observed an enhancement in γ by a factor of 35 relative to β-carotene, which itself has one of the largest molecular γ values reported (*10–12, 22*). We have realized this enhancement of γ without large increases in either the molecular length or the molecular volume, albeit with some loss of transparency. Although it is unlikely that these specific compounds will be used to make practical devices because of their inherent instability with respect to long-term exposure to air and light, our results do validate and expand on the predictions of Garito *et al.* and thus suggest a clear strategy to further enhance γ in a variety of π-conjugated systems.

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Europa's Differentiated Internal Structure: Inferences from Two Galileo Encounters

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Doppler data generated with the Galileo spacecraft's radio carrier wave during two Europa encounters on 19 December 1996 (E4) and 20 February 1997 (E6) were used to measure Europa's external gravitational field. The measurements indicate that Europa has a predominantly water ice-liquid outer shell about 100 to 200 kilometers thick and a deep interior with a density in excess of about 4000 kilograms per cubic meter. The deep interior could be a mixture of metal and rock or it could consist of a metal core with a radius about 40 percent of Europa's radius surrounded by a rock mantle with a density of 3000 to 3500 kilograms per cubic meter. The metallic core is favored if Europa has a magnetic field.

Before the Galileo mission to Jupiter there was little information on Europa's interior structure. Its mean density of 3018 ± 35 kg m^{-3}, determined from previous Jupiter missions (*1*), is consistent with an interior of hydrated silicate minerals with a thin ice cover, or alternatively an interior of dehydrated silicate minerals with a thick ice cover (*2*). Here we report gravitational data from two close passes of Europa by the Galileo spacecraft, E4 and E6, that show that Europa has a more complicated internal structure. Recent Galileo data have shown that Ganymede is differentiated, most likely into a three-layer structure with a large metallic core, a silicate mantle and a thick outer layer of ice (*3*); Io has a large metallic core (*4*); and Callisto is essentially a uniform mixture of ice and rock (*5*).

The Galileo spacecraft flew by Europa on 19 December 1996 (E4) and 20 February 1997 (E6) and measured the Doppler shift in the spacecraft's radio carrier wave. We analyzed these data by fitting a parameterized orbital model, including Europa's gravitational field, to the radio Doppler data by weighted nonlinear least squares (*6*). Europa's external gravitational field was modeled by the standard spherical harmonic representation of the gravitational potential (*7*). For the assumption that the origin of coordinates is at the center of mass and that the orientation of Europa's principal axes is known because it rotates synchronously, only three gravity parameters are needed to specify the gravitational potential through the second degree and order (*8*).

For the two encounters (*9*) the two gravity coefficients are highly correlated, so we imposed the a priori hydrostatic constraint that J_2 is 10/3 of C_{22}. Also, because of an inconsistency in results for E4 and E6, analyzed independently, we added two third-degree gravity coefficients J_3 and C_{33} to the fitting model. The addition of these two harmonics makes the results (Table 1) more consistent and possibly indicates that there are significant nonhydrostatic components in Europa's gravitational field perturbing J_2 and C_{22}. The Jupiter-Europa distance was 671,567,992 m during E4 and 671,569,331 m during E6, so the Jupiter tidal force at Europa's surface differed by a fractional amount, 6×10^{-6}, between the two encounters. This difference is too small to account for the inconsistency in the results. Given that neither E4 nor E6 are ideal encounters for a gravity field determination, it is not possible to relax the $J_2 = (10/3)C_{22}$ a priori hydrostatic constraint or to explore the physical significance of the inconsistency between E4 and E6 in more detail. Additional close encounters with Europa, perhaps with a Galileo extended mission or a future orbiter mission, could reveal the true nature of this inconsistency.

Because of the a priori constraint, the values of J_2 and its uncertainty are nearly 10/3 of C_{22} (Table 1). There is essentially 1 degree of freedom per encounter in the second-degree field. The measured gravity signals corresponding to the values of J_2, C_{22},

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J_3, and C_{33} (Table 1) for E4 and E6 (Fig. 1) are above the noise level, even though the large Doppler shift between the preencounter and postencounter signals can be absorbed in a number of other parameters in the model, most notably GM and the spacecraft orbital parameters. The last column of Table 1 represents a five-dimensional weighted mean of results from E4 and E6. The weighted mean for GM is 3202.86 ± 0.072 $km^3\ s^{-2}$, where the error represents our best estimate of realistic standard error (1σ), as for all other errors reported here (*10*).

We used the theory of equilibrium figures for synchronously rotating satellites (*11*) to infer the internal structure of Europa, as has been done for Io, Ganymede, and Callisto (*3–5*). For a body in rotational and tidal equilibrium, C_{22} is related to the rotational parameter q_r by

$$C_{22} = (3/4)\alpha q_r \qquad (1)$$

where q_r is the ratio of centrifugal to gravitational acceleration at the satellite's surface at its equator ($q_r = 4.97 \times 10^{-4}$ for Europa). The parameter α is a dimensionless response coefficient that depends on the radial distribution of mass within the satellite ($\alpha = 0.5$ for constant density).

Given the differences in the values of J_2 and C_{22} derived from the two encounters with Europa, we separately explored the implications of each set of gravitational coefficients for the internal structure of Europa. We also considered the consequences of weighted mean values of J_2 and C_{22}. We considered only those inferred internal structures that are robust or common to all the sets of J_2 and C_{22} values as plausible interior models of Europa. For the E4, E6, and weighted mean values of C_{22} (Table 1), we find, from (*1*), that α is 0.172 ± 0.082, 0.350 ± 0.034, and 0.310 ± 0.032, respectively. Values of α based on J_2 are essentially identical. These values of α imply, on the basis of equilibrium theory, that Europa's axial moment of inertia C, scaled by MR^2, is 0.264 ± 0.041, 0.347 ± 0.014, and 0.330 ± 0.014. All of these values are small compared with C/MR^2 values of 0.4 for a uniform density body, 0.4 for Callisto (*5*), 0.378 for Io (*4*), 0.334 for Earth, and 0.310 for Ganymede (*3*). The smaller the value of C/MR^2, the larger is the density contrast between the near surface and deep interior of a body. It is clear from the possible values of C/MR^2 for Europa that the satellite is much denser at great depth.

A more quantitative assessment of the radial profile of Europa's internal density can be obtained by solving Clairaut's equation (*12*) for the distortion of hydrostatic satellite models to the rotational and tidal driving forces experienced by Europa, determining values of α from the models, and constraining the models by comparison with

Table 1. Europa gravity results. Gravity parameters $\Delta GM/GM$, J_2, C_{22}, J_3, and C_{33} are in units of 10^{-6}. The total mass (GM) is measured from a reference value of 3201 $km^3\ s^{-2}$; μ is the correlation coefficient between J_2 and C_{22}.

Parameter	E4	E6	Weighted mean
$\Delta GM/GM$	588 ± 17	534.9 ± 8.3	545.9 ± 7.4
J_2	215 ± 102	438 ± 45	389 ± 39
C_{22}	65 ± 31	132 ± 13	117 ± 12
J_3	0 ± 10	0 ± 10	0.1 ± 7.1
C_{33}	6.2 ± 5.8	0.4 ± 2.1	0.6 ± 1.9
μ	0.9989	0.9945	0.9963

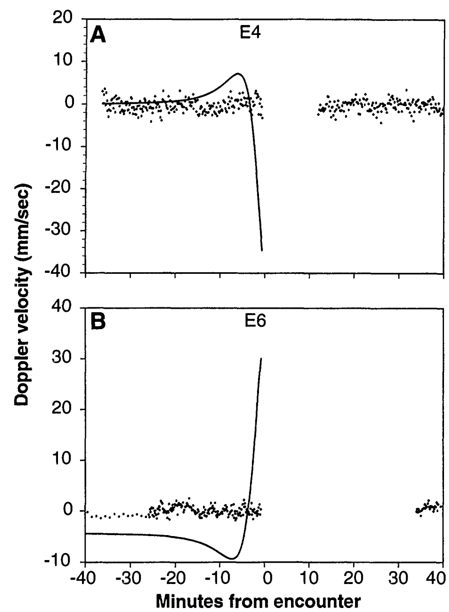

Fig. 1. Doppler residuals (observed Doppler velocity minus model Doppler velocity) for the best fit gravity model (filled circles) and a model in which Europa's gravitational field is represented only by GM (solid curve) at E4 (**A**) and E6 (**B**). For E4 the Doppler velocity is defined by $c\Delta\nu/\nu$, where $\Delta\nu$ is the Doppler frequency shift referenced to the spacecraft's crystal oscillator (one-way Doppler data), ν is the transmitted frequency, about 2.3 GHz, and c is the speed of light. For E6 the Doppler data are coherently referenced to a hydrogen-maser frequency standard at the DSN station and the Doppler velocity is defined by one half the E4 definition. Data included in the fit extend from 16 December 1996, 09:47:30 to 20 December 1996, 02:57:30 UTC for E4 and from 16 February 1997, 16:32:30 to 20 February 1997, 21:58:30 UTC for E6. The gap in the residuals near closest approach for E4 and E6 is caused by the occultation of the spacecraft radio signal by Europa as viewed from Earth. The Doppler shift for the "GM only" model is off scale after egress from occultation by about −48 mm s^{-1} for E4 and about −66 mm s^{-1} for E6 because of the perturbation to the orbital velocity projected along the line of sight caused by Europa's second-degree and higher gravitational field components. The reduced noise in the Doppler velocity at the beginning of the E6 data is caused by a larger sampling interval of 60 s as opposed to a sampling interval of 10 s for the rest of the data shown.

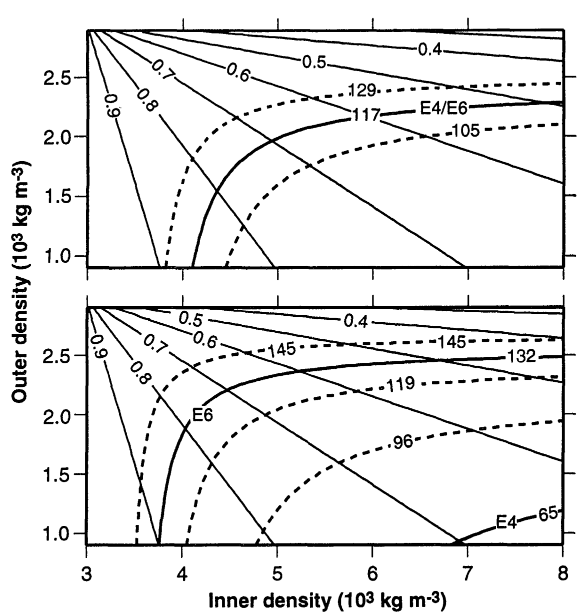

Fig. 2. Two-layer models of Europa consistent with its mean density and C_{22}. Results are based on the weighted mean of the C_{22} values from E4 and E6 (**top**) and the separate C_{22} values from E4 and E6 (**bottom**). The solid curves show results for the nominal values of C_{22} and the dashed curves show results for the $\pm 1\sigma$ values of C_{22}. The thin solid lines slanting from the upper left to the lower right give values of core radius divided by Europa's radius. Possible two-layer Europa models are defined by the points that lie along the C_{22} curves. The points then define the models by the outer and inner density values on the coordinate axes and the normalized core radius given by the slanting thin solid lines. C_{22} values are in units of 10^{-6}.

the inferred value of α for Europa. Europa's measured average density provides a second constraint on possible models, but the availability of only two constraints dictates that we consider only simple models of Europa with a minimum number of unknown parameters. Accordingly, we investigated two- and three-layer models of Europa.

The surface of Europa is known to be predominantly water ice, and it is thought that the ice extends to depths of up to perhaps 100 kilometers. A global liquid water ocean may lie beneath a relatively thin (about 10 kilometers thick) cover of ice (2). We therefore assumed that the outer shell in our models has a density appropriate to a predominantly water ice-liquid composition. The relatively low density of water ice-liquid compared to the density of the rocks and metal that lie beneath the water is in accord with the measured value of α.

The two-layer models of Europa require interior densities that are at the edge of the envelope of acceptable silicate densities (Fig. 2). For the E4/E6 mean value of C_{22}, the density of the deep interior must be greater than about 4100 kg m^{-3}, too dense for a silicate core (the core must be a mix of rock and metal, with a substantial metal component). The radius of the core in this case is about 0.85 R_E (R_E is the radius of Europa). Smaller, denser cores with larger metal fractions, combined with thicker water ice-liquid shells are possible. For the E6 value of C_{22}, the minimum core density is about 3800 kg m^{-3}, just at the outer edge of possible silicate densities (3). The E4 value of C_{22} is so small that Europa would have to be similar to a sphere of Fe surrounded by a shell of water ice-liquid. Based on these two-layer models we conclude that Europa must have a water ice-liquid shell at least about 150 km thick surrounding a dense interior with a substantial amount of metal (density $\geq$ about 4000 kg m^{-3}).

In the three-layer models of Europa (Fig. 3), we assume that the core has the density of Fe (8000 kg m^{-3}) or Fe-FeS (5150 kg m^{-3}). The Galileo magnetometer measured magnetic field perturbations at its initial encounter with Europa that are consistent with the satellite possessing an intrinsic magnetic field (13) and thus a metallic core. For the E4/E6 mean value of C_{22} and silicate densities of 3000 to 3500 kg m^{-3}, an Fe core would have a radius of 0.4 to 0.3 R_E, whereas an Fe-FeS core would have a radius of 0.6 to 0.4 R_E (Fig. 3B). The water ice-liquid shells in these models have thicknesses between about 150 and 200 km. For mantle densities in excess of about 3800 kg m^{-3}, Fig. 3B and the two-layer model results show that smaller metallic cores are possible, but a substantial amount of metal must be mixed into the mantle to achieve the required high density of the mantle. Three-layer model results for the E6 value of C_{22} (Fig. 3A) are similar; the main differences are that the water ice-liquid shell thickness is smaller (about 100 to 150 km) and that the core is smaller or the mantle has less metal. The value of C_{22} is so small for E4 (Fig. 3) that only models with Fe cores of radius 0.6 to 0.5 R_E and outer water ice-liquid shells between 300 and 400 km thick are possible.

For a three-layer model with a mantle density of 3300 kg m^{-3}, typical of dehydrated silicates, and the E4/E6 mean value of C_{22} (Fig. 4, A and C), the core radius would be 0.4 to 0.3 R_E for an Fe core or 0.65 to 0.45 R_E for an Fe-FeS core, independent of the actual density of the water ice-liquid shell. For the Fe core, the water ice-liquid shell is 125 to 250 km thick, and for the Fe-FeS core the water ice-liquid layer is 125 to 300 km thick. The smaller Fe cores in these models make up about 11 to 21% of Europa's mass, whereas the larger iron–iron sulfide cores in the models are about 18 to 47% of Europa's mass. The cores in the E6 models (Fig. 4, B and D) are smaller than those in the E4/E6 models, and the water ice-liquid layer thicknesses are also smaller in the E6 models. The E4 models with Fe cores have large cores and thick water ice-liquid shells (Fig. 4D), whereas E4 models with Fe-

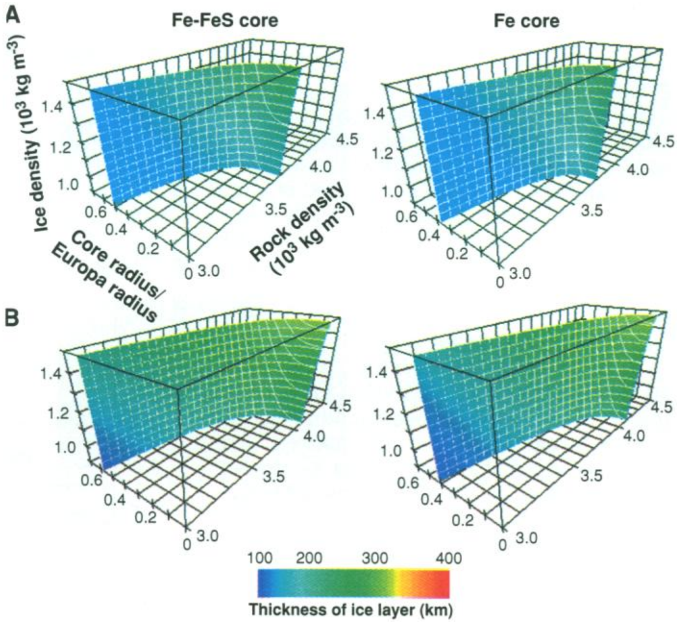

Fig. 3. Three-layer models of Europa consistent with its mean density and C_{22}. Results are based on the C_{22} nominal value from E6 (**A**) and the weighted mean of the C_{22} nominal values from E4 and E6 (**B**). Separate models are shown for Fe (right) and Fe-FeS (left) cores. Model results for the E4 nominal value of C_{22} lie outside the range of the model parameters considered and are not shown. Each surface is the locus of possible models that satisfy the constraints. A point on one of the surfaces defines a model whose parameters are specified by the ice density, rock density, and fractional core radius on the coordinate axes. The thickness of the ice layer (water ice-liquid layer) in a model is indicated by the color scheme on the surfaces of possible models.

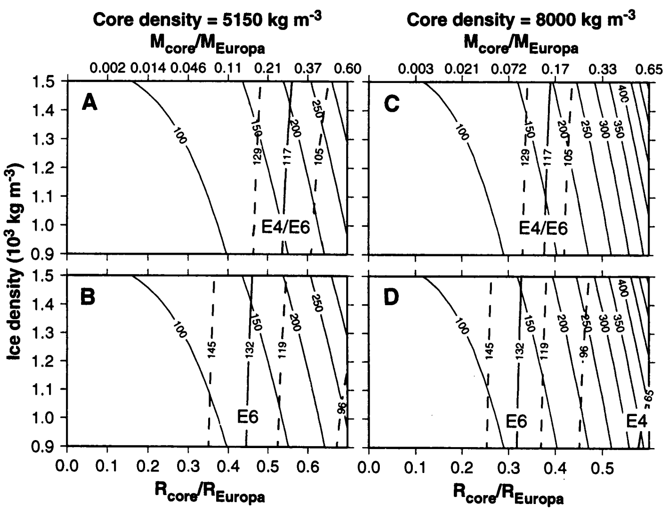

Fig. 4. A cut through the phase space of possible three-layer models of Europa. The restricted class of three-layer models has a rock density of 3300 kg m^{-3}. The models are constrained by the weighted mean of the E4 and E6 C_{22} values (**A**) and (**C**) and the separate E4 and E6 C_{22} values (**B**) and (**D**). The solid curves show results for the nominal values of C_{22} and the dashed curves show results for the $\pm 1\sigma$ values of C_{22}. A point on one of these curves defines a model whose ice density, core mass fraction and fractional core radius are given on the coordinate axes. Ice-layer thickness in kilometers is given by the thin solid curves that slope downward to the right. Separate results are shown for Fe cores with density 8000 kg m^{-3} (C) and (D) and Fe-FeS cores with density 5150 kg m^{-3} (A) and (B). C_{22} values are in units of 10^{-6}.

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.

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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}.
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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.

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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.

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 north-