

## Origin, Internal Structure and Evolution of 4 Vesta

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**Abstract** Asteroid 4 Vesta is the only preserved intact example of a large, differentiated protoplanet like those believed to be the building blocks of terrestrial planet accretion. Vesta accreted rapidly from the solar nebula in the inner asteroid belt and likely melted due to heat released due to the decay of  $^{26}\text{Al}$ . Analyses of meteorites from the howardite-eucrite-diogenite (HED) suite, which have been both spectroscopically and dynamically linked to Vesta, lead to a model of the asteroid with a basaltic crust that overlies a depleted peridotitic mantle and an iron core. Vesta's crust may become more mafic with depth and might have been intruded by plutons arising from mantle melting. Constraints on the asteroid's moments of inertia from the long-wavelength gravity field, pole position and rotation, informed by bulk composition estimates, allow tradeoffs between mantle density and core size; cores of up to half the planetary radius can be consistent with plausible mantle compositions. The asteroid's present surface is expected to consist of widespread volcanic terrain, modified extensively by impacts that exposed the underlying crust or possibly the mantle. Hemispheric heterogeneity has been observed by poorly resolved imaging of the surface that suggests the possibility of a physiographic dichotomy as occurs on other terrestrial planets. Vesta might have had an early magma ocean but details of the early thermal structure are far from clear owing to model uncertainties and paradoxical observations from the HEDs. Petrological analysis of the eucrites coupled with thermal evolution modeling recognizes two possible mechanisms of silicate-metal differentiation leading to the formation of the basaltic

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achondrites: equilibrium partial melting or crystallization of residual liquid from the cooling magma ocean. A firmer understanding of the plethora of complex physical and chemical processes that contribute to melting and crystallization will ultimately be required to distinguish among these possibilities. The most prominent physiographic feature on Vesta is the massive south polar basin, whose formation likely re-oriented the body axis of the asteroid's rotation. The large impact represents the likely major mechanism of ejection of fragments that became the HEDs. Observations from the Dawn mission hold the promise of revolutionizing our understanding of 4 Vesta, and by extension, the nature of collisional, melting and differentiation processes in the nascent solar system.

**Keywords** Vesta · Asteroid · Crust · Mantle · Core · Evolution · Impact

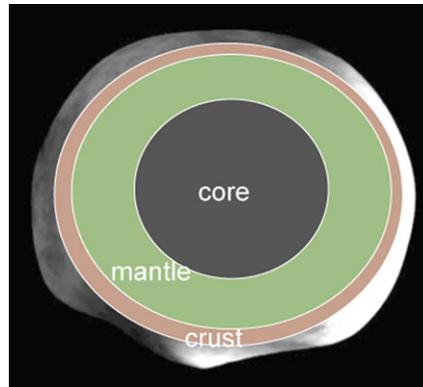
## 1 Large Asteroids as Planetary Embryos

The largest asteroids are central to understanding nascent planetary evolution, and among these 4 Vesta plays a unique role in the reconstruction of the physical and chemical processes that comprise collectively terrestrial planet accretion. Vesta is alone among the largest asteroids in having a basaltic crust (McCord et al. 1970) indicative of silicate volcanic and/or plutonic processes (Binzel et al. 2003). Observations of surface spectra (McCord et al. 1970; Binzel and Xu 1993) in concert with information on the body's size (Thomas et al. 1997b) and mass (Konopliv et al. 2011a) provide convincing evidence for a differentiated interior that includes an ultramafic mantle (Binzel et al. 1997; Gaffey 1997) possibly exposed in the cavity of a massive impact basin (Thomas et al. 1997b), and a likely iron-rich core (cf. Fig. 1). The correspondence of near-infrared spectra of Vesta's surface (McCord et al. 1970) with the composition and mineralogy of a suite of achondrites, the howardites-eucrites-diogenites (HEDs) (Takeda et al. 1983), together with strong evidence for the excavation and delivery of Vesta fragments to the inner solar system (Binzel and Xu 1993), argues that we have abundant samples of this asteroid in meteorite collections, which further underscores the value of this asteroid's detailed study.

Vesta is the type example of a planetary embryo—the sole surviving intact member of a presumed cohort of macro-scale ( $\sim 10^2$  km) bodies in the earliest solar system that assembled into terrestrial planets. Framing how Vesta can inform most effectively the complexity of planetary accretion requires insight into the time scales for accretion and differentiation, bulk composition, nature of chemical stratification and geological and geodynamical aspects of evolution.

In keeping with the theme of this collection of papers, here we review Vesta's current state of knowledge, focusing on current constraints on body's interior structure and composition. We begin with a general overview of Vesta's accretion as part of a family of protoplanets, most of which were subsequently assembled into the terrestrial planets. The timing of Vesta's accretion is critical to its thermal evolution fueled by decay of short-lived radionuclides, and the accreted materials controlled the body's bulk composition. We then review competing models for Vesta's internal structure; all the models agree that the bulk composition was substantially melted and fractionated into core, mantle, and crust during early differentiation. We then consider the properties of the asteroid's surface and explore how they might relate to its magmatic and impact histories. Finally, we posit questions that can advance understanding of Vesta's interior based on anticipated observations from the Dawn mission (Russell et al. 2007; Russell and Raymond 2011).

**Fig. 1** Schematic of Vesta's internal structure. Core size is approximately to scale with respect to base model in Table 2. Crustal thickness is not well constrained and likely exaggerated



## 2 Origin

### 2.1 Before Vesta's Accretion: The Protoplanetary Disk

As for other solar system objects, Vesta accreted from the protoplanetary disk (Wetherill 1989; Lissauer 1993) during the final stage of processing of the pre-solar molecular cloud (Lunine 1997). Astronomical observations of presumably similar disks around nearby young stellar objects (Beckwith et al. 1990; McCaughrean and O'Dell 1996) indicate that these disks span spatial scales comparable to and greater than our present planetary system and would have had at least a few percent of the sun's mass, plausibly considerably more (Chambers 2004). From observational sampling of planetary systems these disks are believed to exist from  $10^5$ – $10^7$  years (Strom et al. 1993; Lawson et al. 1996), which provides an indirect constraint on the timescale of planetary accumulation. Dissipation of the protoplanetary disk was likely due to a combination of ongoing mass infall into the accreting sun, photo-ionization by solar radiation, and winds emanating from the sun during its T Tauri stage before it settled into stable hydrogen burning on the main sequence (Boss 1998; Hartmann 2000).

Available evidence suggests that the protoplanetary disk had a composition like that of the sun (Cameron 1988), and if so then >99% of the disk would have been gaseous and consisted of (mainly) hydrogen along with helium and other volatiles such as carbon monoxide and water. On the basis of observations of young stars, gas in the disk probably dispersed within a few million years (Haisch et al. 2001). Prior to gas loss, <1% of the disk would have been composed of solid, more refractory grains, but this is the material that would eventually accrete into protoplanets like Vesta. The presence of dust within the disk was initially inferred from observations of excess emission of infrared radiation from young stars in comparison to temperatures of their photospheres (Dullemond et al. 2007). Compositional information about solar system objects, specifically a preponderance of refractory elements near the sun with increasing volatile contents with increasing distance from the sun, has been used to infer a radial temperature gradient at the time of solar system formation.

### 2.2 Protoplanet Accretion

The favored theory for the accretion of terrestrial planetary bodies features the growth of planetesimals, of which the largest asteroids like Vesta are preserved examples; the planetesimals subsequently aggregate into planets. The initial stage of planetesimal growth is

the most poorly understood phase of planet formation (Hartmann 1978; Weidenschilling and Cuzzi 1993) due to the difficulty of observing analogous accretion disks at relevant spatial scales, as well as the complexity of identifying and modeling the physical processes that contribute to grain growth (Lunine 1997). The basic idea is that infall and rotation of the turbulent, protosolar molecular cloud caused flattening to a disk (cf. Weidenschilling and Cuzzi 1993). Dust grains from the protoplanetary disk collide, stick together and form clumps that progressively grow in size and mass (Weidenschilling 1980). Sticking of initially micron-sized grains has been hypothesized to occur via a range of processes that includes electrostatic attraction (Marshall and Cuzzi 2001), aerodynamical sticking (Wurm et al. 2001), impact melting (Lewis 2004) and/or vacuum welding (Arrhenius and Asunmaa 1973). As material accumulated, more planetesimal surface area became available to add material so the process accelerated. There is much uncertainty in growth through centimeter and meter sizes because of lack of understanding of the relative importance of contributing processes that include collision and impact melting, charge exchange, gas drag and gravitational instability (Chambers 2004). Modeling growth to 1 to 10 km-sized bodies (Cuzzi et al. 1993; Weidenschilling et al. 1997) is also problematic (Johansen et al. 2007). But beyond that point gravity becomes important and runaway growth can take place (Wetherill 1994; Chambers and Wetherill 1998), though in the asteroid belt perturbations from Jupiter likely complicated the situation. In this phase, collisional velocity relative to escape velocity is the major factor that determined whether collisional interactions led to net accretion or disruption of planetesimals (Leinhardt et al. 2000). During this phase gravitational focusing caused the largest planetesimals to quickly outgrow the rest of the population (Kokubo and Ida 1998).

The mass of material in the present-day asteroid belt is relatively small, only about 0.05% the mass of Earth, but to form the largest asteroids as rapidly as believed requires the asteroid belt to have originally contained at least 100 times as much mass as it does today (Wetherill 1992). Mass loss in the asteroid belt has been thought to have been accomplished by a combination of resonance sweeping and gas drag (Chambers 2004). But more dramatic resonance evolution in the outer solar system (the so-called Nice model) may have provided a much more effective clearing mechanism at a later time (O'Brien et al. 2007). It is also possible that Vesta accreted inside the present main belt. It has been suggested (Bottke et al. 2006) that differentiated asteroids may have actually formed in the terrestrial planet region, and were later perturbed into orbits at greater distance from the sun.

Radiogenic isotope data from meteorites provide the best constraints on timescales of protoplanet accretion (Shukolyukov and Langmuir 2002; Halliday and Kleine 2006). The earliest formed material in the solar system, calcium-aluminum-rich inclusions (CAIs), are either high-temperature condensates or refractory evaporative residues mostly formed within a few  $\times 10^5$  years (Wadhwa and Russell 2000; Amelin et al. 2002) at 4.567 Ga, which is taken as the age of the solar system (Connelly et al. 2008). The age limits set by short-lived isotopic signatures in meteorites are all consistent with model predictions that it would take  $10^5$  to a few times  $10^6$  years to assemble km-sized to embryo-sized objects, respectively, in the asteroid belt (Lugmair and Shukolyukov 2001).

The modern view of planet formation is that asteroids of sufficient size generated heat due to the decay of short-lived isotopes differentiated early and rapidly. Rocky planets accumulated from at least some planetesimals that were differentiated (Alexander et al. 2001). The earlier the accretion, the greater the proportion of live  $^{26}\text{Al}$  and possibly other short-lived radionuclides, and thus the more likely the body experienced large-scale melting. With regard to Vesta, measurements of  $^{53}\text{Mn}$  indicate that the HED parent body underwent differentiation and core formation at  $4564.8 \pm 0.9$  Ma (Lugmair and Shukolyukov 1998), within

**Table 1** Vesta parameters

Parameter	Value	Reference
Mean heliocentric distance, AU	2.3619	JPL Small-body Data Browser (2003)
Orbital eccentricity	0.0886	JPL Small-body Data Browser (2003)
Orbital period, yr	3.63	Millis and Elliot (1979)
Rotational period, h	5.342	Harris et al. (2006)
$GM$ , $\text{km}^3 \text{s}^{-2}$	$17.66 \pm 0.2$	Konopliv et al. (2011b)
Mass, $10^{-12} M_{\text{Sun}}$	$133.1 \pm 1.5$	Konopliv et al. (2011b)
Mean radius	$258 \pm 5$	Thomas et al. (1997b)
Axes of shape, km	$280 \pm 5$ $\times 272 \pm 5$ $\times 227 \pm 5$	Thomas et al. (1997b)
Volume, $10^7 \text{ km}^3$	$7.19 \pm 0.87$	Thomas et al. (1997b)
Mean density, $\text{kg m}^{-3}$	3760	Konopliv et al. (2011b)
$g$ , $\text{m s}^{-2}$	0.32	
Spectral type	V	(Zellner et al. 1985)

0 to 6 Ma of CAI formation (Bouvier and Wadhwa 2010). Hf-W dating of iron meteorites, presumably core material from differentiated asteroids, also points to rapid accretion and differentiation of their parent bodies (<5 to 15 Ma after CAIs) (Halliday and Lee 1999). McSween et al. (2011) review the constraints on time scales of events in Vesta's accretion and differentiation in greater detail.

### 3 Internal Structure

#### 3.1 Mass, Shape/Volume and Bulk Density

Summaries of the current state of knowledge of Vesta's mass (Konopliv et al. 2011b) and shape (Raymond et al. 2011) are discussed in detail elsewhere in this volume. Current best estimates are summarized in Table 1. Vesta's mass has been determined from perturbations of Vesta by other asteroids (Michalak 2000; Baer and Chesley 2008; Kuzmanoski et al. 2010), by the perturbation of Mars' orbit by Vesta (Standish 2001; Pitjeva 2005; Konopliv et al. 2006, 2011a; Fienga et al. 2009), and by perturbation of the orbit of asteroid 433 Eros by Vesta using the range data from the Near Earth Asteroid Rendezvous (NEAR) spacecraft (Konopliv et al. 2002, 2011a, seasonal). Vesta is the second most massive asteroid, though its mass is only 28% of Ceres (Pitjeva 2005); currently Vesta's mass has an uncertainty of  $\sim 2\%$ .

The best model of the shape of Vesta was derived from Hubble Space Telescope (HST) images (Thomas et al. 1997a) and indicates that the asteroid can be fit by a tri-axial ellipsoid (Table 1). This shape model, which has a volume uncertainty of 12%, is in reasonable agreement with previous estimates (McCarthy et al. 1994; Drummond et al. 1998). Knowledge of global shape is the limiting factor in the estimation of the asteroid's bulk density, the current best estimate of which is  $3760 \text{ kg m}^{-3}$ , consistent with the notion of a differentiated silicate-metal interior. In comparison, grain densities contained in chondrites fall in the range  $3340 \pm 0.02$  to  $3690 \pm 0.08$  (Consolmagno and Britt 1998).

### 3.2 Insights from Bulk Composition Estimates

The HED meteorites, a suite that includes howardites (brecciated basalts and pyroxenites), eucrites (basalts and gabbros) and diogenites (pyroxenites and harzburgites) are believed to be samples of Vesta. This linkage is based on the correspondence of surface spectra (McCord et al. 1970; Burbine et al. 2001; Pieters et al. 2005) to the compositions of the HEDs (Drake 2001; McSween et al. 2011). A mechanism of transport to Earth emerged from the discovery of “Vestoids” (Binzel and Xu 1993), an abundance of 5–10-km asteroids spectrally similar to Vesta, emanating from Vesta’s orbit traced to the 3:1 resonance point where at least some were presumably perturbed into Earth-crossing orbits. Follow-up HST images revealing the massive south pole basin on Vesta (Thomas et al. 1997b) represented the “smoking gun” for the likely excavation site for the Vestoids and the HEDs. The composition of the HEDs have been used to estimate the asteroid’s bulk composition and core mass (McSween et al. 2011). Some additional information on bulk composition has been gleaned from models based on chondrites (Alexander et al. 2001; Scott 2007).

Melting experiments (Stolper 1975, 1977) formed the basis of the earliest suggestion that eucrites formed by melting of primitive material. A subsequent study of rare earth elements in eucrites (Consolmagno and Drake 1977) established Vesta’s bulk composition to be consistent with chondrites, but could not constrain the metal content. The composition of the silicate portion (mantle + crust) of Vesta was estimated (Jones 1984) based on mineral-melt partitioning of Mg, Si, and Sc. This bulk silicate composition was equivalent to 75% olivine plus 25% eucrite. The normative mineralogy of that bulk composition is ~75% olivine, 12% orthopyroxene, 9% plagioclase, 4% clinopyroxene, 0.3% ilmenite, and 0.3% chromite. The bulk density of that mineral assemblage is ~3630 kg m<sup>-3</sup>. Other bulk compositions for Vesta, formulated by constraining mixtures of chondrite types to have the HED oxygen isotopic composition and Fe-Mn-Mg abundances, corresponded to 70% ordinary chondrite and 30% carbonaceous chondrite by weight (Boesenberg and Delaney 1997; Righter and Drake 1997). A different approach (Dreibus and Wanke 1980) varied the mixing proportions of eucrite, diogenite, and olivine to achieve chondritic ratios of Al/Sc and Mg/Si. The normative mineralogy of their composition is ~49% olivine, 38% orthopyroxene, 10% plagioclase, 4% clinopyroxene, and 0.3% ilmenite, giving a lower bulk mineral density of ~3420 kg m<sup>-3</sup>.

An early estimate of the mass of Vesta’s core relative to the asteroid mass ( $M_c/M$ ) was 40–50% (Newsom 1985), based on modeling the abundances of siderophile elements (Ni, Co, Mo, W) in eucrites using experimentally-determined partition coefficients. However, later estimates of the core mass are substantially lower. Parent bodies having seven different chondritic compositions were modeled (Righter and Drake 1997) using newer siderophile element partition coefficients, and resulting core mass estimates ranged from 5–25%. Another study calculated two models that differed in terms of density of the bulk silicate fraction of Vesta (Ruzicka et al. 1997). One model utilized the bulk silicate composition of Jones (1984), adjusted for an appropriate degree of partial melting of the mantle. The other model was based on the bulk silicate composition of Dreibus and Wanke (1980). By comparing the bulk silicate densities of these models with the measured bulk density for Vesta (Ruzicka et al. 1997), core masses of 4 and 6% with an upper limit of <30% were determined. The total bulk density for Vesta used for these calculations was ~3540 kg m<sup>-3</sup>, lower than the ~3760 kg m<sup>-3</sup> calculated from the most recent determination of Vesta’s mass (Konopliv et al. 2006) and HST diameter measurements (Thomas et al. 1997a). The higher measured bulk density suggests that the core may be larger than these minimum estimates.

The crust of Vesta consists of some mixture of basalts (eucrites) and plutonic rocks (cumulate eucrites and diogenites). Warren et al. (2009) estimated the mixing ratio of basaltic eucrite to diogenite in howardite regolith breccias to be constant at 2:1. If the regolith mixing ratio applies to the bulk crust, its normative mineralogy would be ~60% orthopyroxene, 25% plagioclase, 10% clinopyroxene, 2% olivine, with 1% chromite and ilmenite. Assuming minimal porosity, this mineral assemblage corresponds to a crustal density of  $\sim 3170 \text{ kg m}^{-3}$ . However, it was suggested (Warren et al. 2009) that the 2:1 ratio might be an upper limit because of impact sampling bias against deeper crustal materials (diogenite), and that a 1:1 ratio might be more accurate. In that case, the crustal density would be higher.

### 3.3 Crustal Structure

In a layered crust model of Vesta (Takeda 1997), the crustal column consists of a megaregolith that is the source region of the howardites and other breccias (polymict eucrites), underlain by basaltic lava flows that are the source of unbrecciated basaltic eucrites. At greater depths are plutons composed of cumulate eucrites and unbrecciated diogenites.

The eucrites and howardites have igneous textures that indicate melting and crystallization in a body with a substantial gravity field, consistent with the expectation for Vesta (see Table 1). The compositions of these two meteorite classes have been interpreted to indicate that Vesta's surface consists of a mixture of pyroxene and plagioclase, consistent with the idea of Vesta as a differentiated asteroid with a basaltic crust. Rotational reflectance spectra indicate that the crust displays spatial heterogeneity (Gaffey 1997).

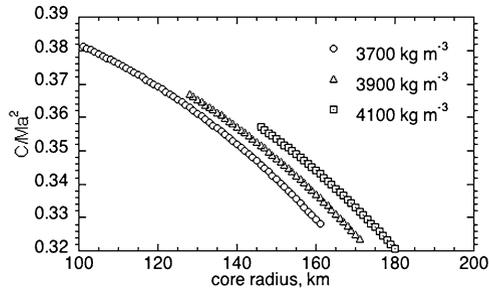
The eucrites display both cumulate and non-cumulate textures. Some non-cumulates are unequilibrated and thus cooled rapidly, and so probably formed as basaltic lava flows at Vesta's surface (Keil 2002), but most basaltic eucrites have been thermally metamorphosed. The cumulate eucrites are coarse-grained, mostly unbrecciated, and metamorphosed (Keil 2002). Cooling rates have been estimated for a range of these rocks and yield values of a couple of tenths to a few hundreds of degrees per ka (Miyamoto and Takeda 1994; Miyamoto et al. 2001). Depending on assumptions of thermal diffusivity, burial depths of as much as 100 km are possible, but such depths seem excessive. Most published estimates are shallower, generally 20–40 km (e.g., Ruzicka et al. 1997), and may place limits on the thickness of the basaltic crust. Hf–W ages for eucrite metals postdate CAI formation by about 20 Ma and may reflect impact-triggered thermal metamorphism in the crust (Kleine et al. 2009).

The diogenites are coarse-grained cumulates that formed in fractionally-crystallized magmas (Bowman et al. 1997); the existence of olivine-bearing diogenites (Beck and McSween 2010) indicate that these magmas did not crystallize orthopyroxene alone. The diogenites constitute the deepest component of the layered crust model (Takeda 1997). However, trace element abundances in diogenites suggest that they formed in separate plutons, rather than as a deep crustal layer having a common magmatic origin (Mittlefehldt 1994; Barrat et al. 2008, 2010). Oddly, cooling rates are more rapid than for the presumed more shallowly situated cumulate and non-cumulate eucrites. The diogenite cooling rates have been suggested to reflect the rate of cooling of impact-exhumed fragments (Zema et al. 1997). Recent major and trace element comparisons with Mg isotopes indicate that the diogenites formed prior to basaltic eucrites, with the full period of magmatic differentiation responsible for the diogenite suite being perhaps as short as 0.2 Ma (Schiller et al. 2010).

### 3.4 Moments of Inertia and Interior Structure

Models of the interior structure vary within the uncertainties of the bulk composition from meteorite studies as discussed above. Additional information on the radial distribution of

**Fig. 2** Range of plausible bulk densities for ranges of polar moment of inertia and core density. Calculation assumes a model of Vesta with a mantle density of  $2700 \text{ kg m}^{-3}$  to  $3500 \text{ kg m}^{-3}$  and a core density of  $7000 \text{ kg m}^{-3}$



internal mass can come from the moments of inertia. Of particular interest is the polar moment, which can be related to the density of the interior. To first order we can consider a simple model of an ellipsoidal Vesta with shape axes  $(a \times b \times c, a = b)$ . The model Vesta consists of a core and mantle, with the mantle an ellipsoid of revolution and the core as a sphere. The polar moment of inertia is

$$I_{zz} = \frac{2}{5} \left( \rho_m \frac{4}{3} \pi a^2 c \right) a^2 + \frac{2}{5} \left( (\rho_c - \rho_m) \frac{4}{3} \pi r_c^3 \right) a^2, \tag{1}$$

where the first parenthesis represents the mass of the ellipsoidal mantle and the second parenthesis is the mass of the spherical core with radius  $r_c$ . The normalized polar moment of inertia ( $\bar{I}_{zz}$ ) can be expressed

$$\bar{I}_{zz} = I_{zz} / \left( \bar{\rho} \frac{4}{3} \pi a^2 c \right) a^2, \tag{2}$$

where  $\bar{\rho}$  is the mean density. The normalized polar moment can then be written

$$\bar{I}_{zz} = \frac{2}{5} \frac{\rho_m}{\bar{\rho}} + \frac{2}{5} \frac{(\rho_c - \rho_m)}{\bar{\rho}} \frac{r_c^5}{a^4 c}. \tag{3}$$

The constraint on density is (i.e., mass of ellipsoidal mantle plus spherical core)

$$\rho_m \frac{4}{3} \pi a^2 c + (\rho_c - \rho_m) \frac{4}{3} \pi r_c^3 = \bar{\rho} \frac{4}{3} \pi a^2 c \tag{4}$$

or

$$\rho_m = \frac{\bar{\rho} a^2 c - \rho_c r_c^3}{a^2 c - r_c^3}. \tag{5}$$

Figure 2 plots the relationship of polar moment of inertia factor  $C/Ma^2$ , where  $M$  is planetary mass, and core size for three mantle densities that span the range allowable by HED compositions. A “base” model of the interior, also consistent with HED compositions (Ruzicka et al. 1997), is given in Table 2. This model, used later herein, favors the lower range of mantle density.

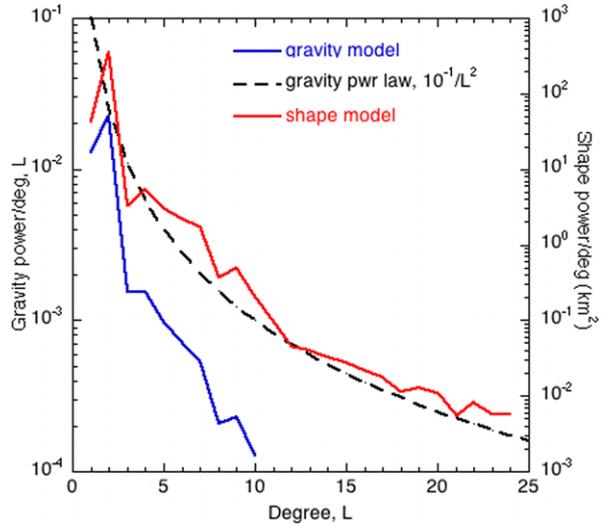
Power spectra of Vesta’s topographic shape (red) and gravitational field (blue), assuming the base model of internal structure, are given in Fig. 3. Note that the power of shape decreases with degree more rapidly than for gravity, which is dominated by the internal mass. These examples are intended to be illustrative and convey the extent of present knowledge of Vesta’s internal structure based on meteorite geochemistry, remote surface spectral information, and geophysical measurements.

**Table 2** Base model of internal structure

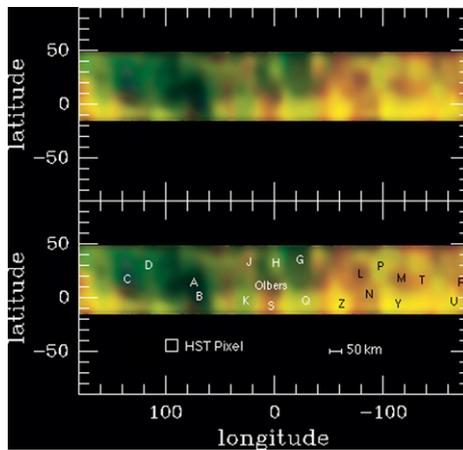
	Thickness (km)	Density (kg m <sup>-3</sup> )	Mass (kg/10 <sup>19</sup> )
Upper crust	Shape-214 <sup>a</sup>	2800	8.0
Lower crust	14	3200	2.6
Mantle	80	3976	10.4
Core	120	7870	5.7

<sup>a</sup>shape-214 is a spherical harmonic expansion of the Thomas et al. (1997b) shape model

**Fig. 3** Power spectra of shape (Thomas et al. 1997a) and gravity assuming the internal structure in Table 2. The similarity of the curves is due to the fact that gravity is derived from shape. A gravitational power of  $10^{-1}/L^2$ , where  $L$  is spherical harmonic degree is shown for comparison



**Fig. 4** (Top) False-color map of Vesta constructed from HST images, reproduced from Binzel et al. (1997). (Bottom) The same map with select regions labeled in order of increasing depth within the 1- $\mu$ m spectral filter, most likely correlated with increasing concentrations of pyroxene and/or olivine, in the absence of weathering effects



### 3.5 Physiographic Constraints on Vesta’s Interior and Tectonics

Disk-resolved imaging of Vesta’s surface, albeit at poor spatial resolution, has been accomplished by HST (Binzel et al. 1997; Thomas et al. 1997b) and ground-based imaging from Keck (Zellner et al. 2005). As shown in Fig. 4, Vesta’s eastern and western hemispheres are distinctive (Binzel et al. 1997; Gaffey 1997). The eastern hemisphere is brighter and marked

by large features, presumably craters, perhaps analogous morphologically to the lunar highlands or cratered terrains on Mercury. The western hemisphere is marked by darker expansive areas that could conceivably be similar to mare basalts. In this regard Vesta is analogous to the Moon, Mars and Pangean Earth in having developed dichotomous hemispheres.

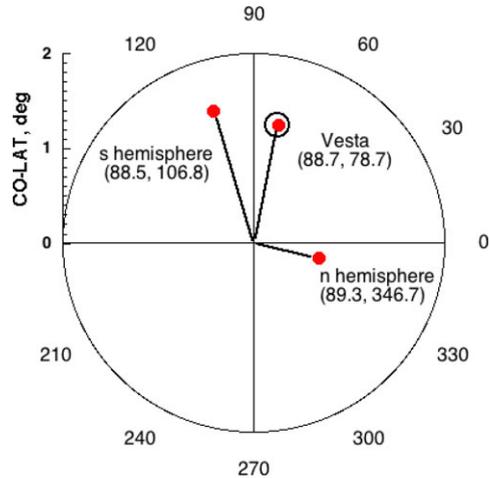
The most prominent surface feature is Vesta's massive, southern hemisphere basin (Thomas et al. 1997b), which has a diameter of  $\sim 460$  km, one and a half times the asteroid's radius. Although some workers have speculated that this basin may have excavated mantle material, the most ultramafic HED samples (diogenites, especially those that bear olivine) have trace element compositions that suggest they formed in crustal plutons (Barrat et al. 2008). Other presumed craters with diameters of about 150 km have also been resolved, as has a large dark patch named Olbers in honor of Vesta's discoverer.

For a geopotential that assumes a homogeneous interior, Vesta's large basin has a depth of about 13 km and has a massive central peak that rises as high as the basin rim (Thomas et al. 1997b). Scaling to planetary gravity (Holsapple 1993), the expectation is that a basin that size would be of order a factor of two deeper for its size. While experiments (Fujiwara et al. 1993) predict somewhat shallower (by  $\sim 20\%$ ) depths for basins that are large compared to the planetary radius such that planetary curvature is important, this does not explain the geometry of Vesta's basin. Applying a geopotential assuming a differentiated interior alternatively yields a depth (20–25 km) and a central peak 5 km below the rim that is more in line with expectations from scaling (Kattoum and Dombard 2009). In this study the authors considered a range of internal structures consisting of a crust, mantle and core (2900, 3300,  $7500 \text{ kg m}^{-3}$ ), with the nominal model containing a core with dimensions  $140 \text{ km} \times 100 \text{ km}$ .

The location of Vesta's large basin on the south pole suggests that the impact caused the asteroid to re-orient (Thomas et al. 1997b). Vesta does not have a hydrostatic shape and the basin has caused its flattening to be greater than that which would be consistent with its current rotation period. While we do not know Vesta's orientation at the time of the impact, we can make a simple estimation of how much the basin has changed the principal moment of inertia by seeing how much the pole would shift from the current position if the shape of the northern hemisphere is mirrored to the south, assuming the internal structure in Table 2. The results of the calculation (Fig. 5) indicate that the pole would shift about a degree and a half (from the pole to  $88.7$  latitude as shown in the figure), which indicates that the south polar basin is largely compensated. Dawn's measurement of the gravitational flattening of Vesta to about 5% will provide more quantitative information on the basin's compensation state.

Given the current spatial resolution of remote imaging of Vesta's surface, evidence for volcanic or tectonic structures has not yet been identified. However, the igneous nature of HEDs and the spectral observations consistent with a basaltic surface suggest collectively that volcanic flows may be preserved, and complex subsurface structure due to emplaced plutons is likely. Alternatively, the fact that most HEDs are breccias may suggest that flows have largely been obliterated by impacts. Tectonic structures could plausibly have formed in response to a myriad of processes that include global cooling, internal dynamics, disruption associated with the large impact, subsequent planetary re-orientation due to that impact, and or stresses associated with lesser impacts. Ejecta from the south polar basin is expected to have been considerable in volume and its distribution over much of Vesta's surface has been modeled (Jutzi and Asphaug 2011); it is proposed to have formed multiply-folded and abruptly-terminating sequences due to its extended emplacement as the asteroid rotated.

**Fig. 5** North pole-centered view illustrating the shift of Vesta's principal moment of inertia axis from present position for the internal structure in Table 2 and the northern hemisphere shape and structure mirrored to the southern hemisphere. The calculation shows to first order the effect of the south polar basin on the principal inertia axis

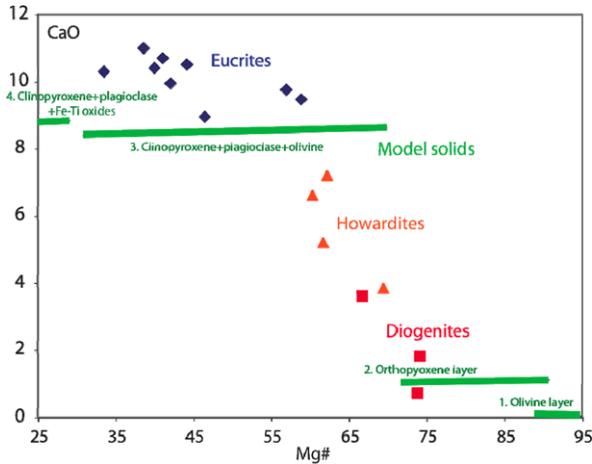


### 3.6 Thermal Evolution

The coincidence of near-infrared spectra (McCord et al. 1970) with the composition of eucrites (Mittlefehldt et al. 1998) supports the idea that Vesta has melted extensively if not globally. Homogeneity in HED oxygen isotopic composition (Greenwood et al. 2005) is also consistent with large-scale melting, although a few eucrites have aberrant compositions. Experiments of silicate-metal partitioning (Righter and Drake 1996) support the idea that Vesta had a magma ocean. However, it is not possible to reconcile all the geochemical characteristics of the diogenites with a magma ocean model. Although diogenites have been thermally equilibrated, some trace elements retain their original igneous traits. These compositions might be explained by complex, polybaric crystallization models (e.g. Righter and Drake 1997), but serial magmatic activity, perhaps following the solidification of a magma ocean, seems more likely (McSween et al. 2011). A magma ocean model is often preferred for Vesta, based on the difficulty of accounting for multiple heating events. However, thermal models (e.g. Ghosh and McSween 1998) indicate internal heating over perhaps 100 my, as do the range of radiometric ages for HED crystallization.

The melting of Vesta and other meteorite parent bodies has been attributed to the presence of short-lived radioactive  $^{26}\text{Al}$  produced by a supernova near the time of solar system formation, and the importance of this source has been supported by isotopic evidence for its decay product and by thermal models (Ghosh and McSween 1998; McSween et al. 2003). The decay of  $^{60}\text{Fe}$  has also been suggested as a heat source, but its importance has not yet been borne out by thermal models of Vesta (Ghosh and McSween 1998), even when rapid core segregation takes place.

Two scenarios have been proposed for the differentiation of Vesta, or more generally for silicate-metal partitioning in basaltic achondrites. The first involves equilibrium partial melting of chondrites (Consolmagno and Drake 1977; Stolper 1977), variations of which indicate that the eucrites can be explained by rather considerable ( $\sim 10\%$  to  $20\%$ ) melting. This scenario requires multiple heating events, which are arguably difficult to justify. The other scenario involves formation of the basaltic achondrites as residual liquids remaining at the end of cooling of the magma ocean (Ikeda and Takeda 1985; Warren 1985; Longhi and Pan 1988). While the residual melt scenario is consistent with isotopic evidence indicating that core formation in Vesta preceded the formation of the eucrites (Hewins and



**Fig. 6** The simplest magma ocean model for Vesta, with no conductive lid and with perfect crystal settling, predicts mantle cumulates with compositions shown in *green* and compared with a suite of HED meteorites. The basic relationship of diogenites as cumulates, howardites as mixtures, and eucrites as melts, is reproduced here. The howardites are mixtures of the eucrites and diogenites and thus do not provide independent information, but serve to place the other observations in context. *Numbers* indicate the order of fractionating minerals from the solidifying magma ocean

Newsom 1988), the most recent thermal models have difficulty in cooling Vesta quickly enough to explain the expected early formation time of these meteorites (Gupta and Sahijpal 2010). Fractional crystallization models (e.g. Ruzicka et al. 1997) do not adequately account for trace element abundance; trace element compositions have been satisfied, however, assuming equilibrium crystallization.

While the thermal models of Vesta developed thus far are illustrative, there are considerable uncertainties due to the complexity of the physics and chemistry of accretion and differentiation. Since basaltic achondrites formed subsequent to CAIs, some short-lived radiogenic isotopes already decayed, leading to uncertainty in the amount of heat available post-accretion (Federico et al. 2011). Models do not consider core formation over a finite period of time, leading to uncertainties in depth distribution of heating.

The processes of initial solidification of a magma ocean on a small body like Vesta are poorly understood. While an anorthosite flotation crust is the hallmark of a magma ocean on the Moon, Vesta may have no such single unmistakable mineralogical marker; Vesta's small gravity field was likely insufficient to drive complete flotation and separation of minerals and melt. Similarly, minerals may not have settled completely in the magma ocean's depths.

Here we use the bulk composition of Righter and Drake (1997) and fractionally solidify the Vestan magma ocean over its pressure range using mineral assemblages based on experiments (Bartels and Grove 1991). A simple fractional solidification model of a Vestan magma ocean (Elkins-Tanton et al. 2008), however, can broadly reproduce the compositions of the Vestan meteorites. The wide range of Mg#s (where Mg# = molar Mg/(Mg+Fe)) is a characteristic of fractional solidification, and variation in other major elements (in Fig. 6 we show CaO) indicates varying the assemblage of solidifying minerals. Processes on Vesta, however, may include secondary melting and mixing events.

Rates of melt generation and the dynamics of melt migration and convection also need to be treated explicitly. Internal melting driven by radiogenic heating can create either a partial or a complete magma ocean. Melt from this initial differentiation event may remain in the

interior and solidify or it may erupt onto the Vestan surface. Depending on the manner in which aluminum (and hence  $^{26}\text{Al}$ ) was partitioned, the removal of melt could have resulted in greater melting of residuum; if this occurred then melt migration could have accelerated core-mantle separation (McSween et al. 2003). An insulating crust would have had a significant effect on surface heat loss and would have increased the degree of melting and slow cooling (Gupta and Sahijpal 2010), but is difficult to model due to disruption by ongoing impacts subsequent to accretion, as well as uncertainty in its thickness in space and time. The additional effects of non-radiogenic heat sources, such as collisional heating or solar nebular electromagnetic heating, are very difficult to estimate (McSween et al. 2003).

Clearly more work is needed on modeling Vestan solidification and attempting to match with observations. The fluid dynamics of a planetesimal magma ocean are poorly understood; the occurrence of fractional vs. equilibrium crystallization will depend upon solid fraction, grain size distribution, and heat flux. In turn these depend upon the existence of a conductive lid and the temperature of the magma ocean. To produce more complete models of solidification the physics and chemistry need to be combined and the model results compared to major and trace element compositions of HED meteorites.

#### 4 Looking Forward to Dawn

The Dawn mission (Russell et al. 2007; Russell and Raymond 2011) promises observations that will do much to advance our understanding of Vesta in the context of the accretion and early evolution of terrestrial planets. Information from the gravity (Konopliv et al. 2011b) and topography (Raymond et al. 2011) investigations will provide important information on the internal structure, and thereby the extent and nature of differentiation. The gamma-ray and neutron detectors (GRaND) (Prettyman et al. 2011) will yield elemental abundances that, combined with spectral information from the Visual and InfraRed (VIR) (De Sanctis et al. 2011) spectrometer, will improve considerably constraints on the bulk composition that bear on thermal history, and the nature of shallow compositional layering. The Framing Camera (FC) (Sierks et al. 2011) will map surface morphology at a level that will allow geology to be linked to composition and internal evolution. Using these instruments, the discovery of unmelted (chondritic) materials on Vesta could address the question of partial versus wholesale melting.

With careful attention to topographic errors, which increase over increasing length scales, stereo topography and gravity from radio tracking (Konopliv et al. 2011b) will be combined to study the structure of the lithosphere, as well as the tradeoffs between the properties, compositions and dimensions of internal layers. The determination of Vesta's low degree gravity, spin pole and rotation rate from perturbations of Dawn's orbit measured from radio tracking, will collectively provide constraints on the asteroid's radial density structure, particularly core size. These constraints will be improved by factoring in understanding of the asteroid's bulk composition from HED meteorite studies and orbital spectroscopic information.

Analysis efforts will include distinguishing between scenarios for Vesta's differentiation, by understanding if or how its magma ocean formed and evolved, and investigating whether its magmatic history was dominated by a single, presumably massive, early melting event, or whether melting occurred in temporal and spatial pulses. We also eagerly anticipate insight into the compensation state and thermal structure of Vesta at the time of its major impact structure, the internal and external dynamical consequences of this event, and its implications for asteroid collisional histories. We hope and expect to learn the reason for

the hemispheric-scale heterogeneity of Vesta's surface, and what that could imply for its volcanic and/or impact history.

In the best of scenarios, observations will enable informed contemplation of even more difficult questions. Arguably the most fascinating question is "Why did only one Vesta survive to the present day?" How many differentiated parent bodies formed in the nascent solar system? If there were many, then were the preponderance gravitationally perturbed out of the asteroid belt (Scott et al. 2009)? Is Vesta really unique, or did its survival somehow defy probability?

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