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Editorial

Composition of dwarf planet Ceres: Constraints from the Dawn spacecraft mission

Ceres holds pride of place as the largest (Fig. 1) and first-discovered body in the main asteroid belt. In response to a redefinition by the International Astronomical Union, asteroid 1 Ceres has been classified as a dwarf planet. Following the exploration of asteroid 4 Vesta, the Dawn spacecraft achieved orbit around Ceres on March 6, 2015 (Russell et al. 2016) and has remotely analyzed the body for more than 3 years. The spacecraft carried Framing Cameras (FC), a Visible and Infrared Spectrometer (VIR), and a Gamma Ray and Neutron Detector (GRaND) that, in addition to gravity science from radio tracking, have been used to analyze and map the global composition of Ceres.

True to its reclassification, Ceres has proved to be more planetary than asteroidal. It is a volatile-rich world of hydrated phyllosilicates, salts, and water ice, chemically differentiated but not in the same way as rocky planets. A relatively strong crust of silicates, salts, and ice overlies a weaker (muddy?) mantle and a core of undetermined character. Distinctive salts and water ice excavated by recent craters reveal information about its interior composition, and cryovolcanism and bright spots in craters indicate ongoing geologic activity. Organic matter has been found locally. No meteorites from Ceres have been recognized, as opposed to Vesta which has been sampled by more than a thousand achondrites.

First results from Ceres were published in *Science* (vols. 353 and 355) and *Nature* (vols. 528, 535, 536, and 537). Concurrent special issues in *Icarus* focus on geologic maps and a time scale for Ceres, an assessment of the surface mineralogy by quadrangle, and the geology of Occator crater. A general conclusion from those papers is that globally mapped geologic units, defined by morphology and time of formation, do not correlate with differences in surface composition—this reflects the globally pervasive extent of alteration.

This special issue describes discoveries about the global composition of Ceres made by the Dawn mission, as well as experimental studies relevant to understanding Dawn's remote-sensing measurements. McCord and Castillo-Rogez (2018) provide the historical context for Ceres's exploration and an overview of Dawn's major results. McSween et al.

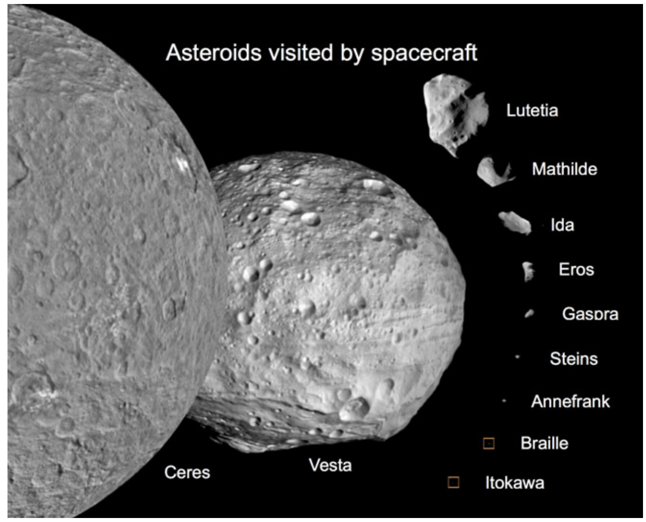

Fig. 1. Bodies in the main asteroid belt visited by spacecraft. Unlike most asteroids, dwarf planet Ceres (diameter ~940 km) and Vesta (diameter ~526 km) are intact planetesimals. Images compiled by C. A. Raymond. (Color figure can be viewed at wileyonlinelibrary.com.)

(2018) make the case that Ceres has a bulk composition like carbonaceous (CI/CM) chondrites, with mineralogical differences resulting from more extensive alteration appropriate to its large size relative to the meteorite parent bodies. Variations in high-energy gamma rays, determined by GRaND and corrected for differences in hydrogen (water ice), correlate with average atomic mass (Lawrence et al. 2018). These data permit some local areas to have iron contents similar to CI/CM chondrites, although previous work indicates that most of the surface has lower iron, consistent with ice/rock fractionation. Geochemical models of Ceres's evolution (Castillo-Rogez et al. 2018) support extensive global alteration at high hydrogen fugacity, driving formation of a relatively reduced mineralogy, as previously predicted for large icy bodies, and the formation of clathrates, as suggested as an explanation for Ceres's mechanically strong outer shell.

The mineralogical composition of Ceres's surface derived from modeling VIR's visible/near-infrared spectra is a mixture of ammoniated clay; Mg-serpentine;

Mg-carbonate; and a darkening agent, possibly magnetite and/or graphite; with localized deposits of water ice, Na-carbonate, ammonium salts, and aliphatic organic matter (De Sanctis et al. 2018). Dantu, a crater within an ancient impact basin, has excavated the deep crust and indicates that ammoniated clay occurs throughout the crust (Stephan et al. 2018). The identification of smectite as the ammoniated clay phase is confirmed by spectral investigations of experimentally altered phyllosilicates (Ehlmann et al. 2018). The nature of salts on Ceres is explored by a number of studies. A mineralogical analysis of Haulani crater, among the youngest surface features on Ceres, indicates the presence of both hydrous and nonhydrous Na-carbonates, implying that dehydration may be ongoing (Tosi et al. 2018). Spectral comparisons in the visible/near-infrared region using FC bands may also indicate a transition between anhydrous and hydrous mineralogy in a carbonaceous chondrite background (Schaefer et al. 2018). Laboratory study of the stability of hydrated magnesium sulfate precludes its occurrence as a component of Ceres's regolith (Bu et al. 2018).

Although the surface composition of Ceres is mostly uniform, there are exceptions. The classification and distribution of bright and dark materials on Ceres suggest that both materials tend to gradually evolve toward the average surface albedo over time (Thangiam et al. 2018). The geologic context for the organic matter detected on Ceres is consistent with either an endogenic or exogenic origin (Pieters et al. 2018).

The composition of Ceres's interior is inferred from geophysical data. Mass and hydrostatic flattening constraints on three-layer density models suggest the possible presence of a core, but cannot specify whether it consists of hydrous or anhydrous silicates, with or without a metal fraction (King et al. 2018). Travis et al. (2018) provide two-dimensional numerical simulations that suggest that Ceres's core is still above freezing, and that hydrothermal convection can occasionally deliver brines to the surface, consistent with Dawn's observations.

Ceres, as revealed by Dawn, is now arguably the solar system's best-characterized icy world, and its composition, ongoing geologic activity, and accessibility render it a viable and attractive target for astrobiological exploration.

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