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Dawn at Vesta: Testing the Protoplanetary Paradigm

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The Dawn spacecraft targeted 4 Vesta, believed to be a remnant intact protoplanet from the earliest epoch of solar system formation, based on analyses of howardite-eucrite-diogenite (HED) meteorites that indicate a differentiated parent body. Dawn observations reveal a giant basin at Vesta's south pole, whose excavation was sufficient to produce Vesta-family asteroids (Vestoids) and HED meteorites. The spatially resolved mineralogy of the surface reflects the composition of the HED meteorites, confirming the formation of Vesta's crust by melting of a chondritic parent body. Vesta's mass, volume, and gravitational field are consistent with a core having an average radius of 107 to 113 kilometers, indicating sufficient internal melting to segregate iron. Dawn's results confirm predictions that Vesta differentiated and support its identification as the parent body of the HEDs.

Meteoritic evidence indicates that Vesta probably formed within 2 million years of the first condensation of solids within the nebula of gas and dust that became our solar system (*1*). Short-lived radioactive nuclides, ^{26}Al and ^{60}Fe, were present in these first few million years (*2*), trapping heat inside objects accreting at that time. Bodies that formed very early and incorporated the live radioactive material should have melted and differentiated (*3*), whereas bodies of a slightly younger age may not have. These early-forming objects, both differentiated and undifferentiated, are considered to be protoplanets and constitute the material that coalesced to form the terrestrial planets. Determining whether Vesta was a surviving protoplanet became the objective of Dawn, NASA's ninth Discovery mission, designed to orbit successively the two most massive survivors from the earliest days of the solar system, 4 Vesta and 1 Ceres. On 27 September 2007, Dawn began its 4-year trip to Vesta. After a Mars gravity assist in February 2009, Dawn reached Vesta on 16 July 2011 and slipped into orbit with no critical injection burn.

Vesta is substantially larger than anybody encountered by previous reconnaissance missions within the main asteroid belt (Fig. 1), dwarfed only by its sibling Ceres. It appears to be an intact original protoplanet that has survived the collisional environment of the asteroid belt since its formation over 4.56 billion years ago. Vesta has been identified as the source of a very common class of meteorites, the howardite-eucrite-diogenites (*5*), which make up ~6% of the meteorites seen to fall on Earth. These meteorites appear to have been liberated from the crust and possibly the mantle of a small differentiated body. Unlike the explorations of the Moon, Mercury, Mars, and Venus, which were undertaken initially without prior knowledge of the target's composition, our exploration of Vesta begins with a rich petrologic and geochemical understanding. Dawn will be providing the geological context for this insight.

Dawn arrived in vestan southern summer, allowing a complete survey of the south polar region. Rheasilvia, a giant impact basin (*6*), dominates this region. Its large central peak is higher than Mauna Kea on Hawaii (with respect to the underlying ocean floor) and rivals the height of Olympus Mons on Mars (Fig. 2). This impact alone could have liberated most of the material that composes the Vestoids, which display orbits and reflectance spectra similar to those of Vesta (*7*, *8*), possibly as recently as 1 billion years ago (*9*). The giant Rheasilvia impact has resulted in a strong dichotomy between the northern and southern hemispheres, reflected in surface albedo and crater densities, but did not erase evidence of an older, underlying large impact basin, possibly providing an earlier additional source of HEDs.

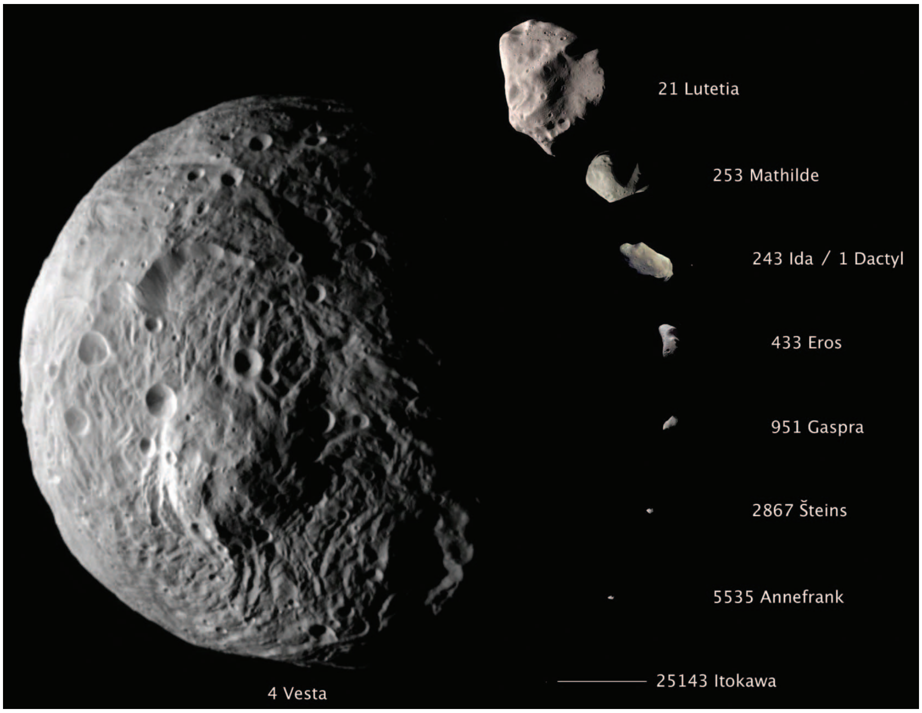

Fig. 1. Collage of Vesta in comparison with other asteroids visited to date for which good images exist. This south polar view of Vesta shows the south pole mountain and the Rheasilvia impact basin surrounding this central peak.

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Dawn's orbital mission provides the surface coverage, observation time, and spatial resolution necessary to comprehensively characterize Vesta's complex structure and composition. Spectral mapping reveals a diverse surface consistent with the mineralogy of the HED meteorites (*10*). Tracking and imaging allowed improvements in geophysical parameters relevant to understanding Vesta's internal structure and dynamics (Table 1). The average density, a key parameter in deducing its interior structure, is determined from the volume of our image-derived shape model (*11*); and the mass is determined by means of radiometric tracking (*12*). Before Dawn's arrival, the best estimates of Vesta's mass depended on the asteroid's perturbation of Mars, whose position can be determined to within about 5 m from landers and orbiters. The perturbation of the Dawn spacecraft by Vesta's gravitational field (*12*) yields a mass within the bounds of error of estimates from the Mars data (*13*) but with a significantly reduced uncertainty (Table 1).

Extensive imagery and tracking data from orbit enable the development of a high-accuracy control point network to determine the spin axis orientation (*14*), significantly different than that derived from Hubble Space Telescope (HST) observations (Table 1). The spin period has also been refined. The north pole was dark upon Dawn's arrival and will remain so until about 20 August 2012; the unmeasured shape of the northern polar region results in a small uncertainty in the current volume estimate. The shape model was also used to calculate a best-fit ellipsoid (Table 1). The new volume estimate, using the previous HST shape model (*15*) to fill in the unmapped northern polar region, is 74.970 × 10^6 km^3, yielding an average density of 3456 kg m^{-3}. This value is at the lower end of bulk densities previously derived, which ranged from 3500 to 3900 kg m^{-3} and were uncertain within a range of 3100 to 4700 kg m^{-3} (*15*). It is comparable to bulk silicate compositions having densities of 3320 to 3630 kg m^{-3} predicted by HED analyses (*16*) that assume negligible porosity. Although bulk density is formally accurate to better than 1 part in 10^3, a conservative estimate of uncertainty is ±1% (*17*); the final answer depends on the shape determined after the complete surface has been mapped.

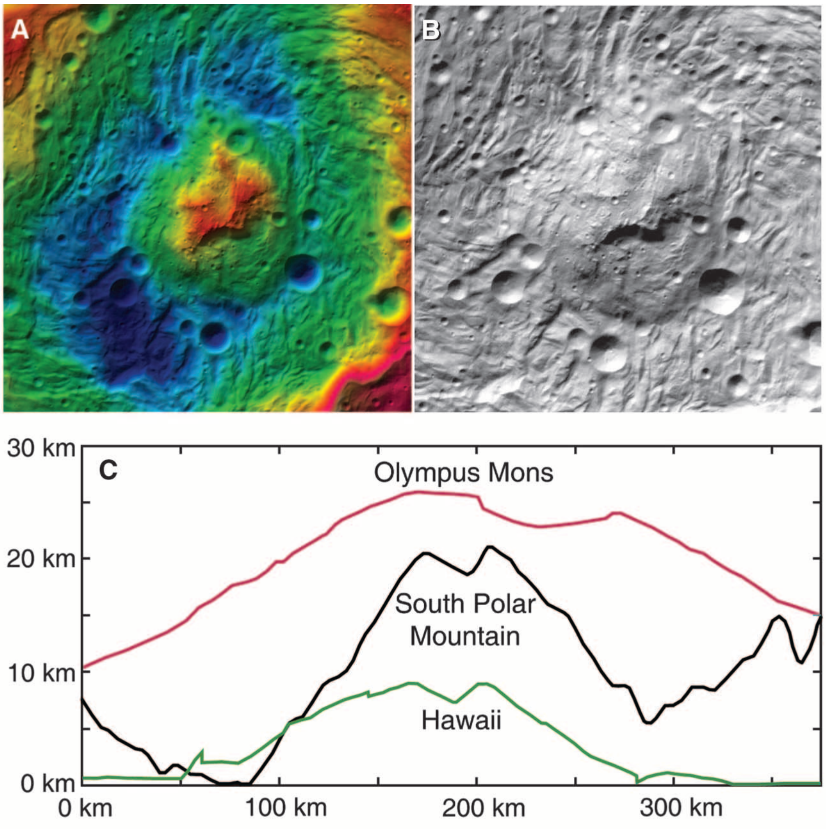

Fig. 2. Cross sections of the central peak of the Rheasilvia impact basin, shown in color-contoured topography (**A**) and as an orthorectified image mosaic (**B**) compared with the cross section of Olympus Mons on Mars and Hawaii on Earth (**C**). The topography of the Rheasilvia basin is relative to a reference ellipsoid of 285 × 285 × 229 km.

Table 1. Vesta physical parameters from Dawn compared to the previous HST values.

Parameter	Dawn	Previous knowledge
Major axes (km)	(286.3/278.6/223.2) ± 0.1	(280 × 289 × 229) ± 5 (*15*)
Mean radius (km)	262.7 ± 0.1	264.6 ± 5 (*15*)
Volume (km^3)	74.970 × 10^6	77.60 ± 8.7 × 10^6 (*15*)
Mass (kg)	2.59076 ± 0.00001 × 10^{20}	2.6 ± 0.3 × 10^{20} (*13*)
Bulk density (kg m^{-3})	3456 ± 1%	3800 ± 15.8% (*15*)
Gravitational flattening ($\bar{J}_2$)	0.0317799 ± 0.0005%	—
Spin pole right ascension (deg)	309.03 ± 0.01	301° ± 5° (*15*)
Spin pole declination (deg)	42.23 ± 0.01	41° ± 5° (*15*)
Rotation rate (deg/day)	1617.333119 ± 0.000003	1617.332776 (*15*)

This density estimate is combined with Dawn's measurement of 0.03178 for the gravitational moment $\bar{J}_2$ (*18*) derived from radiometric tracking to explore the range of models of Vesta's interior consistent with the geophysical and geochemical constraints. The $\bar{J}_2$ predicted from Vesta's shape for a homogenous density is 0.0350. Thus, the measured $\bar{J}_2$ confirms the presence of a central mass concentration. The size of $\bar{J}_2$ resulting from this central mass concentration depends on its density and shape. Ignoring nonhydrostatic contributions (*19*), a mass-balance approach was used to investigate Vesta's internal structure to obtain constraints on the size of the core, as a function of its shape, from a sphere to an oblate spheroid with flattening $(a\text{-}c)/a$ of 0.15, where a and c are the major and minor axes, respectively, of the elliptical cross section. A flattening of a factor of 0.14 is predicted if Vesta's shape of mean radius 263 km has reached hydrostatic equilibrium, whereas the flattening of the core is expected to be smaller. The measured flattening of Vesta is ~0.21. The difference between the predicted and measured values could be the result of the massive excavation of the south polar basin due to giant impacts.

For assumed core densities of 7100 and 7800 kg m^{-3}, consistent with densities of iron meteorites (*1*, *20*), the core size and bulk silicate density were derived using a two-layer mass-balance model that can reproduce $\bar{J}_2$ (Fig. 3). The assumption of an iron-nickel core is supported by the observed siderophile element depletion seen in HEDs (*21*). It is difficult to estimate the sulfur content of the cores of differentiated bodies, but studies of iron meteorites suggest small sulfur abundances at the weight % level (*22*), so we have not made density corrections for sulfur. For

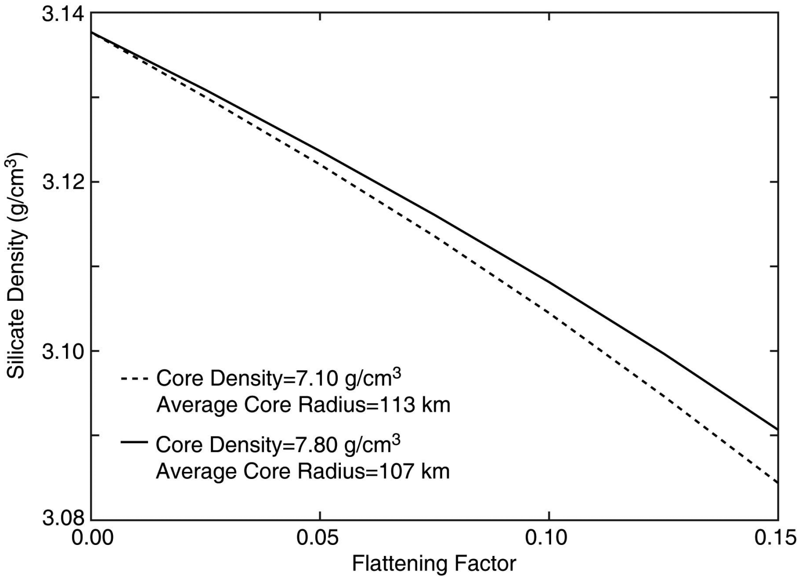

Fig. 3. Forward calculations of the bulk silicate densities and core-flattening factors that match the observed $\bar{J}_2$ of Vesta for two values of core density and their derived average equivalent spherical core sizes.

flattening greater than zero and less than 0.15, the range of values of core size and silicate density that fits $\bar{J}_2$ is constrained narrowly, indicating that the unknown shape of the core does not lead to a significant error in the size estimate. The resulting average core size (equivalent spherical core size) has a radius of 107 to 113 km, resulting in a core mass fraction (~18%) similar to that deduced from analysis of the HEDs (*16*, *21*). The core size and shape that fit $\bar{J}_2$ are only weakly dependent on the core density; rather, the density of the silicate fraction controls the fit for a given flattening.

The derived core size, constrained by the densities of iron meteorites, the chemistry of the HEDs, and petrogenic models of Vesta's interior evolution (*16*, *23*, *24*), is consistent with a magma ocean scenario (*16*). A vestan mantle of olivine plus orthopyroxene having diogenite compositions (*25*) will have a bulk silicate density of 3400 to 3500 kg m^{-3}, assuming zero porosity. The bulk silicate density for this range of iron core density, size, and shape, however, is 3085 to 3138 kg m^{-3}, which is lower than previous estimates that neglect porosity (*16*, *26*, *27*). When the less dense crustal layer is taken into account, the mantle density will be higher (~3200 kg m^{-3}). Although it is clear that neglecting nonhydrostatic contributions to $\bar{J}_2$ results in an error in the derived bulk silicate density (*19*), it is nevertheless low compared to nonporous HED densities (*16*), and it does agree with recent HED bulk densities that include porosity, which cluster between 2800 and 3200 kg m^{-3} (*27*). The lower bulk density estimate derived from Dawn data suggests 5 to 6% porosity in the mantle and crust, which is consistent with Vesta's intense bombardment history as revealed by Dawn.

As detailed here and in accompanying papers, Dawn's exploration has confirmed that Vesta is a surviving protoplanet whose properties are as inferred from HED meteorites. Vesta appears to have accreted early and differentiated, forming an iron core that may have sustained a magnetic dynamo (*28*). The surface of Vesta records its collisional evolution over its 4.5-billion-year history (*8*, *29*). The Rheasilvia impact basin is consistent with the production of the HEDs and the Vestoids (*6*). Vesta's thick regolith has the mineralogy expected for HED meteorites (*10*). Still, it preserves the record of its early magmatic processing, reflected in distinct surface regions with more color variation than other asteroids (*30*). Dawn has also provided geologic enigmas: the circumplanetary troughs (*29*), patches of bright and dark material (*10*, *29*, *30*), and significant mass wasting (*29*), all revealing a complex petrologic, geochemical, and tectonic history. Vesta's rapid growth, large size, and massive iron core may help explain how this protoplanet was able to withstand the intense pummeling to which it obviously has been subjected.

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11. Vesta's volume was estimated using three methods: (1) a stereophotoclinometrically derived (SPC) shape model that filled in the unmeasured northern latitudes with spherical harmonics fit to the measured region; (2) the SPC shape model that used the Thomas shape model (*11*) to fill in the northern cap; and (3) the stereophotogrammetrically derived shape model filled in the north with the SPC harmonics. The differences were 0.28% between models 1 and 2 and 0.059% between 1 and 3, indicating that the unmeasured northern cap is unlikely to cause a large uncertainty in the volume estimate. Model 2 is used throughout this report.
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17. The error in bulk density was estimated by assuming uncertainties in the axial dimensions of a best-fit ellipsoid of 100 m equatorial and 500 m polar, and forward-calculating the density variation. The quoted value is three times that estimate.
18. $\bar{J}_2$ is the gravitational moment associated with the normalized spherical harmonic coefficient of the Legendre polynomial $\bar{p}_2 - \bar{c}_{20}$ and is related to the gravitational flattening (*31*).
19. Vesta's shape and the values of $\bar{J}_2$, C_{22}, and S_{22} (C_{22}, 0.0043590 ± 0.0000003; S_{22}, 0.000254 ± 0.000005) indicate that Vesta is not currently in hydrostatic equilibrium, but its rotation dominates the second harmonic of its gravity field. Vesta may have been closer to hydrostatic equilibrium at the time of core formation, in which case its core may have frozen in an oblate shape. The dependence of the derived bulk silicate density on the core's shape demonstrates that its influence is weak.
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Supplementary Materials

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Supplementary Text
Figs. S1 and S2

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