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Gravitational constraints on the internal structure of Ganymede

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BEFORE the arrival of the Galileo spacecraft in the jovian system, there was little information on the interior structure of Jupiter's largest moon, Ganymede. Its mean density (1,940 kg m^{-3}), determined by the Pioneer and Voyager spacecraft[1-3], implies a composition that is roughly 60% rock and 40% ice, which could be uniformly mixed or differentiated into a rocky core and icy mantle[4]. Here we report measurements by the Galileo spacecraft of Ganymede's overall density and the spherical harmonics, J_2 and C_{22}, of its gravitational field. These data show clearly that Ganymede has differentiated into a core and mantle. Combined with the recent discovery of an intrinsic magnetic field[5,6], our gravity results indicate that Ganymede has a metallic core of radius 400--1,300 km surrounded hy a silicate mantle, which is in torn enclosed by an ice shell ~800 km thick. Depending on whether the core is pure iron or an alloy of iron and iron sulphide, it could account for as little as 1.4% or as much as one-third of the total mass. If the ice were stripped away, it appears that Ganymede would look much like Io[7] in terms of its size and internal mass distribution.

The data were analysed by fitting a parametrized orbital model to the radio Doppler data by weighted nonlinear least squares[8] 'O. The two encounters between Galileo and Ganymede (on 27 June and 6 September 1996) were analysed independently. Ganymede's external gravitational field was modelled by the standard spherical harmonic representation of the gravitational potential[11]. Because wc assumed that the orientation of Ganymede's principal axes is known, only two non-zero coefficients (J_2 and C_{22}) were included in the model, All other harmonic coefficients were assumed to be exactly equal to zero. The two included coefficients 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 Ganymede (radius r, latitude ϕ, and longitude λ), where longitude is measured from the Ganymede - Jupiter line in an equatorial system dc.fined by Ganymede's spin axis, the gravitational potential is

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

(AUTHOR: please define G, M and R) The two encounters were intentionally targeted to optimize gravitational field measurements; the first was a near-equatorial pass at an altitude of 835 km, while the second was a near-polar pass at an altitude of 261 km. The closest-approach location for the first was at $\phi = 30.394°$ and $\lambda = 112.129°$ (west longitude), while the second was at $\phi = 79.282°$ and $\lambda = 122.444°$. **The first** encounter was most sensitive to C_{22}, while the second was most sensitive to J_2. However, for both encounters the two gravity coefficients were highly correlated, so we imposed the *a priori* hydrostatic constraint that J_2 is exactly 10/3 of C_{22}.

Gravity results for the two encounters arc summarized in Table 1. Although the two gravity coefficients, because of the 10/3 constraint, were perfectly correlated *a priori*, the correlation after fitting tbc data is significantly less than unity for both encounters. This implies that there is considerable freedom for the two coefficients to differ from their hydrostatic values. To the contrary, it can be concluded from Table 1 that the non-hydrostatic perturbation to the second-degree field is only 0.2% with 1σ uncertainty of 1.9%. It is highly unlikely that non-hydrostatic components contribute more than 6% to the Ganymede gravity field.

The value of GM is found to bc 9,886.63 0.5 $km^3 s^{-2}$ Masses derived from GM determinations depend on the gravitational constant G. The currently accepted value[12] is (6.672559 ±0.00085) x 10^{-20} km' s" ^{2}kg-]. This yields a mass of (1.48167 ± 0.00020) x 10^{23} kg for Ganymede. Under the assumption that the volume of Ganymede is equal to that of an equivalent sphere of radius 2,6343 10 km (ref. 13) its mean density is 1,936:1 22 kg m^{-3} where the uncertainty is determined by the uncertainty in tbc radius.

Formal error estimates from the least-squares covariance matrix are based on an assumption of independent measurements drawn from a gaussian noise distribution. The reduced Galileo radio Doppler data are gaussian, but their power spectral density follows an $f^{-2/3}$ **(Author: please define f)** law arising from propagation of the radio carrier wave through solar plasma]'. The variance of spectral estimates of a signal roughly follows the same power-law dependence as the noise spectrum, so the Galileo gravity signals arc better determined at higher Fourier frequencies. Our data weighting, with an assumed variance approximately equal to tbc variance of the Doppler residuals (0.04 $mm^2 s^{-2}$ at a sample interval of 60s), is about right for the Ganymede gravity signals, where the peak Fourier components are around 2 x 10^{-3} Hz. We therefore retain the formal errors for the satellite gravity parameters for tbc first encounter. However, because of the closer approach of tbc spacecraft during the second encounter, wc increase the formal errors by a factor of three in order to account for possible gravity perturbations by non-hydrostatic components. All errors reported here are our best estimates of realistic standard error.

A synchronously rotating satellite in tidal and rotational equilibrium (such as Ganymede) **(Author: OK?) takes** the shape of a triaxial ellipsoid with dimensions a, b and c ($a > b > c$), The long axis of tbc ellipsoid is along the planet-satellite line and the short axis is parallel to the rotation axis. The distortion of the satellite depends on the magnitude of the rotational and tidal forcing and the distribution of mass with radius inside the body. The distortion of the satellite and its internal mass distribution determine the satellite's gravitational field[15-18]. The gravitational coefficient C_{22} is related to the difference in the equatorial moments of inertia by

$$C_{22} = \frac{B - A}{4MR^2} \tag{2}$$

(AUTHOR: arc M and R here the same as in equation (l)? If not, please usc different symbols) where the ellipsoidal satellite's principal moments of inertia are A, B, and C ($C > B > A$). For a body in Notational and tidal equilibrium, the gravity coefficient C_{22} is related to the rotational parameter q_r by

$$C_{22} = \frac{3}{4}\alpha q_r \tag{3}$$

with similar equations for J_2. Here α is a dimensionless response coefficient that depends on tbc distribution of mass witbin the. satellite (α = 1/2 for constant density) and q_r is the ratio of centrifugal to gravitational acceleration at tbc equator (q_r = 1.903 x 10^{-} for Ganymede). For purposes of geophysical interpretation, we adopt the weighted mean of the two values of C_{22} in Table 1. The result is C_{22} = (38.18 ± 0.87) x 10^{-6} and the corresponding value of a from equation (3) is 0.2675:1 0.0061 (the value from the weighted mean of J_2 is a = 0.2679 ± **0.0056).** The satellite's **axial moment of** inertia, normalized 10 the total mass M times the square of the satellite's radius R, follows from equilibrium theory. **(see earlier comment on symbols)** We **obtain** C/MR^2 = 0.310s,1 0.0028.

The axial moment of inertia provides a direct constraint on the internal mass distribution[7,19]. For a uniform density body C/MR^2 = 0.4. The smaller the value of C/MR^2, the more concentrated is the body's mass towards its centre. We note that the value of C/MR^2 for Ganymede is among the smallest of any planet rrr sate.iiitcinti]cSolal System. Io's value[7] of C/MR^2 is 0.378; Earth's value **is** 0.334. Only **the giant outer** planets have C/MR^2 values smaller **than** Ganymede's **value.** Accordingly, **it is immediately clear that** Ganymede **is strongly** differentiated **with a large** concentration **of mass** toward **its** centre.

A more. quantitative description **of** Ganymede's **internal mass** distribut ion can be given in terms of a model of the interior density $\rho(r)$, where r *is* the radial distance from the centre of Ganymede. **(AUTHOR:** is **this the same** r **and used earlier? Please use a different symbol if not)** Consistent with the small number of constraints we can apply to the density distribution, the overall density and the value of C_{22}, we adopt a three-layerrnodelwith a core anti two overlying spherical shells. A two-layer model is of course a special case of the three-iayer model and corresponds either toa zero-thicknessoutershcil ora zero-radiuscmcin the three-layer model. We solve Clairaut's equation[20] for the distortion of tile model to the tidal and rotational potentials and determine the family of model parameters consistent with the observed value of a. There arc more model parameters than avail able constraints, even for a two-layer model, and no unique model of Ganymede's internal mass distribution can be determined. Instead, we must restrict the model parameter space with reasonable **assumptions** about the nature of Ganymede's interior. We have emphasized above that Ganymede's moment of inertia requires that it is strongly differentiated and its overall density requires that it has a large water-ice component. The existence of a magnetic field[5] suggests that Ganymede has a metallic core. we therefore consider models in which the core density is either the density of Fe (8,000 kg m^{-3}) or the density of Fe-FeS (5,150 kg m^{-3}). **We** also assume that the outer shell of the. model is predominantly watt.r ice.

Allowable three-layer models consistent **with** Ganymede's **overall** density and C_{22} **arc shown** in Fig. 1 for the two assumed values of core density. There arc three additional model parameters that arc unknown *a* priori', the densities of the ice and rock shells anti the radius of the metallic core. The surfaces shown in the figure delineate the acceptable combinations of these parameters; the colours on the surface give the radius of the ice-rock interface. **(Note.** that the radius of the core and of the ice–rock interface arc given in units of R_G, the radius of Ganymede.) **(Author:** OK?) Two-layer models can be explored by the intersections of the surfaces with the plane representing core radius equal to zero. Because the core density is of no consequence when the core radius is zero, there. is only one distinct intersection. The intersection is shown in Fig. 2 for the models based on the adopted value of C_{22} anti for additional models not shown in Fig. 1 that correspond to the 1σ uncertainties in C_{22}. Two-layer models have rock densities larger than ~3,400 kg m^{-3} (in two-layer models, rock refers to silicates and metal), with the rock- ice interface at radii between about 0.64 anti 0.73 of Ganymede's radius. Rock densities in excess of 3,800 kg m^{-3} arc probably too large to be consistent with a silicate–metal mixture eat the temperatures and pressures of Ganymede's interior, at least for approximately solar abundances of the relevant elements. However, rock densities between about 3,400 and 3,800 kg m^{-3} arc plausible, For example, if the metal and silicates in Io were rehomogenized and subject to ganymedean conditions, the density **of** the resultant **mixture might** be 3,600 or 3,700 kg m^{-3} (D. J. Stevenson, personal communication). Thus, while two-layer models **of** Ganymede's interior **arc**

possible, just on the basis of the gravity data, we favour instead a three-layer structure of Ganymede with a metallic core, in light of the existence of a ganymedean magnetic field[5,21].

For such a tbrcc-layer model of Ganymede, **Fig. 3** shows the intersections of the surfaces in Fig. 1 with the. plane representing a rock density of 3,300kgm'3, a reasonable density for the silicates alone. The figure also shows similar intersections for models based on the 1 σ uncertainties in C_{22}. For the Fe–FeS core (core density, 5,150 kg n-3), the core radius cannot exceed $\sim 0.5\, R_G$ (that is, a fractional core radius of 0.5) without the complete disappearance of the silicate mantle. Possible models of Ganymede have core.s with radii between about 0.2 R_G and 0.S R_G, masses between about 2% and 33% of Ganymede's mass, ice densities between about 1,000 and 1,300 kg m⁻3 and rock--ice iotc]-faces at radii between about $0.6\, R_G$ and $0.73\, R_G$. For similar parameters and an Fe core, Fig. 3 indicates that the core radius is between about $0.15\, R_G$ and 0.4 R_G, the core mass is between about 1.4'% and 26% of Ganymede's mass, the ice density is between about 1,000 and 1,350 kgm'3, and the rock--ice interface is between about 0. 53 ,- R_G and 0.73&If the fractional core radius is larger than $\sim$0.4 in these models, there is no silicate mantle.

The formation of a metallic core in Ganymede requires heating of the satellite to at least tbc Fe–FeS eutectic melting temperature (-1 ,325K) at some time in the past. Accretional and radiogenic sources can provide this level of heating'"', but not much more. Ganymede could also have been tidally heated during passage through a temporary resonance in its orbital and thermal evolution[21,22]. Io, which is in a resonance with Ganymede and Europa, is at present tidally heated[4,23,24] and it may have been differentiated in the past by this mechanism. Io and Ganymede may not only have structural similarities, but they may have experienced similar heating and differentiation episodes in the past, even though Ganymede is not at present tidally heated. [1

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DISPLAY ITEMS: Gig. 1*a*, *b* colour; Fig. 2 b/w; Fig. 3a, *b* b/w; Tables 1; Galley no.: 913

FIG. 1 'Ihreo-layer models of Ganymede consistent with observations of its overall density and C_{22}. *a*, Models with a core density of 5,150 kgm"³ (Fe-FeS); *b*, models wfth a core density of 8,000 kg m^{-3} (Fe), Any point on one of these surfaces defines a possible model of Ganymede's Internal mass distribution with the values of Ice density, rock density, and core-radius/Ganymede radius determined by the plots. The colours on the surfaces indicate the value of the ice–rock Interface radius/Ganymede radius ($R_{ice\ rock}/R_G$).

FIG. ? Two- layer models of Ganymede consistent with Its overall density and C_{22}. Ihe curves labelled 39.05, 38.18 and 37.31 define possible Ganymede models for the nominal and plus and minus 1σ values of C_{22} = **(38,184 0,87) x 10^{-6}. The other** curves give the value of ice–rock radius/Ganymede radius.

FIG. 3 Three-layw models of Ganymede with **a** rock density of 3,300 kg m^{-3}. a, Assuming an Iron core with density 8,000 kg m^{-3}; *b*, assuming a Fe–FeS core with density 5,150 kg m^{-3}. The curves labelled 39.05, 38.18 and 37.31 define possible Ganymede models for the nominal and plus and minus 1σ values of $C_{22} = (38.18 \pm 0.87) \times 10^{-6}$. The other curves give the value of Ice-rock radius/Ganymede radius. The upper horizontal scale is anonlinear scale giving the fractional core mass (core mass/Ganymede mass). The fractional core radius Is core-radius/Ganymede radius.

TABLE 1 Ganymede gravity results

	Encounter 1	Encounter 2
J_2	$(126.0 \pm 6.0) \times 10^{6}$	$(127.8 \pm 3.0) \times 10^{6}$
C_{22}	$(37.8 \pm 1.8) \times 10^{8}$	$(38.3 \pm 1.0) \times 106$
ρ	0.7399	0.5870

J_2 and C_{22} are defined In the text; p is the correlation coefficient, (AUTHOR: **please** replace rho here by another symbol (not r or R) to avoid **confusion** wtth **density**)

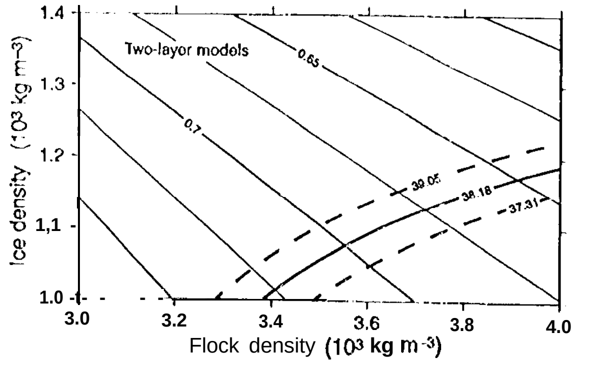
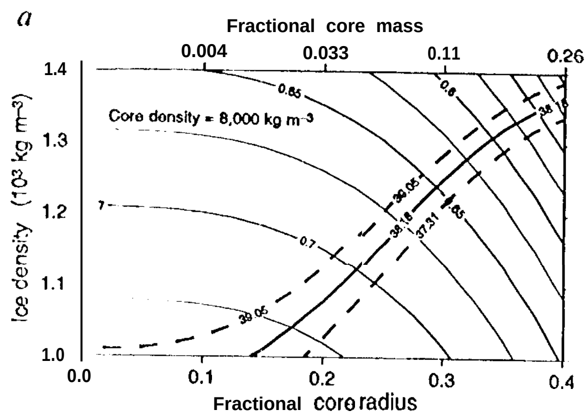


FIGURE N6913F2



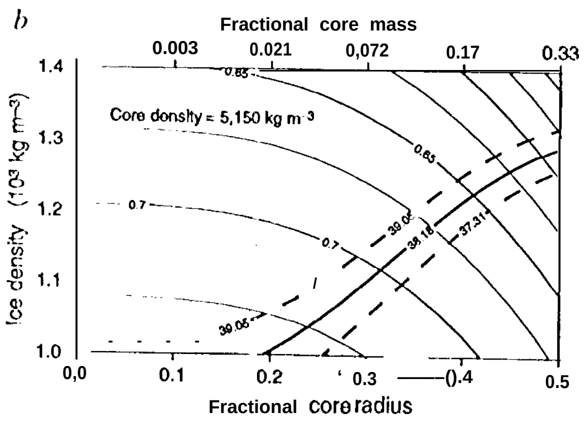


FIGURE N6913F3

FIGURE N69 3F1 (COLOUR TO FOLLOW)