Chemie der Erde 75 (2015) 273–285

Contents lists available at ScienceDirect

Chemie der Erde

journal homepage: www.elsevier.de/chemer

Invited review

Asteroid (4) Vesta II: Exploring a geologically and geochemically complex world with the Dawn Mission

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ARTICLE INFO

Article history:
Received 9 May 2014
Accepted 1 December 2014
Editorial handling - K. Keil

Keywords:
Asteroid
Craters
Impacts
Meteorites
Dawn mission

ABSTRACT

More than 200 years after its discovery, asteroid (4) Vesta is thought to be the parent body for the howardite, eucrite and diogenite (HED) meteorites. The Dawn spacecraft spent ~14 months in orbit around this largest, intact differentiated asteroid to study its internal structure, geology, mineralogy and chemistry. Carrying a suite of instruments that included two framing cameras, a visible-near infrared spectrometer, and a gamma-ray and neutron detector, coupled with radio tracking for gravity, Dawn revealed a geologically and geochemically complex world. A constrained core size of ~110–130 km radius is consistent with predictions based on differentiation models for the HED meteorite parent body. Hubble Space Telescope observations had already shown that Vesta is scarred by a south polar basin comparable in diameter to that of the asteroid itself. Dawn showed that the south polar Rheasilvia basin dominates the asteroid, with a central uplift that rivals the large shield volcanoes of the Solar System in height. An older basin, Veneneia, partially underlies Rheasilvia. A series of graben-like equatorial and northern troughs were created during these massive impact events 1–2 Ga ago. These events also resurfaced much of the southern hemisphere and exposed deeper-seated diogenitic lithologies. Although the mineralogy and geochemistry vary across the surface for rock-forming elements and minerals, the range is small, suggesting that impact processes have efficiently homogenized the surface of Vesta at scales observed by the instruments on the Dawn spacecraft. The distribution of hydrogen is correlated with surface age, which likely results from the admixture of exogenic carbonaceous chondrites with Vesta's basaltic surface. Clasts of such material are observed within the surficial howardite meteorites in our collections. Dawn significantly strengthened the link between (4) Vesta and the HED meteorites, but the pervasive mixing, lack of a convincing and widespread detection of olivine, and poorly-constrained lateral and vertical extents of units leaves unanswered the central question of whether Vesta once had a magma ocean. Dawn is continuing its mission to the presumed ice-rich asteroid (1) Ceres.

Published by Elsevier GmbH.

Contents

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http://dx.doi.org/10.1016/j.chemer.2014.12.001
0009-2819/Published by Elsevier GmbH.

1. Introduction

Of all the processes that have shaped the rocky planets of the Solar System, none has been as critical as differentiation. Rocky planets and asteroids accreted from essentially cosmic sediments of mixed silicates, metal, sulfides and, in some cases, ice. These cosmic sediments are preserved as chondritic meteorites. Yet chondritic meteorites are unlike any rock found on any of the terrestrial planets. Melting, differentiation and gravitational segregation separated the disparate components of chondrites, producing the layered metallic core, ultramafic silicate mantle and mafic/silicic crust structure so well-known on Earth and present in the other rocky planets and some asteroids. Despite sitting at the top of such a layered structure, we still have an incomplete understanding of how this fundamental process first occurred in the earliest history of our planet. This stems in part from an incomplete sampling of the layers and in part from the subsequent processes – including impact, plate tectonics, and mixing between layers – that has followed over the past 4.56 Ga on Earth.

While Mercury, Venus, Earth and Mars all experienced dramatic geologic events subsequent to their initial differentiation, the same cannot be said of asteroids that melted and differentiated. With their high surface to volume ratio, they radiated heat effectively after melting and, hence, cooled quickly. In most cases, internal heating stopped within 100–150 Ma after the birth of the Solar System (Wadhwa et al., 2006). The only dominant process altering them since that earliest epoch has been impact bombardment. For this reason, asteroids serve as the ideal subjects to understand early Solar System differentiation. It was this logic that led the Dawn mission to explore asteroids (4) Vesta and (1) Ceres.

2. Asteroid (4) Vesta

On January 1, 1801, Giuseppe Piazzi first discovered an asteroid that would be rediscovered exactly one year later by Franz Xaver von Zach and named (1) Ceres. On March 29, 1807, H.M. Wilhelm Olbers discovered asteroid (4) Vesta (henceforth for simplicity referred to as Vesta), the last discovery of an asteroid for 38 years (Russell and Raymond, 2011). It was named for the virgin goddess of home, hearth and family from Roman mythology. As early as 1879, E.C. Pickering estimated the diameter of Vesta at 513 ± 17 km, close to the modern value, although subsequent measurements varied by nearly 100 km in diameter (Hughes, 1994). Bobrovnikoff (1929) discovered rotational color and albedo variations attributed to composition. In 1966, Vesta's gravitation perturbations of asteroid (197) Arete were used to estimate its mass (Hertz, 1968). Vesta is the second most massive asteroid, behind Ceres, and third in volume behind Pallas. Vesta was detected by radar by Ostro et al. (1980).

Interest in Vesta accelerated with the pioneering work of McCord et al. (1970), who showed that the spectral reflectance of Vesta was markedly similar to that of the basaltic eucrite Nuevo Laredo. Nuevo Laredo is a member of the howardite–eucrite–diogenite (henceforth HED) clan of meteorites, the largest group of achondrites (igneous stony meteorites) in our collections. For example, the HEDs comprise ~62% of the achondrites in the US Antarctic Meteorite Collection and provide ~50 kg of mass for laboratory study in that collection alone (Corrigan et al., 2014). If Vesta is indeed the parent body of the HED meteorites, our opportunities for simultaneous geologic, geophysical and geochemical exploration of this largest differentiated asteroid expand significantly. A compelling impediment to arguing for the linkage between HED meteorites and Vesta was the semi-major axis of Vesta at 2.36 AU, far from the preferred meteorite delivery locations in the 3:1 resonance (where an asteroid would orbit three times for each orbit of Jupiter) at 2.5 AU or the ν_6 resonance (a perihelion secular resonance between asteroids and Saturn). This objection was nullified by Binzel and Xu (1993), who observed smaller asteroids that were spectrally and dynamically linked to Vesta – the vestoids – between the 2.36 AU orbit of Vesta and the 2.5 AU 3:1 resonance. It is these smaller asteroids that provide a path for the meteorites. The likely source of the vestoids was revealed by Thomas et al. (1997) based on Hubble Space Telescope (HST) observations of Vesta in 1996 (Fig. 1). These authors fit Vesta's shape with an ellipsoid of 289 by 280 by 229 km, yielding densities (using a known range of masses) of 3.5–3.9 g/cm^3. Further, these authors discovered on the asteroid an ~460 km diameter crater (now named Rheasilvia, after the mother of Romulus and Remus, the legendary founders of Rome) at the south pole, with a total relief of ~24 km, and color measurements consistent with excavation of a high-calcium, pyroxene-rich crust or olivine-rich upper mantle within this impact crater.

It is particularly interesting to consider the difference between mankind's exploration of the Moon and asteroid Vesta. For more than four centuries, humans have trained telescopes at the Moon and naked eye observations of the Moon were conducted for

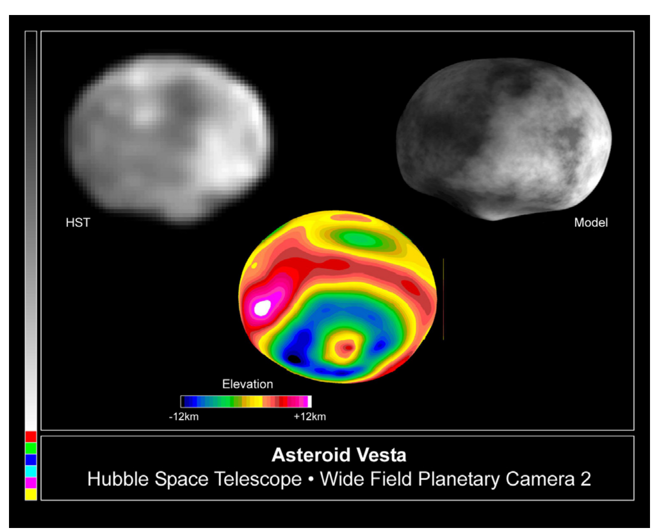

Fig. 1. Composite image of Hubble Space Telescope image. At top left is a Hubble Space Telescope image of Vesta. At top right is a digital shape model. Both images exhibit a prominent projection at the flattened south pole, which is interpreted as the central uplift of a large basin. Shading on the digital shape model is artificial and not indicative of albedo differences. Bottom center is a dynamic height solution projected onto Vesta's shape model and viewed from 33°S. Image courtesy of Ben Zellner (Georgia Southern University), Peter Thomas (Cornell University) and NASA.