ROADMAP FOR THE EXPLORATION OF DWARF PLANET CERES. J. C. Castillo-Rogez[1], C. A. Raymond[1], C. T. Russell[2], A. S. Rivkin[3], M. Neveu[4], Ceres afficionados all over the world. [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA (Julie.C.Castillo@jpl.nasa.gov), [2] Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA. [3]Applied Physics Laboratory, John Hopkins University, Laurel, MD. [4]School of Earth and Space Exploration, Arizona State University, Tempe, AZ.

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. The Dawn mission has revolutionized our undertanding of Ceres in a decade that has also seen major breakthroughs in solar system dynamical modeling, cosmochemistry, and the rise of ocean worlds. 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. This goes above and beyond pre-Dawn predictions. This and other discoveries from the Dawn mission are raising new questions and setting the stage for future exploration, as described in this presentation.

Post-Dawn State of Knowledge of Ceres: Ceres is one of the best explored solar system bodies thanks to the extensive observation campaign achieved by the Dawn Mission. The combination of mineralogical, elemental, geological, and geophysical observations set standards for future missions. These led to key findings, including the confirmation that Ceres has been subjected to the hydrothermal processing of its materials at the global scale, likely fueled by short-lived radioiostope heat [1]; the discovery that that environment involved ammonia- and carbon-rich compounds, pointing to an origin of Ceres' materials from the outer solar system; a geology driven in part by volatile abundance in multiple forms, including ground ice, persistently shadowed regions, and icy regolith toward high latitudes [2, 3, 4]; the likely role of brines in driving cryovolcanism in the form of several outstanding features (Ahuna mons and Occator bright spots, as well as potential ancient features in the same vein) [5]; and the signature of volatile activity driven by solar wind [6].

Dawn's observations have been complemented over the past years by investigations with the Hubble Space Telescope leading to the finding of abundant carbon on Ceres' surface, as well as, potentially, sulfur rich species [7]. The discovery of water vapor by the Herschel Space Observatory [8] is consistent with the detection of many ice-rich sites, suggesting that ice is present below a thin regolith and regularly exposed via landslides and small impacts.

These pieces of information allow for a fresh assessment of Ceres' astrobiological significance, which was identified prior to Dawn's arrival [1] and have led Ceres to turn from a "*credible*" possible ocean world to a "*candidate*" ocean world [9]. Specifically, in the frame of the Roadmap 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?*

Dawn's discoveries at Ceres also introduced new evidence (or context) for addressing questions of broad interest. First, the presence of ammonia adds to the story of early Solar system migration although alternative scenarios are possible [10]. Also the nature of oceanic material on Ceres' surface, including sodium carbonate [11], a species found only on Earth and Enceladus' plumes [12], can help better understand the geochemical processes ongoing in other ice rich bodies. Indeed, per its size and water abundance, Ceres belongs to a class of objects that could host relatively alkaline conditions as was suggested for Europa [13] and inferred from Cassini observations of Enceladus [14]. It has been suggested that the deep oceanic material could be exposed via the removal of an ice shell via impact-induced sublimation [15]. 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 aboud the chemical evolution and habitability potential of Ocean Worlds.

Key Open Questions: *Workings and Life*: The next step in the assessment of Ceres' astrobiology significance is to evaluate the extent of liquid in its interior. This is a difficult endeavor for bodies that are not subject to tidal deformation and sources of seismological activity. This question might be addressed by studying the interaction of Ceres with the solar wind although this remains to be quantified. Comparison between images returned by Dawn and a future mission could be used to search for the signature of a deep liquid layer in Ceres' rotation [16] and possibly also reveal telling changes in surface properties. Indeed the key to evaluating Ceres' internal structure might come from the long-term observation of the faculae (bright deposits) observed in the Occator crater. The exposure age of those deposits appears inconsistent with the ~100My age of the crater and may indicate that the reservoir involved in the formation of these features is not yet at thermal equilibrium.

If pursuing the exploration of Ceres in the context of the Roadmap for Ocean Worlds, a future mission to Ceres could address the following questions, e.g., *Goal II (Characterize the Ocean), A.1 What is the thickness, salinity, density and composition of the ocean? How do these properties vary spatially and /or temporally? Goal III. (Characterize the Habitability), A.1 What environments possess redox disequilibria, in what forms, in what magnitude, how rapidly dissipated by abiotic reactions, and how rapidly replenished by local processes? B.1 What is the inventory of organic compounds, what are their sources and sinks, and what is their stability with respect to the local environment? B.2 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?*

Origins: Despite the evidence for ammonia and carbon compounds the origin of Ceres remains uncertain; several competing theories can explain an origin of Ceres at its current location with supplies of solar system planetesimals [17] or even from ammonia-rich organics formed in the inner solar system [18] These various hypotheses may be addressed via isotopic chemistry of low-z elements, and especially hydrogen, oxygen, and nitrogen isotopes. However, the extensive hydrogeochemistry that modified Ceres' materials also likely altered their original isotopic signature. Hence answers to volatile migration might be better addressed at more primordial objects (e.g., comets, smaller C-type asteroids, main-belt comets).

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 could focus on assessing habitability (the natural next step in the ROW framework) by investigating the chemical fingerprints contained in bright deposits to infer constraints on the environment in which they formed. Geophysical measurements are required to assess the extent of a deep liquid layer including high-resolution gravity measurements to study the endogenic processes driving cryovolcanic features. 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).

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 a (relatively) small gravity body, exogenic processes altering its surface, 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 begnin 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.

Acknowledgements: This work is being carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to NASA.

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