ROADMAP FOR THE EXPLORATION OF DWARF PLANET CERES

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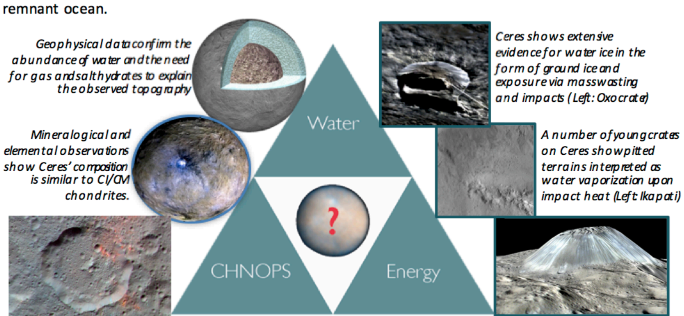
Introduction: Ceres, the largest asteroid, and only dwarf planet found in the inner solar system, offers a playground for testing hypotheses pertaining to the early Solar system evolution as well as the habitability potential of large volatile-rich bodies. Probably the most significant finding from the Dawn mission is **unambiguous evidence for oceanic material** right on Ceres' surface associated at least in one place with a **recent cryovolcanic feature**. These discoveries call for a follow-on missions focused on evaluating past habitability potential and the extent of a possibly remnant ocean.



Geophysical data confirm the abundance of water and the need for gas and salt hydrates to explain the observed topography

Ceres shows extensive evidence for water ice in the form of ground ice and exposure via masswasting and impacts (Left: Oxo crater)

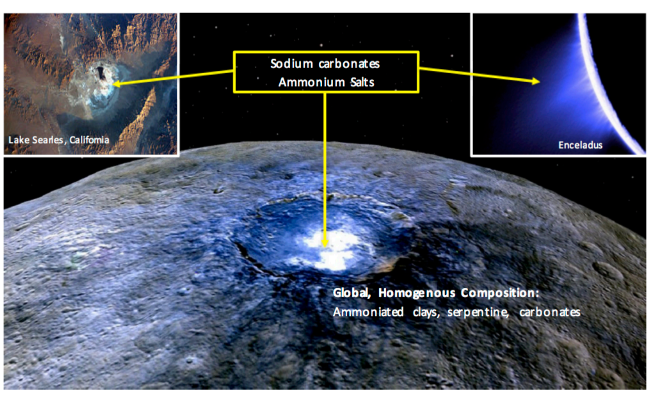
Mineralogical and elemental observations show Ceres' composition is similar to CI/CM chondrites.

A number of young crates on Ceres show pitted terrains interpreted as water vaporization upon impact heat (Left Ikapati)

The recent detection of organics in at least two places on Ceres' surface (Above: Ernutet crater), and the suspected presence of carbon and sulfur all over the surface from UV observations confirm Ceres possesses all key elements for prebiotic chemistry.

Discrete expressions of recent cryovolcanism point to the role of remnant radiogenic heating in preserving melt and possibly driving activity (Above: Ahuna Mons)

Post-Dawn State of Knowledge of Ceres: These pieces of information allow for a fresh assessment of Ceres' astrobiological significance, which was identified prior to Dawn's arrival and have led Ceres to turn from a "*credible*" possible ocean world to a "*candidate*" ocean world [ROW]. In the frame of the Road map for Ocean Worlds Goals, Dawn brought positive answers to the following questions: *Goal 1 (Identify Ocean Worlds), A.1 Is there remnant radiogenic heating? B.1 Do signatures of geologic activity indicate the possible presence of a subsurface ocean? B.7 Can the surface composition be linked with the presence of a sub-surface ocean?*



It has been suggested that the deep oceanic material could be exposed via the removal of an ice shell via impact-induced sublimation. This combined with clues for carbon suggests that the study of Ceres' surface directly addresses the ROW *Goal II B.3 "Characterize the ice-ocean interface"* and offers **a playground for testing hypotheses about the chemical evolution and habitability potential of Ocean Worlds**.

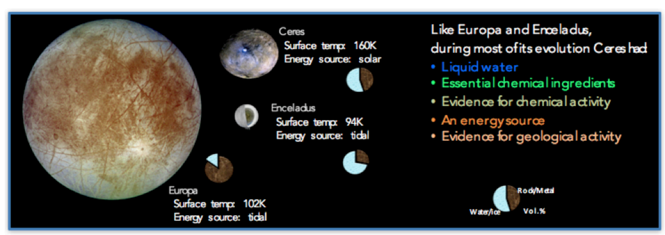
A Roadmap for Ceres Exploration: The in situ investigation of outstanding landmarks is an obvious next step in the exploration of Ceres and might be accomplished within the constraints of the Discovery program. Key objectives include assessing the lifetime of a deep liquid layer and the possibility for extended liquid bodies in Ceres, and investigating the chemical fingerprints contained in bright deposits to infer constraints on the environment in which they formed. A Dawn follow-on mission could also aim to clarify the nature of the dark material covering the surface and the mechanisms involved in its formation (hydrothermal, space weathering).

Theme	Key Questions for Future Mission(s) to Ceres	Possible Measurements
Life / Roadmap for Ocean Worlds / Workings of Solar System	*What is the thickness, salinity, density and composition of the ocean? How do these properties vary spatially and /or temporally?*	Variations in Ceres' pole position since Dawn; Interaction with solar wind; High resolution gravity field
	What is the salinity and composition of the ocean?	Petrology of landmarks believed to be emplaced via endogenic activity; Seismology and high resolution gravity field for subsurface structure and residual liquid
	Does Ceres possess redox disequilibria, in what forms, in what magnitude, how rapidly dissipated by abiotic reactions, and how rapidly replenished by local processes?	Locally resolved elemental and mineralogical composition (including organics) in context with geological and geophysical observations; isotopic chemistry
	What is the inventory of organics compounds, theirs sources and sinks; what is their stability in the local environment?	Organics distribution with geological and geophysical context; elemental characterization of Ceres' dark material
	What is the abundance and chemical form of nitrogen, oxygen, phosphorus, sulfur, and inorganic carbon, what are their sources and sinks, and are there processes of irreversible loss or sequestration relative to the liquid environment	Locally resolved elemental distribution (light elements) with geological and geophysical context; isotopic chemistry; mass spectrometry of the ubiquitous dark and the spotty red materials to search for basic information on structures by measuring molecular fragments of masses up to a few thousand amu
Origins	What is Ceres' origin?	Isotopic chemistry for H, C, N, O, Cl

The answers to these questions would drive the third step in Ceres' exploration, with regard to better understanding "*how life might exist at each ocean world and search for life*" [ROW *Goal IV*]. Exploration strategies developed for Mars may be applicable there, in particular planetary protection technologies.

Finally, the exploration of Ceres and large icy satellites requires a theoretical framework and experimental progress to assess, e.g., the stability and thermophysical properties of salt-rich materials, the physics driving endogenic processes in low gravity, exogenic processing, and the development, thriving, and preservation of life and biosignatures in salt-rich environments.

Ceres as a Stepping Stone for the Exploration of Ocean Worlds: Ceres represents a critical data point for understanding the chemical evolution of volatile-rich worlds and especially their potential for forming and preserving organic compounds. With it low gravity and relative benign environment, Ceres also offers easy surface access (in comparison to Mars or Europa) whereas the roundtrip light-time to/from Ceres requires the introduction of semi-autonomous techniques for advanced surface operations. Hence a long-term exploration program of Ceres is compelling, not just for the anticipated science return, but also because it will help us practice and hone new technologies of relevance to the future exploration of ocean worlds, such as surface operations, planetary protection, and end-to-end sample collection and return to Earth.



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