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Introduction to the special issue: The formation and evolution of Ceres' Occator crater

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ABSTRACT

Ceres, the largest body in the asteroid belt, was explored from orbit for the first time by the Dawn mission. The ~92 km-diameter Occator crater contains bright regions, or faculae, which are one of the most remarkable discoveries of Dawn's exploration of Ceres. A pit within the center of the crater contains both the Cerealia Facula and a central dome. The Vinalia Faculae are located in the eastern crater floor. Occator's faculae are composed mostly of sodium carbonate and their single scattering albedo is the highest of any material on Ceres' surface. The faculae do not occur in other impact craters on Ceres and Occator's extensive interior lobate materials are unusual. Understanding the driving forces behind the formation of Occator crater and its faculae has the potential to lead us to a new understanding of the processes and conditions in Ceres' past, and to possibly provide constraints about the present-day internal state. In this special issue we present a variety of investigations, which use Dawn data, theoretical modeling and laboratory experiments to investigate Occator crater and its faculae. The results of these investigations are summarized and synthesized in the final paper of this collection. Herein we introduce Ceres and the Dawn mission and summarize the geophysical, geological, mineralogical and geochemical properties of Ceres as derived from Dawn data. We also discuss the regional setting of Occator crater and introduce Occator crater itself.

1. Introduction to Ceres and the Dawn mission

1.1. Pre-Dawn investigations of Ceres

Ceres is the only dwarf planet in the inner solar system, and is the largest object in the asteroid belt, with a mean radius of 469.7 ± 0.2 km (Russell et al., 2016) and an orbital semi-major axis of ~2.8 AU. Following its discovery by Piazzi in 1801, telescopic observations and thermal evolution modeling were used to study Ceres. Pre-Dawn telescopic spectra indicated Ceres' surface contained a small amount of water ice, an opaque material (carbon and/or magnetite), hydrated/ammonia-bearing clay minerals, carbonates, and/or brucite (e.g. McCord and Gaffey, 1974; Larson et al., 1979; Lebofsky et al., 1981; King et al., 1992; Rivkin et al., 2006; Milliken and Rivkin, 2009). Observations by the Herschel Space Observatory indicated the release of water vapor from the surface during Dawn's cruise to Ceres (Küppers et al., 2014). Hubble Space Telescope and adaptive optics observations, combined with thermal evolution modeling, suggested that Ceres differentiated into a hydrated silicate core, covered by a water-rich layer, after accreting a few million years after the beginning of the solar system (Thomas et al., 2005; McCord and Sotin, 2005; Parker et al., 2006; Castillo-Rogez and McCord, 2010; Drummond et al., 2014). Thermal evolution models found that it was possible for a global subsurface ocean to exist underneath a water ice shell for several hundreds of millions of years after Ceres' initial formation (e.g. McCord and Sotin, 2005; Castillo-Rogez and McCord, 2010). Finite element simulations of the behavior of the water-ice-rich shell predicted a mostly relaxed surface, because of pervasive viscous relaxation (Bland, 2013).

1.2. Dawn's exploration of Ceres

Dawn is the first spacecraft to visit Ceres. It began to orbit the dwarf planet in March 2015 (Russell et al., 2016) and continued to explore Ceres until 2018. Dawn investigated Ceres' geophysical properties, geology and composition from orbit using its Framing Camera (FC) (Sierks et al., 2011), Visible-Infrared Mapping Spectrometer (VIR) (De Sanctis et al., 2011), Gamma Ray and Neutron

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Detector (GRaND) (Prettyman et al., 2011), and gravity science investigation (Konopliv et al., 2011).

1.2.1. Geophysical properties of Ceres

Dawn observations find that Ceres has a mean density of $2{,}162 \pm 3\,kg/m^3$ and is partially differentiated into a rocky interior and a more volatile-rich crust (Park et al., 2016; Russell et al., 2016). The simple-to-complex transition diameter of impact craters, which occurs at a diameter of ∼7.5–12 km, suggests that Ceres' crust is a mixture of icy and stronger (rock-like) materials (Hiesinger et al., 2016). Impact craters have generally not undergone viscous relaxation, which indicates that there is only an average of < 30–40% (by volume) water ice in Ceres' crust (Bland et al., 2016). This is in contrast to pre-Dawn predictions of a water-ice-dominated shell (see Section 1.1 and references therein). Finite element simulations shed more light on the nature of the crust, which is found to be a mixture of ice, phyllosilicates and/or carbonates, salts and a strong but low density material, interpreted as clathrate hydrates (Fu et al., 2017). Solar energetic particle events are found to sputter near-surface water ice from Ceres, forming an occasional transient atmosphere (Villarreal et al., 2017). Landis et al. (2017) use coupled thermal and vapor diffusion modeling to show that short-lived exposures of water ice, excavated by impacts or landslides, are the most likely source for the water vapor observations of Küppers et al. (2014).

The ubiquitous distribution of phyllosilicates across Ceres' surface (Ammannito et al., 2016) is interpreted as evidence for global scale alteration in an ocean, likely triggered by the decay of short-lived radioisotopes (Castillo-Rogez and McCord, 2010). The occurrence of global aqueous alteration on Ceres requires that Ceres formed < 5 Myr after calcium-aluminum-rich inclusions (CAIs) (Castillo-Rogez and McCord, 2010). Within this 5 Myr window, formation likely occurred > 3 Myr after CAIs because otherwise the dwarf planet would be more fully physically differentiated than is observed (Castillo-Rogez and McCord, 2010). While the majority of an ancient Cerean ocean would freeze early within its history, intriguingly, the predicted thermal and geochemical conditions within Ceres' present-day subsurface allow for the existence of pockets of briny liquid (Castillo-Rogez and McCord, 2010; Neveu and Desch, 2015; Travis et al., 2017; Castillo-Rogez et al., 2017). These pockets of briny liquid could exist at depths equivalent to the thickness of the present-day crust (e.g. Castillo-Rogez et al., 2017), which is found to be $\sim 41^{+3}_{-5}$ km (Ermakov et al., 2017a) or ∼43 to ∼50 km (Mitri et al., 2017) thick on average. These average crustal thicknesses are based on two-layer interior models derived from Dawn's gravity and shape observations, and are supported by modeling of relaxation of topography (Fu et al., 2017).

There are indications that the thickness of the crust varies across Ceres. For example, the crust underlying Kerwan crater (Fig. 1) is proposed to be ∼10 km thick, which is significantly thinner than average (Bland et al., 2018). In contrast, analysis of the Samhain Catenae fractures within the Hanami Planum region, which is the regional setting for Occator (Fig. 1), is consistent with the crust underlying Hanami Planum being thicker than average (approximately ≥58 km) (Scully et al., 2017) (see Section 2 and references therein for further discussion of Hanami Planum).

1.2.2. Mineralogical and geochemical properties of Ceres

Ceres' surface has a relatively low average single-scattering albedo of 0.09–0.11 (Li et al., 2016). Dawn finds that Ceres' mineralogical and geochemical properties are broadly consistent with a CM/CI carbonaceous chondrite composition that has been modified by advanced alteration (McSween et al., 2018) and the occurrence of ammonia. Ceres' global spectrum, as observed by VIR, is best fit by a mixture of ammonia-bearing phyllosilicates, magnesium-serpentine, carbonates and a dark component (De Sanctis et al., 2015). The presence of ammonia may suggest that either Ceres accreted material that originated in the outer solar system, or that Ceres itself migrated inwards from the outer solar system (e.g. De Sanctis et al., 2015; McSween et al., 2018). Ceres' surface composition on a regional scale is investigated by studies in a mineralogical mapping special issue, which is consistent with earlier global observations, all of which show Ceres underwent global aqueous alteration processes (McCord and Zambon, 2018).

Dawn's observations of Ceres' surface composition can be used to constrain models of Ceres' geochemical and thermal evolution. As Ceres' ancient ocean froze (see Sections 1.1, 1.2.1 and references therein), sodium carbonate is predicted to precipitate out of solution first, followed by ammonium chloride, potentially leaving pockets of residual liquid enriched in sodium chlorides, potassium chlorides and ammonia (Neveu and Desch, 2015; Castillo-Rogez et al., 2017). Thus, these models predict that Ceres' crust should contain sodium carbonate, consistent with VIR observations that have identified sodium carbonate across Ceres' surface. Some of these occurrences are in relatively small impact craters, such as Oxo (∼10 km in diameter) (e.g. Carrozzo et al., 2018). These observations indicate that sodium carbonate is spread throughout Ceres' crust. A large impact into Ceres could provide sufficient heat for crustal sodium carbonate and ammonium chloride to go into solution with impact-melted water, as suggested for Occator crater (Zolotov, 2017). Thus, sodium carbonate could be concentrated in an impact-induced melt reservoir; as the reservoir cooled, and the water was lost due to Ceres' surface conditions, the sodium carbonate would precipitate out, potentially forming features such as Occator's faculae (Zolotov, 2017).

There are regions across Ceres' surface that have distinct compositions. For example, the region surrounding Ernutet crater (Fig. 1) contains material that is consistent with the 3.4 μm absorption feature of aliphatic organic molecules (De Sanctis et al., 2017). This organic material is associated with fresh, small craters, a few 100 s of meters in diameter. It is not currently possible to definitively conclude if the original source of the material is exogenic or endogenic (De Sanctis et al., 2017; Pieters et al., 2017). In addition, there are nine locations where water ice has been detected on Ceres' surface (Combe et al., 2018). The first detection of water ice occurred in Oxo crater (Combe et al., 2016) (Fig. 1) and is attributed to recent exposure by mass wasting (Combe et al., 2016; Nathues et al., 2017a; Hughson et al., 2018).

1.2.3. Geological properties of Ceres

Ceres' surface displays ∼15 km of relief and is covered by numerous impact craters: there are ∼500 impact craters >20 km in diameter (Buczkowski et al., 2016; Hiesinger et al., 2016; Marchi et al., 2016). In Framing Camera color data, fresher impact craters tend to be associated with a decreasing reflectivity with increasing wavelength from 438 to 965 nm, which results in a relative surface bluing (e.g. Schmedemann et al., 2016; Nathues et al., 2016). The surface materials of these fresh craters are relatively blue because of impact processing of the materials and/or because other terrains have been exposed to space weathering effects for comparatively longer timescales (Stephan et al., 2017).

There are also numerous linear features across Ceres' surface, which are interpreted as either impact-derived secondary crater chains or fractures and faults (Buczkowski et al., 2016; Scully et al., 2017; Buczkowski et al., 2018). The pervasiveness of polygonal craters, whose straight sides are interpreted to be controlled by pre-existing fractures and/or faults, suggest a dense network of fractures and faults are spread throughout the subsurface (Buczkowski et al., 2016; Otto et al., 2016).

Ahuna Mons (Fig. 1) is a ∼4 km high and ∼21 km long dome, which is interpreted as a viscous cryovolcanic dome formed by the extrusion of cryolavas on Ceres' surface (Ruesch et al., 2016).

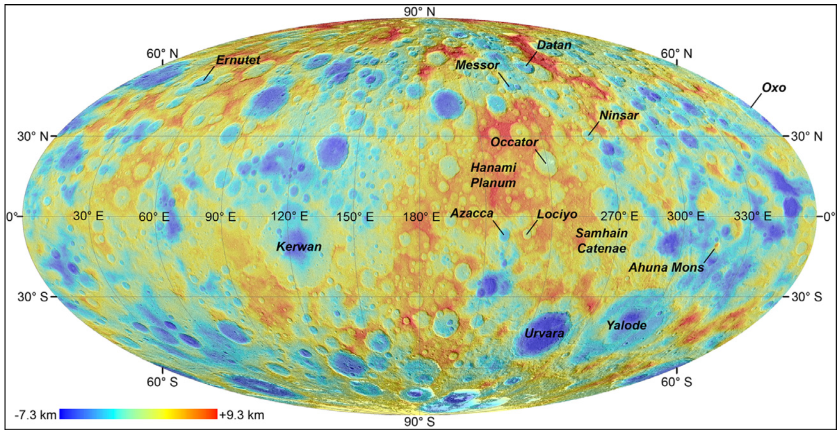

Fig. 1. The location of Occator crater is shown here on the global shape model of Ceres, which is overlain onto the global Framing Camera clear filter mosaic, both of which have a Mollweide projection. Many of the features discussed in the text are labeled. The global shape model is provided by DLR and has a lateral spacing of 60 pixels per degree, corresponding to ~135 m/pixel, a vertical resolution of < 100 m, and an intrinsic height accuracy of ~12 m (Preusker et al., 2016). The global mosaic of clear filter Framing Camera images, with a spatial resolution of ~35 m/pixel, is made by the German Aerospace Center (DLR) (Roatsch et al., 2017).

These cryolavas may have incorporated liquid water as brines in the melt component and/or water ice in the solid component. Ahuna Mons appears to be a young feature, approximately <100 million years old, and displays evidence for carbonates on its flanks (Zambon et al., 2017). Unlike the region in which Occator is located, Ahuna Mons is located within a region with a strong positive Bouguer anomaly (Ermakov et al., 2017a).

Pitted terrain, found in a subset of Cerean craters, is thought to form by the loss of volatiles heated by the impacts (Sizemore et al., 2017). Moreover, particular types of lobate flows are morphologically analogous to water-ice-rich flows on Earth, Mars and icy satellites (Buczkowski et al., 2016; Schmidt et al., 2017). They increase in abundance towards the poles, which is consistent with thermal modeling that shows surface and subsurface water ice is more stable at the cooler poles than at the warmer equator (Hayne and Aharonson, 2015), and is also consistent with GRaND observations of higher concentrations of elemental hydrogen at the poles, which indicate that the water ice concentration in the shallow subsurface increases with latitude (Prettyman et al., 2017). The occurrence of surficial water ice has been suggested in a few high-latitude, permanently shadowed craters (Schorghofer et al., 2016; Platz et al., 2016; Ermakov et al., 2017b).

Geologic mapping of Ceres reveals the following global-scale geologic history (Mest et al., 2018; Williams et al., 2018 and references therein):

(1) The cratered terrain dominates the surface, is the stratigraphically oldest geologic unit and is interpreted as the oldest identifiable crust.
(2) There is a widespread geologic unit of smooth material, which surrounds the 284 km-diameter Kerwan crater (Fig. 1). It may have been formed by a Kerwan-impact-induced resurfacing event that post-dates the cratered terrain.
(3) Yalode (260 km diameter) and Urvara (170 km diameter) impact craters (Fig. 1) are surrounded by ejecta deposits that are smooth in parts and rugged in others. These ejecta deposits dominate the geology of the southern hemisphere. Urvara partially superposes Yalode, indicating that the Yalode impact occurred first. Both are interpreted to post-date the smooth material surrounding Kerwan.
(4) After the formation of Kerwan, Yalode and Urvara, younger impact craters were formed. The most distinctive of these younger impact craters have the previously discussed relatively blue surface materials (e.g. Schmedemann et al., 2016; Nathues et al., 2016; Stephan et al., 2017), are surrounded by ejecta deposits and their interiors are composed of a variety of geologic units, including hummocky or smooth floor materials and crater terrace material.

A chronostratigraphy for Ceres is currently under construction and it will include absolute model ages of the aforementioned geologic units (Mest et al., 2018). There will be two model ages for each geologic unit because there are two different Cerean chronology systems currently in use: the lunar-derived chronology system and the asteroid-flux derived chronology system (further details in Hiesinger et al., 2016).

2. The regional setting of Occator crater

Occator is located within Hanami Planum (Fig. 1), a ~500 km wide, topographically high region that has the strongest negative Bouguer anomaly (~ −250 mGal) on Ceres (Park et al., 2016; Ermakov et al., 2017a; Konopliv et al., 2018). The isostatic anomaly within Hanami Planum is also negative, which implies supercompensation. For example, if Airy isostasy is assumed, this implies overthickening of the crust in comparison to an isostatic model (Ermakov et al., 2017a). A large fraction of the observed negative anomaly in Hanami Planum is caused by the sectorial component of degree-2. If the degree-2 contribution is excluded from the isostatic anomaly, there are two local minima to the southeast and northeast of Occator and one local maximum west of Occator. The location of these structures and, even their presence, depends on the maximum degree considered in the spherical harmonic expansion of gravity. It is possible that the true gravity anomaly structure around Occator is not resolved with the Dawn gravity model. Available gravity and topography data cannot give a unique interpretation for the Hanami Planum negative gravity anomaly, but possibilities include: (i) a regional buoyancy-driven anomaly, combined with a thicker and higher rigidity crust than average, or (ii) a low regional density due to a compositional difference.

On its northern, eastern and western sides, Occator crater and its ejecta are surrounded by cratered terrain that is ~3–4 billion years old (Buczkowski et al., 2018; Scully et al., 2018). To the south, Occator's ejecta is bounded by ejecta from Yalode crater (Buczkowski et al., 2018). The cratered terrain and/or Yalode ejecta are cross-cut by younger craters such as Datan (60 km diameter), Azacca (50 km diameter), Messor (40 km diameter), Ninsar (40 km diameter) and Lociyo (38 km diameter) (Fig. 1). These craters share many similarities with Occator: they are all complex craters, they contain a variety of interior geologic units, they are surrounded by

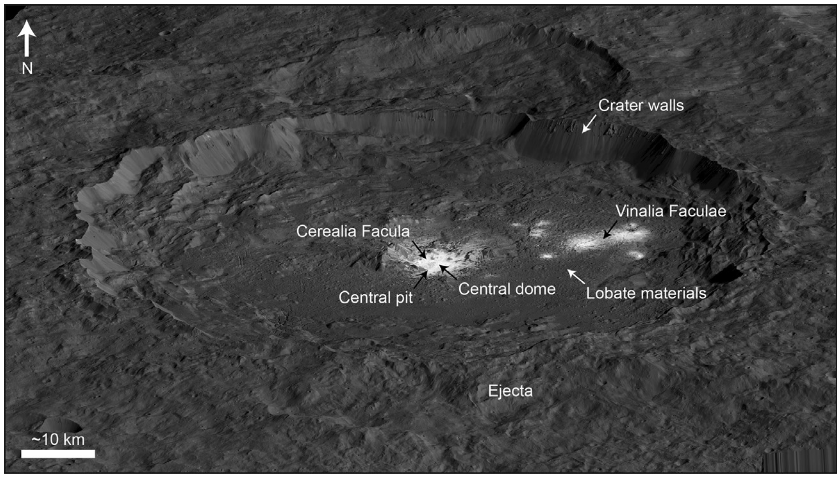

Fig. 2. Occator crater in a perspective view. Features discussed in the text are labeled. The ejecta deposits fill the majority of the frame that is outside of the crater. This perspective view has no vertical exaggeration and was made by David P. O'Brien (Planetary Science Institute) by overlaying Framing Camera clear filter images (spatial resolution of ~35 m/pixel) onto the digital terrain model of Occator made by DLR, which has a lateral grid spacing of ~35 m/pixel, a mean intersection error of +/−2.8 m and an intrinsic height accuracy of ~1.5 m (Jaumann et al., 2017).

distinctive ejecta deposits and they are placed into the youngest of Ceres' stratigraphic time periods (Mest et al., 2018; Williams et al., 2018). However, the characteristics that set Occator apart from these craters are that it is the largest (~92- km diameter) and youngest of these craters (Buczkowski et al., 2018). The majority of the terrain surrounding Occator has Ceres' average surface composition (Ammannito et al., 2016), except in the case of Azacca crater and its ejecta, which contains sodium carbonate (Carrozzo et al., 2018).

3. Introduction to Occator crater

Occator crater is a ~92 km diameter complex crater that is located at 20 °N, 239 °E. The crater rim is located at a maximum elevation of + 4.8 km, and the lowest point in the crater floor is located at an elevation of −1.1 km, with respect to a geodetic reference ellipsoid (Jaumann et al., 2017). Occator is the most well known feature on Ceres' surface because of the prominence of its interior bright regions, called faculae. Li et al. (2016) find that the faculae have a single scattering albedo of 0.67–0.80, which is much greater than Ceres' average (0.09–0.11). The average visual normal albedo of the central region of the faculae is ~0.6, at a spatial resolution of 1.3 km/pixel, which is approximately six times Ceres' average (Schröder et al., 2017). There are two regions of faculae: (1) the central region, called the Cerealia Facula, and (2) multiple additional faculae in the eastern crater floor, together called the Vinalia Faculae (Fig. 2). Cerealia Facula is located in a central pit that is ~9 km wide and ~800 m deep (Fig. 2). Within this pit is a central dome that is ~300–700 m high and has a fractured surface (Fig. 2) (Nathues et al., 2015; Schenk et al., 2016). The faculae have a distinct composition in comparison to Ceres' average surface: they are composed mostly of sodium carbonate and are proposed to be the solid residues of crystallized brines (De Sanctis et al., 2016).

In Framing Camera color data from 438–965 nm, Occator's walls (Fig. 2) have a positive spectral slope (relatively red surface materials), the crater interior has a negative spectral slope (relatively blue surface materials), and the faculae have a neutral or average spectral slope, which may reflect an age progression from oldest to youngest (e.g. Jaumann et al., 2017). There are extensive lobate materials (Fig. 2) within the crater floor, for which a variety of interpretations have been proposed. Krohn et al. (2016) and Jaumann et al. (2017) proposed that the lobate material in the northeastern crater interior flowed uphill from a possible origination point within the region containing the central pit. This could be explained by a feeding zone supplying low-viscosity material, or by subsidence of the crater center, or by lateral oscillations during the emplacement of impact melt. Alternatively, Nathues et al. (2017b) suggested that the lobate materials are a debris avalanche deposit from collapse of the southeastern crater wall, while Schenk et al. (2016) interpreted the lobate materials as an impact melt sheet. Based on crater counts of different regions of Occator and its ejecta (Fig. 2), the lobate materials and the faculae are proposed to be younger than Occator's ejecta (Nathues et al., 2017b and references therein).

4. Goals of this special issue

We are motivated to study Occator crater and its faculae for a variety of reasons, which include:

i. Occator's faculae are unique in comparison to other Cerean craters and the extensive interior lobate materials are unusual (e.g. Nathues et al., 2015; Schenk et al., 2016);
ii. Ceres is billions of years old, yet Occator crater and its faculae are young, less than tens of millions of years old, making them some of the youngest features on Ceres' surface (Nathues et al., 2017b);
iii. Occator's faculae are compositionally analogous to Ahuna Mons, which is also a young feature (approximately <100 million years old) (Ruesch et al., 2016; Zambon et al., 2017);
iv. Occator's faculae are the largest deposits of carbonates in the Solar System (excluding those on Earth) discovered to date (De Sanctis et al., 2016);
v. Hanami Planum, upon which Occator crater is located, is an intriguing location because its strong negative Bouguer anomaly, the largest on Ceres, suggests that its subsurface structure is different to surrounding regions (Ermakov et al., 2017a).

In this special issue, we seek to identify the driving forces behind the formation of Occator and its faculae. Are the faculae-forming materials sourced from an exogenic/impact-derived melt and hydrothermal system? Alternatively, are the faculae-forming materials sourced from an endogenic, sub-surface reservoir of briny relict ocean liquid? Or are the driving forces a combination of both: for example, are the faculae-forming materials sourced from a sub-surface reservoir of briny relict ocean liquid that was excavated by the impact or accessed by impact-induced fractures?

Unraveling the mystery of the driving forces behind the formation of Occator and its faculae will lead to a new understanding of the processes and conditions that occurred in Ceres' past. In addition, the relative youth of Occator and its faculae means that this new understanding may constrain Ceres' present-day internal state. The above questions are addressed by the set of investigations presented in this special issue, which use Dawn data, theoretical modeling and laboratory experiments to investigate Occator crater and its faculae. The following studies primarily investigate Occator crater and its faculae through the use of Dawn data:

- Scully et al. (2018a) create a detailed geologic map of Occator crater and its ejecta, and interpret the natures and formation mechanisms of the mapped features.
- Nathues et al. (2018) explore the geologic properties of Occator crater, primarily through the use of high spatial resolution color data (~35 m/pixel) from the Framing Camera.
- Ruesch et al. (2018) analyze the geomorphology of Occator's faculae and provide hypotheses for their formation.
- Buczkowski et al. (2018) undertake a tectonic analysis of fractures inside Occator crater and its ejecta, and compare these fractures to analogs on different planetary bodies.
- Neesemann et al. (2018) use their crater counts to derive model ages for various geologic units of Occator crater.
- Raponi et al. (2018) present a detailed mineralogical analysis of Occator crater and its faculae.
- Longobardo et al. (2018) use VIR data to derive the photometric properties of Occator and its faculae.
- Schenk et al. (2018) evaluate the geologic characteristics of Occator crater, its faculae, central pit and central dome, in comparison to other impact craters on Ceres and to other planetary bodies.
- Stein et al. (2018) survey, categorize and interpret bright regions across Ceres, including Occator's faculae.
- Palomba et al. (2018) identify compositional differences between Occator's faculae and other bright regions on Ceres, using VIR data.

The following studies primarily investigate Occator crater and its faculae through the use of theoretical modeling:

- Bowling et al. (2018) simulate the formation of Occator crater, in order to explore whether a purely impact-driven process could form the faculae.
- Quick et al. (2018) model the thermal and compositional evolution of a putative brine reservoir underneath Occator, and evaluate whether it could contribute to the formation of the faculae.

The following studies primarily investigate Occator crater and its faculae through the use of laboratory experiments:

- Bu et al. (2018) use laboratory experiments under low-pressure conditions to examine the stability of hydrated carbonates on Ceres.
- Thomas et al. (2018) investigate the effect of freezing rate on the composition of brines, under laboratory conditions comparable to Ceres.

Each of these studies provides pieces of evidence towards unraveling the mystery of Occator, its faculae, and the past, and potentially present, processes and conditions on and within Ceres that resulted in their formation. In the summary paper (Scully et al., 2018b), we synthesize the results of these studies and discuss the resultant insights that can be derived about Ceres' past and present states.

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