

Vesta

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Abstract— This paper reviews what is known about the asteroid Vesta. It examines the physical properties, spin, and the surface properties of Vesta, and finally looks at the way many of these facts make Vesta the likely source of the Howardite, Eucrite and Diogenite (HED) meteorites. Connecting the HED meteorites to Vesta would make Vesta the only planetary body besides the moon, Mars and the Earth that we have samples of. The geochemistry of the HED meteorites can tell us about how much Vesta melted and about its core. Vesta can be seen as an infantile planet so the information about Vesta can also be used to speculate about the history of the solar system's rocky planets.

Introduction

The asteroid Vesta can be used as a possible model for the infantile stages of the planets. It is also has also been studied extensively as the likely source of Howardite, Eucrite and Diogenite (HED) meteorites. Vesta is usually considered the second largest asteroid of the solar system, although it is within error of the size of Pallas (Drake, 2001). The information that we have today on Vesta comes from remote sensing with telescopes at 1 AU (telescopes on or orbiting Earth) and from the HED meteorites. Vesta has been studied in a variety of ways since its discovery in 1807 (Drake, 2001). Specifically, the 1.5 m telescope at the Starfire Optical Range of the USAF Phillips Laboratory in New Mexico was used to obtain data about Vesta's surface composition (Drummond, 1997).

And rotationally cued spectroscopy observations were done at the 2.2m telescope at the University of Hawaii (Gaffey, 1997). In 1996 Vesta's orbit was the closest it had been to Earth in ten years, and the Hubble Space Telescope pointed its Wide-Field Planetary Camera 2 (WFPC2) at it to investigate Vesta (Thomas *et al.*, 1997a and b). Optimal viewing happens every 18 months when Vesta, Earth, and the sun align in their orbits. But because of Vesta's elliptic orbit, each alignment is not equal in viewing quality. The best viewing situation happens when Vesta is at perihelion and also aligned with Earth and the sun. Geochemical analysis of HED meteorites can tell us about the composition of Vesta, and from there we can infer how the asteroid developed and hardened.

Physical Properties

Images from the WFPC2 show Vesta to have an imperfect tri-axial ellipse shape with the semi axes of 289, 280, and 229 kilometers (Thomas *et al.*, 1997a). There are departures of 15-20 km from a smooth ellipsoidal shape (Thomas *et al.*, 1997b). The most major surface indentation is a huge crater at the south pole, 20-30 km deep and about 200 km across (Thomas *et al.*, 1997b). As we will see later this large crater is evidence that Vesta might be parent to the HED meteorites on Earth.

Using the mean radius of 266 km and the formula $\frac{4}{3}\pi r^3$, volume for Vesta is 78,800,000 km³. For comparison, the moon's volume is 279 times larger. Vesta's mass was found by examining its effect on asteroid 197's orbit and Mars' orbit and was recorded as being between 2.75×10^{23} g and 2.99×10^{23} g (Thomas *et al.*, 1997b). This puts the density—the mass divided by the volume—at about 3.7 g/cm³ (Thomas *et al.*, 1997a). Vesta's density is compared to the density of other asteroids and rocks, and the

composition can be guessed. Based on the cosmic abundances of the elements, there are relatively few choices for the composition of a rocky planet. The majority of rocky planets and asteroids are made of combinations of olivine, pyroxene, feldspar and iron. Ordinary rock (like rock made of olivine, pyroxene, or feldspar) has a density of about 3 g/cm³, but iron has a density of 7.9 g/cm³. Just from these facts we can say that Vesta's composition must be about 86% rock and 14% iron.

The gravity of Vesta is found using the mass and the formula: $F = (GMm)/R^2$, where G is the universal gravitational constant, M and m are the masses of Vesta and the object attracted by Vesta's gravity, and R is the distance between the center of Vesta and this object. The gravity of Vesta is calculated to be 0.22m/s². This is 7.4 (+0.8) times less than the moon's (Thomas *et al.*, 1997a). Because of the low gravity, impacts on Vesta throw debris further and leave secondary impacts. Many of the craters on Vesta have central peaks that form when the shock waves from the impacting meteors go through the crust material and reflect off the mantle boundary (Consolmagno and Schaefer, 1994). It is possible that gravity is also related to central peaking in craters. If this is true then gravity scaling compared with the moon shows us that Vesta requires that a crater be at least 460 km wide (as compared to 60 km on the moon) in order to produce a central peak (Thomas *et al.*, 1997a). Meteor impacts are the only way the surface of Vesta is altered and these seem to be relatively few, so Vesta has an old crust that has remained nearly the same as when it formed (Gaffey, 1997). It has no atmosphere, wind, or water to erode features, and is only subjected to the pummeling of all the tiny particles flying through space—debris and solar winds— and the occasional larger meteor impact.

(The old age of the crust is also made evident by the darkening of the surface eucrite, a process observed on Gaspra and Ida as well (Gaffey, 1997).)

Based on the presence of basaltic melts, Vesta likely had a period of viscous relaxation that let it reach a near equilibrium shape (Thomas *et al.*, 1997b). When Vesta hardened it was not spinning fast enough (nor is it now) to have an equatorial bulge, so it retained a spherical shape. The present-day deviation from this can be accounted for by the impacts Vesta has suffered (Thomas *et al.*, 1997b). Because of Vesta's small size, it does not return to a sphere after an impact, as a more massive body like the Earth does. Even a very large impact like the one responsible for the huge south pole crater may not have fully relaxed Vesta to equilibrium shape. As on Venus, a planet with a composition analogous to Vesta's, volcanism has been more important than viscous relaxation of craters, so again it is unlikely that many impacts caused enough melting to bring dents back to equilibrium but quite probable that Vesta melted with volcanism early in its history.

Surface Properties

The surface minerals of Vesta can be deduced using spectroscopy. Spectroscopy studies the sunlight reflected off a body and analyzes its spectrum. Because of the unique configuration of mass and charge in each mineral's atoms, the different atoms take different amounts of energy to absorb light (electrons moving up in energy levels) and emit light (electrons moving down in energy levels). When the light is reflected from a mineral back to your eye it is depleted in the energies that were absorbed. These energies correspond to wavelengths, and the different wavelengths (colors) create a different

spectrum for each mineral. By recording the spectrum of light reflected off Vesta, scientists discovered which minerals were present on the surface. Thomas (1997a) reports that spectroscopy readings from HST pointed to a basaltic crust. Basalt is generally composed of plagioclase, pyroxene, and olivine. In general agreement, Gaffey (1997) says the surface is dominated by iron- and calcium- rich pyroxenes. Basalt is formed when molten rock cools quickly on the surface and pyroxenes are usually caused by magmatic differentiation, so this confirms that Vesta had volcanic activity and tells us what sort of material the erupted or melted mantle was.

The crust is not all homogeneous. In fact there appears to be hemispheric variations in the surface materials (Gaffey, 1997). This is found by looking at Vesta's albedo. The albedo is the measure of the lightness or darkness of a body. For Vesta it shows a dark background surface with various lighter regions that rotate with Vesta's rotation (Thomas *et al.*, 1997a). The low albedo (dark) background is identified as eucrite darkened with age (eucrite is plagioclase-pyroxene basalt). One lighter region that can easily be seen rotating is an olivine-bearing unit near the equator hypothesized to be an impact crater that has exposed mantle material. The other light areas are also thought to be the result of impacts, all exposing the olivine and diogenite rich material of the mantle (Gaffey, 1997).

Thomas's team (1997a) investigated the variation of composition with depth in crater regions. On the large crater on the south pole of Vesta the spectroscopy data gave evidence either that there was a higher calcium content and coarser grained pyroxene-rich plutonic assemblage deep within the crust or that part of an olivine mantle was exposed.

Summarizing, the crust is primarily basalt/eucrite (plagioclase and pyroxene) with regions of olivine showing through from the mantle.

Spin State

The rotational pole of Vesta was found (as reported in Thomas *et al.*, 1997b) by choosing five points on the planet that were especially bright or dark and could be easily seen in pictures, and recording their movement during rotation. The points will not move with respect to one another(!) but will trace out either straight lines and the rotation pole will be perpendicular to the lines, or concentric arcs whose center can be calculated (depending on whether the observations are taken facing the side or facing the pole.). This data is then combined with the results from a second method using limb and terminator coordinates. Vesta was found to rotate with a period of 5.342 hours (Thomas 1997a) around a pole with $\alpha = 308^\circ \pm 10^\circ$, $\delta = 48^\circ \pm 10^\circ$, J2000 (Thomas, 1997b), where α refers to the degrees that the rotation pole is around the celestial equator from the first point of Aries, and δ refers to the declination of the rotation pole up from the celestial equator. (The celestial equator is the plane of Earth's equator. The first point of Aries is the star that makes a line with Earth and the sun on the spring equinox.) Based on this tilt, Vesta must face different sides more towards the sun during different parts of its year and must therefore experience seasons.

Meteorites associated with Vesta

Five percent of all meteorites found on earth HED meteorites. There is strong evidence that Vesta is the source of the HED meteorites on Earth. This is an important

possibility because it would make Vesta one of only four bodies in the solar system that have rock samples available to us on Earth. These types of meteorites are classified by composition: all are achondrite stones and those that are specifically plagioclase-pyroxene basalts are eucrites, those that are mostly pyroxene are diogenites, and howardites are clasts of eucrites and diogenites formed from impact comminution and lithification of regolith (Drake, 2001).

The moon was ruled out as a possible source because the lunar basalts returned from missions to the moon do not match the meteorites (Drake, 2001). Vesta's spectrum shows about the same composition as the HED meteorites, so either it is the source of the meteorites or it has the same evolutionary history as the meteorite parent bodies (Gaffey, 1997). So far no other major asteroids have been found with the same spectral reflectance curve, albedo, and polarimetric properties that Vesta shares with the meteorites and cannot match the composition of the howardite, eucrite, and diogenite meteorites to the extent that Vesta does. There is a crater on the south pole of Vesta that shows that about 1% of the asteroid was lost, and this is enough volume to account for the HED meteorites (Drummond, 1998).

One suggested point against the probability that the HED meteorites came from Vesta is its location. The position is not conducive to producing a flux of asteroids toward Earth. However, it has been suggested that Vesta's large size makes up for this and should still be the source of a large number of the meteorites on Earth (Gaffey, 1997). In 1993 a group of asteroids was found stretching from the area near Vesta to a region close to the Earth's path. The meteors may have been shot out from a 3:1 orbit-orbit resonance with Jupiter. This was convincing evidence that Vesta could supply asteroids to hit Earth,

and it strengthened acceptance of the theory that Vesta was the parent body to the HED meteorites (Gaffey, 1997).

Inferences from Geochemistry

If we assume that the HED meteorites are pieces of Vesta, we can make many inferences from their geochemistry. One reason Vesta is a good model for an early planet is that it is one of very few large asteroids that differentiated (Drake 2001). The composition of the HED meteorites indicate again that Vesta experienced melting. The abundances of Ni, Co, Mo, W, and P in Vesta's mantle are consistent with equilibrium between metal and molten silicates (Drake, 2001). Differentiation from melting caused the heavy elements in Vesta's composition, especially iron, to separate and sink to the center to form a core. Evidence of this metal core was shown with strontium abundances and metal/silicate partitioning experiments. These experiments use the fact that all metals have to separate out from the mantle material before the mantle can melt and produce eucrites. Since the eucrites are present and we can see that the mantle experienced partial melting, these metals must have separated out, and, being heavy, must have sunk to the center of gravity and formed a core (Drake, 2001). The degree of melting necessary to create the eucrites is a bit controversial. Earlier researchers said that only 10% of Vesta only would have needed to melt in order to produce its eucrites. But later it was argued that in order to produce the certain eucritic compositions there needed to have been substantial melting to cause a magma ocean with crystals that then cooled very slowly (Drake, 2001). The current consensus seems to be that Vesta experienced extensive

melting but did not become completely molten due to impacts (Thomas, 1997b) (Thomas, 1997a).

The molten iron core stirs and circulates as it cools. It conducts electricity and creates a current, and the rotation of this current (by Vesta's spin) produced Vesta's magnetic field (Consolmagno and Schaefer, 1994). If one assumes that the meteorites on earth are indeed from Vesta then we can infer from their isotopic ages of 4.5 Gyr that Vesta's heating occurred when it was very young (Thomas *et al.*, 1997b), at the time the rocky planets were forming.

Vesta's core and active past make it much more like a small planet than like a simple chunk of rock. Vesta formed at the same time and in the same solar system environment as the terrestrial planets, but Vesta never grew to planetary size because of the formation of Jupiter at 5.2 AU (which caused disruptive resonance in the asteroid belt). So, we can look to Vesta for evidence of what the Earth and other rocky planets were like early in their history.

Conclusion:

We conclude that Vesta is very like a small terrestrial planet with a core and lava flow on the surface. Understanding the physical characteristics of Vesta provides insight into its geological history and this in turn supplies important evidence as to the beginning properties and conditions of terrestrial planets. The evidence is very strong that the HED meteorites are indeed from Vesta. No other major asteroids have the same spectral aspects that match the HED meteorites', Vesta looks to have sustained an impact that

could have produced the meteorites, and the trail of Vesta rock near the 3:1 orbit-orbit resonance with Jupiter provides evidence that meteorites could get from Vesta to Earth.

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