CERES AND VESTA: DIVERSE, ENIGMATIC SMALL PLANETS FROM THE DAWN OF THE SOLAR SYSTEM.

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Introduction: Vesta and Ceres, the two largest bodies in the main asteroid belt, are unique, diverse fossils from the earliest epoch of our solar system. Vesta appears to be a surviving archetype of a differentiated, volatile-poor protoplanet, while Ceres is rich in volatiles. Ceres, the only dwarf planet in the inner solar system, bears affinity to outer solar system bodies.

What we knew: Stimulated by the study of lunar samples in the context of Apollo's exploration of the moon, a program was initiated to search for parent bodies of distinct classes of meteorites. Early on it was recognized that Vesta's mineralogy inferred from its reflectance spectrum was similar to the Howardite-Eucrite-Diogenite (HED) clan of basaltic achondrite meteorites. Laboratory spectra of HEDs were obtained that were a perfect match to Vesta [1]. That early success was not repeated at other asteroids, establishing Vesta's uniqueness, and study of the HEDs and Vesta became a focal point for understanding protoplanetary evolution. Although Vesta was the presumed solitary parent, certain trace and minor element variations raised the question of multiple Vesta-type parent bodies [2].

Characterization of Ceres' surface properties started in the mid-70s with the introduction of new detector and ground-based measurement techniques. Sensitive photometric measurements provided diagnostic electronic and molecular absorptions for planet-forming minerals and led to the first population surveys in the infrared. At Ceres, that technique revealed secondary phyllosilicates like clay minerals, plus a darkening agent that is similar to but not exactly like carbonaceous chondrites [3-6] The discovery of water and OH spectral features confirmed that relationship [7]. These observations led to the early realization that Ceres could be internally differentiated (while presenting a pristine, aqueously altered surface [8]). Characterization of Ceres' physical properties started in the mid-80s, leading to density estimates confirming the asteroid is water-rich, with up to 47vol.% free water ice (see [9] for a review) and the first evidence for OH emission in the same timeframe [10].

The Dawn mission launched in 2007 on a history-making ion-propelled journey to visit these two bodies comprising 45% of the mass of the main asteroid belt, and learn about the conditions and processes that shaped the early solar system. Dawn explored Vesta and Ceres using its framing camera (FC), visible- infrared spectrometer (0.4-5µm; VIR), gamma-ray and neutron detector (GRaND) and by mapping the topography and gravity. The best pre-Dawn Hubble Space Telescope images of Ceres and Vesta are shown in Figure 1, compared against the mosaics constructed from Dawn's rich data sets. The main results and implications of the investigations of these two bodies are described below.

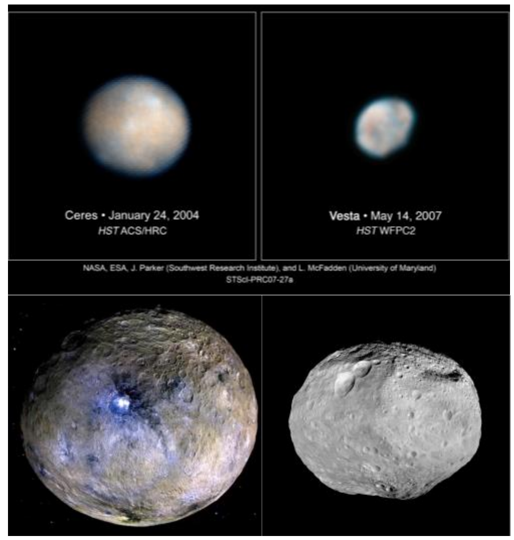

Figure 1: Top: HST images of Ceres and Vesta. Bottom Left: False color rendering of Ceres (~940-km avg diameter), draped on topography; Right: Gray-scale mosaic of Vesta (~530-km avg diameter) on topography.

Vesta: Dawn confirmed the Vesta-HED connection via surface lithologic mapping using VIR spectra [11, 12] and elemental chemistry from GRaND [13, 14], that showed most of the vestan surface is composed of howardite-like material with localized enrichments of eucrite and diogenite (Figure 2). A 110-km iron core was inferred from gravity and shape data, consistent with HED predictions [15]. While Vesta was found to be differentiated, as predicted by the HED paradigm, it appears to have experienced a complex magmatic history that resulted in lithologic diversity [e.g., 16]. Unexpectedly, broad, dark regions shown to be hydrogen-rich by GRaND [13] also exhibit an OH absorption feature at 2.8 µm in VIR spectra [17], interpreted to result from a few % of exogenic CM carbonaceous chondrite mixed into the regolith [18, 19]. Dawn also found pitted terrains [20] in young craters interpreted to be the result of outgassing of volatile- rich material, and gullies [21] thought to result from transient flow of water, both associated with impact processes. The discovery of hydrated material on Vesta's surface implies delivery of volatiles to the inner solar system by primitive asteroids.

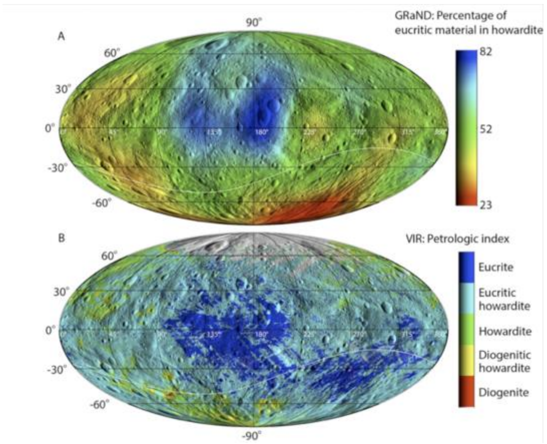

Figure 2. Howardite, Eucrite and Diogenite on Vesta, as mapped by GRaND (top) and VIR (bottom); from [18].

Ceres: Prior to Dawn's arrival, Ceres was already known to be a dark, wet dwarf planet with evidence for altered minerals and water vapor emissions, from decades of ground- and space-based observations, and was thought to be at least partially differentiated. Dawn found a heavily-cratered very dark surface that was punctuated by isolated, extremely bright areas [22] (Figure 1). This contradicted pre-Dawn model predictions of an ice- rich, viscously-relaxed smooth surface [23]. Ceres is shown to have a mechanically strong crust and is gravitationally relaxed at long wavelengths, implying that the strong crust overlies a weaker interior [24, 25]. Compositionally, Ceres' surface is dominated by dark material, ammoniated Mg-phyllosilicates, and carbonates [26-28]. The ubiquitous presence of ammoniated material suggests formation in a colder environment, likely in the giant planets region, while the overall mineralogy indicates Ceres' interior experienced pervasive alteration. Water ice has been observed in fresh craters at high latitudes, and elemental measurements indicate a shallow ice table [29]. These observations, along with Ceres gravity field [30] confirm that Ceres at least partially differentiated, providing evidence for an ancient subsurface ocean that may persist to the present as pore-filling brines or localized pockets. The presence of sodium carbonates in many sites, the third detection of that material in the solar system (after Earth and Enceladus), further suggests Ceres is a relict ocean world [26]. Local morphology such as crater floor deposits, isolated mountains and the enigmatic bright areas indicate active processes on Ceres that likely involve brine-driven cryovolcanism [31].

Future Directions: Radial mixing in the protoplanetary disk is evidenced in the history of these two sibling protoplanets. Vesta's uniqueness remains a mystery. The ever increasing capability of ground-based telescopes and future space-based systems will allow a
more comprehensive search and confident identification of objects related to Vesta, and how they differ. Improved understanding of these early-forming basaltic achondrites will improve understanding of disk chemistry and accretionary processes. The pervasive presence of salts across Ceres' surface and their suspected role in geological activity opens new areas of research for understanding the evolution fo large, water-rich bodies. The energy source driving Ceres' activity and the liquid source feeding volcanic features remain to be understood though. These and other important questions about Ceres' origin, evolution and astrobiological potential represent the foundation of future missions to the gem of the asteroid belt.

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