination of the dipole moment to the directions of the spin axis $\mathbf{\Omega}$ and of the ambient magnetic field. The spin axis direction is also the direction of Jupiter's field at Europa's orbit averaged over a full rotation of Jupiter. Approximate alignment with $\pm\mathbf{\Omega}$ is likely for a dynamo-generated internal magnetic field if Coriolis forces are a dominant part of force balance, although other styles of dynamo action are possible. A dipole moment generated as a paramagnetic response to an imposed field, $\mathbf{B}_o$, is likely to be aligned with $\pm\mathbf{B}_o$ although, because of Europa's finite conductivity, there may be a phase lag between the applied external field and the induced internal field which could account for different alignments. In a paramagnetic response the surface magnitude cannot exceed $3B_o$ (9), providing a strict upper limit. Because this upper limit occurs for infinite paramagnetic susceptibility and planetary materials generally have low susceptibility, this upper limit is improbable.

With these considerations in mind, we can compare the magnetic properties inferred from Galileo measurements for the Galilean moons other than Callisto (10), whose estimated surface field is weak enough that localized internal sources like magnetic anomalies in the crust or purely external sources are more probable than a source that is driven within its interior. Io's putative internal magnetic moment and Ganymede's well-established magnetic moment are rather closely aligned antiparallel to the spin axis, $\mathbf{\Omega}$, consistent with expectations for a core dynamo (Table 1). The alignment is also parallel to the ambient magnetic field, consistent with symmetries expected for the response to an imposed field and for the perturbations arising from plasma currents. The surface field does not exceed the upper limit for a paramagnetic response, which is one reason why the interpretation of Io's signature (3) remains somewhat ambiguous. For Ganymede (2), the dipole moment makes an angle of 34° with the ambient field, inconsistent with the response to an imposed field and the surface field exceeds the upper limit for a paramagnetic response (9). Europa is different because the estimated dipole moment is not approximately aligned with the spin axis, but its orientation is not readily interpreted in terms of currents coupling the moon with the magnetospheric plasma. Possible reasons for these alignments include effects of higher order multipoles, temporal phase lags in the response to time-varying externally imposed fields, comparable contributions from internal sources and external plasma sources, or dominant contributions from several different current systems in the plasma.

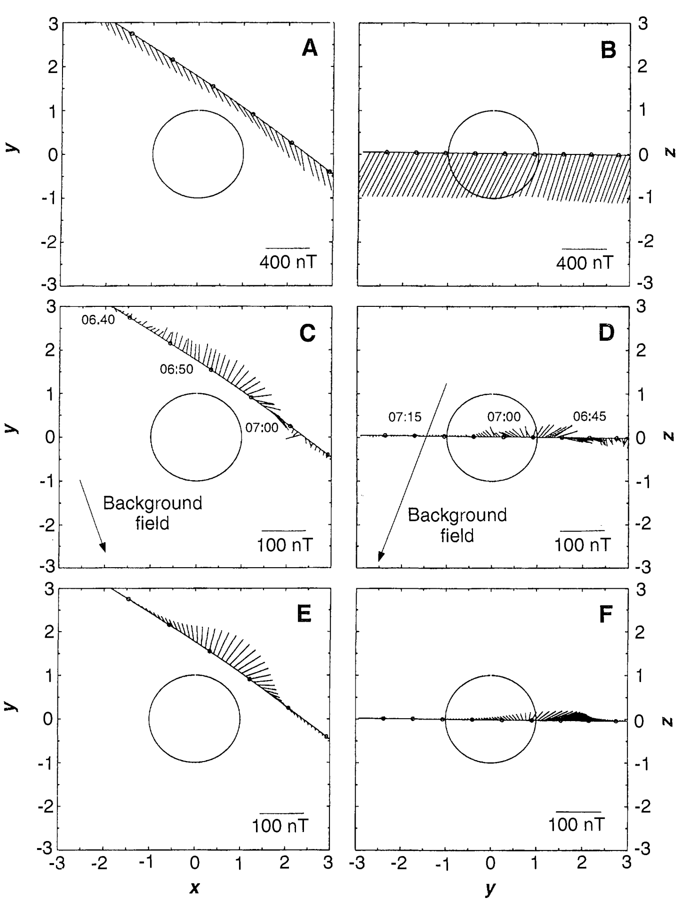

Fig. 2. Measured magnetic field and measured and modeled magnetic field perturbations at Galileo during the closest approach to Europa. Trajectory of Galileo past Europa on 19 December 1996 indicated by line with small circles. The interval between circles is 5 min. The trajectory is plotted in a Europa-centered coordinate system in which x is along the direction of corotational flow, z is parallel to Jupiter's spin axis (approximately parallel to Europa's), and y, radially in toward Jupiter, is orthogonal to the other two directions. Projections of averages of the magnetic field are plotted along the trajectory projected (**A**, **C**, and **E**) into the x-y plane and (**B**, **D**, and **F**) into the y-z plane. (A) and (B) are 50-s averages of the measured field. A fit to the trend of the background field data was subtracted from the observed field to provide perturbations which are plotted as 30-s averages in (C) and (D). Projections of the dipole fit are plotted as 30-s averages along the trajectory in (E) and (F). The background field of Jupiter's magnetosphere was southward-oriented, and its projections are indicated in (C) and (D). Closest approach to Europa is ~06:53 UT.

REFERENCES AND NOTES

1. M. G. Kivelson, K. K. Khurana, J. D. Means, C. T. Russell, R. C. Snare, *Space Sci. Rev.* **60**, 357 (1992).
2. M. G. Kivelson *et al.*, *Nature* **384**, 537 (1996).
3. M. G. Kivelson *et al.*, *Science* **273**, 337 (1996). Note that the labels on the ordinates of figure 4 are incorrect. The correct ranges on the panels from bottom to top are −2100 to −1100 nT, −500 to 500 nT, and −500 to 500 nT; M. G. Kivelson *et al.*, *ibid.* **274**, 396 (1996).
4. K. K. Khurana, *J. Geophys. Res.*, in press.
5. J. E. P. Connerney, M. H. Acuna, N. F. Ness, *ibid.* **96**, 19,023 (1991).
6. ———, *ibid.* **92**, 15329 (1987).
7. J. D. Anderson, W. L. Shogren, G. Schubert, *Science* **272**, 709 (1996); J. D. Anderson, E. L. Lau, W. L. Sjogren, G. Schubert, W. B. Moore, *ibid.* **276**, 1237 (1997).
8. G. Schubert, K. Zhang, M. G. Kivelson, J. D. Anderson, *Nature* **384**, 544 (1996).
9. C. T. Russell, M. G. Kivelson, K. K. Khurana, in preparation.
10. K. K. Khurana, M. G. Kivelson, C. T. Russell, R. J. Walker, D. J. Southwood, *Nature* **387**, 262 (1997).
11. A. J. Dessler, in *Physics of the Jovian Magnetosphere*, A. J. Dessler, Ed. (Cambridge Univ. Press, New York, 1983), p. 498. The standard System III defined in this reference has been modified so that ϕ increases in the right-hand sense, thus measuring East longitude.

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