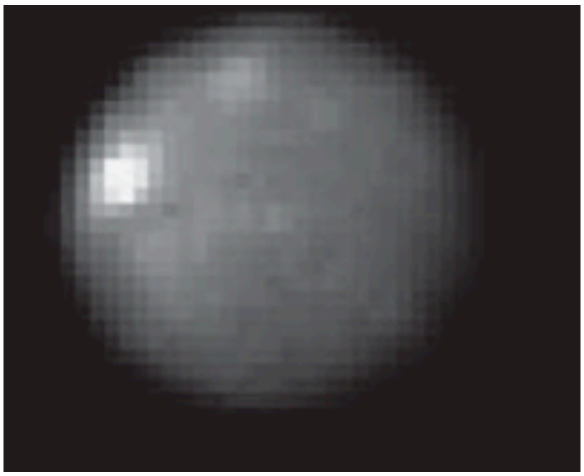
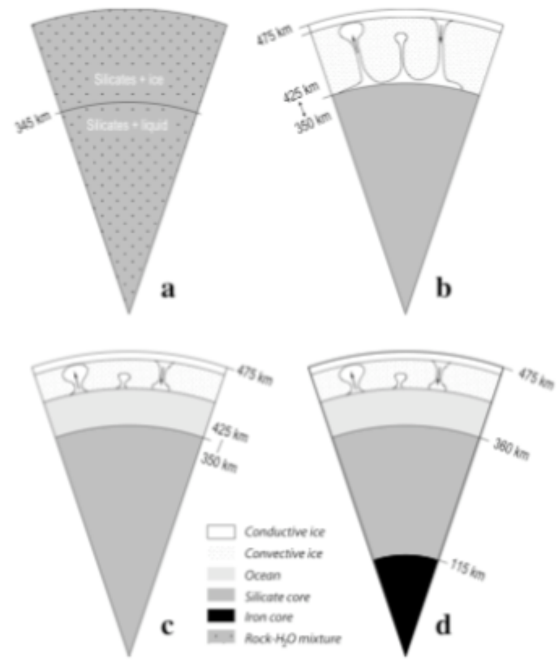
The Case for Ceres: Report to the Planetary Science Decadal Survey Committee





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Executive Summary

Ceres is the largest object in the asteroid belt. With a diameter of 950 km and a density of 2.1 g/cm^3 (Table 1), it accounts for one-third of the mass found between Mars and Jupiter. Since the last decadal survey our knowledge of Ceres has blossomed. Observations, modeling, and theory are converging on a paradigm of a severely aqueously altered body with an icy mantle covering a rocky core. Ceres is intermediate in nature between the rocky bodies of the inner solar system and the icy satellites. This paradigm is still in its infancy, however, and recent work has proposed alternatives including an undifferentiated object, and even an origin in the outer solar system. While Dawn will begin the spacecraft reconnaissance of Ceres and provide a wealth of data, geophysical, geochemical, and astrobiological considerations show Ceres to be uniquely compelling as a target for continued ground-based and space-based investigation in the coming decade. We recommend Ceres be considered a candidate for a New Frontiers mission in the 2015-2022 timeframe, with mission architectures to be studied based on results from *Dawn* and other sources. We also recommend support for continued observational, theoretical, and laboratory studies of Ceres and related objects.

Background and Motivation

Interest in Ceres has greatly increased over the past decade. Russell et al (2004) and McCord et al. (2006) suggested the largest asteroids, Ceres, Pallas, and Vesta, are best considered as protoplanets. Recent modeling on planetary accretion by Morbidelli et al. (2009) shows that planetesimals may have grown very quickly up to several hundred km in size, consistent with this view; Ceres can be seen as one of the best remaining examples of the intermediate stages of planetary accretion. Ceres is also the only presently recognized dwarf planet in the asteroid belt, and a body potentially considerably different from most asteroids as usually pictured.

In addition, increased interest in Ceres naturally reflects its status as a target for the *Dawn* mission, which visits Vesta in 2011 and moves on to Ceres, entering orbit there in 2015. *Dawn* will no doubt revolutionize our understanding of Ceres, but it is not too early to look to the investigations that will support and build upon *Dawn*'s time at Ceres.

Radius (km)	476.2±1.7	Thomas et al. (2005)
Density (kg/m^3)	2077±36	Thomas et al. (2005)
Rotation Period (h)	9.075	Chamberlain et al. (2007)
Semi-Major Axis	2.76 AU	http://ssd.jpl.nasa.gov
V-band Geometric Albedo	0.090±0.003	Li et al. (2006)

Table 1. Main physical and dynamical properties of Ceres.

Consideration of its density (Table 1) leads to the conclusion that it contains up to 30% ice if its porosity is low. Thermal models by McCord and Sotin (2005) showed that, if so, Ceres has likely differentiated into an object with an icy mantle over a rocky core and perhaps a shallow liquid layer above the core remaining today. Recent interior modeling has emphasized Ceres' warm surface temperature as an important factor for promoting the presence of a deep ocean, given sufficient salinity (Castillo-Rogez and McCord 2009).

Taking the modeling, mapping, and spectral data all together, a paradigm is emerging for Ceres as an ice-rich world whose optical surface indicates severe aqueous alteration, possibly in Ceres' interior prior to eruption driven by aqueous activity, with the observed minerals remaining behind after any ice sublimed from the relatively warm surface. The spectral data for Ceres do not match known carbonaceous chondrites in many wavelength regions, though direct comparisons are frustrated in part by relatively few laboratory spectra of the most apt meteoritic analogs.

Observations of Ceres' shape (Thomas et al. 2005, Carry et al. 2008) are consistent with differentiation, but observational uncertainty in these measurements prevents a definitive conclusion. An alternative model posits that Ceres is made up of hydrated silicates with significant porosity (Zolotov 2009), which has only increased interest in Ceres' true nature.

Using HST data, Li et al. (2006) extracted spatially-resolved photometric properties and mapped surface features in three visible-wavelength filters (features also seen in the UV by Parker et al. 2002). Near-IR observations by Carry et al. (2008) using Keck adaptive optics extended maps of Ceres into the infrared. These maps show a surface with muted albedo contrast (~±5%), but unmistakable surface features.

Our understanding of Ceres' surface composition has also advanced. Ceres has long been associated with the carbonaceous chondrites based on its visible and near-IR (0.4–2.5 µm) spectrum. Observations at longer wavelengths have given more specific compositional information, providing definitive identifications of minerals on Ceres' surface: new observations in the 3-µm region using IRTF's SpeX instrument (Rayner et al. 2003) and reevaluation of mid-IR data by Cohen et al. (1998) have been interpreted as showing carbonates, brucite, and iron-rich clays (Rivkin et al. 2006, Milliken and Rivkin 2009), as opposed to earlier interpretations of ammoniated clays (King et al. 1992) or water ice (Lebofsky et al. 1981). Rotationally resolved IR spectra (Rivkin and Volquardsen, in press) show subtle but consistent spectral variation correlated with the surface features found by Li et al. and Carry et al. Submillimeter observations also find variation in thermal properties across Ceres' surface, although intriguingly, the albedo variation alone cannot explain the variation in thermal properties (Chamberlain et al. 2009).

The prospect that Ceres could host an icy shell, and possibly a deep ocean containing organic material, along with relatively warm temperatures, has captured the attention of the astrobiology community (e.g., Castillo and Vance, 2008, McFadden et al. 2009). The conditions at Ceres may have been favorable for the preservation, transformation, and synthesis of organic compounds, and serve as a reminder that we must be alert for potential extraterrestrial reservoirs for prebiotic material in the solar system in addition to just Mars, Europa, Titan and Enceladus.

Unresolved, High-Priority Ceres Science Questions

The current state of Ceres research shows it to be a unique object, potentially holding keys to understanding of disparate solar system populations in multiple disciplines. We have identified the following as important science questions concerning Ceres: How did it form and evolve and what is its present-day state?

1) ***Did Ceres form near its present position or was it transported from the outer solar system?*** *What were Ceres' starting materials? How much mixing occurred between different planetesimal and protoplanet reservoirs to create Ceres*?

Since the last decadal survey, dynamicists have recognized that the jovian planets may have migrated early in solar system history due to the cumulative effects of scattering small bodies, constructing a scenario called the "Nice Model" incorporating the consequences. The Nice Model predicts that objects that formed beyond Neptune could have been transported to the inner solar system in large numbers, populating Jupiter's Trojan clouds and providing the D-class objects found in the outer asteroid belt (Levison et al. 2009).

Ceres' low density implies an ice to rock ratio comparable to TNOs. This, plus consideration of the Nice Model and the relative frequency of Ceres-sized objects in the inner and outer solar system, led McKinnon (2008) to suggest the possibility that Ceres itself was formed as a TNO and later brought to its current orbit. While the most straightforward history for Ceres includes formation near its current location and kinship to other C-class asteroids, establishing Ceres' birthplace will be necessary to fully understand its context. The origin of Ceres has direct implications for its long-term evolution as it determined Ceres' content in volatiles and accretion timeframe (which determines the amount of accreted short-lived radioisotopes.) Means to test this hypothesis are given below.

2) ***What is the nature of Ceres' interior?*** *Is it differentiated? Does it have an iron core? Does it still support liquid water (within an icy shell)?*

Ceres' shape can be explained by either a differentiated or undifferentiated internal structure. Thermal evolution models indicate that a differentiated interior is the most likely outcome for Ceres (e.g., McCord & Sotin 2005; Castillo-Rogez & McCord, 2009). Conversely, Zolotov (2009) has recently argued that Ceres' density and shape remain uncertain and do not preclude an undifferentiated interior. For example, Ceres' low density may be due to a high-porosity interior, since its internal pressures are not sufficient to ensure extensive compaction. Furthermore, Zolotov used geochemical arguments to conclude that the surface composition of Ceres would be different if it had an internal ocean, one able to erupt to the surface. Understanding Ceres' interior and validating these models will be invaluable for comparative planetological studies of Ceres and other large low-albedo asteroids (like Pallas, Hygiea, or Cybele) and similar-sized icy satellites (like Tethys, Dione, or Ariel) to delimit the phase space where differentiation can be expected, among other comparisons. As an example, the existence of the Main Belt Comets and their association with the Themis asteroid family shows that ice still exists in those bodies (Hsieh and Jewitt 2006). Modeling may ultimately demonstrate whether the ice within these comets is essentially primordial or whether, in contrast, the Themis family parent body was Ceres-like before breakup.

3) ***What is the geological history of Ceres?*** *Did Ceres experience cryovolcanism? If so, how long did it persist? How much material was exchanged between Ceres' interior and surface? Were there periods when Ceres' surface was icy? Or will Ceres be revealed as geologically dead? What will Ceres' cratering record tell us about its surface and near sub-surface?*

If Ceres is differentiated, the melting and freezing of its volatile component would have resulted in tectonic activity (e.g. faulting). The low ice viscosity resulting from the relative warmth of Ceres' surface may have led to geologically rapid relaxation of impact craters and other topographic features, especially near Ceres' equator, where temperatures are highest (Ceres' obliquity is very low). Similar to Europa, Ceres may be undergoing resurfacing possibly in the form of cryovolcanism or venting of water vapor (Li et al. 2006). The slow freezing of an internal ocean, as Ceres' radiogenic heat wanes, in particular should lead to extensional stresses at the planet's surface, which would be conducive to such eruptions or venting.

4) ***What is the nature and origin of Ceres' present surface?*** *Is it primordial rock+ice crust that somehow avoided foundering or was re-exhumed? Or is it a deposit of rocky material that was brought to the surface by water or ice, and left after the ice sublimed or was sputtered*

away? How has space weathering affected Ceres' surface? What are the as-yet unidentified constituents of its surface?

Ceres is unique as an ice-rich body with a surface on which ice is unstable. It is unclear whether the current surface of Ceres is a lag deposit of a former (frozen) ocean surface or the non-ice remains of cryovolcanic flows. Another possibility is that it retains remnants of an original mixed rock-ice crust that managed to escape foundering, or which was exhumed after overlying ice was removed by sublimation.

We have an incomplete understanding of Ceres' surface composition. While carbonates and brucite have been identified on Ceres' surface, there are other absorption bands that have not been associated with specific minerals. A broad band in the near-infrared, also seen in some carbonaceous chondrites, could be due to either magnetite (Fe_3O_4) or phyllosilicates. Features in the mid-IR have been seen at some times but not others, while interpretation of an absorption consistently seen in the UV has been hampered by a lack of laboratory spectra of analog materials at the relevant wavelengths. Conceivably, the mineralogy on Ceres' surface could support or refute the hypothesis that Ceres formed farther out in the Solar System.

5) ***What is the astrobiological potential for Ceres, and/or its complement of prebiotic material?*** *What are the potential mechanisms and frequency of materials recycling and renewal that may affect the potential habitability of Ceres surface or interior? What are the potential geochemical pathways for the transformation and synthesis of indigenous Cerean organic species, now or in the past?*

Only in the last few years have we realized that Ceres is a site of astrobiological significance. It has experienced aqueous alteration, it has carbon-bearing species and its pre-alteration assemblage was likely organic-rich. It is apparently ice-rich, and liquid water may persist to this day. Understanding the interactions of organics and water in Ceres' interior and near-surface may also provide valuable insight into the prebiotic material available for Earth's accretion.

Ceres' surface composition identified by Milliken and Rivkin (2009) indicates conditions that are much less oxidizing than Mars, and less reducing than Titan, both of which have been considered as key astrobiological targets (Shapiro and Schulze-Makuch 2008). This oxidation state may result in key differences from the chemical reactions found on Mars and Titan, making Ceres' evolution more pertinent to Earth's than either of the former objects.

6) ***Does Ceres have an appreciable atmosphere or exosphere?*** *If so, what is its composition, and is it largely caused by outgassing, sputtering, or other processes? Can its composition constrain Ceres' origin and internal structure? If Ceres has no such atmosphere or exosphere, what does that imply about its interior and/or volatile content?*

Observations of Ceres by the International Ultraviolet Explorer (IUE) by A'Hearn et al. (1992) provided hints of ^{-}OH emission off of Ceres' sunlit pole. These were interpreted as possible evidence of ice sublimation. Since the end of IUE, repeating these observations has been difficult, though groundbased work with improved sensitivity over IUE found no emission (Rousselot et al. 2008). The possibility of near-surface ice (Fanale and Salvail 1989) and a reservoir of a subsurface ice and potential ocean increases the likelihood of a thin atmosphere,exosphere or transient venting existing today.

Understanding volatile transport on Ceres will greatly improve our understanding of volatile transport on objects like the Moon, Pluto, and the icy satellites. Measuring any atmosphere on Ceres would also provide constraints on Ceres' overall volatile content, with implications for

Ceres' history as well as the history of other objects in the main belt. Measurement of D/H in the gas phase, as has been recently done by the Cassini INMS for Enceladus (Waite et al. 2009), would offer the most definitive test of an in situ vs. Kuiper belt origin for Ceres.

Recommendations

- **Continue Earth-based observations of Ceres especially using new capabilities (ALMA/JWST/HST UV Spectroscopy) and unexplored wavelength regions**.

The highest resolution instrument now in operation on HST, the Wide-field and Planetary Camera 3 (WFC3) has improved capabilities over WFC2, increasing its utility in the UV where Ceres has interesting photometric and spectral behavior (Li et al. 2006). UV observations with WFC3 and the newly repaired Space Telescope Imaging Spectrograph provide the opportunity to confirm the IUE observations suggesting possible outgassing that were mentioned above.

The next generation James Webb Space Telescope should provide additional opportunities to observe Ceres. Scheduled to begin science operation in 2014, the telescope will extend Hubble-style capabilities into the infrared. While the instrument set is already selected, the complete filter and grism sets have not been finalized. *It is vital that the planetary community stay involved in discussions and planning both for the JWST and for future planned facilities in order to optimize the filters for use on solar system targets that are often too bright for astronomical instrumentation.* For Ceres, the ability to use the Near Infrared Camera (NIRCam) which has 0.013"/pixel resolution from 1-5 µm, as well as the Mid Infrared Instrument from 5-25 µm in both imaging or spectral mode can provide both support and complementary observations to the *Dawn* mission as well as the potential for improved near and mid-infrared observations.

ALMA, the Atacama Large Millimeter/Submillimeter Array, will come online during the next decade, able to produce temperature maps with a similar resolution as the HST maps of Ceres. Rotational studies of Ceres and other large asteroids should provide unique information about their thermal properties.

- **Place Ceres into context by increasing complementary planetology studies of its kin: large asteroids and similar-sized satellites.**

The recent findings about Ceres' surface and interior properties show it to be intermediate between populations. It and 10 Hygiea, the 4^{th}-largest asteroid (~400-km across), have nearly identical spectra over the 0.4-4.0 µm region, suggesting that Hygiea's surface composition is very close to that of Ceres and thus they may have had similar histories. The shape information available for Hygiea, however, suggests that it is not currently in hydrostatic equilibrium. Some of the larger water-rich objects in the asteroid belt may have differentiated as Ceres has been argued to have done, but the size difference between Ceres and other objects in the asteroid belt may have sufficient to prevent differentiation and hydrostatic relaxation in the smaller group. Additional modeling is necessary to establish the most likely scenarios.

While Ceres has long been assumed to have been "born and raised" between Mars and Jupiter, it also shares some affinities with icy objects in the outer solar system. Direct comparisons to the Galilean satellites are not straightforward since they are so much larger, but six satellites in the saturnian and uranian systems are between 500-1500 km in diameter, as are a number of TNOs. Further understanding of Ceres thus allows it to be a constraint and a check on interior models of those objects. A possible thrust for Ceres exploration would be via missions to the other large objects in the main asteroid belt. Reconnaissance missions to objects like Themis, Hygiea, or Davida (for instance) could be done on a Discovery budget either as part of a tour or as a sole target. Such early missions to "protoplanets" like Ceres would help define the context in which Ceres should be understood as well as be worthwhile in their own right and would form an even broader basis after Dawn to return to Ceres.

- **Support modeling and laboratory studies relevant to the outstanding science questions outlined above for Ceres.**

Modeling and laboratory work must be supported to allow it to keep pace with continuing observations. Models are important tools for supporting the planning and interpretation of observations by the Dawn Mission. In order to increase the pertinence of geophysical models, it is crucial to increase the database of thermophysical and mechanical properties of chondrites and icy assemblages involving impurities such as hydrated salts, organics, and/or clathrates, based after cosmochemical models and carbonaceous chondrites. Although these materials are also expected to be involved in icy satellites, the experimental research on impure ice has been very limited, and the current laboratories with the capabilities to perform measurements on "exotic" icy materials are scarce. Additional spectral data for the most aqueously altered carbonaceous chondrites (CI, CM, and CR) as well as artificially altered surface materials should be taken as potential analogs for Ceres' surface and as input to spectral models. Spectral studies of the mineral assemblages expected from model thermal histories for Ceres also need to be performed both for Ceres studies and for comparison to the spectra of other asteroids.

- **Plan for post-*Dawn* nominal mission spacecraft exploration of Ceres**

We expect *Dawn's* visit to Ceres to produce a huge leap in our understanding of Ceres, providing sub-km multispectral maps of its surface, its shape and density structure and gravity to degree and order 5, and subhemispheric-scale elemental maps. We will understand whether Ceres is differentiated or not, the extent to which tectonic activity has occurred, and the degree of variation in surface composition. We also will be able to place upper limits on any outgassing/atmosphere, or detect one if present above that limit.

What we learn from *Dawn* will set the stage for further exploration of Ceres. Because *Dawn*'s visit to Ceres comes early in the 2013-2022 timeframe considered by the Decadal Survey, it is not too soon to consider follow-ups based both on expected results, new findings that Dawn will not be able to optimally study, and overall NASA programmatic considerations.

Orbital missions to Ceres still can provide important information, even in a post-*Dawn* era. The availability of a magnetometer would provide measurements about the existence and extent of an ice/water mantle in Ceres. A laser altimeter would provide detailed shape information critical for geological and geophysical understanding of Ceres. Both of these two instruments were originally planned for *Dawn* but were not flown. Their usefulness remains for future mission concepts to realize. Shallow radar sounding would provide information about deposits close to the surface. If Ceres has an atmosphere or plume activity, an ion and neutral mass spectrometer (INMS) would provide diagnostic information about its composition and origin. A thermal/mid-IR imager would allow study of Ceres' thermal properties, and discovery of any thermal anomalies and can constrain surface mineralogy. A mission carrying some of these instruments, complementary to the science to be obtained by the ongoing Dawn mission, could plausibly be done on a Discovery budget.

A landed mission is an obvious subsequent step for the study of Ceres. Such a mission, whether a Phoenix-type lander or a MER-type rover, will provide a critical link between the remote sensing available from the ground and from *Dawn* and geochemical studies performed in earthbound laboratories. Such a mission could also be seen as a useful operational bridge between the missions performed on Mars and those envisioned for airless icy satellites like Europa in future decades. It is not clear that any such mission could be carried out under the Discovery cost cap (a rover mission is certainly unlikely), though a New Frontiers Ceres lander/rover is conceivably achievable. The specific case for such an advanced mission will probably have to wait until the return of *Dawn* data, but *Dawn's* Ceres phase occurs early in the time period considered here, and it is not too early to prepare for such an mission so that we may expeditiously take advantage of *Dawn's* findings. ***We strongly advocate exploration of Ceres to answer the science questions listed above as a specified goal of a mission on the New Frontiers mission list during the NF4 and later rounds.*** Finally, we recommend the maximum use of assets already in place and/or en route to Ceres. Extended mission opportunities for *Dawn*, or use of the SALMON process to participate in foreign Ceres missions in the coming decade can provide excellent science for small incremental cost.

References

A'Hearn, M. F., Feldman, P. D., 1992. *Icarus,* **98**, 54-60.
Castillo, J. and Vance S. 2008. *Astrobiology* **8**, 344-346.
Castillo-Rogez, J. C., McCord, T. B. 2009. *Icarus*, doi: 10.1016/j.icarus.2009.04.008
Carry, B., et al. 2008 *Astron. Astrophys*. **478**, 235-244.
Chamberlain, M. A., Sykes, M. V., Esquerdo, G. A. 2007. *Icarus* **188**, 451–456.
Chamberlain, M.A., et al.. 2009. *Icarus* **202**, 487-501.
Cohen, M., et al.. 1998. *Ast. J.* **115**, 1671-1679.
Fanale, F. P., Salvail, J. R., 1989. *Icarus* **82**, 97-110.
Hsieh, H.Y., Jewitt, D., 2006 *Science* **312,** 561-563.
King, T. V. V., et al., 1992. *Science,* **255,** 1551-1553.
Lebofsky, L. A., et al., 1981. *Icarus* **48**, 453-459.
Levison, H. F., Bottke, W. F., Gounelle, M., Morbidelli, A., Nesvorný, D., Tsiganis, K. 2009. *Nature* **460**, 364-366.
Li, J.-Y., et al. 2006. *Icarus* **182**, 143-160.
Li, J.-Y., et al. 2009. *40th Lunar and Planetary Science Conference*, abstract 2101.
McCord, T.B., Sotin, C., 2005. *J. Geophys. Res*. **110**. E05009.
McCord, T. B., et al. 2006. *EOS, Trans. AGU*, **87**, doi:10.1029/2006EO100002
McFadden, L. A. et al. 2009. *The Search for Life in the Universe: Space Telescope Science Institute Spring 2009 Symposium*
McKinnon, W. B., 2008. *Asteroids Comets Meteors 2008, LPI Contrib. 1405*, paper 8389.
Morbidelli, A., et al. 2009. *Icarus*, in press, doi:10.1016/j.icarus.2009.07.011.
Milliken, R. E., Rivkin A. S., 2009. *Nature Geoscience* **2,** 258-261.
Parker, J. W., et al. 2002. **123**, 549-557.
Rayner, J. T., et al. 2003. *Pub Ast. Soc. Pac.* **115,** 362.
Rivkin, A. S., et al. 2006. *Icarus* **185**, 563-567.
Russell, C.T., et al. 2004. *Planet. Sp. Sci.* **52**, 465-489.
Rousselot, P., et al. 2008. *Asteroids Comets Meteors 2008, LPI Contrib. 1405*, paper 8337.
Shapiro, R., Schulze-Makuch, D. 2008. *Astrobiology* **9**, 335-343.
Thomas, P.C., et al. 2005. *Nature* **437**, 224-226.
Waite, J. H., et al. 2009. *Nature* **460** 487-490.
Zolotov, M. Yu. 2009. *Icarus* doi:10.1016/j.icarus.2009.06.011