Science Drivers for the Future Exploration of Ceres: From Solar System Evolution to Ocean World Science

Julie Castillo-Rogez, Marc Neveu, Vassilissa Vinogradoff, Kelly E Miller, Michael M Sori, Federico Tosi, Britney Schmidt, Jennifer E C Scully, Mohit Melwani Daswani, Kynan Hughson, et al.

https://doi.org/10.3847/PSJ/ac502b

Science Drivers for the Future Exploration of Ceres: From Solar System Evolution to Ocean World Science

Julie Castillo-Rogez[1], Marc Neveu[2,3], Vassilissa Vinogradoff[4], Kelly E. Miller[5], Michael M. Sori[6], Federico Tosi[7], Britney Schmidt[8], Jennifer E. C. Scully[1], Mohit Melwani Daswani[1], Kynan Hughson[9], Harry McSween[10], Cristina De Sanctis[7], Lynnae Quick[2], Anton Ermakov[11], Guneshwar Thangjam[12], Katharina Otto[13], Katrin Krohn[13], Paul Schenk[14], Andreas Nathues[15], and Carol Raymond[1]

[1] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91009, USA

[2] NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771, USA

[3] University of Maryland, College Park, MD 20742, USA

[4] Aix-Marseille University, CNRS, Physics of the Interaction of Ions and Molecules Laboratory, UMR 7345, Centre Saint-jerome, 13013 Marseille, France

[5] Southwest Research Institute, 6220 Culebra Road, San Antonio, TX 78238, USA

[6] Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN 47907, USA

[7] Istituto Nazionale di AstroFisica, Istituto di Astrofisica e Planetologia Spaziali, Via del Fosso del Cavaliere 100, I-00133 Roma, Italy

[8] Department of Astronomy, Cornell University, Carpenter Hall, 313 Campus Road, Ithaca, NY 14853, USA

[9] University of Alaska, 3211 Providence Drive, Anchorage, AK 9950, USA

[10] University of Tennessee in Knoxville, Knoxville, TN 37996, USA

[11] Space Sciences Laboratory, University of California, Berkeley, CA 94720, USA

[12] School of Earth and Planetary Sciences, National Institute of Science Education of Research, Khurda, Pipli, Near, Jatni, Odisha 752050, India

[13] Deutsches Zentrum für Luft- und Raumfahrt, Rutherfordstraße 2, D-12489 Berlin, Germany

[14] Lunar Planetary Institute, Universities Space Research Association, 3600 Bay Area Boulevard, Houston, TX 77058, USA

[15] Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, D-37077 Göttingen, Germany

Science Drivers for the Exploration of Ceres: From Solar System Evolution to Ocean World Science

Abstract

Dawn revealed that Ceres is a compelling target whose exploration pertains to many science themes: as a large ice- and organic-rich body, potentially representative of the population of objects that brought water and organics to the inner solar system, as well as a brine-rich body whose study can contribute to ocean world science. The Dawn observations have led to a renewed focus on planetary brine physics and chemistry based on the detection of many landforms built off or suspected to be emplaced via brine effusion. Ceres' relative proximity to Earth and direct access to its surface of evaporites evolved from a deep brine reservoir make this dwarf planet an appealing target for follow-on exploration that would address science questions pertinent to the evolution of ocean worlds and the origin of volatiles and organics in the inner solar system.

1. Introduction

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 H_2O and silicates (i.e., radioisotopes) to host subsurface liquid water throughout its history, leading to a layered interior structure with a high degree of aqueous alteration (Ermakov et al. 2017; Fu et al. 2017). Deposits of bright carbonates and phyllosilicates are indicative of pervasive and global aqueous alteration (Ammannito et al., 2016; De Sanctis et al., 2016; Carrozzo et al. 2018). The Dawn mission also revealed evidence for recent and even ongoing geological activity on Ceres (Ruesch et al. 2016; De Sanctis et al. 2020), the presence of liquid – at least locally – below an ice-rich crust (Ruesch et al. 2019a; Scully et al. 2020), high concentrations of organic matter (locally) and carbon (globally) in the shallow subsurface (De Sanctis et al. 2017; Marchi et al. 2019; Prettyman et al. 2017), and the presence of an exosphere and volatile transport (Villarreal et al. 2017; Formisano et al. 2018). Even though the evidence for a global liquid layer in Ceres at present is circumstantial, Ceres displays evidence for the past and recent occurrence of a variety of processes that are relevant to ocean worlds.

This paper reviews the state of knowledge of Ceres after Dawn, including emerging interpretations about its evolution and the state of its residual liquid brine (Section 2). Then, we review how knowledge of Ceres contributes to better understanding the evolution of other large water-rich bodies and we describe the relevance of Ceres' study to other science themes (Section 3). Based on these considerations, we offer recommendations for the future research and exploration of Ceres with the purpose to further contribute to the fields of planetary origins and ocean world science (Section 4).

2. Key Dawn Results at Ceres

Pre-Dawn, Ceres was known to be a volatile-rich body that accreted ice and carbonaceous material early in the age of solar system formation (O'Brien and Sykes, 2011). Given the comparatively high temperatures on Ceres' surface, water ice sublimates when exposed at the surface and could only be detected in a few locations by Dawn, the largest located in Oxo crater (Combe et al., 2016) and the smaller patches in the northern hemisphere where persistently shadowed regions are present (Platz et al., 2016). However, the Dawn mission revealed several lines of compelling evidence for an ice-rich crust. (1) Gravity inversions yield a low crustal density of ~1200 kg/m^3 (Ermakov et al., 2017). (2) Crater morphometry nearly exactly matches that of icy satellites (Hiesinger et al., 2016). Consideration of crater relaxation is consistent with the shallow subsurface being up to 40% ice by volume, though this ice content may vary laterally and with depth (Bland et al., 2016; Otto et al., 2019; Sizemore et al., 2019). (3) Distinct morphologic features can be attributed to a large fraction of ice in Ceres' crust. These features include known volatile-related morphologies such as fractures related to intrusion (uplift), pitted terrains and flow-like mass wasting features (Schmidt et al., 2017; Scully et al., 2017; Sizemore et al., 2019). Furthermore, the occurrence of small ring-mold craters and 100 m scale hills with pingo-like morphologies (Schmidt et al., 2020) within the Occator crater suggests localized water ice reservoirs in the shallow and lower subsurface (Krohn et al., 2018). (4) Global, pervasive aqueous alteration of surface material (Ammannito et al., 2016) and abundant morphologic evidence, such as pervasive fracturing or mounds, hint at the existence of deep liquid throughout Ceres' history.

Flow features have been found in and around craters. Occator's interior exhibits extended plains of ponded material and extensive lobate materials, which may be representative of water or ice-rich flows (e.g., Krohn et al., 2016; Scully et al., 2018; Schenk et al., 2016). Those features are also found around the craters Haulani, Kupalo, Ikapati (Krohn et al., 2016), Kerwan, Yalode and Urvara (e.g., Williams, 2018; Bland, 2019). Multiple flow stages and discrete feeding sources may be consistent with a cryovolcanic origin for these flows (Krohn et al., 2016), although they are likely expressions of impact-generated melt in an icy crust (Schenk et al., 2020). (5) Detection of salt compounds, in particular sodium carbonate, locally in high concentrations (Carrozzo et al. 2018), Thermodynamic models suggest that in addition to water, other volatile compounds were accreted by Ceres, in particular ammonia and carbon dioxide (De Sanctis et al., 2015; Castillo-Rogez et al., 2018).

While some of these individual arguments can be debated (e.g., Johnson and Sori, 2020, Zolotov 2020), when taken together these convincingly show that Ceres has abundant water in ice, brines and minerals. In this section, we address salient open questions about Ceres' interior, in particular evidence for the presence of a residual ocean or regional brine reservoirs and the nature of that environment.

2.1 Evidence for Deep Brines in Ceres at Present and Recent Activity

Both geophysical evidence and surface observations suggest the presence of brines in the subsurface. Geophysical and geological observations hint at the existence of a former subsurface ocean whose remnants are still shaping the geology of the surface today (Ruesch et al., 2019a,b

The Dawn geophysical data indicate that a rocky mantle starts at about 40 km below the surface, on average (between 35–55 km; Fu et al., 2017; Ermakov et al., 2017) (Figure 1). The nature of this interface, a transition to solid rock or muddy ocean, is debated. The mantle density inferred by Ermakov et al. (2017) of 2430 kg/m^3 may be significantly lower than the grain density predicted by chemical modeling (Castillo-Rogez et al., 2018), suggesting possible high porosity. However, a mantle density of up to ~2800 kg/m^3 may be possible if Ceres has retained a fossil shape (Mao and McKinnon 2018), in which case the bulk porosity may be <10vol.%. Additional global constraint on the presence of a deep liquid layer comes from the topography relaxation models performed by Fu et al. (2017). These authors find that a ~40-45 km high-strength shell above a low viscosity layer, i.e., at the top of the mantle, best reproduces Ceres' topography. However, the viscosity of the upper mantle is poorly constrained at $<10^{21}$ Pa s.

Occator crater is a relatively young (~20 My; Neesemann et al., 2019), large crater with bright materials, including sodium carbonates and salt-rich materials, that represent evaporites from recent resurfacing (<2 My; Nathues et al., 2020). The morphology of Cerealia Tholus, a ~600 m high mound at the center of Cerealia Facula, is reminiscent of putative cryolava domes on Jupiter's moon Europa (Fagents, 2003; Quick et al., 2017). Emplacement mechanisms for the sodium carbonates and salt-rich bright materials in Occator include brine-driven cryovolcanism from a deep reservoir beneath the crust (e.g., De Sanctis et al. 2016; Krohn et al., 2016; Quick et al. 2019; Ruesch et al. 2019a) and a shallower melt chamber produced by impact-generated heat (Bowling et al., 2019; Scully et al., 2020; Schmidt et al., 2020; Raymond et al., 2020). The latter was estimated to be at least six kilometers in diameter and twenty kilometers deep (Bowling et al., 2019). The lifetime for that chamber was estimated by thermal modeling to be 10 My at most (Hesse and Castillo-Rogez, 2019) and likely much less when all evolutionary processes are accounted for. Hence, long-lived activity in Occator likely involved the contribution of a perennial deep brine reservoir whose connection with the surface was enabled by fractures created by the impact (Quick et al., 2019; Raymond et al., 2020). The dual origin for the brine can also explain the difference in evaporite deposit morphologies: at the center of the crater, Cerealia Facula is thick and continuous; whereas the Vinalia Faculae, distributed along the fractures on the eastern side of the crater floor, are thin, discontinuous, and somewhat diffuse (Ruesch et al. 2019b; Scully et al. 2020). Additionally, the existence in Occator crater of hydrated sodium chloride, a salt that dehydrates on a timescale of only centuries, suggests the presence of subsurface liquid brines today (De Sanctis et al., 2020).

A dozen craters, including Occator crater, display floor fractures that have been explained by shallow, cryomagmatic intrusions (Buczkowski et al., 2018, Krohn et al. 2020). Similarly to Occator, these intrusions may indicate the presence of underlying reservoirs, forming domes that uplift and fracture the overlying, brittle crater floor (Buczkowski et al., 2018, Krohn et al., 2020).

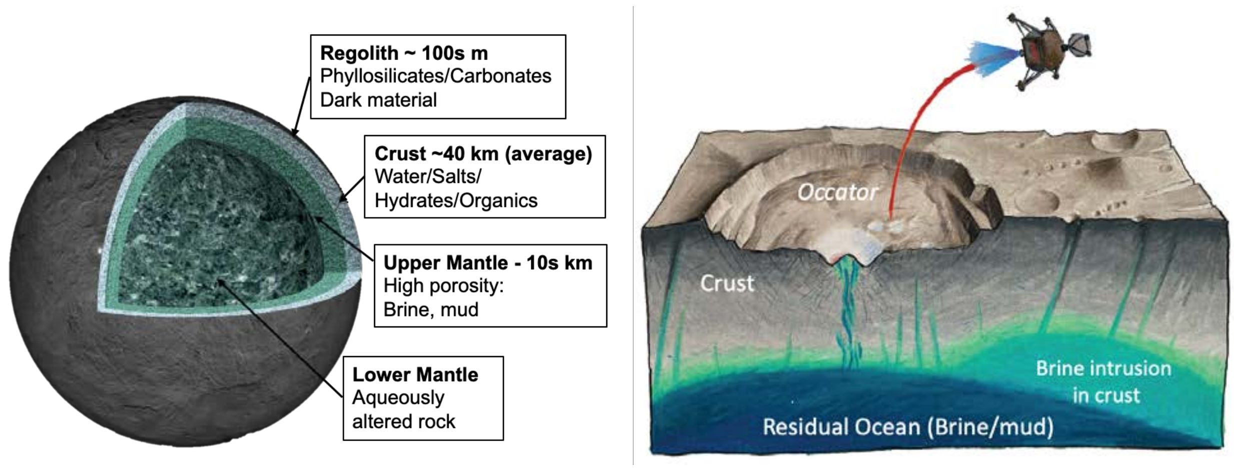

Figure 1. Left: Current understanding of the global interior structure for Ceres after Ermakov et al. (2017) and Fu et al. (2017): a strong crust overlays a briny mud and low-density rocky mantle. Right: Possible structure of the crust and upper mantle inferred below the 90-km diameter Occator Crater (~50-km thick crust) (Ermakov et al. 2017). The impact crater created a transient melt chamber and also introduced or reactivated fractures allowing for the long-term upwelling of deep brines (Raymond et al. 2020). [Credit: J. T. Keane]

The ~4 km tall Ahuna Mons is a steep, young mountain proposed to be a cryovolcanic construct formed in the past tens or hundreds of Myr (Ruesch et al., 2016). Bright streaks on its flanks contain sodium carbonates (Zambon et al., 2017). The emplacement of this large volume of material requires a low-viscosity material (Ruesch et al., 2016). Geophysical observations indicate that the mount material is dense and was sourced from the top of the mantle (Ruesch et al., 2019a). These combined observations indicate an origin involving a mud- or brine-rich material. Other mountains and domes (Buczkowski et al., 2016) have also been argued to be older, degraded cryovolcanic constructs on the basis of geophysical and geomorphological arguments (Sori et al., 2017; 2018), although some of them may also have been formed by intrusive processes instead (Bland et al., 2019).

2.2 Assessing Ceres' Past and Current Habitability Potential

In addition to the above evidence for subsurface liquid water, the surface of Ceres is blanketed with products of the interaction between rock and liquid water, which can supply chemical energy and bioessential elements in inorganic or organic form – the basic requirements of a habitable environment. That most of the compositionally homogeneous dark surface was likely emplaced early in solar system history, whereas select areas of the surface appear geologically very recent and compositionally distinct, provides information about the habitability of environments on Ceres both in the geologic past and at recent (perhaps present) times.

Bioessential elements. Local concentration of organic carbon has been detected on the surface as a prominent 3.4-μm spectral absorption feature and an inorganic carbon source is also available from carbonates. Combination of the data from the Dawn visible and infrared mapping spectrometer and the gamma ray and neutron detector also indicates that the global regolith contains 10 to 20 wt.% of amorphous carbon (Marchi et al., 2018). From laboratory mixtures, a similar amount is proposed (as a mixture of aliphatic and aromatic carbons) to fit the spectral abundance of the organic matter (OM) observed at Ernutet crater (De Sanctis et al., 2019). The large amount of such organic matter and amorphous carbon found in the regolith may be representative of the crust composition or may have been concentrated by an unknown mechanism. Nitrogen has been detected as a constituent of ammonium salts. The possible presence of sulfate salts provides a potential source of S. If the core is chondritic, then S and P can be inferred (for example as sulfides and schreibersite, respectively). O and H are implied as components of organics, sulfates, ammonium salts. Aliphatic-dominated organic matter has been found in the region of Ernutet crater with at least 3–4 times greater abundance than in carbonaceous chondrites (Kaplan et al., 2018; De Sanctis et al., 2019). The precise composition of this OM could not be derived from the Dawn observations. However, the mixing of the organic signatures found at Ernutet crater with other surface material (phyllosilicates, carbonates) suggests these organics formed inside Ceres (De Sanctis et al. 2019) although an exogenic origin cannot be definitely discarded.

Chemical energy. Theoretical energy sources could be provided by organics on their own (fermentation) or as half-reactions with sulfates, for example, in anaerobic respiration. However, these assessments require greater knowledge of the chemistry of the organic material. Other sources of chemical energy are possible (see Section 3.1).

Habitability potential early in solar system history. The overall homogeneity of Ceres' heavily cratered surface suggests a global emplacement at an early time when liquid water was ubiquitous in Ceres' interior, with short-lived radionuclides and accretional energy as possible heat sources (e.g., Castillo-Rogez et al., 2010; Neveu and Desch, 2015; Travis et al., 2018; Castillo-Rogez et al., 2019). That dark surface is mainly composed of an unknown darkening agent (likely carbon and/or Fe compounds; Marchi et al., 2019), Mg-bearing serpentine, ammonium-bearing clays, and Ca- and/or Mg-bearing carbonates (De Sanctis et al., 2015; Ammannito et al., 2016). Modeling suggests that these compounds can together result from the complete reaction between liquid water and chondritic material in presence of CO_2 and NH_3, which generates alkaline conditions (pH > 7). Specifically, and although this remains to be confirmed experimentally, the presence of NH_4 suggests formation at pH > 10 and temperatures lower than 50ºC, yielding ionic strengths of order 0.1-1 (Neveu et al., 2017; Castillo-Rogez et al., 2018). It may be that earlier conditions were hotter but that the incorporation of ammonium into clays occurred at later, colder conditions. Early redox conditions are constrained to hydrogen fugacities between 10^{-8} and 10^{-5} bar by the coexistence of relatively oxidized carbonates and of relatively reduced nitrogen (as ammonium clays), as well as amorphous or organic carbon (Neveu et al., 2017; Castillo-Rogez et al., 2018).

Habitability potential today. The current physicochemical conditions of Ceres' brine reservoirs or residual liquid layer, if it exists, are not well constrained. Bounds can be derived on temperature based on the mineralogy observed in recently exposed evaporites. Minerals displayed by the Occator faculae display sodium carbonate (>70 vol.%), ammonium chlorides (up to 7 vol.%), and in the case of Cerealia Facula, a few percent of hydrohalite (Raponi et al., 2019; De Sanctis et al., 2020). At Ahuna Mons, sodium carbonate has been found at a level of 7–10vol.% (Zambon et al., 2017). These observations suggest that the source temperature should be at least 245 K (Castillo-Rogez et al., 2019). On modern Ceres, although sodium carbonate is indicative of an alkaline environment (pH~7-10; Castillo-Rogez et al., 2018) and surface expression of cryovolcanism points to subsurface liquid reservoirs on the verge of complete freezing, more specific constraints are lacking on the conditions (redox, pH, ionic strength, temperature, etc.) in Ceres' deep, cold, concentrated brines and whether that environment is within the limits that psychrophilic and halophilic organisms can tolerate (e.g., Pikuta et al., 2007).

3. Big Picture significance – Contribution of Ceres Science to Other Fields

As an ice-rich body, a dwarf planet, and the largest member of the main asteroid belt, the exploration of Ceres provides insights into properties and processes that affect all three populations of planetary bodies (Figure 2). In that respect, Ceres is unique in the solar system. Ceres shows many similarities to ocean worlds in the outer solar system per its differentiated interior and brine composition that is partly similar to Enceladus' plume grains (Postberg et al., 2011; De Sanctis et al., 2016). Recent and likely ongoing exposure of evaporites in Occator Crater makes it a compelling place for testing habitability paradigms by determining the environmental properties of Ceres' residual ocean, either with in situ exploration and/or with 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 planetesimals that supplied Earth with the majority of its volatiles (e.g., De Sanctis et al., 2015; Budde et al., 2019). 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).

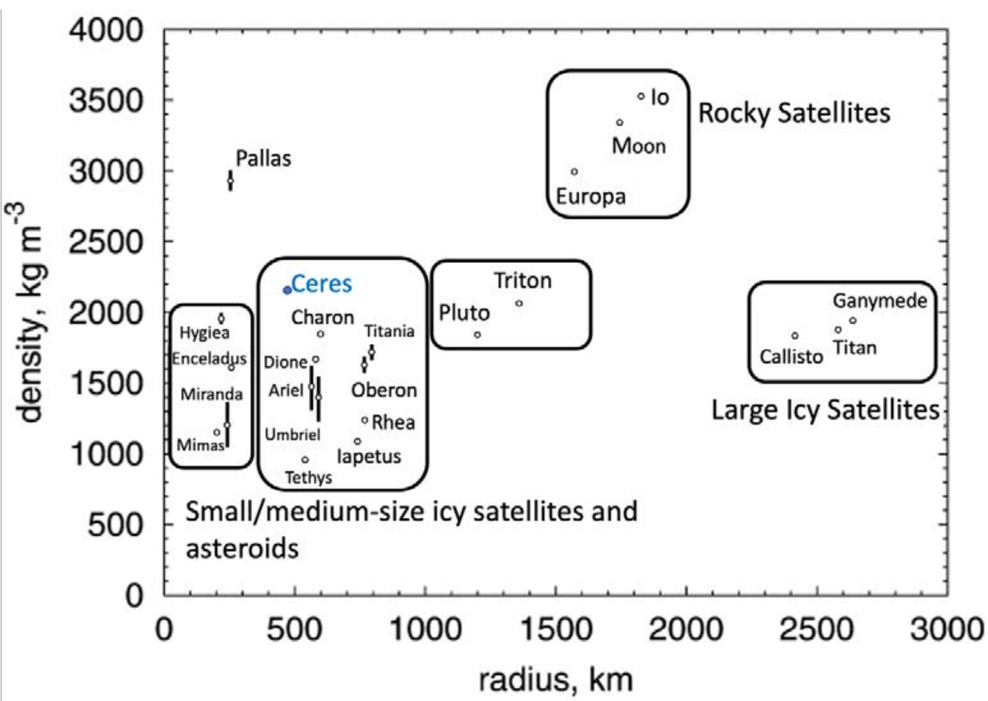

Figure 2. Basic physical properties for ice-rich bodies (and Io) highlight similarities between Ceres and mid-sized icy moons (Figure based on Hussmann et al., 2006). Hence, knowledge gained at Ceres can inform the evolution of icy moons, and vice versa.

3.1 Contribution of Ceres Exploration to Ocean World Science

Extent of Internal Evolution in Water-Rich Bodies

Insights to date from laboratory investigations of planetary materials indicate lesser degrees of aqueous alteration than inferred for Ceres. Thus, Ceres provides an opportunity to understand the effects of water-rock interaction at higher proportions of water relative to rock on the internal evolution of worlds with a water content similar to, or approaching, that of ocean worlds in the outer solar system (Figure 2).

Among planetary materials investigated in the laboratory, the CM and CI carbonaceous chondrites were likely formed in relatively small (<100 km diameter) planetesimals (Brearley, 2006). Alteration scales for these chondrites are based mainly on petrologic compositions (Browning et al., 1996; Rubin et al., 2007) and modal proportions (Howard et al., 2015), and to some extent on the abundances and isotopic compositions of volatiles (Alexander et al., 2013). A progressive sequence of reactions first produces Fe-serpentine and tochilinite, which are then converted to Mg-serpentine, magnetite, clay, and sulfates (Howard et al., 2011). Organic matter is modified and carbonates are also produced during alteration (see for example Alexander et al., 2015). In CM and CI parent bodies, these reactions occurred at relatively low temperatures and, although they required liquid water, the water:rock ratios were low and water did not separate from rock on a global scale.

The alteration mineralogy determined from Ceres' surface spectra is similar to the most highly altered carbonaceous chondrites but is more extreme (McSween et al., 2018). Ceres is spectrally similar to a few other C-class asteroids which may have also experienced extensive aqueous alteration, such as 10 Hygiea (e.g., Rivkin et al., 2014). These bodies, like Ceres, are among the largest asteroids, suggesting that the degree of alteration (and differentiation) of water-bearing planetesimals is related to size (McSween et al., 2018). Although the alteration mineralogy of even larger ocean worlds is not well constrained, Ceres serves as a bridge linking smaller, altered but undifferentiated planetesimals to larger bodies with subsurface oceans.

Neveu and Desch (2015) assumed aqueous alteration of a CM chondrite precursor by NH_3-bearing fluid. In their model, hydrated chondrules sank to form a rocky core, leaving an overlying muddy mantle consisting of ice and aqueously altered fines. Castillo-Rogez et al. (2018) used thermodynamic models of a carbonaceous chondrite precursor to determine that Ceres' surface mineralogy reflects advanced alteration under high hydrogen fugacity and the mineralogy shows a weak dependence on pressure. They also predicted clathrate hydrates in the interior, which could explain the low density and high strength of the crust inferred from geophysical observations. Although the global uniformity of the surface mineral compositions (Ammannito et al., 2016) implies that the surface assemblage was excavated from depth, evidence for iron fractionation in the crust (Prettyman et al., 2017) suggest the surface mineralogy may not be representative of the mantle (Castillo-Rogez et al., 2018).

A key question is the extent of thermal evolution of the mantle and whether it reached metamorphic conditions leading to partial dehydration. Ceres' mantle density is uncertain, between 2400-2800 kg/m^3 (Ermakov et al. 2017; Mao and McKinnon 2018). A dehydrated mantle composed of olivine and pyroxene would produce a bulk density higher than observed for Ceres, so, it is possible the mantle did not dehydrate, some fluid must have been retained to allow retrograde formation of some hydrous phases, or the mantle has retained some porosity filled in by brines. The presence of amphibole (tremolite), chlorite (clinochlore), and serpentine (chrysotile) in a carbonaceous chondrite clast in a ureilite breccia implies greenschist-facies metamorphism at a temperature and pressure higher than for other CM and CI chondrites, possibly consistent with conditions in the interior of a Ceres-sized asteroid (Hamilton et al., 2020). That parent body is considerably larger than envisioned for other carbonaceous chondrites, so the meteorite likely provides insights into Ceres' deep interior. Multiple reports for the presence of dehydrated material on the surface of Ceres (e.g., De Sanctis et al. 2015; Raponi et al. 2021) might be evidence for thermal metamorphism in the mantle. However, the emplacement of that material into Ceres' regolith remains to be explained. Contamination from exogenic material that may include anhydrous or dehydrated material is another possible explanation (Marchi et al. 2018).

Long-term persistence of liquid water in the absence of tidal heating

Tidal dissipation is thought to enable subsurface liquid water and related surface activity on many solar system moons, such as Enceladus and perhaps Mimas and Dione in the Saturn system, possibly Miranda and Ariel in the Uranian system, and on Neptune's moon Triton (e.g., Hendrix et al., 2019). On larger objects such as Europa, Ganymede, Callisto, and Titan, radiogenic heating alone can maintain the subsurface oceans whose signatures were detected by the *Galileo* and *Cassini* missions, although tidal dissipation may enhance associated activity, e.g., at Europa. Ceres, which does not orbit a giant planet, never experienced any significant heating from tidal dissipation. That its interior still harbors liquid water on the verge of refreezing is therefore very informative of the ability of radiogenic heating, augmented perhaps to a small extent by the heat of accretion (Bierson et al., 2020) and later impacts (Bowling et al., 2019), to sustain subsurface liquid water.

In the absence of tidal heating, the persistence of liquid water mainly depends on the body's size (the ratio of heat production – which scales with volume – to heat loss – which scales to first order with surface area – being proportional to the radius); the rock mass fraction, which determines the abundance of long-lived radioisotopes; the presence of salt, hydrates, or volatile impurities able to change the interior's physical and chemical properties (freezing point, insulation, strength); and to a lesser extent the heliocentric distance that largely sets the temperature at the surface (Hussmann et al., 2006). The evidence at Ceres (radius of 470 km) therefore suggests that larger worlds (radius > 700 km) such as Uranus' moons Titania and Oberon, and transneptunian objects such as Pluto, Eris, Haumea, and Makemake may, too, host subsurface liquid today. Indeed, there are hints that Pluto may harbor an ocean (Nimmo et al., 2016; Keane et al., 2016; Denton et al., 2021). On the other hand, Pluto's moon Charon, with a radius ≈ 600 km and heliocentric distance of ≈40 AU, seems to have fully refrozen (Desch and Neveu, 2017).

An object's size and heliocentric distance are readily determined, but the crux of estimating ocean persistence in the absence of obvious surface expression or major tidal dissipation lies in understanding the feedbacks between interior physical and chemical processes. The recent exploration of Ceres (and of the Pluto system) has hinted at how complex such feedbacks may be. Salts and gas hydrates possibly affect the near-surface strength (Bland et al., 2016) and therefore the means by which heat is transferred to the surface and lost to space by convection (Formisano et al., 2020) or conduction (Neumann et al., 2020; Kamata et al., 2019). Water-rock reactions, including those able to produce Ceres' surface composition, may change the distribution of radionuclides and generate or consume antifreeze species (Neveu et al., 2017), as well as enhance or inhibit deep convection in porous rock, which tends to homogenize temperatures in the interior, keeping ice melted at depth (Neveu et al., 2015). The relative densities of the crust and subsurface fluids, which depend on their chemical composition, affects the surface expression of fluids through volcanism (Ruesch et al., 2019a). Ceres offers the opportunity to investigate how this interplay of planetary physics and chemistry affects the persistence of oceans and their surface expression, with the tidal heating variable separated out.

The energy source driving late activity in Ceres is not well understood. Long-lived radioisotopes by themselves would not be able to preserve a deep liquid layer, especially if the shell is convecting heat. In most models, the bulk of the ocean would freeze on a timescale of about 200 million years. However, a residual liquid layer enriched in ammonia and chlorides could exist as a minimum, based on pre-Dawn models (Castillo-Rogez and McCord, 2010; Neveu and Desch, 2015). Three explanations have been suggested for the existence of substantial liquid, at least locally, inside Ceres at present (Figure 3).

First, the possibility that convection onset in Ceres' crust was precluded based on the inference that the crust is at least three orders of magnitude stronger than water ice (Bland et al., 2016), even though its density is only slightly greater than that of water ice. Two interpretations have been suggested: the shell is enriched in clathrate hydrates, whose thermophysical properties are consistent with these observations (Bland et al., 2016; Fu et al., 2017) and that are expected to form in Ceres' early ocean (Castillo-Rogez et al., 2018); as an alternative, pinning of the ice grain boundaries with silicate particles could also increase the overall strength of the crust (Qi et al., 2018). The main difference between the two models is that the thermal conductivity of clathrate hydrates is also a factor 5 to 10 lower than ice. Hence the clathrate-rich model would lead to warmer interiors than the ice-rich crust model (Castillo-Rogez et al., 2019).

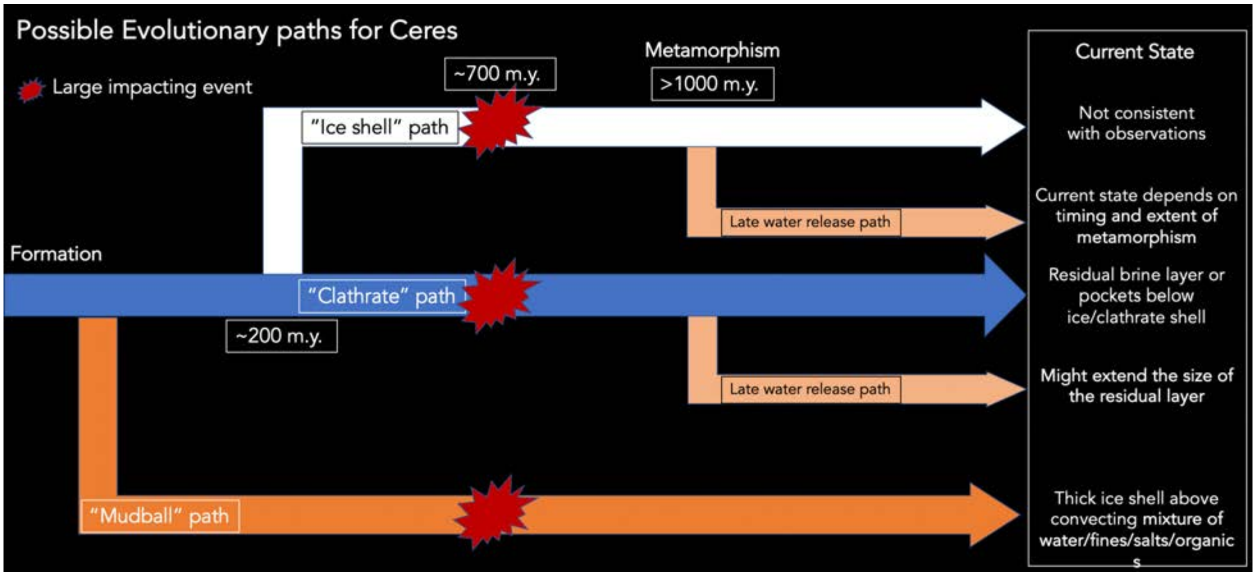

Figure 3. Possible explanations that have been suggested for explaining late activity in Ceres. All three scenarios assume a similar early evolution involving global melting from short-lived radioisotope decay heat. The top pathway is based on pre-Dawn models that assume an ice-dominated shell that might be convecting. In those models, thermal metamorphism was expected to happen but not fully modeled. The middle pathway assumes a shell rich in clathrate hydrates or ice-rock mixture such that convection onset is unlikely. That path enables the preservation of brines, with the potential addition of volatiles produced from thermal metamorphism. The bottom pathway assumes Ceres' heat transfer was driven by slow hydrothermal circulation in a thick ocean that remains at present. In that case, the mantle temperatures remain too low (<100^{o}C) for thermal metamorphism to develop.

The second hypothesis for explaining the presence of liquid in Ceres at present is the release of volatiles as a consequence of thermal metamorphism in the mantle (Melwani Daswani et al., 2021). This prospect was considered in several pre-Dawn models but its consequences on the state of the hydrosphere was not fully modeled. The timing of that event depends on the properties of the rocky mantle, and in particular its thermal conductivity, a parameter that is not well constrained. Hence, a wide range of evolution outcomes are possible. The most likely period for the onset of thermal metamorphism would be around 1 Gy, the time at which accumulated radiogenic heat reaches a maximum before decreasing as heat transport outpaces the exponentially decreasing heat production (Castillo-Rogez and McCord, 2010). Whether liquid release at the base of the crust or added to the residual ocean at the time would be preserved until present remains to be modeled.

Third, a different evolution pathway was proposed by Travis et al. (2018) whose "mudball" model assumes long-lived convection of an ocean loaded in silicate particles. In that model, a thick ocean remains until present and the mantle temperature remains below 100°C throughout Ceres' history. Pros and cons for that model are summarized in Castillo-Rogez and Bland (2021). The main open question is whether fine rock particles would remain in suspension for billions of years and avoid processes such as hydrolysis (Sirono, 2013) and flocculation (e.g., Kranck, 1973).

On top of these global evolution models, impacts may also act in creating transient melt (e.g., Bowling et al., 2019). In particular, basin-forming impacts in Ceres' early history (Marchi et al., 2016) likely created a significant amount of deep melt although this process and its consequences have not been modeled.

All of these processes are relevant to icy bodies and have already been proposed for some of them. For example, clathrate hydrates have been suggested as potentially being responsible for the preservation of liquid of other bodies with limited heat budget, such as Pluto and Callisto (Kamata et al., 2019). The occurrence of clathrate hydrates in icy moons has been predicted by previous models, e.g., Titan (Lunine and Stevenson, 1985, 1987) and Enceladus (Fortes, 2007) but their detection remains elusive. A future mission to Ceres that brings the geophysical tools necessary to probe Ceres' subsurface could distinguish between a clathrate-rich and an ice-rich crust.

Chemical evolution of water-rich worlds

Ceres' small heliocentric distance relative to other water-rich objects (e.g., icy moons of the giant planets and transneptunian objects) is such that water ice is not stable at its surface. Hence, the large deposit on Ceres' surface exposes products of water-rock interaction (including salts, phyllosilicates, carbonates, oxides, volatile and organic compounds) that are telling about chemical evolution (Section 2.1). By contrast, at other water-rich worlds, hints of non-ice compounds are instead largely diluted or masked by surface water ice, especially in the case of salts. This complicates even a first-order assessment of their chemistry unless non-ice materials are expressed in another way (e.g., the plume of Enceladus, or – for volatiles – the atmospheres of Titan, Triton, and Pluto), and some non-ice components may be radiation products rather than reflective of planetary interior chemistry (e.g., Brown and Hand, 2013).

It follows that the chemical investigation of Ceres, which has bulk properties (density ≈2000 kg/ m^3; volume-averaged radius 470 km) broadly similar to many water-rich moons and dwarf planets (densities ≈1000–3000 kg/m^3; radii ≈200–2500 km, e.g., Hussmann et al., 2006; Figure 2), provides a unique window into their water-rock chemistry. This includes an inference of the starting rocky and icy materials that these worlds accreted, the products of their interaction, and the partitioning of these products between the interior (solids and aqueous solution), surface, and outgassing.

In making such extrapolations, it is important to consider possible sources of differences in chemical evolution. A first source is the diversity of formation conditions as suggested by, e.g., the factor-of-three diversity in bulk densities across water-rich worlds. A second is a diversity of evolution pathways linked to different dynamical environments (collisions, tidal interactions) or heliocentric distances (e.g., affecting volatile escape). Nonetheless, the broad similarity between the observed or inferred distribution of these products at Ceres relative to other water-rich bodies confirms the usefulness of Ceres in providing information about the chemistry of other water-rich worlds (Neveu et al., 2017). The variety of surface ages on Ceres (Section 2.1) facilitates an assessment of the chemical changes that occurred throughout the significant fraction of solar system history spanned by these ages.

Several processes that affect the long-term evolution of Ceres' ocean (Figure 3) are also relevant to other mid-sized and large icy moons. First, a freezing ocean concentrates solutes, leading to saturated solutions, as might be the case for Ceres. Chemical alteration could proceed to equilibrium in Ceres, after which the ocean system would become chemically nonreactive. Release of mantle volatiles to the ocean by thermal metamorphism (Melwani Daswani et al., 2021), as well as radiolysis (e.g., Bouquet et al., 2017; Altair et al., 2018), can reintroduce chemical gradients into the ocean and/or shift ocean redox and pH conditions, maintaining limited disequilibrium (Figure 4). The effect of mantle devolatilization may be small in the case of a thick ocean but could be significant in the case of a residual liquid layer, as is expected in Ceres if the brine temperature is significantly below 273 K (Castillo-Rogez et al., 2019). Lastly, large impacts could potentially reach Ceres' ocean, at least when the crust was thinner, and introduce diverse material serving as substrate for late aqueous alteration.

The composition of evaporites recently exposed on Ceres' surface would inform the deep brine reservoir environmental conditions (Castillo-Rogez et al., submitted) and test whether these indicate a primary origin (residual endogenic liquid) or result instead from a second generation of liquid (e.g., impact melt). In order to fully investigate the nature of the brines, spatial variations of their texture, mineralogical, isotopic, elemental measurements, and phase relationships need to be resolved at the nanoscale (see Chan et al., 2018).

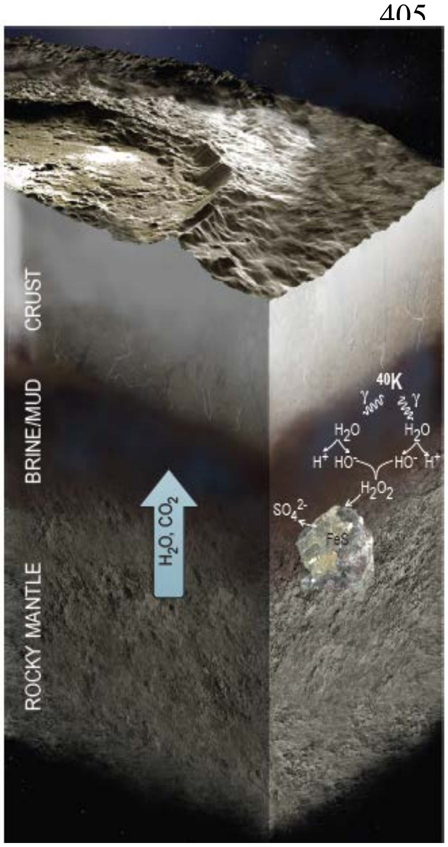

Figure 4. Summary of processes that may alter the chemical properties of a deep ocean over time: loss of volatile from the mantle upon thermal metamorphism, radiolysis, and impacts. Based after Altair et al. (2018); background rendering from Raoul Ranoa).

Carbon partitioning and fate of organic matter in long-lived liquid reservoirs

Organic matter (OM) in carbonaceous chondrites and carbonaceous interplanetary dust particles presents a high diversity of several thousands of organic compounds with structural and molecular continuum (Remusat et al., 2015; Alexander et al., 2017). In carbonaceous chondrites, which have been more extensively studied, organic matter is usually divided into two fractions: i) a soluble organic fraction (SOM), made of thousands of different small molecules (including carboxylic acids, amino acids, sugars, aliphatic, alcohols, e.g., Schmitt-Kopplin et al., 2010); ii) an insoluble organic fraction (IOM), represented as a macromolecular structure composed of aliphatic and aromatic carbon units with some heteroatoms (O, N, S) showing a high degree of cross-linking (Remusat et al., 2010) in interaction with a more volatile aromatic fraction containing molecular diversity (Danger et al., 2020). The diversity and abundance of organic matter identified to date in carbonaceous chondrites may both reflect a diversity of organic materials present in the protosolar nebula before planetary accretion (e.g., Kerridge 1999), and further enhancement via hydrothermal synthesis in chondritic parent bodies at conditions revealed in their mineral makeup (e.g., Brearley, 2006). The degree of organic matter transformation during hydrothermal activity is a major question in astrochemistry with implications for carbonaceous asteroids, Ceres, icy moons, as well as Mars' surface. The analysis of CM chondrites indicate that the proportion of IOM in CM chondrites diminishes with increasing alteration, while carbonate abundance increases concomitantly (Alexander et al. 2015), indicating a degradation of OM. Also, for amino acids found in some specific CC meteorites, such as CI, CM, CR, and the ungrouped Tagish Lake (e.g., Pizzarello et al., 2001, Pizzarello and Holmes, 2009), the relative abundance of amino acids declines with increasing degree of alteration in the CC, indicating that aqueous alteration processes altered the organic matter (Glavin et al. 2010).

Experimental studies showed that organic molecules are transformed during simulated aqueous activity (Kebukawa et al., 2013, 2020; Vinogradoff et al., 2018), producing numerous new soluble molecules and an insoluble organic matter with time and temperature. The nature and extent of organic matter evolution likely depends on the nature of the molecules, the interaction with the minerals, and the fluid properties (Vinogradoff et al., 2020; Haas et al., 2020; Gil-lozano, 2020). The correlation of organic material with phyllosilicates and carbonates observed at the surface of Ceres (De Sanctis et al., 2019; Raponi et al., 2017), suggests a close relationship between these phases and a possible co-evolution during hydrothermal processing. Ceres being the first main belt object at which strong and incontestable OM signature has been detected, further observations and analysis of this assemblage is of primary importance for understanding the evolution of organic matter in hydrothermal systems. Quantifying the extent of organic matter transformation in Ceres requires new observations, models and experiments in order to better constrain the role of the abundance of minerals, the water to rock ratio, and the salinity. Developing that knowledge will also be valuable for predicting the chemical evolution of organic material in carbonaceous-rich asteroids and ocean worlds.

Observations of organic matter in carbonaceous chondrites reveal a close association of likely soluble compounds with minerals, especially Mg-phyllosilicates after hydrothermal alteration (Le Guillou et al., 2014; Vinogradoff et al., 2017). Considering the similar composition of organic matter on Ceres' surface and its association with silicates, the differentiation event may have led to accumulation of organic matter in the rocky crust, simultaneously to geochemical processes. Fundamental thermodynamic considerations identify graphite, methane, and carbonate as the stable endmember carbon compounds depending on geochemical parameters including temperature, redox state, and pH, and assuming a long-lived system. Kinetic factors may play a role in the long-term evolution of natural carbon systems, and metastable organic compounds, such as kerogen of intermediate oxidation state (Seewald et al., 1998), may be important carbon reservoirs on long timescales (e.g., Shock & McKinnon, 1993; Neveu et al., 2017). Increased temperature, clay catalysts, and increased brine concentration tend to make water a better solvent for organics, and as a result the organics tend to be more reactive (less stable) in those environments (Siskin and Katritzky, 2001). On the other hand, if the system stayed cold, for example, then even over billions of years the kerogen-like insoluble organic matter may be preserved because of kinetics. Insoluble organic matter should start to evolve at temperatures above ~125 °C, which is expected in Ceres' mantle if the latter is compact (Castillo-Rogez et al. 2019). As the temperature of an aqueous system approaches the critical temperature for water, increased solubility of organic compounds and thermodynamic laws may lead to greater reactivity.

This process is consistent with observations of long-lived terrestrial fluids. Fracture fluids from the Kidd Creek mine in Canada, which have been dated to 2.6 Ga (Holland et al., 2013), may represent the best terrestrial analog for abiotic carbon chemistry in long-lived liquid reservoirs. Sherwood Lollar et al. (2021) identified three unique characteristics for Kidd Creek fluids in comparison to other terrestrial fluids: high concentrations of formate and acetate, acetate/formate molar ratios > 1, and ^{13}C enrichments of acetate. They attributed these characteristics to abiotic organic synthesis, including both mineral catalysis and radiolytic production, and suggest that the ^{13}C enrichment may be linked to a dissolved inorganic carbon source. In particular, they noted that the shorter residence times and lower acetate and formate concentrations reported at Witwatersrand Basin (Kieft et al., 2018; Onstott et al., 2006a,b) and the longer residence times and higher concentrations of acetate and formate at Kidd Creek are consistent with experimental radiolytic production rates for formate and acetate from carbonate and/or bicarbonate ions derived from dissolution of carbonates (Costagliola et al., 2017). Thus, radioactive decay of U, Th, and/or K may drive carbon chemistry away from thermodynamically stable carbonates towards organic acids. Such a scenario may ideally represent aging of carbon phases in aqueous systems.

Radiolysis may drive the environmental conditions towards more reducing conditions that eventually favor CH_4 production. Modeling of H_2 production suggests that for an intermediate-sized body like Ceres, radiolysis may contribute significantly to H_2 (Bouquet et al., 2017). While it has been suggested that the reduction of CO_2 to CH_4 may be kinetically inhibited in conditions relevant to Ceres (McKinnon, personal communication), the low H_2/CH_4 ratio of Kidd Creek fluids may provide evidence for formation of CH_4 in long-lived natural systems, perhaps via mineral catalysts (Sherwood Lollar et al., 2002; Reeves and Fiebig, 2020). Such considerations have previously been used to distinguish between modern and ancient formation of H_2 at Enceladus (Waite et al., 2017). The rate of radiolysis would be highest early in solar system history; however, the long half-lives of U and Th especially would lead to continued, significant radioactivity into the present era. Equilibrium speciation suggests U and Th remain in mineral phases under plausible ocean world conditions (Neveu et al., 2017), while K may leach into aqueous phases. Hydrothermal models of Ceres interior predicted serpentinization may cease within 2 to 3 Myr, but that radiogenic heating would maintain a mud mantle slurry with intimately intermixed mineral and fluid phases (e.g., Travis et al. 2018).

On Ceres, analyzing the detailed brine composition and searching for organic compounds embedded in the evaporites would help assess the state of the organic matter in Ceres' crust and residual ocean. The understanding of the co-relationship of salts and organic compounds upon freezing in conditions relevant to planetary bodies (e.g., potential flash freezing on an airless surface) is limited by lack of experimental work and relevant terrestrial analogs, although work in this area is expanding (Thomas et al., 2019; Buffo et al., 2020; Fox-Powell et al., 2021). In particular, two examples of extraterrestrial halite clasts have been found in the meteorite collections (Rubin et al., 2002) whose study has revealed various types of organic compounds on a scale of a few nanometers (Chan et al., 2018). Although the origin of these clasts is unknown, they are likely representative of the evaporite material found at Ceres (e.g., Fries et al., 2014).

Role of impacts in enabling subsurface-surface material transfer

Fractures created by large impacts on Ceres' surface could tap shallow fluid pockets in the crust, as has been suggested in the case of Occator crater (Quick et al., 2019; Raymond et al., 2020). More generally, evidence for old evaporites has been found in association with floor fractures at large craters such as Dantu (Stephan et al., 2018). Hence, it is likely that large impacts helped open pathways between the deep interior and the surface throughout Ceres' history. Domes found across the surface further indicate that volcanic or intrusive activity could have been a widespread process in space and time (Sori et al., 2018), but whether impact-induced fractures enabled that process is unknown. Davison et al. (2015) suggested that larger, basin-forming impacts could potentially excavate Ceres' upper mantle, which could potentially lead to regional-scale distribution of mantle material (Marchi et al., 2016).

Transfer of material in Ceres is expected to be unilateral, helped by the fact that the residual brine layer or reservoir is likely under pressure (e.g., Neveu and Desch, 2015). On the other hand, impactors could have contributed new material to the crust. Indeed, recent studies emphasized that an icy crust can retain a large fraction of impactor material. Bowling et al. (2019) modeled that up to 70wt.% of impactor material could be embedded in the melt chamber created by the impact-produced heat. Similarly, Marchi et al. (2018) showed that a large fraction of impactor material would accumulate in Ceres' outer 5-10 km.

In summary, impacts can facilitate material transfer and introduce new material into the crust. As shown in the case of Occator crater, impacts energetic enough to create fractures that reach below the crust can lead to the mixing of brine material with impact melt in the shallow subsurface. This situation can introduce geochemical gradients in the crust. The redistribution of impact-induced or residual deep and crustal brines can be driven by the thermal alteration of the surface after impact, driving brines through the subsurface and towards the surface through a combination of hydrologic, topographic, and material gradients (Schmidt et al., 2020), which is common in terrestrial environments with freezing or frozen ground. Similar cryo-hydrologic and hydraulic formation of surface features, including shallow brine zones, has been proposed for Europa (Schmidt et al., 2011; Schmidt, 2020) and may be relevant for Ceres (where it could be investigated in relative detail) and other ocean worlds. Since the freezing of brines can chemically fractionate this potential mixture of initial and impactor material (e.g., Buffo et al., 2020; Buffo et al., 2021, Fox-Powell et al., 2021), much about drivers of chemical evolution in crustal water solutions could be learned from geophysical probing of the region below Occator crater. Such probing includes visualization of its fracture network and the geometry of the residual impact melt chamber using radar techniques and electromagnetic sounding (Grimm et al., submitted).

3.2 Other Ceres Science Themes

Early Solar System History and Dynamical Evolution

The widespread occurrence of ammoniated phyllosilicates and salts and carbon on the surface of Ceres suggests that Ceres must have formed in a region of the Solar System where primordial thermodynamic conditions allowed it to effectively retain large amounts of nitrogen and carbon. Places of formation located in the main asteroid belt, in the interplanetary disk between the orbits of Jupiter and Neptune, or in the Kuiper belt located beyond the orbit of Neptune, can be considered, assuming that Ceres (or the materials from which Ceres formed) then migrated from those regions up to today's position.

While the Jupiter-Saturn region has been proposed as the source of most C-type (carbonaceous and hydrated) asteroids and may represent Ceres' most likely formation region (e.g., Raymond and Izidoro, 2017; Raymond and Nesvorny, 2020), in recent times the possibility has materialized that the core of Jupiter itself may have formed further from the Sun and then migrated inward, dragging with it a multitude of minor bodies (Bosman et al., 2019). The overabundance of elemental nitrogen measured in Jupiter's atmosphere with respect to the protosolar value (Atreya et al., 2018) implies that the planet's core must have formed outside or just inside the N_2 ice line (Öberg and Wordsworth, 2019; Bosman et al., 2019). The position of the latter is difficult to quantify in the primordial Solar System, but it is of the order of a few tens of AU, which moreover would point toward a pebble accretion or gravitational instability origin for Jupiter (Bosman et al., 2019). Alternatively, of amorphous ice with adsorbed volatiles may have drifted inward to enrich the gaseous phase of the protosolar nebula with elements such as N, once this ice complex crosses the amorphous ice snowline, that is the amorphous-to-crystalline ice transition zone.

The rapid formation of Jupiter likely destabilized the orbits of nearby planetesimals. Under the action of the aerodynamic drag due to nebular gas, a fraction of planetesimals was deposited onto stable orbits inside Jupiter. This process is effective in populating the main outer belt with C-type asteroids that originated from a large region (5-20 AU) of the disk (Raymond and Izidoro, 2017). However, this scenario implies that we should find many other small bodies in the asteroid belt with a composition similar to Ceres, whereas Ceres' bulk composition is atypical compared to C-type asteroids. An explanation for this apparent paradox may be that Ceres may have undergone a certain degree of pebble accretion before being scattered inwards. Because the efficiency of this process is directly proportional to the size of planetesimal (Johansen et al., 2015), a primordial body the size of Ceres could have grown more volatile-rich from pebbles that originated in the outer solar system than similar bodies of smaller size (Kretke et al., 2017). Alternatively, Ceres could have started out from the same composition as C-types but now displays a different surface composition because its physico-chemical evolution was different. (e.g., more prolonged and/or hotter aqueous alteration, material concentration on the surface).

A competing origin for the high abundance of ammonia found at Ceres is that it was released from the metamorphism of organic compounds (McSween et al., 2018). Experimental work by Pizzarello and Williams (2011) suggests that pressures of tens of megapascals and temperatures of a few hundred degrees are sufficient to drive organic breakdown on a short timescale. These conditions are expected to have prevailed in Ceres' mantle for an extended period of time (Castillo-Rogez and McCord, 2010).

In summary, the origin of Ceres is a major open question with fundamental implications about the origin of volatiles and organic matter in the inner solar system (e.g., Budde et al., 2019), the mechanisms driving the solar system architecture, and the role that large planetesimals could have played by impacting the growing planets (e.g., Salmon and Canup, 2019). Castillo-Rogez et al. (2020) pointed out that analysis of returned material from Ceres in Earth's facilities is the best approach to resolving the origin of Ceres because the complex and evolving chemical and dynamical framework describing the early solar system warrant adaptability in the measurements to be carried out, and because of additional complications specific to dealing with a very large planetesimal (e.g., pebble accretion, alteration during evolution).

Ceres as a natural laboratory to study geological processes in ice-rich crust

Geological history is well recorded on Ceres relative to resurfaced worlds like Europa. Ceres may also represent an advanced, less active state of worlds like Europa, and thus represents a major endmember on the varied spectrum of icy objects. In both ways, Ceres may serve an analogous– and as important–role in our understanding of icy worlds as the Moon does in our understanding of terrestrial planets.

As a result of Ceres' special role in our understanding of icy worlds, many icy geological processes that operate throughout the Solar System would be elucidated by further study at Ceres (Figure 5). Impact cratering, one of the dominant geological processes in the Solar System, has been shown to result in similar crater sizes and morphologies on Ceres as on other icy bodies (Hiesinger et al., 2016; Schenk et al., 2021), and thus Ceres holds promise for more detailed study of impacts into icy targets. Cryovolcanism has likely been an important process of interior-surface exchange on a number of icy worlds (e.g., Enceladus, Spencer and Nimmo, 2013), and Ceres provides an opportunity for further study of its mechanisms and products. Geophysical analysis of icy crustal structure has been performed on Ceres with more precise data than on any other icy object (Park et al., 2020), but can be greatly improved upon with future missions. Tectonic processes likely also occur on Ceres (e.g., Bland et al., 2019; Ruiz et al., 2019) and may elucidate icy tectonics in general. Geologic processes on Ceres including tectonics, landslides and other material flows (e.g., Schmidt et al., 2017; Hughson et al., 2019) as well as cryo-hydrologic features (Schmidt et al., 2020) may involve a mixture of silicates, ice, and water common to glacial environments on the Earth and Mars, and thus represent another opportunity to explore this understudied physical regime. Additional study of Ceres' interor structure would inform when and how ice-rich bodies differentiate, a process with major implications for planetary evolution. Finally, analysis of the Dawn data raised the question of the level of exogenic inputs to the surface and shallow subsurface of water-rich airless bodies (Vernazza et al. 2017; Marchi et al. 2018). This topic is critical because the introduction of exogenic material into the crust, especially if it also involves impact melt, carries the potential to significantly alter the crustal composition (Bottke et al., 2013). In many ways, Ceres thus provides an accessible natural laboratory for understanding icy geological processes.

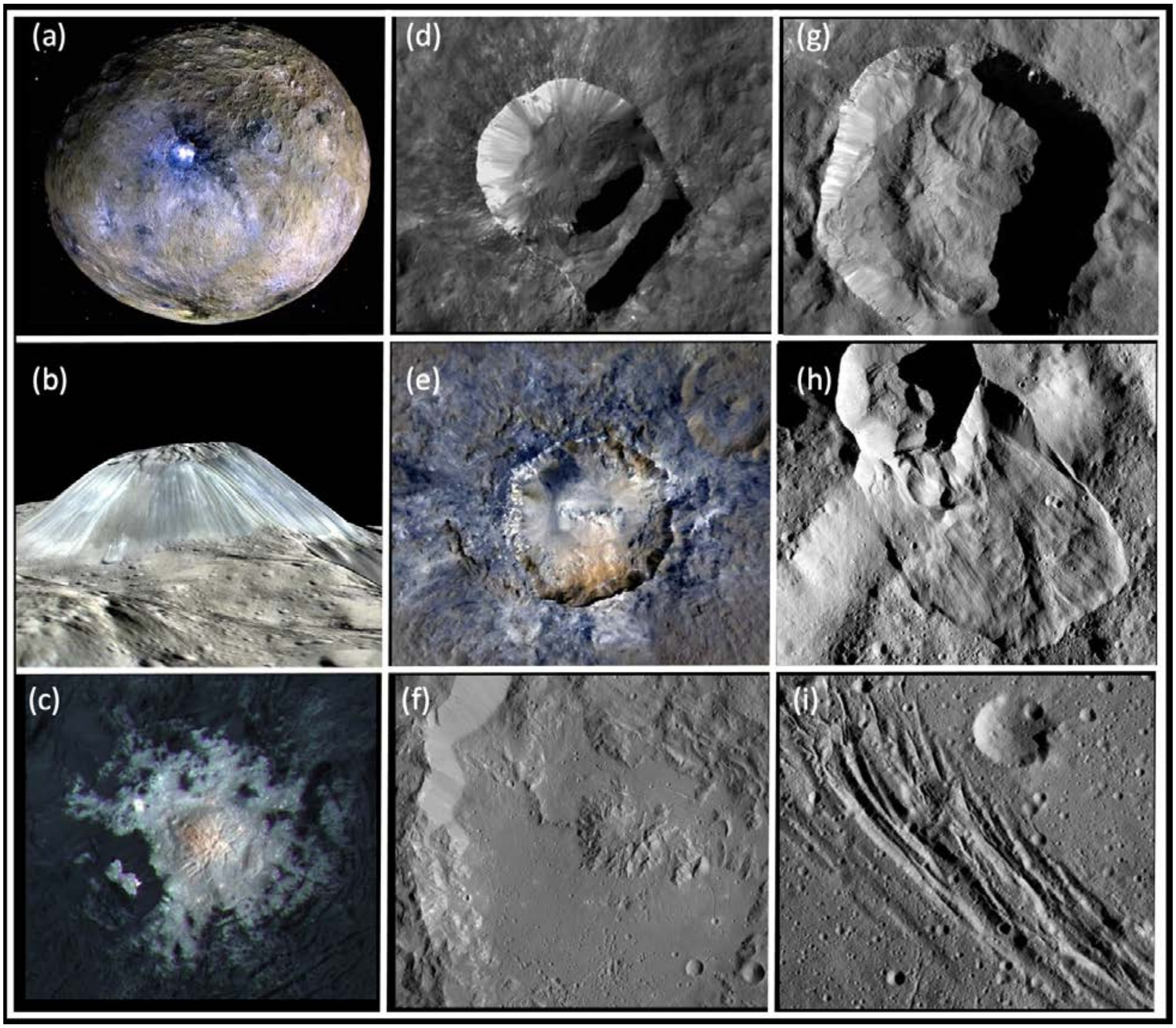

Figure 5. Examples of landforms found at Ceres that make it a natural laboratory to study geological processes in ice-rich crust. Left column: Expressions of brine-driven activity: (a) recent evaporite exposure in Occator crater; (b) Ahuna Mons, a volcano built with rock and brine (Ruesch et al., 2016, 2019a); (c) close-up view of Cerealia Facula. Cerealia Tholus in the center displays evidence of hydrohalite at its top (here appearing in light pink in this enhanced color version, De Sanctis et al., 2020). Middle column: influence of ice on crater properties: (d) direct exposure of ice at Oxo crater (Combe et al., 2016); (e) fresh salt-rich ejecta and central crest in Haulani crater (Tosi et al., 2018); (f) flat floor resulting from impact-generated heat and melting in Ikapati crater. Right column: other ice-driven landforms found on Ceres' surface: (g) glacier-like features in Juling crater (Raponi et al., 2018); (h) landslide whose morphology indicates a high ice content (Schmidt et al., 2016); (i) Normal faulting in an ice rich crust at Nar Sulcus in Yalode crater (Hughson et al.,

2018). Credit: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA, based on PIA22090 that contains details information on the origin of these pictures.

Ceres as a natural laboratory for understanding processes affecting airless bodies

Transient atmospheres and exospheres of airless bodies are known on Mercury, the Moon, and some icy moons of the outer solar system. These are caused either by an interaction of the space environment (meteorites, radiation) with the surface or by endogenic processes. Thus, a systematic study of these phenomena can reveal important clues on the nature of surfaces and subsurface geologic processes.

Water ice sublimation due to solar irradiation and solar wind particle bombardment are possible mechanisms for Ceres' weak exosphere (e.g., Landis et al., 2018). Some of the released water molecules can be re-trapped in permanently shadowed polar depressions, leading to thin ice deposits (Schorghofer et al., 2016; Platz et al., 2017). In addition, endogenic sources of various molecules (H_2O, CH_4, CO_2) are conceivable (Nathues et al., 2017). Cryovolcanic processes, as suggested for Occator crater (e.g., Nathues et al., 2020), could be responsible for the development of a transient exosphere composed of different molecules and particles. Thus, Ceres is expected to be an ideal target to characterize the exosphere or transient atmosphere of an airless body. However, the search for these features has proved difficult. While a thin OH exosphere was concluded from observations of the International Ultraviolet Explorer by A'Hearn and Feldman (1992), other studies using ground-based and space-based telescopic data could not confirm its existence (Rousselot et al., 2011; Roth et al., 2016, 2018). Kueppers et al. (2014) reported occasional water vapor from spectral data of the Herschel space observatory. Further evidence of a transient cerean atmosphere was derived from observations of Dawn's Gamma Ray and Neutron Detector upon arrival at Ceres (Villarreal et al., 2017), likely correlated with solar activity. However, since the Dawn payload was not designed to detect an exosphere or a thin atmosphere, their density and composition are until today largely unexplored.

Exposed water ice, which could be a possible source for an exosphere, was detected at several sites (Combe et al., 2016, 2018); even a seasonal variation of ice exposure in the Juling crater has been reported by Raponi et al. (2018). In addition, high phase angle imaging with the Dawn Framing Camera revealed an unusual light scattering behavior associated with the Occator faculae. This unique light scattering was attributed to an additional component to the solid surface, i.e., an optically thin and near-surface haze layer (Nathues et al., 2015, 2019; Thangjam et al., 2016). The hydrohalite detected by De Sanctis et al. (2020) at Occator tholus is a possible source for the ongoing production of water and haze. The database on exospheric observable effects, events, and sources at Ceres is still sparse and requires follow-on observations to derive radial density distribution, composition, and flux rates.

4. Approaches to the Future Exploration of Ceres

This section addresses approaches to further the exploration of Ceres, with future spacecraft but also via theoretical and experimental research, field work at terrestrial analogs, and Earth-based observations.

4.1 Future Missions

A future mission to Ceres could address open questions about Ceres' past and current habitability potential and address some of the aforementioned processes in greater depth. Direct surface access of material evolved from the deep brines provides a unique opportunity to investigate the evolution of long-lived oceans. A recent study developed under NASA's Planetary Mission Concept Study (PMCS) program showed that significant progress in our understanding of Ceres as an evolved ocean world requires resources offered by NASA's *New Frontiers* and *Flagship* programs (Castillo-Rogez et al., submitted). The PMCS study identified two mission architectures that can address a majority of the science questions listed above 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 (Figure 6). 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 (Grimm et al., in press).

Ceres' low gravity renders wheeled platforms mostly impractical but a lander can access multiple sites on Ceres via thruster-assisted hopping (Figure 5). The number and separation of sites that may be reached depend on mass budget and risk posture. Scully et al. (accepted) demonstrated that many potential landing sites are available in the regions of interest based on the best resolution data returned by the Dawn mission. Furthermore, that study assessed the accessibility of sites at Haulani craters and Ahuna Mons, which are also of scientific interest: Haulani's ejecta are excavated from the shallow crust, which records the conditions in Ceres' early ocean, whereas a greater understanding of Ahuna Mons' composition, flank structure, and subsurface structure would help narrow down the mechanism driving the transfer of material from the upper mantle brine region to the surface.

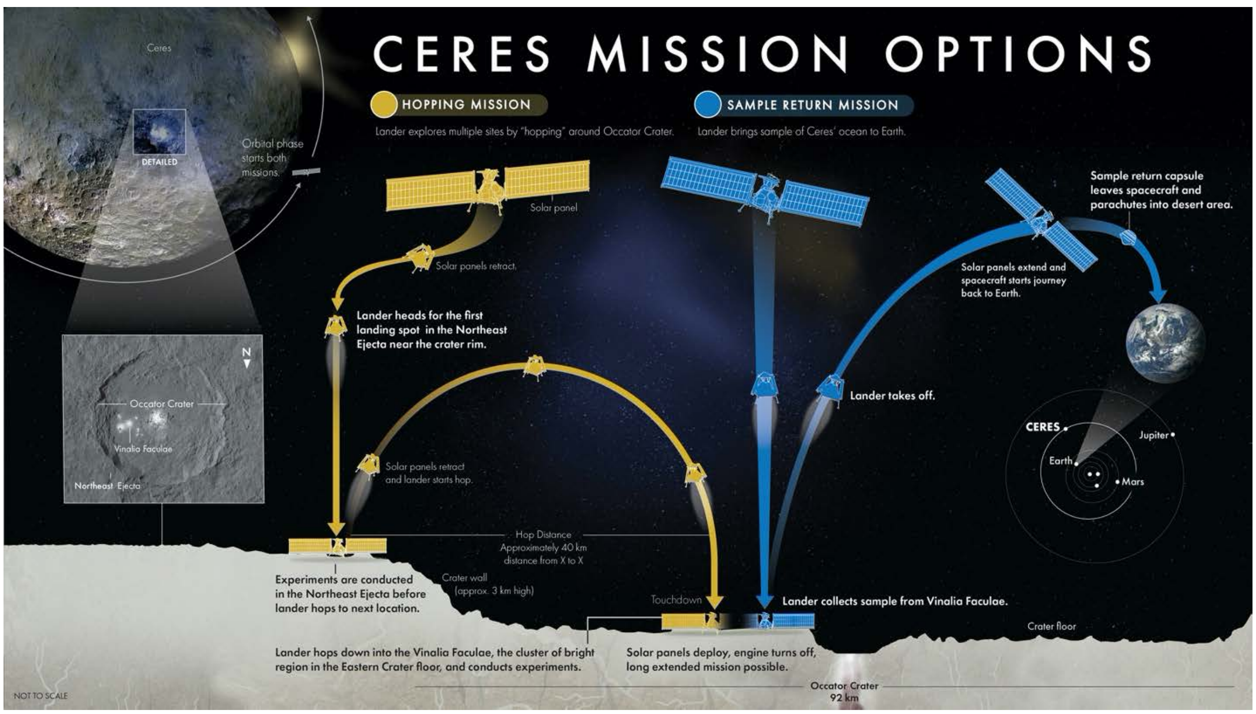

Figure 6. Two architectures proposed for addressing key open questions about Ceres' endogenic activity, habitability potential, and origin. The in situ architecture is a hopper that explores two sites at Occator crater, the first one at the northeastern ejecta blanket called Homowo Regio and the second one in the Vinalia Faculae. The second concept would return a sample from the Vinalia Faculae. Both concepts would include an orbital phase during which high-resolution imaging and gravity data are acquired at key landforms of potential cryovolcanic origin. Also, in both concepts, the in situ phase includes an electromagnetic investigation that would map the distribution of brines below Occator crater, down to 50 km depth (Castillo-Rogez et al., submitted). Credit: Raoul Ranoa.

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 already leverage investments for previous projects, e.g., terrain relative navigation (Mars 2020) and throttleable descent engines (Europa Lander pre-project).

4.2. Supporting Activities

The list of activities below needed to progress with our understanding of Ceres and prepare for future exploration is not exhaustive but illustrates possible pathways.

Data Analysis: In order to increase the science return from the Dawn mission and prepare for a follow-on mission to Ceres, we recommend continuous support to the following areas; (1) Data Analysis Programs would support a vast array of investigations by the broad community that build on, revisit, and expand upon previous analyses of the Dawn data; (2) 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; (3) 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 importance 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 a Ceres-like body (e.g., Chan et al. 2018); 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; 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 and evaporite deposit age 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; synthesis and characterization of analog materials to provide comparison datasets at appropriate conditions for Ceres' surface, and to support the definition and development of new instruments, e.g., to investigate organic carbon in mud and/or salt 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 specific interest are soda lakes (Castillo-Rogez et al., 2020), hydrothermal systems, landslide and ejecta deposits, salt domes and other salt tectonics structures, and periglacial features such as rock glaciers, protalus lobes, and pingos (Schmidt et al., 2017, 2020). Potential analog sites on Earth can be used for testing relevant planetary instruments, surveying strategies, and sampling systems required for future missions to Ceres. This is particularly relevant for landed assets where little is currently known about the sub-meter scale geology and physical properties of the surface.

Periglacial environments on Earth are also scientifically interesting analogs for various locations on Ceres because of its inferred subsurface ice content (e.g., Prettyman et al., 2017) and myriad surface features whose morphologies suggest an icy origin (e.g., Schmidt et al., 2017, 2020; Hughson et al., 2019). Beyond magnetotelluric sounding identified in the PMCS to investigate Ceres' deep subsurface (Grimm et al., submitted), techniques such as ground penetrating radar, frequency- and time-domain electromagnetic sounding could further reveal Ceres' shallow stratigraphy. Deploying these techniques in analog periglacial environments would enhance the interpretation of future electromagnetic geophysical results from Ceres (e.g., https://schmidt.eas.gatech.edu/pingo-starr/). While glaciers and ice sheets have been extensively subjected to geophysical investigation, more Ceres-like analogs such as protalus lobes, alpine tundra, and pingo covered landscapes have remained relatively understudied. Understanding how electromagnetic systems respond in both evaporitic and periglacial environment, as well as a deeper geophysical understanding of periglacial systems on Earth are critical for preparing for landed geophysical exploration of Ceres.

Ground-Based Observations: Telescopic observations from Earth or near-Earth space should continue, for example to address the following questions: (a) the origin of Ceres' sporadic outgassing activity with regular (perihelion and seasonal) and reactive observations following the release of solar energetic protons (Villarreal et al., 2017); (b) additional constraints on Ceres' surface composition from observations in the ultraviolet (e.g., Hubble Space Telescope) and mid-infrared wavelengths (e.g., James Webb Space Telescope Mid-InfraRed Instrument), which are complementary to the 0.4-5 µm range observed by Dawn. The next generation of space telescopes could also revolutionize the study of Ceres. The Large UV, Optical and InfraRed Surveyor mission (LUVOIR), a 15 m or 8 m primary space telescope being considered for selection by the 2020 Astrophysics decadal survey, made the case for further spatially resolved imaging (11-20 km/pixel) and spectroscopy (tens of km) of the surface of Ceres. The high spectral resolution of LUVOIR or similar telescopes across the UV-near IR wavelength range would allow global studies of Ceres' composition, and searches for outgassing in the UV (LUVOIR Team 2019).

5. Conclusions

Ceres is a rich destination that displays evidence for features pertinent to ocean world science, such as forms of brine-driven effusion, organic matter, geological processes, impact melt, etc. It is also the large ice-rich object closest to Earth, accessible for in situ exploration and/or sample return under a *New Frontiers*- or small *Flagship*-class cost cap because of its relative low gravity. Sampling freshly exposed evaporites would provide insights into the chemical and physical properties of a long-lived brine reservoir and test hypotheses of interest to ocean worlds, such as the prospect for the late enrichment of a residual ocean in volatiles released from the mantle and radiolysis as a long-term chemical energy source. Long-lived activity in Ceres requires processes or crustal properties that remain to be confirmed but are expected to also apply to other dwarf planets and icy moons. More generally, Ceres might be the first example of "muddy" ocean world, a class of bodies that might be frequent among mid-sized icy bodies whose hydrosphere may be frozen but whose mantle porosity is filled in with brines for an extended period of time. Processes known to occur in Earth' sediments, such as organic chemistry or radiolysis, are presumably relevant and their occurrence in Ceres may be tested in future exploration.

Per its high content in nitrogen and carbon, Ceres (or at least the materials from which it formed) is suspected to originate from the outer solar system, although competing hypotheses remain. Resolving this question is fundamental to firmly anchor our understanding of early solar system evolution and the origin of water and organics in the inner solar system. Hence, determining 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 are additional drivers for the future exploration of Ceres.

Several recent mission concepts have independently emphasized science objectives that include a quantification of Ceres' past and current habitability and use Ceres as a test case for unraveling the habitability, over time, of volatile-rich bodies. The Ceres Planetary Mission Concept Study concluded that significant progress along the Roadmap to Ocean Worlds (Hendrix et al., 2019) can be achieved with in situ exploration, either at multiple sites, or at a single site and with a sample return. However, only a sample return mission can fully retire questions about Ceres' origin and the habitability potential of its residual brines. 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 (Burbine and Greenwood, 2020; Gassot et al., 2020; Shi et al., submitted).

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. 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.

Acknowledgements: Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

REFERENCES

A'Hearn, M. F., & Feldman, P. D. (1992). Icarus, 98(1), 54–60. https://doi.org/10.1016/0019-1035(92)90206-M

Alexander C. M. O'D., Howard K. T., Bowden R., and Fogel M. L. 2013. *Geochimica et Cosmochimica Acta* 123, 244-260.

Alexander, C. M. O'D., Bowden R., Fogel M. L., and Howard K. T. 2015. *Meteoritics & Planetary Science* 50, 810-833.

Alexander, C. M. O'D., et al. (2017) *Chem. Erde - Geochem.* 77, 227–256, doi:10.1016/j.chemer.2017.01.007.

Ammannito, E., DeSanctis, M.C., Ciarniello, M., et al. (2016) Science 353, aaf4279. https://doi.org/10.1126/science.aaf4279

Atreya, S.K., Crida, A., Guillot, T., et al. In: Saturn in the 21st Century, ed. K. Baines et al. (Cambridge: Cambridge Univ. Press), 5 (2018). Doi: 10.1017/9781316227220.002.

Bierson, C.J., Nimmo, F. and Stern, S.A. (2020) *Nature Geoscience* 13, 468-472.

Bland, M.T., Raymond, C.A., Schenk, P.M., et al., 2016. *Nature Geosci* 9, 538–542. https://doi.org/10.1038/ngeo2743

Bland, M.T., et al. (2019) *Nature Geosciences* 12, 797-801

Bosman, A.D., Cridland, A.J., Miguel, Y. A&A 632, L11 (2019). Doi: 10.1051/0004-6361/201936827.

Bottke, W.F., Vokrouhlický, D., Nesvorný, D. and Moore, J.M. (2013) *Icarus* 223, 775-795. https://doi.org/10.1016/j.icarus.2013.01.008

Bouquet, A., Glein, C.R., Wyrick, D. and Waite, J.H., 2017. *The Astrophysical Journal Letters* 840, L8. https://doi.org/10.3847/2041-8213/aa6d56

Bowling, T.J., Ciesla, F.J., Davison, T.M., et al. (2019) *Icarus* 320, 110-118.

Brearley A. J., 2006. In *Meteorites and the Early Solar System II*, editors Lauretta D. S. and McSween H. Y., pp. 587-624, University of Arizona Press.

Brown, M., Hand, K. (2013), *Astronom. J.* 145.

Browning L. B., McSween H. Y., and Zolensky M. E. 1996. *Geochimica et Cosmochimica Acta* 60, 2621-2633.

Buczkowski, D. L., et al. (2016) Science 353, id.aaf4332.

Buczkowski, D. L., et al. (2018) JGR 123, 3188-3204.

Budde+ (2019) *Nature Astron.* 3, 736-741.

Buffo, J. J., B.E. Schmidt, C. Huber, C. C. Walker (2020) *JGR* Planets. https://doi.org/10.1029/2020JE006394

Buffo, J. J., Meyer, C. R., Parkinson, J.R.G, (2021) In revision, JGR: Planets, posted online at ESOARXIV https://doi.org/10.1002/essoar.10504589.1

Burbine, T., Greenwood, R. (2020) *SSR* 216:59.

Carrozzo, F. G., et al. (2018) *Science Advances* 4, e1701645.

Castillo-Rogez J. C. and McCord T.B., 2010. Icarus 205, 443-459.

Castillo-Rogez, J., Neveu, M., McSween, H.Y., et al. (2018) Meteoritics & Planetary Science 53, 1820–1843. https://doi.org/10.1111/maps.13181

Castillo-Rogez, J. C., et al. (2019) *Geophys. Res. Lett.* 46, 1963-1972.

Castillo-Rogez, J. C. (2020) *Nature Astron.* 4, 732-734.

Castillo-Rogez, J. C., et al. (2020) *Astrobiology*, Feb 2020.269-291.

Castillo-Rogez, J. C., et al. submitted to *The Planetary Science Journal*, in revisions.

Castillo-Rogez and Bland (2021) Cambridge University Press, in press.

Chan, Q., et al. (2018) *Science Advances* 2018;4: eaao3521.

Combe, J.-P., McCord, T.B., Tosi, F., et al. (2016) *Science* 353, aaf3010. https://doi.org/10.1126/science.aaf3010

Combe, J.-P., Raponi, A., Tosi, F., et al. (2018) Icarus, 318, 22–41. https://doi.org/10.1016/j.icarus.2017.12.008

Costagliola, A., Vandenborre, J., Blain, G., et al. 2017. The Journal of Physical Chemistry C 121, 24548-24556. https://doi.org/10.1021/acs.jpcc.7b07299

Danger, G., Ruf, A., Maillard, J., et al. 2020, Planet Sci J, 1, 55, https://iopscience.iop.org/article/10.3847/PSJ/abb60f

Davison et al. (2015) 46th Lunar and Planetary Science Conference, LPI contrib. no. 1832, p.2116.

De Sanctis, M.C., Ammannito, E., Raponi, A., et al. (2015) Nature 528, 241–244. https://doi.org/10.1038/nature16172

De Sanctis, M.C., Raponi, A., Ammannito, E., et al. (2016) Nature 536, 54–57. https://doi.org/10.1038/nature18290

De Sanctis, M. C.,et al. (2017) *Science* 355, 719-722.

De Sanctis, M. C., et al. (2019) MNRAS 482 2407–2421, https://doi.org/10.1093/mnras/sty2772

De Sanctis, M. C., Ammannito, E., Raponi, A., et al. (2020) *Nat Astron* 4, 786–793. https://doi.org/10.1038/s41550-020-1138-8

Denton+ (2021) *Geophys. Res. Lett.* 48.

Desch, S., Neveu, M. (2017) *Icarus* 287, 175-186.

Ermakov, A., et al. (2017) *Journal of Geophysical Research* 122, 2267–2293.

Fagents, S. A. (2003) *Journal of Geophysical Research* 108, 5139.

Formisano, M., et al. (2018) *JGR* 123, 2445-2463.

Formisano, M., Federico, C., Castillo-Rogez, J., De Sanctis, M.C. and Magni, G. (2020) *Monthly Notices of the Royal Astronomical Society* 494(4), 5704-5712.

Fortes, A. D. (2007) Icarus 191, 743-748.

Fox-Powell, M., Cousins, C. R. (2020) *J. Geophys. Res.* Planets 126, ee2020JE006628

Fries, M., et al. (2014) Workshop on the Habitability of Icy Worlds, held 5-7 February, 2014 in Pasadena, California. LPI Contribution No. 1774, p.4078.

Fu, R. R., et al. (2017) The interior structure of Ceres as revealed by surface topography, *EPSL* 476, 153-164.

Gassot et al. 2020 Acta Astronautica https://doi.org/10.1016/j.actaastro.2020.12.050.

Gil-lozano 2020 *Scientific report*, DOI: 10.1038/s41598-020-71657-9

Glavin, D. P., Callahan, M. P., Dworkin, J. P., Elsila, J. E. (2010) *MaPS* 45, 1948–1972. doi:10.1111/j.1945-5100.2010.01132.x

Grimm, R., et al., Submitted to *Icarus*.

Haas et al, 2020, *Communication Chemistry* doi.org/10.1038/s42004-020-00387-w

Hamilton V. E., Goodrich C. A., Treiman A. H., et al. (2020) *Nature Astron*omy, doi.org/10/1038/s41550-020-01274-z.

Hendrix, A. R., et al. (2019) The NASA Roadmap to Ocean Worlds, Astrobiology, 19:1.

Hesse, M. A., Castillo-Rogez, J. C. (2019) *Geophysical Research Letters* doi.org/10.1029/2018GL080327

Hiesinger, H., et al. (2016), *Science* 353, aaf4759, doi:10.1126/science.aaf4759

Holland, G., Sherwood Lollar, B., Li, L., et al., 2013. *Nature* 497, 357-360 https://doi.org/10.1038/nature12127

Howard K. T., Benedix G. K., Bland P. A., and Cressey G. 2011. *Geochimica et Cosmochimica Acta* 75, 2735-2751.

Howard K. T., Alexander C. M. O'D., Schrader D. L., and Dyl K. A. 2015. *Geochimica et Cosmochimica Acta* 149, 206-222.

Hughson, K. H. G., Russell, C. T., Schmidt, B. E., et al. (2018) *Geophys. Res. Lett.* 46, 80-88.

Hughson, K. H. G., Russell, C. T., Schmidt, B. E., et al. (2019). *JGR* Planets. https://doi.org/10.1029/2018JE005666

Hussmann, H., Sohl, F. and Spohn, T. (2006) *Icarus* 185, 258-273

Johansen, A., Mac Low, M.-M., Lacerda, P., Bizzarro, M. Science Advances 1 (3), id. 1500109 (2015). Doi: 10.1126/sciadv.1500109.

Johnson and Sori (2020) *J. Geophys. Res. Planets* 125.

Kamata, S., Nimmo, F., Sekine, Y., et al. (2019) *Nature Geoscience* 12, 407-410.

Kaplan, H., et al. (2018) Geophys. Res. Lett. 2018, 45, 5274–5282, doi:10.1029/2018GL077913.

Keane, J.T., Matsuyama, I., Kamata, S. and Steckloff, J.K. (2016) *Nature* 540, 90-93.

Kebukawa, Y., Kilcoyne, D., Cody, G. (2013) ApJ 771 19.

Kebukawa, Y., et al, 2020 Icarus 347.

Kerridge, J. F. (1999) In: *Composition and Origin of Cometary Materials*, Eds. K. Altwegg, P. et al., *Space Science Series of ISSI* 8, Springer, 275-288.

Kieft, T.L., Walters, C.C., Higgins, M.B., et al. (2018) Organic geochemistry 118, 116-131. https://doi.org/10.1016/j.orggeochem.2018.02.003

Kranck, K. (1973) *Nature* 246, 348-350.

Kretke, K.A., Bottke, W.F., Levison, H.F., et al. (2017) Accretion: Building New Worlds Conference, Proceedings of the conference held 15-18 August, 2017 in Houston, Texas. LPI Contribution No. 2043, id.2027. https://www.hou.usra.edu/meetings/accretion2017/pdf/2027.pdf.

Krohn, K., et al. (2016) *GRL* 43, 11,994-12,003.

Krohn, K., et al. (2018) *GRL* 45, 8121-8128.

Krohn, K., et al. (2020) *PSS* 187, id. 104955.

Küppers, M., O'Rourke, L., Bockelée-Morvan, D., et al. (2014) Nature, 505(7484), 525–527. https://doi.org/10.1038/nature12918

Landis, M., et al. (2017) *JGR* 122, 1984-1995.

Landis, M. E., Byrne, S., Combe, J.-P., et al. (2019) Journal of Geophysical Research: Planets, 124, 61–75 https://doi.org/10.1029/2018JE005780

Le Guillou, C., et al. (2014) Geochimica et Cosmochimica Acta 131, 368–392.

Lunine, J. I., Stevenson, D. (1985) *AJ Suppl. Series* 58, 493-531.

Lunine, J. I., Stevenson, D. (1987) *Icarus* 70, 61-77.

LUVOIR Team, 2019. The LUVOIR mission concept study final report. arXiv preprint arXiv:1912.06219.

Marchi, S., et al. (2016) *Nature Comm.* 7, 12257.

Marchi, S., et al. (2019) *Nature Astron.* 3, 140-145.

Mao X., McKinnon W. B., 2018. *Icarus* 299, 430-442.

Matthewman, R., Martins, Z. and Sephton, M.A., 2013 *Astrobiology* 13, 324-333 https://doi.org/10.1089/ast.2012.0820

McCord, T.B., Sotin, C., 2005. Ceres: Evolution and current state. J. Geophys. Res. 110, E05009. https://doi.org/10.1029/2004JE002244

McSween H., Emery J.P., Rivkin A.S., et al. (2018) *Meteoritics & Planetary Science* 53, 1793-1804.

Melwani Daswani *et al.,* submitted to *Geophys. Res. Lett.*

Mousis, O., Ronnet, T., Lunine, J.I. The Astrophysical Journal, 875:9. Doi: 10.3847/1538-4357/ab0a72.

Nathues, A., Hoffmann, M., Schaefer, M. et al. Nature 528, 237–240 (2015). https://doi.org/10.1038/nature15754

Nathues et al. 2019, *The Astronomical Journal* 158, Number 2

Nathues et al. (2017), The Astronomical Journal,153:112(12pp).

Nathues, A., Schmedemann, N., Thangjam, G. et al. Nat Astron 4, 794–801 (2020). https://doi.org/10.1038/s41550-020-1146-8

Neesemann, A., Van Gasselt, S., Schmedemann, N., et al. (2019) *Icarus* 320, 60-82. https://doi.org/10.1016/j.icarus.2018.09.006

Neumann, W., et al. (2020) A&A 633, id. A117.

Neveu M. and Desch S.J., 2015. *Geophysical Research Letters* 42, 10,197-10,206.

Neveu, M., Desch, S.J. and Castillo-Rogez, J.C., 2015. *Journal of Geophysical Research: Planets* 120, 123-154.

Neveu, M., Desch, S.J. and Castillo-Rogez, J.C. (2017) *Geochimica et Cosmochimica Acta*, 212, 324-371.

Nimmo, F., Hamilton, D.P., McKinnon, W.B., et al. (2016) *Nature* 540, 94-96.

O'Brien, D.P., Sykes, M.V., 2011. Space Science Reviews 163, 41–61. https://doi.org/10.1007/s11214-011-9808-6

Öberg, K.I. and Wordsworth, R. (2019) *The Astronomical Journal* 158, 194. https://doi.org/10.3847/1538-3881/ab46a8

Onstott, T.C., Lin, L.H., Davidson, M., et al. 2006a. Geomicrobiology Journal 23, 369-414. https://doi.org/10.1080/01490450600875688

Onstott, T.C., McGown, D., Kessler, J., et al. (2006b) Astrobiology 6, 377-395. https://doi.org/10.1089/ast.2006.6.377

Otto, K.A., et al. (2019) *JGR* 125, 1188-1203.

Park, R. S., et al. (2020) *Nature Astronomy* 4, 748-755.

Pikuta, E.V., Hoover, R.B. and Tang, J. (2007) *Critical reviews in microbiology*, 33, 183-209. https://doi.org/10.1080/10408410701451948

Pizzarello S., et al. (2001) *Science* 293, 2236-39.

Pizzarello, S., Holmes, W. (2009) *GCA* 73, 2150–2162. doi:10.1016/j.gca.2009.01.022

Pizzarello S. and Williams L. B. 2012. The Astrophysical Journal 749:161–167.

Platz, T., Nathues, A., Schorghofer, N., et al. (2016) *Nature Astronomy* 1, 1–6. https://doi.org/10.1038/s41550-016-0007

Platz, T., Nathues, A., Sizemore, H.G., Crown, et al. (2018) *Icarus* 316, 140–153. https://doi.org/10.1016/j.icarus.2017.08.001

Postberg et al. 2011 *Nature* 474:620-622.

Prettyman T. H., Yamashita N., Toplis M. J., et al. (2017) *Science*, 355, 55-59.

Qi, C., et al. (2018) *Geophys. Res. Lett.* 45, 12757-12765. https://doi.org/10.1029/2018GL080228

Quick, L.C., Glaze, L.S., Baloga, S. M. (2017) *Icarus* 284, 477-488.

Quick, L. C., et al. (2019) *Icarus* 320, 119-135.

Raponi, A. et al. (2019) *Icarus* 320, 83-96.

Raponi, A., De Sanctis, M. C., Frigeri, A., et al. (2018) *Science Advances*, 4(3). https://doi.org/10.1126/sciadv.aao3757

Raponi, A., et al, (2017) *Icarus*, doi:10.1016/j.icarus.2017.10.023.

Raponi, A., et al. (2021) *Life 11*, 9, doi:10.3390/life11010009.

Raymond, S.N, and Izidoro, Icarus 297, 134-148 (2017). Doi: 10.1016/j.icarus.2017.06.030.

Raymond, S.N., and Nesvorny, D. ArXiv: https://arxiv.org/pdf/2012.07932.pdf.

Raymond, C. A., et al. (2020) *Nature Astron.* 4, 741-747.

Reeves, E.P. and Fiebig, J., 2020. Elements: An International Magazine of Mineralogy, Geochemistry, and Petrology 16, 25-31. https://doi.org/10.2138/gselements.16.1.25

Remusat, L., et al, (2010) *ApJ* **713** 1048.

Remusat, L. 2015, in EMU Notes in Mineralogy - 15: Planetary Mineralogy, ed. M. R. Lee, & H. Leroux (The European Mineralogical Union), 33

Rivkin A. S., Asphaug E., Bottke W. F. (2014) *Icarus* 243, 429-439.

Roth, L. (2018) *Icarus* 305, 149-159.

Roth, L., Ivchenko, N., Retherford, K. D., et al. (2016) Geophysical Research Letters, 43, 2465–2472. https://doi.org/10.1002/2015GL067451

Rousselot, P., Jehin, E., Manfroid, J., et al. (2011) The Astronomical Journal, 142(4), 125. https://doi.org/10.1088/0004-6256/142/4/125

Rubin, A. E., Zolensky, M. E., Bodnar, R. J. (2002) Meteoritics & Planetary Science, 37, 125-141

Rubin A. E., Trigo-Rodriguez J. M., Huber H., and Wasson J. T. 2007. *Geochimica et Cosmochimica Acta* 71, 2361-2382.

Ruesch, O., et al. (2016) *Science* 353, aaf4286.

Ruesch, O., et al. (2019a) *Nature Geosci.* 12, 505-509.

Ruiz, J., et al., (2019) Nat. Astron. 3, 916-921.

Ruesch, O., Quick, L.C., Landis, M.E., et al. (2019b) *Icarus* 320, 39-48.

Salmon, J., Canup, R. (2018) Science Adv. 4, eaar6887

Schenk, P. M., et al (2019). *Icarus* 320, 159–187

Schenk, P., et al. (2020). *Nature Comm.* 11, 3679.

Schenk, P., Castillo-Rogez, J. C., et al. (2021) *Icarus*, https://doi.org/10.1016/j.icarus.2021.114343. .

Schmidt, B. E , Blankenship, D. D., Patterson, W., Schenk, P. (2011) Active chaos formation over shallow subsurface water on Europa, Nature 479 502-505.

Schmidt, B.E., Hughson, K.H.G., Chilton, H.T., et al. (2017) Nature Geosci 10, 338–343. https://doi.org/10.1038/ngeo2936

Schmidt, B., et al. (2020) Post-impact cryo-hydrologic formation of small mounds and hills in Ceres' Occator Crater, *Nature Geosci.* 13, 605-610.

Schmitt-Kopplin et al, 2010, which indeed show the presence of thousand compounds in the SOM.https://www.pnas.org/content/107/7/2763.short

Schörghofer, N., Mazarico, E., Platz, et al., (2016). Geophysical Research Letters, 43, 6783–6789. https://doi.org/10.1002/2016GL069368

Scully, J. E. C., et al. (2018) Icarus 316, 46-62.

Scully, J.E.C., Buczkowski, D.L., Schmedemann, N., et al., 2017. Geophysical Research Letters 44, 9564–9572. https://doi.org/10.1002/2017GL075086

Scully, J. E. C., et al. (2020) *Nature Comm.* 11, 3680.

Scully, J., et al., submitted to the *Planetary Science Journal.*

Seewald, J.S., Benitez-Nelson, B.C. and Whelan, J.K., 1998. Geochimica et Cosmochimica Acta 62, 1599-1617. https://doi.org/10.1016/S0016-7037(98)00000-3

Shi, X., et al. (2019) GAUSS -- A Sample Return Mission to Ceres, *White Paper to ESA's Voyage 2050.*

Sherwood Lollar, B.S., Westgate, T.D., Ward, J.A., Slater, G.F. and Lacrampe-Couloume, G., 2002. Nature 416, 522-524. https://doi.org/10.1038/416522a

Sherwood Lollar, B., Heuer, V. B., McDermott, J., et al., 2021. Geochimica et Cosmochimica Acta 294, 295-314. https://doi.org/10.1016/j.gca.2020.11.026

Shock, E.L. and McKinnon, W.B. (1993) *Icarus* 106, 464-477. https://doi.org/10.1006/icar.1993.1185

Sirono, S. (2013) *Earth Planets Space*, 65, 1563–1568.

Siskin, M., Katritzky, A. R., 2001. Reactivity of Chemical Reviews 101, 825-835. https://doi.org/10.1021/cr000088z

Sizemore H. G., Schmidt B. E., Buczkowski D. A., et al. (2019) *J. Geophys. Res. - Planets* 124, 1650-1689. https://doi.org/10.1029/2018JE005699

Sori, M., et al. (2017), *Geophys. Res. Lett.* 44, 1243–1250.

Sori, M., et al. (2018) *Nature Astron.* 2:946-950.

Spencer, J., Nimmo, F. (2013) AREPS 41, 693-717.

Stephan, K., et al. (2018) *MAPS* 53, 1866-1883.

Thangjam et al. 2016, *The Astrophysical Journal Letters*, 833:L25(9pp), doi:10.3847/2041-8213/833/2/L25

Thomas, E.C., Vu, T.H., Hodyss, R., Johnson, P.V. and Choukroun, M. (2019) *Icarus* 320, 150-158. https://doi.org/10.1016/j.icarus.2017.12.038

Travis, B.J., Bland, P.A., Feldman, W.C. and Sykes, M.V., 2018. Meteoritics & Planetary Science 53, 2008-2032. https://doi.org/10.1111/maps.13138

Vernazza, P., *et al.* (2017) *Astron. J.* 153, 72.

Villarreal, M. N., Russell, C. T., Luhmann, J. G., et al. (2017) *The Astrophysical Journal Letters*, 838(1). https://doi.org/10.3847/2041-8213/aa66cd/

Vinogradoff, V., et al. (2017) *Geochimica et Cosmochimica Acta* 212, 234-252.

Vinogradoff, V. et al. (2018) *Icarus* 305, 358-370.

Vinogradoff et al., 2020, *Geochimica et Cosmochimica Acta* 269 150-166.

Waite, J.H., Glein, C.R., Perryman, R.S., et al. (2017) *Science* 356, 155-159. https://doi.org/10.1126/science.aai8703

Williams, D., et al. (2018) Icarus 316, 1-13.

Zambon, F., et al. (2017) Geophys. Res. Lett. 44, 97-104. https://doi.org/10.100 2/2016GL071303

Zolotov, M. Y. (2020) *Icarus* 135, 113404.