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Harmonic and statistical analyses of the gravity and topography of Vesta

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ABSTRACT

We examine the gravity and topography of the asteroid 4 Vesta, as recently revealed by the Dawn mission. The observed gravity is highly correlated with the observed topography, and suggests little lateral variation in density. The variance spectra of both gravity and topography follow power laws which are very similar to those seen for the Moon, Mars, Venus, and Earth. A significant way in which Vesta differs from these larger silicate bodies is that both gravity and topography are significantly anisotropic, with more north–south variation than east–west variation. Rapid rotation plausibly contributes to this anisotropy, but only at harmonic degree two. The remainder of the anisotropy appears related to the large impacts which formed the Rheasilvia and Veneneia basins. We note that, as usual, gravitational inverse problems are non-unique. While the observed gravity and topography of Vesta do not preclude existence of a metallic core, they certainly do not require it.

1. Introduction

The Dawn mission (Russell and Raymond, 2011) has completed its mapping of the asteroid 4 Vesta, and successfully concluded the planned investigations of topography (Raymond et al., 2011) and gravity (Konopliv et al., 2011). Initial results of those investigations are reported in (Jaumann et al., 2012) and (Konopliv et al., 2014). The objective of the present study is to examine the broad patterns of variations in gravity and topography of Vesta, and compare those patterns with what is seen on the Moon, Mars, Venus, and Earth.

Even prior to Dawn's arrival at Vesta, a reasonable amount was known about the body (Zuber et al., 2011). The mass had been estimated from orbital perturbations of Mars and other asteroids, and a shape model had been derived from telescopic observations. Vesta appears to be a major source for a significant group of basaltic achondrite meteorites, specifically the howardite, eucrite, and diogenite (HED) meteorites (McCord et al., 1970; Binzel and Xu, 1993; Marzari et al., 1996; Asphaug, 1997). As a result, the mineralogy and elemental composition of those meteorites strongly influence existing models of the interior of Vesta (Righter and Drake, 1997; Drake, 2001; Ghosh and McSween, 1998; McSween et al., 2011). Geochemically motivated models of Vesta suggest significant radial differentiation, including a low density crust, a higher density olivine mantle, and an iron core (Zuber et al., 2011; Russell et al., 2012).

The Dawn mission has also mapped surface variations in color and albedo of Vesta (Reddy et al., 2012), using the framing camera (Sierks et al., 2011; Le Corre et al., 2011), and variations in elemental composition (Prettyman et al., 2012), using the gamma ray and neutron detector (Prettyman et al., 2011). The extent to which these surface characteristics reflect deeper subsurface compositional variations can be tested by comparing them with the newly mapped gravity and topography.

An important feature of Vesta, which was not known prior to Dawn's arrival there, is a large family of linear structural features on the surface (Roatsch et al., 2012; Buczkowski et al., 2012). These appear to be related to the polar impacts which formed the basins Veneneia and Rheasilvia (Marchi et al., 2012; Schenk et al., 2012; Bowling et al., 2012, 2013; Jutzi et al., 2013). The longest of them is Divalia fossa, which is just south of the equator, 5 km deep, 10 km wide, and 450 km long. It maintains nearly constant distance from Rheasiliva. Saturnalia fossa is another long, linear trough, which is more nearly centered on Veneneia.

The fact that these two largest impact basins, Rheasilvia and Veneneia, are both located close to the south pole (Thomas et al., 1997; Marchi et al., 2012; Schenk et al., 2012), is at least suggestive of re-orientation of Vesta subsequent to the impacts (Kattoum and Dombard, 2009; Matsuyama and Nimmo, 2011).

Our analysis will include both spatial domain and spectral domain views of the gravity and topography of Vesta. In the spatial domain, we will see that the gravity and topography maps are very similar in form, and that the Bouguer anomaly is generally much smaller than the free-air anomaly. It will emerge that the very high level of correlation seen between gravity and topography suggests

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that lateral mass variations associated with surface topography is the dominant cause of the observed gravity, and that lateral density variations play only a minor role. The variance spectra of gravity and topography on Vesta are both very similar to those seen on other silicate bodies, including Moon, Mars, Venus, and Earth.

An issue which somewhat complicates the analysis is the relatively rapid rotation of Vesta. It is quite far from spherical, in shape, and is rotating rapidly enough that a fluid body with the same density would also be notably non-spherical. For bodies like Earth and Mars, where the rotational flattening is substantial, but much less than on Vesta, the primary influence is seen at harmonic degree 2. For Vesta, we compute and remove contributions to the shape and gravity field which would be appropriate for a fluid body. In this case, the corrections are non-negligible up to higher harmonics degrees.

Despite these similarities to the larger silicate bodies, Vesta has several significant differences. The gravity/topography admittance spectrum generally follows the trend for homogeneous density, but there is a notable dip in admittance at harmonic degrees 5–8. Also, the gravity and topography are both significantly non-isotropic, with larger variations in the north–south direction than in the east–west direction. We will argue that these two features may both be explained by large scale fracturing of the body, and displacements along those fractures, associated with the impacts which formed Veneneia and Rheasilvia.

In an early review of Dawn mission results for Vesta (Russell et al., 2012) it was noted that the topography and gravity data "are consistent with a core having an average radius of 107–113 km". As stated, the claim is misleading, since the data are also consistent with a larger core, or none at all. We will examine this point in more detail below, in the section dealing with the gravitational inverse problem.

2. Gravity and topography of Vesta

In this section, we begin our description of the gravity and topography of Vesta. The process of extracting a high fidelity gravity model for Vesta, from the range and range-rate data of the Dawn mission, is described by (Konopliv et al., 2014). The surface topography model (Jaumann et al., 2012; Raymond et al., 2011) has a much higher spatial resolution than the gravity model. We will represent both topography and gravity in terms of spherical harmonic series.

The topographic data described by Jaumann et al. (2012) has a gap in coverage poleward of 50 degrees north latitude. Additional data were collected after the cut-off time for that report. The topography harmonic model we use here was derived as part of the analysis of Konopliv et al. (2014)) and has essentially global coverage.

2.1. Spherical harmonic models

In particular, the surface topography, or radial distance from the center of mass to the free surface, at latitude θ and longitude ϕ, is represented by the series

$$s[\theta,\phi] = R\sum_{n=0}^{nMax}\sum_{m=0}^{n}\sum_{k=1}^{2} Y_{n,m,k}[\{\theta,\phi\}]\ H_{n,m,k} \tag{1}$$

where R is a reference radius, and the spherical harmonic functions are

$$Y_{n,m,1}[\{\theta,\phi\}] = \overline{P}_{n,m}[\lambda]\ \cos[m\ \phi] \tag{2}$$

$$Y_{n,m,2}[\{\theta,\phi\}] = \overline{P}_{n,m}[\lambda]\ \sin[m\ \phi] \tag{3}$$

where $\overline{P}_{n,m}[x]$ is an normalized associated Legendre function of degree n and order m,

$$\lambda = \sin[\theta] \tag{4}$$

and the corresponding dimensionless coefficients are $H_{n,m,k}$. We use spherical harmonics normalized such that

$$\int_0^{2\pi}\int_{-1}^{1}\left(Y_{n,m,k}[\{\lambda,\phi\}]\right)^2\ d\lambda\ d\phi = 4\pi \tag{5}$$

Similarly, the gravitational potential, at an external point with spherical coordinates (r,θ,ϕ), is represented by the series

$$\Phi[r,\theta,\phi] = \frac{G\ M}{r}\left(1+\sum_{n=2}^{nMax}\left(\frac{R}{r}\right)^n\sum_{m=0}^{n}\sum_{k=1}^{2}Y_{n,m,k}[\{\theta,\phi\}]\ G_{n,m,k}\right) \tag{6}$$

where dimensionless coefficients are $G_{n,m,k}$. The absence of coefficients of degree $n = 1$ is a consequence of using the center of mass as the origin of the coordinate system. The degree one topography coefficients thus represent an offset between the center of figure and center of mass. The gravitational potential scale factor

$$\mu = G\ M = (17.288245 \pm 0.000012)\ \mathrm{km}^3/\mathrm{s}^2 \tag{7}$$

is the product of Vesta's mass M and the gravitational constant G. Using the value (Mohr et al., 2012)

$$G = (6.67384 \pm 0.00080)\times 10^{-11}\ \mathrm{m}^3\ \mathrm{kg}^{-1}\ \mathrm{s}^{-2} \tag{8}$$

yields a mass estimate of

$$M = (2.59045 \pm 0.00031)\times 10^{20}\ \mathrm{kg} \tag{9}$$

with the error dominated by that of G.

The gradient of the potential gives the gravitational acceleration which would be experienced by a point mass at that location. The radial component of the acceleration is given simply by

$$g[r,\theta,\phi] = \frac{\partial\Phi}{\partial r} = \frac{GM}{r^2}\left(1+\sum_{n=2}^{nMax}\left(\frac{R}{r}\right)^n(n+1)\sum_{m=0}^{n}\sum_{k=1}^{2}Y_{n,m,k}[\{\theta,\phi\}]\ G_{n,m,k}\right) \tag{10}$$

and the gravity anomaly is just that value, minus the monopole contribution

$$\Delta g[r,\theta,\phi] = \frac{GM}{r^2}\sum_{n=2}^{nMax}\left(\frac{R}{r}\right)^n(n+1)\sum_{m=0}^{n}\sum_{k=1}^{2}Y_{n,m,k}[\{\theta,\phi\}]\ G_{n,m,k} \tag{11}$$

A more appropriate function, for a body as non-spherical as Vesta, might be the normal component of gravity (Heiskanen and Moritz, 1967), or projection of the gradient of the potential onto either the normal to the ellipsoidal surface or the normal to the equipotential surface. For Vesta, the ellipsoidal normal vector deviates from the radial direction by as much as 12°. For consideration of Vesta's gravitational field in terms of ellipsoidal harmonics, see Park et al. (2014). The conventional unit for gravity anomalies is the "gal", named in honor of Galileo Galilei, and equal to

$$gal = cm/s^2 \tag{12}$$

2.2. Potential from mass distribution

Recall that the gravitational potential due to a point mass M, at distance d, is just

$$\Phi = \frac{G\ M}{d} \tag{13}$$

If the source and receiver locations are given in spherical coordinates, so that $\mathcal{S} = \{r_s,\theta_s,\phi_s\}$ and $\mathcal{R} = \{r,\theta,\phi\}$, then the distance is

$$d[\mathcal{R},\mathcal{S}] = \sqrt{r^2 + r_s^2 - 2\ r\ r_s\cos[\gamma]} \tag{14}$$