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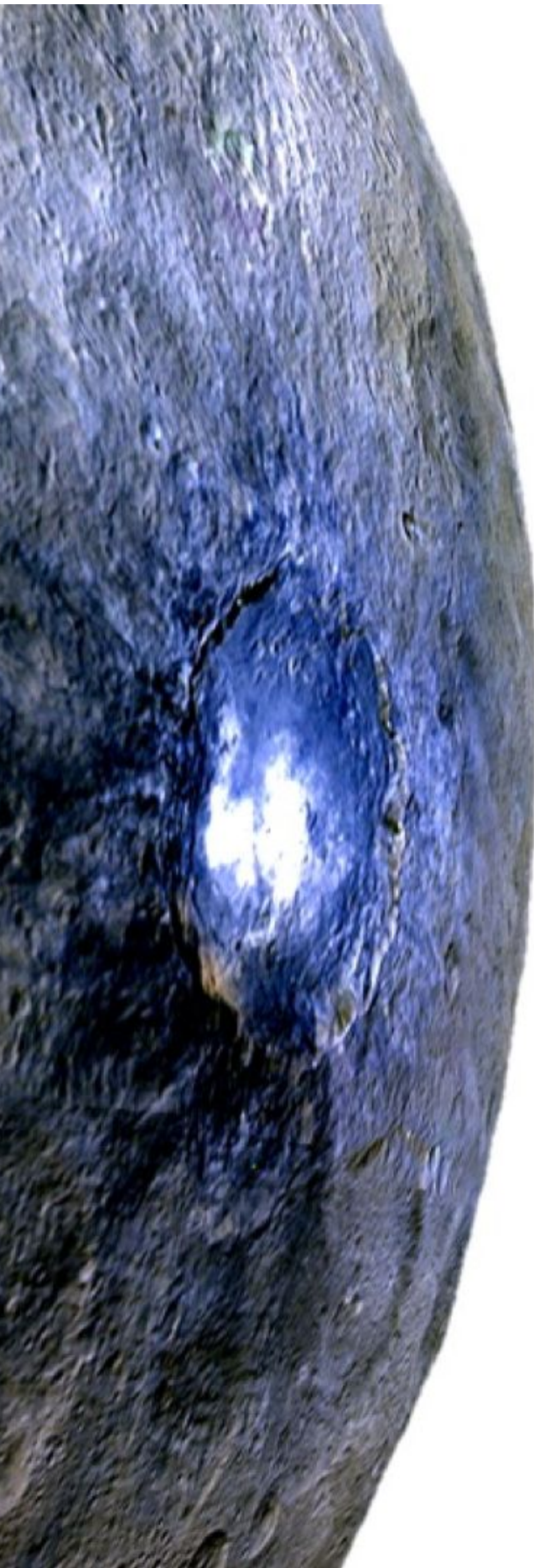
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Science Motivations for the Future Exploration of Ceres

Community White Paper for the Planetary Decadal Survey, 2023-2032

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Executive Summary

In the last decade of planetary exploration, the investigation by the Dawn mission of the dwarf planet Ceres, the most water-rich body in the inner solar system after Earth and largest object in the main asteroid belt, proved to be a major milestone. Ceres has sufficient water and silicates (i.e., radioisotopes) to host a deep ocean throughout its history, leading to a layered interior structure with a high degree of aqueous alteration [1]. The Dawn mission revealed evidence for recent and even ongoing geological activity on Ceres [2,3], the presence of liquid below an ice-rich crust [2,4], high concentrations of organic matter (locally) and carbon (globally) in the shallow subsurface [5,6], and presence of an exosphere and volatile transport [7]. Recent brine-driven exposure of material onto Ceres' surface can be found at Occator Crater [2], and the recent ~4-km tall mountain Ahuna Mons [3]. Available evidence for deep liquid and long-lived energy sources has led Ceres to be recognized as an ocean world [8,9].

The next steps in the exploration of Ceres should progress along the Roadmap of Ocean Worlds (ROW [10]) to (1) Assess Ceres' current habitability and use Ceres as a test case for unraveling the habitability, over time, of volatile-rich bodies; (2) Determine Ceres' origin, the relationship of its volatiles and organics to other inner solar system bodies (icy moons and other dwarf planets), and implications for solar system dynamical evolution. The Ceres Planetary Mission Concept Study [11] concluded that significant progress along the ROW can be achieved with in situ exploration, either at multiple sites, or at a single site and with a sample return. A mission returning a sample from Ceres' evaporites would address **cross-cutting astrobiology goals pertinent to ocean worlds** and is also being recommended by independent groups [12,13,14], hence opening prospects for international partnerships. As Ceres is very accessible from Earth, and thanks to its low gravity, **in situ exploration or sample return can be achieved under the New Frontiers program**. Supporting scientific work, in the form of experimental research on Ceres material analogs, ground-based telescopic observations, and continued analysis of the Dawn data, is needed to further **increase the science return from the Dawn mission** and pave the way for follow-on exploration. Should NASA create an Ocean Worlds program, we recommend Ceres be included as its study can inform the evolution of ocean worlds in the outer solar system [10]. Lastly, a future mission to Ceres that would optimistically kick off in the mid-2020s and return a sample by 2045 requires the participation of a diverse, inclusive, and thriving community.

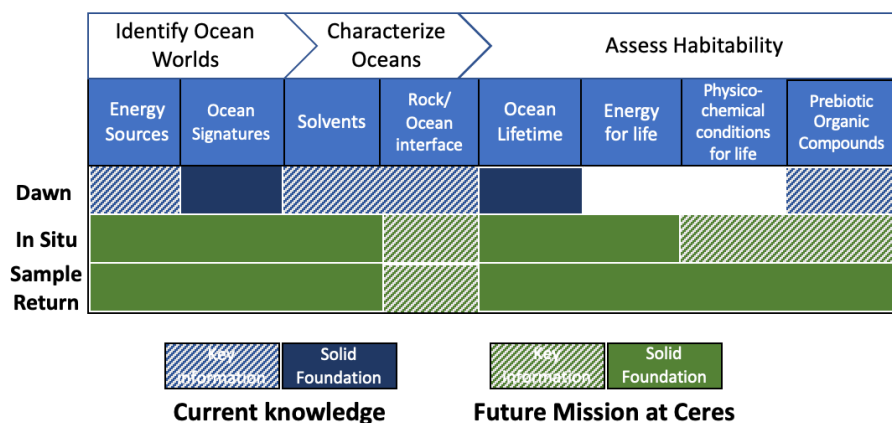


Figure 1. Knowledge of Ceres in the context of the roadmap to ocean worlds [9]. The Dawn results led to the identification of Ceres as an ocean world. A future New Frontiers class mission is poised to significantly progress along this roadmap [11].

State of Knowledge of Ceres and Future Mission Objectives

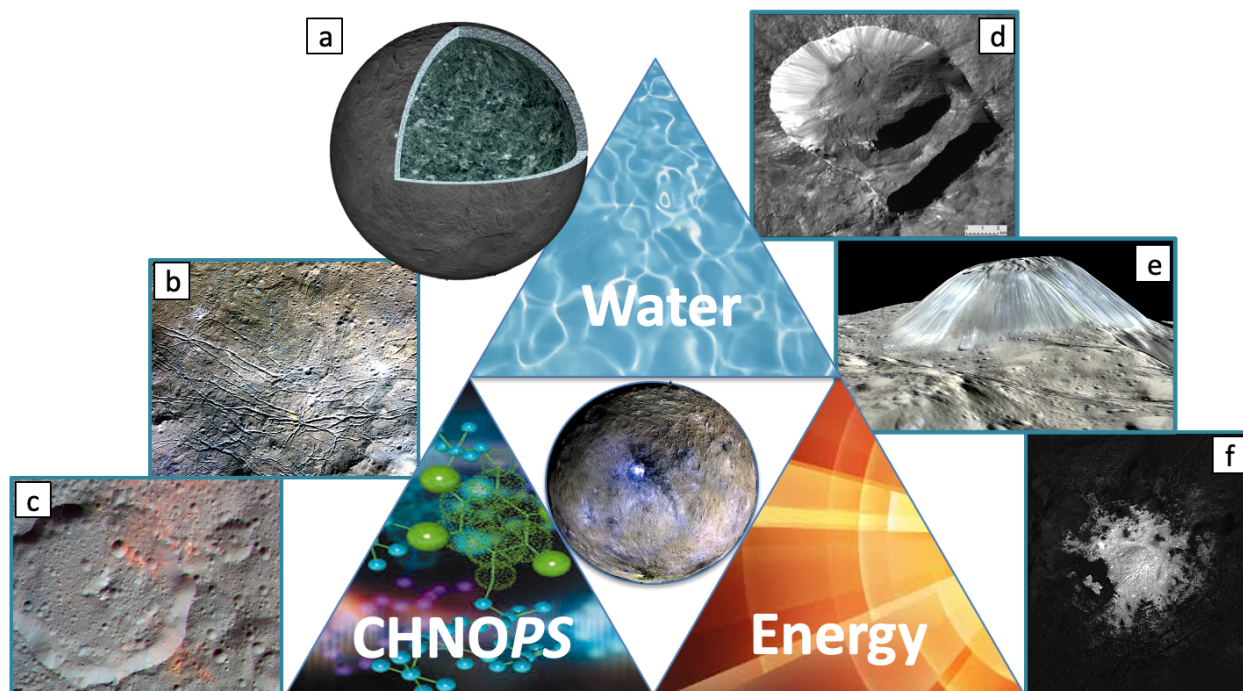


Figure 2. The Dawn mission at Ceres observed evidence of the ingredients for life: water, C-H-N-O-P-S elements, and energy. (a) Geophysical data suggest the presence of extensive water ice and the need for salts and/or clathrate hydrates to explain the observed topography and crustal density. (b) Various types of carbonates and ammonium and sodium chloride have been found in different sites across Ceres' surface (e.g., salts exposed on the floor of the ~126 km diameter Dantu crater). (c) Ernutet crater (~52 km) and its surrounding area present carbon species in three forms (reduced in C_xH_y form, oxidized in the form of carbonates and intermediate as graphitic compounds.) (d) Ceres shows extensive evidence for water ice in the form of ground ice and exposure via mass wasting and impacts (image: Oxo crater, ~9 km.) (e) Recent expressions of volcanism point to the role of low-eutectic brines in preserving melt and driving activity (image: Ahuna Mons, ~4.5 km tall, ~20 km diameter.) (f) Impacts could create local chemical energy gradients in transient melt reservoirs throughout Ceres' history (image: Cerealia Facula, ~14 km diameter.)

Topic: Identify Ocean Worlds

Energy Sources: Both Ahuna Mons and Occator's faculae are geologically young, implying recent transfer of mantle material (brines, mud) to Ceres' surface. In particular, the presence of hydrohalite ($NaCl \cdot 2H_2O$) on the top of Cerealia tholus indicates a very recent (tens or hundred years) emplacement [2]. Furthermore, haze suggested at Occator crater [15] might be further evidence for activity associated with the exposure of material at Cerealia, although its existence is debated [16]. The processes driving activity at present in an object that is presumably heat-starved are unknown.

A future mission should (a) expand geophysical observations of landmarks on Ceres' surface that appear of volcanic origin to constrain the extent of brine intrusions into Ceres' crust through time and understand the mechanism(s) driving that activity; (b) confirm the existence and mechanism driving the potential Occator haze.

Topic: Characterize Oceans

Solvents: Chlorides and carbonates found at the Occator evaporites [2] indicate a source that is likely a concentrated brine whose temperature is at or above the hydrohalic eutectic (~ 245 K) [17]. A more complete mineral inventory is needed to constrain the nature of the brines.

A future mission should determine the nature of Ceres' brines, which would in turn constrain the degree of freezing of the ocean, via measuring the mineralogical and elemental composition of evaporites exposed in Occator crater.

Rock/Ocean Interface: According to the *Dawn* data analysis, a rocky mantle starts at about 40 km below the surface, on average (between 35-55 km [1]). The nature of this interface, a transition to solid rock or muddy ocean is debated. There is a major (at least 30%) difference between the mantle density inferred by [1] and the grain density predicted by chemical modeling [17] suggesting high porosity. However, a higher density mantle is possible depending on assumptions on set on the inversion of the gravity data [18].

A future mission should determine the true moments of inertia of Ceres and obtain gravity-topography admittance up to degree 30-40 for direct crustal density estimation.

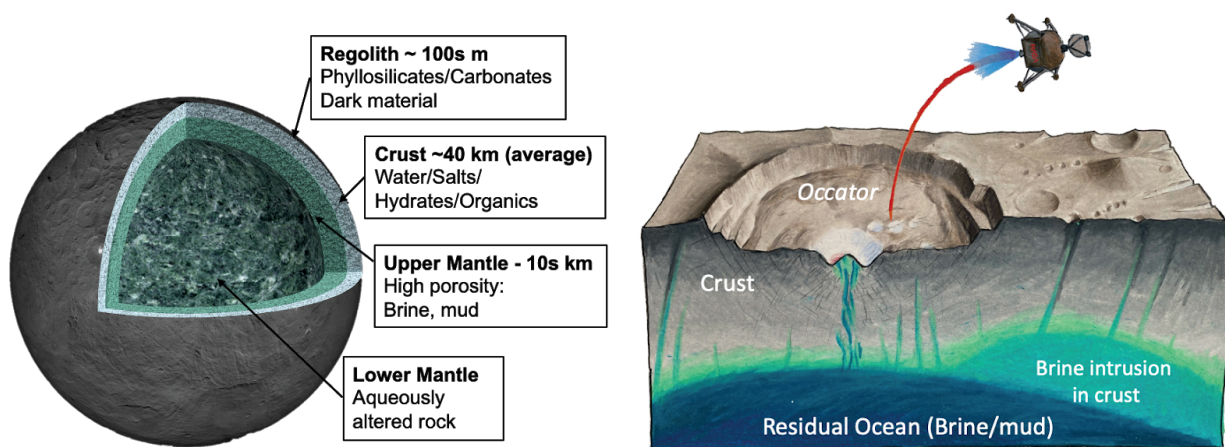


Figure 3. Left: Global interior structure for Ceres after [1, 19, 20]: a strong crust overlays a briny mud [20]. Right: Possible structure of the crust and upper mantle inferred below Occator Crater (~ 50 -km thick crust) [1]. The impact crater created a transient melt chamber and also introduced or reactivated fractures allowing for the long-term upwelling of deep brines. [21]. [Credit: J. T. Keane]

Topic: Assess Habitability

Physicochemical Conditions for Life: Although sodium carbonate is indicative of an alkaline environment, constraints are lacking on the conditions (redox, pH, ionic strength, temperature, etc.) in Ceres' deep brines and whether that environment is favorable to prebiotic chemistry. Different mechanisms could impact the residual ocean properties over the long term, for example the introduction of exogenic material via large, basin-forming impactors, or the release of fluids from the rocky mantle as a consequence of thermal metamorphism.

A future mission should quantify the habitability of Ceres' brine environment by characterizing the mineralogical, elemental, and isotopic composition of evaporites exposed in Occator crater.

Energy for Life: Surface mineralogy suggests aqueous alteration led to (near) chemical equilibrium [17]. However, impactor material could be retained in an impact melt chamber (Fig. 3), introducing new redox gradients. Domes found across the surface further indicate that volcanic or intrusive activity could have been a widespread process in space and time [22].

A future mission should (a) assess whether chemical energy is still present in Ceres' brine region by investigating the mineralogy of the Occator evaporites and (b) search for additional evidence for mantle intrusions or extrusions to test their role in the production of surface features, for example via high-resolution gravity measurements.

Prebiotic compounds: Aliphatic-dominated organic matter (OM) has been found in the region of Ernutet crater with at least at 3-4 times greater abundance than in carbonaceous chondrites [5]. Other species are likely present but could not be detected by *Dawn*'s instruments. The mixing of the organics found at Ernutet crater with other surface material suggests these organics formed inside Ceres [5,23] although an exogenic origin cannot be discarded. The global regolith contains up to 20 wt.% amorphous carbon [6]. The large amount of OM may reflect OM production in Ceres [24], Ceres' accretion in an environment rich in OM [6], or concentration in the shallow subsurface during differentiation. However, abundant carbonates found at landforms sourced from Ceres' mantle [e.g., 3] instead suggest oxidizing conditions in the residual ocean.

Future exploration of Ceres should determine the inventory of prebiotic compounds present on Ceres, determine their origin and the extent of their processing in Ceres' evolved ocean.

Topic: Origin of Ceres

The presence of ammonium compounds and abundant carbon suggests Ceres' volatiles formed beyond the main belt of asteroids [25]. However, the specific region (between the orbits of the giant planets vs. transneptunian region) is unknown. It is also possible Ceres formed in situ and accreted volatile-rich material from the outer solar system, e.g. via pebble accretion [26].

A future mission should test the origin of Ceres by investigating the isotopic composition of volatiles and minor species in Ceres refractory material (i.e., non-evaporite material).

Big Picture significance

Ceres shows many similarities to ocean worlds in the outer solar system per its differentiated interior [1] and brine composition that is partly similar to Enceladus' plume grains [27]. Recent and likely ongoing exposure of evaporites in Occator Crater makes a compelling place for testing habitability paradigms by determining the environmental properties of Ceres' residual ocean, either with in situ exploration and/or sample return. Furthermore, Ceres is a likely representative of the population of planetesimals that brought organics and water to the inner solar system and might even be an example of large planetesimal that supplied Earth with the majority of its volatiles [25,28]. Lastly, in situ/sample return exploration of Ceres in the next decade would be complementary to the ongoing sample return missions from C-type near earth asteroids (NASA's OSIRIS-REx, JAXA's Hayabusa-2) and to ocean world missions in the outer solar system that will be launched in the mid-2020s (NASA's Europa Clipper and Dragonfly, ESA's Jupiter Icy Moons Explorer (JUICE)).

Approaches to the Future Exploration of Ceres

New Frontiers-Class Architectures: A study developed under NASA's Planetary Mission Concept Study program showed that significant progress in our understanding of Ceres as an evolved ocean world requires resources offered by the *New Frontiers* and *Flagship* programs [11]. **The PMCS study has identified two mission architectures that can address a majority of the science objectives listed above (see Figure 1) under a New Frontiers cost cap:** a sample return from an evaporite-rich site in Occator crater or a hopper that explores the evaporites and an additional site. Both concepts include an orbital phase for landing site selection and certification prior to high-precision landing. For little additional cost, the orbiter can accommodate high-resolution imaging and gravity measurements at a handful of sites of interest to address past and current activity. Landed investigations are required for interior probing and compositional analysis either via sample return or using a combination of instruments for elemental, mineralogical, and isotopic measurements of evaporites and floor (non-evaporite) material. Electromagnetic sounding was identified as the most promising approach for probing Ceres' interior for deep brine distribution. Ceres' low gravity renders wheeled platforms mostly impractical but a lander can access multiple sites on Ceres via thruster-assisted hopping. The number and separation of sites that may be reached depend on mass budget and risk posture.

Flagship-Class Architectures: The architectures described above can be augmented with the capability to (a) search for outgassing, (b) increase the number of landing and sample sites, (c) study the relationship between the regolith and the crust via ground-penetrating radar, and (d) extensive geological and gravity mapping of the surface at high-resolution with a long-lived orbiter. However, the additional return of these options to the sample return and multi-site concepts described in the PMCS report was perceived as incremental. **A mission within the New Frontiers program would capture the majority of the above science objectives and offer the best science return per dollar.**

Required Technologies for Future Missions to Ceres: Few new technologies are required for a future in situ or sample return mission at Ceres. An important one identified by the Ceres PMCS is the certification of existing retractable solar arrays in Ceres-relevant environments. Other required technologies leverage investments for previous projects, e.g., terrain relative navigation (Mars 2020), throttleable valve (Europa Lander pre-project), etc.

Supporting Activities

The list of activities below needed to progress with our understanding of Ceres and prepare for future exploration is not exhaustive. If an Ocean World Research Program is created as part of NASA's Planetary Science Division, then Ceres should be included as an example of an ocean world whose advanced evolution can help us understand other ocean worlds.

Data Analysis: In order to increase the science return from the Dawn mission and prepare for a follow-on mission to Ceres, we recommend:

- ❑ A healthy Discovery Data Analysis Program to support a vast array of investigations by the broad community that build on, revisit, and expand upon previous analyses of the Dawn data.

- ❑ High-quality geologic map(s) of regions of interest for future landed missions would be integral to planning future observations for landing site reconnaissance and selection.
- ❑ Comparative analysis of the morphologies of ejecta deposits, debris flows, structures, and constructional features on Earth, Mars, Ceres, and icy moons.

Theoretical and Experimental Research: Future exploration of Ceres would benefit from work on terrestrial and laboratory analogs with a focus on better understanding the physics and chemistry of brines, organic matter, and mud mixtures in mid-size bodies, which are emerging topic of important to ocean worlds. Specific support for the following studies is recommended:

- ❑ Laboratory research on salt clasts present in meteorite collections, which have been suggested to come from Ceres or Ceres-like body [30].
- ❑ Thermophysical properties of brines, hydrated salts, and clathrates; mechanical response of evaporites to impacts, a key input to deriving the faculae model ages based on crater counts, which is key to many science drivers.
- ❑ Effect of radiolysis in the creation of redox gradients in ocean worlds, for example, to understand the efficiency of this process and its potential to create local habitable zones.
- ❑ Irradiation processes (ion, UV) that modify the infrared signatures of minerals and organic compounds. [29]
- ❑ Behavior of brine and mud mixtures in zero-pressure surface environments at Ceres temperatures, e.g., flow properties such as fluid-rich debris flows and impact ejecta; devolatilization process of the evaporites in a vacuum for water budget estimates.
- ❑ Experimental simulation of brine/organic/mud convection to inform the understanding of thermal evolution and material transfer in the interiors of mid-sized icy bodies. .
- ❑ Continued support to identify and characterize analog materials to provide comparison spectra at appropriate conditions for Ceres' surface in the UV and mid-infrared; e.g., determine the detection limit of organic carbon in mud mixtures or salts mixtures.

Work on Terrestrial Analog Sites: Geomorphological and first-order geochemical analog sites for regions of interest on Ceres exist throughout the solar system, especially on the Earth and Mars. Of particular interest are soda lakes [27], hydrothermal systems, landslide and ejecta deposits, salt tectonic structures, and periglacial analogs [31]. Potential analog sites on Earth can be used for testing relevant planetary instruments, surveying strategies, and sampling systems required for future landed missions to Ceres. Support via, e.g., NASA's Planetary Science and Technology from Analog Research (PSTAR) is recommended.

Ground-Based Observations: Telescopic observations from Earth or near-Earth space should continue, in particular to address the following questions:

- ❑ Origin of Ceres' sporadic outgassing activity with regular (perihelion and seasonal) and reactive observations following the release of solar energetic protons [32].
- ❑ Ground-based radar observations provide constraints on Ceres' surface roughness [33], which is important both to understand the evolution of Ceres' regolith and inform a future landed mission. The next favorable apparition of Ceres from Arecibo will be in 2023.
- ❑ Observations of Ceres in ultraviolet (e.g., Hubble Space Telescope) and mid-infrared wavelengths (e.g., JWST MIRI), which are complementary to the 0.4-5 micron range observed by Dawn.

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