Icarus 299 (2018) 430–442

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Faster paleospin and deep-seated uncompensated mass as possible explanations for Ceres' present-day shape and gravity

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ARTICLE INFO

Article history:
Received 12 March 2017
Revised 22 August 2017
Accepted 23 August 2017
Available online 24 August 2017

Keywords:
Asteroid Ceres
Interiors
Rotational dynamics

ABSTRACT

We show that Ceres' measured degree-2 zonal gravity, J_2, is smaller by about 10% than that derived assuming Ceres' rotational flattening, as measured by Dawn, is hydrostatic. Irrespective of Ceres' radial density variation, as long as its internal structure is hydrostatic the J_2 predicted from the shape model is consistently larger than measured. As an explanation, we suggest that Ceres' current shape may be a fossil remnant of faster rotation in the geologic past. We propose that up to ~7% of Ceres' previous spin angular momentum has been removed by dynamic perturbations such as a random walk due to impacts or a loss of satellite that slowed Ceres spin as it tidally evolved outward. As an alternative, we also consider a formal degree-2 admittance solution, from which we infer a range of possible non-hydrostatic contributions to J_2 from uncompensated, deep-seated density anomalies. We show that such density anomalies could be due to low order convection or upwelling. The normalized moments-of-inertia derived for the two explanations – faster paleospin and deep-seated density anomalies – range between 0.353 ± 0.009 and 0.375 ± 0.001 for a spherically equivalent Ceres, which can be used as constraints on more complex Ceres interior models.

1. Introduction

The Dawn mission has accurately determined the mass and shape of Ceres. Ceres' gravity field has been determined to at least degree and order 8 (Park et al., 2016) and the topography to much higher degree and order (Ermakov et al., 2015). Significantly, the degree-2 zonal gravity (J_2) calculated from Ceres' shape assuming a uniform interior density (304×10^{-4}) is substantially larger than the measured value (265×10^{-4}), which implies a degree of central mass concentration or differentiation (Park et al., 2016). Moreover, differentiated Ceres models that assume its zonally averaged shape is hydrostatic also predict a greater J_2 value than observed (Ermakov et al., 2015; Mao and McKinnon, 2016). Equivalently, Ceres possesses 2.5 km of excess flattening, i.e., the difference between its physical flattening and its less oblate "geoid." In this paper, we suggest two solutions to reconcile Ceres' measured J_2 and rotational flattening.

We argue that an ice-rich crust or layer of varying thickness, whether isostatically supported or not, is an unlikely explanation for Ceres' excess equatorial bulge, although it is plausible (if not likely) for higher degrees and orders on Ceres (Ermakov et al., 2015, 2016). We instead suggest that Ceres may have rotated faster in the past (by up to about 7%), and that the shape observed today is partly a fossil remnant, because a faster rotation increases geoid flattening for fixed J_2 (Murray and Dermott, 1999). We later discuss mechanisms by which Ceres' original spin period may have evolved and decreased. Alternatively, deep seated but uncompensated density anomalies, such as caused by convection or upwelling, could explain Ceres' unusual gravity/topography relationship at degree-2 (the sectorial admittance is negative; Ermakov et al. (2016)). Ultimately, we conclude that some combination of a faster paleospin and deeper, uncompensated mass or masses is the most likely explanation overall, the models for which set useful limits on Ceres' average moment of inertia.

2. Methods

We begin by revisiting internal models of Ceres based on its shape and density alone (i.e., as in Thomas et al. (2005)), updating our earlier results (Mao and McKinnon, 2016) and illustrating our general methods. Ceres' best-fit shape is slightly triaxial (±1 km along the equator; Park et al. (2016)), but we model Ceres as an oblate spheroid because of its relatively rapid spin and lack of tidal interaction with other large bodies, with a mean equatorial

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http://dx.doi.org/10.1016/j.icarus.2017.08.033
0019-1035/

Table 1
Ceres physical parameters.

Parameters	Value	Reference
GM	62.6285 ± 0.0008 km^3 s^{-2}	Park et al. (2016)
Spin Period (P)	9.074170 ± 0.000002 h	Chamberlain et al. (2007)
Equatorial Radius (a)[a]	483.1 ± 0.2 km	Park et al. (2016)
Equatorial Radius (b)	481.0 ± 0.2 km	Park et al. (2016)
Polar Radius (c)	445.9 ± 0.2 km	Park et al. (2016)
Bulk Density (ρ)[b]	2162.1 ± 1.6 kg m^{-3}	Calculated
Surface Gravity (g)	0.28 m s^{-2}	Calculated
J_2	$(2649.9 \pm 0.1) \times 10^{-5}$	Park et al. (2016)
J_4	$-(171.2 \pm 0.6) \times 10^{-5}$	Park et al. (2016)
C_{22}[c]	23.83×10^{-5}	Park et al. (2016)

[a] We take the mean equatorial radius to be 482.0 ± 0.2 km.
[b] Bulk density is formally calculated from mass and ellipsoidal volume, and is slightly different from that in Park et al. (2016), where $\rho = 2162 \pm 8$ kg m^{-3} is based on a three-dimensional stereo-derived shape model.
[c] Principal axis value.

radius $\bar{a} = 482.0 \pm 0.2$ km. Adopting published parameters (Table 1), we apply a sixth-order recursive method based on the ellipsoidal theory of figures from Tricarico (2014) and construct two-layer models of Ceres in hydrostatic equilibrium. This method assumes uniform density layers and ellipsoidal level surfaces, and is accurate for Ceres' oblateness and rotation rate (Tricarico, 2014). Similar methods have been applied to icy satellites such as Enceladus (McKinnon, 2015; Beuthe et al., 2016). We assume a range of outer shell densities from 920 to 2000 kg m^{-3}, representing the spectrum from pure water ice to a mixture of hydrated silicates, salts, and/or clathrates (e.g., Bland et al., 2016). We calculate the corresponding shape eccentricity ($e \equiv \sqrt{1-(c/\bar{a})^2}$) and gravity terms for each shell density and average shell thickness

$$d = \sqrt[3]{\bar{a}^2 c} - \sqrt[3]{{a_c}^2 c_c}, \tag{1}$$

where c and $\bar{a}$ are Ceres' polar and average equatorial radius, respectively, and c_c and a_c are the corresponding radii of the aligned ellipsoidal core. Acceptable solutions are found when the exterior size and shape ($\bar{a}$, c) match that of Ceres. This is essentially the procedure of Thomas et al. (2005), but now the numerical method is more accurate for Ceres' spin rate and oblateness, and most critically, Dawn gravity now serves as an independent check and constraint.

3. Results

3.1. Differentiated internal structures of Ceres from hydrostatic shape modeling

Fig. 1 shows our shape-fitting solutions for Ceres at its current spin period, with estimated uncertainties. The average shell thickness d ranges from 11 to 89 km (Fig. 1a), and corresponds to a large but rather low density core. The precision of Dawn measurements apparently formally rules out a completely homogeneous Ceres, *based on shape alone*, although a trivially thin icy shell is permitted within the uncertainties. Considering shape uncertainties, a less flattened or more flattened Ceres, determined by appropriately varying the equatorial and polar radii by $\pm 3\sigma$ (± 0.6 km), still has a finite average shell thickness for our minimum shell density solutions, as indicated by the two dashed lines in Fig. 1a. From these results, we would conclude that Ceres is a differentiated body, albeit a very much less differentiated one when compared with previous results (Ermakov et al., 2015; Park et al., 2016). Whereas average shell thickness is quite insensitive to assumed shell density, especially when the latter is $<$1500 kg m^{-3}, outer shell thickness does increase rapidly for higher shell density solutions. Our nominal (central) solutions point to a shell thickness less than 100 km, which indicates a limited separation of ice from rock in Ceres' evolution. This is consistent with the evidence for limited viscous relaxation of large craters on Ceres (Bland et al., 2016).

That Ceres appears to only be partially differentiated is not a novel conclusion (see Park et al. 2016). What is remarkable is that the degree of differentiation appears to be so small in these solutions. For a pure ice shell, the outer layer is only ~10 km thick on average (Fig. 1a). Put another way, the shape of Ceres is nearly that appropriate to a uniform density oblate (or Maclaurin) spheroid. This can also be seen from the zonal gravity J_2 calculated from our hydrostatic shape models, 2953×10^{-5} (Fig. 1c), which is only 3% less than that of a homogeneous Ceres, 3033×10^{-5} (calculated from its oblate ellipsoidal shape) or 3040×10^{-5} (calculated from a full three-dimensional shape model; Park et al., 2016), all these J_2 values being referenced to a mean radius of 470 km. Within Ceres' shape and density uncertainties, Ceres could essentially *be* a Maclaurin spheroid, or very near to it (Fig. 2). Indeed, if shape were all that mattered, and Thomas et al. (2005) had the Dawn results for Ceres' shape and density, they would have likely concluded that Ceres was undifferentiated.

What is more important in Fig. 1 is that the J_2 calculated from our hydrostatic shape (and interior) models is substantially greater than the actual value measured by Dawn, $(2649.9 \pm 0.1) \times 10^{-5}$ (Park et al., 2016). The uncertainty in our shape-based J_2 determination (Fig. 1c) does not allow agreement between Ceres' shape and its measured J_2, even if Ceres is less oblate than nominal by the full 3σ in $\bar{a}$ and c, in which case the outer shell is relatively thicker, and the core relatively denser for a given shell density. In other words, the solutions in Fig. 1 cannot be the correct ones, because they do not predict the correct J_2.

The difference between the measured and model hydrostatic J_2 implies (in the context of an oblate planetary body) that Ceres must be centrally condensed or differentiated to a larger degree than indicated by Fig. 1. This is also implied from a comparison of Ceres' J_2 with that estimated from a uniform Ceres (Park et al., 2016), but what is important here is that Ceres' J_2 cannot be explained with a hydrostatic, 2-layer, ellipsoidal level surfaces model (or indeed with any hydrostatic interior model, as we will show below). In other words, Ceres' zonal second-degree gravity is non-hydrostatic at the 10% level.

3.2. Ceres' rotational geoid

That Ceres' ellipsoidal shape cannot be fully hydrostatic can also be seen by directly calculating the shape of its exterior equipotential surface (or geoid). Setting the exterior potential equal at the equator and pole yields the following recursive relation for the flattening of a biaxial, oblate level surface

$$\frac{a}{c} = 1 + \left[\frac{1}{2} + \left(\frac{a}{c}\right)^3\right] J_2 + \frac{\omega^2 a^3}{2GM} + \ldots, \tag{2}$$

where a and c are the equatorial and polar radii, G is the gravitational constant, M is Ceres' mass, $\omega = 2\pi/P$, where P equals the spin period, and for this and the following equation, J_2 and J_4 are normalized to a ($\equiv \bar{a}$ for this calculation, or 482.05 km), not the mean radius (470 km). For Ceres this yields $a/c = 1.07716$ ($a - c = 34.4$ km) vs. the observed $a/c = 1.08107$ (or $a - c = 36.15$ km). If we extend Eq. (2) to degree-4 (uniform, biaxial ellipsoidal bodies contribute to all even J_n),

$$\frac{a}{c} = 1 + \left[\frac{1}{2} + \left(\frac{a}{c}\right)^3\right] J_2 + \left[-\frac{3}{8} + \left(\frac{a}{c}\right)^5\right] J_4 + \frac{\omega^2 a^3}{2GM} + \ldots, \tag{3}$$

which yields $a/c = 1.07536$ ($a - c = 33.6$ km) vs. the observed $a/c = 1.08107$ ($a - c = 36.15$ km). Extending this relation to J_6 and beyond is not yet warranted because the change in $a - c$ would be at the 100 m level and Ceres' published gravity field is insufficiently accurate beyond degree 5 (Park et al., 2016).