CERES AND ITS COUSINS IN THE POST-DAWN ERA A. S. Rivkin[1], J. C. Castillo-Rogez[2], C. A. Raymond[2], [1]JHU/APL (andy.rivkin@jhuapl.edu), [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

Introduction: Our understanding of the largest asteroids has flowered in the last decade. A combination of new telescopic capabilities, improved mass and size estimates, dynamical and collisional modeling, and updated solar system formation theories all lead to an emerging recognition of the importance of the large, low-albedo, water- and organics-rich objects of the asteroid belt.

Recent studies of the dwarf planet Ceres have been central to this recognition. A decade of work including ground-based and HST observations and interior/thermal history modeling, and culminating in the ongoing Dawn rendezvous, has shown Ceres to be more interesting than even the most optimistic boosters had expected. Carbonates, first discovered in ground-based spectra of Ceres, have proven to be pervasive on its surface and its famous "bright spots" have been found to have very high concentrations of carbonate. Spectral features that have been the subject of decades of back-and-forth debate are currently interpreted as due to ammoniated minerals by the Dawn team De Sanctis et al (2015) argue that this points toward a possible outer solar system origin for Ceres or at least some of its starting material.

Along with these findings about Ceres, we have come to realize that the similarity between Ceres and many other large asteroids can be deeper than simply sharing low albedos. When we look at the largest objects (200+ km diameter) in the asteroid belt, we find a population with infrared spectra dominated by hydroxyl- and organics-rich minerals, and ice frost in some cases. Spectrally, several of these large asteroids have the same spectral features as Ceres in the 3-µm region, where features due to hydroxyl, organics, and other volatile species are found. In addition, they appear to have densities consistent with Ceres. Surprisingly many of the largest asteroids, including Ceres and objects with similar 3-µm spectra, appear to to be unsampled in the meteorite collection. Collectively we refer to this group of large objects with similar reflectance spectra over the 0.5-4 µm region as "Ceres' cousins" below for convenience.

Collisional models tell us that objects over ~100-200 km in diameter are very difficult to disrupt (Bottke et al. 2005), and are likely to be intact from the time of their formation. The most recent models of planetesimal formation suggest that objects of that size accreted directly from cm-size pebbles. These planetesimals are beyond the detection capabilities of even the most optimistic planned exoplanet search plans, and therefore they must be studied in our Solar System for their role in planetary accretion and in delivery of prebiotic materials to the inner solar system, to be understood.

The Question of Location: As noted, the interpretation of ammoniated clays on Ceres' surface has led to speculation that it formed in the outer solar system where ammonia is stable and was delivered later to the asteroid belt. This is an intriguing idea, and an origin for Ceres among the other dwarf planets could qualitatively explain some of Ceres' properties. However, the necessity for Ceres' ammonia to be obtained from the outer solar system has not been demonstrated. Furthermore, the existence of Ceres' cousins suggests that Ceres' history was repeated more than once—Ceres' presence in the main asteroid belt cannot be a low-probability fluke. If Ceres and other large low-albedo asteroids can be shown to have formed among or beyond the ice giants, they would be the most accessible representatives of that region, and their study would improve our understanding of large TNOs directly (and tremendously).

Ocean Worlds Where the Tide Is Out: With the Dawn spacecraft rendezvous with Ceres, we have additional insights into that body and its history. The best current data suggests that Ceres is partially differentiated, with a mixed ice-rock mantle (<40% ice) above a rocky core. This was a surprise, as models suggested Ceres should be fully differentiated with a very high ice fraction in its subsurface. While new models are still being developed, one suggestion is that Ceres' near-surface ice was steadily lost to a combination of impacts and sublimation. We might easily imagine that other spectrally-similar objects may share Ceres' history and are either partially differentiated or fully differentiate into an ice shell over a rocky core.

Early in its history and prior to this ice loss, however, there is evidence that Ceres would have had many features of astrobiological interest: an abundant subsurface layer of liquid water, organic materials, and energy to drive aqueous alteration reactions. As such, it can serve as an important data point showing the conditions under which astrobiological processes (presumably) stall out (Castillo-Rogez et al, this workshop).

Recurring Ceres? In addition to the objects with Ceres-like mineralogies mentioned above, other large outer belt asteroids show spectral evidence of ice frost at their surfaces, along with organic signatures [ref]. It is not obvious whether these bodies are undifferentiated, primordial mixtures of ice and rock or if they were differentiated like Ceres, disrupted after large impacts, and reaccumulated into the ice-rock mixtures we see today. Given expectations that the early asteroid belt was 150-200 times more massive than today's and that objects in this size class have impacted the terrestrial planets, Ceres-like objects could have been important vectors for delivery of prebiotic material.

Proposed Roadmap: The specific questions we have about Ceres and its "cousins" can be broadly grouped into a few overarching questions*: Where did they form? How far along the path to habitability did they progress? Are they active today? How commonly shared is Ceres' history?* As is fitting for objects with such importance to planetary geochemistry and geophysics, astrobiology, and exoplanet studies, a full understanding of Ceres and its cousins will require a range of studies from modeling, laboratory and astronomical measurements, and in-depth and reconnaissance-level missions.

Progress over the next several years will be made through continued study of data in hand and use of Earth-based facilities. Spectral mixing models have thus far largely made use of inputs that were found in public databases—measurements of candidate minerals in vacuum at relevant temperatures can be straightforwardly made using lab spectrometers. The release of Dawn Ceres data to public archives will allow the full extent of compositional variation to be determined.

Planetary astronomy will play a continuing role in understanding this group of asteroids. Observations in the UV and mid-IR, spectral regions where Ceres is known to have spectral features that were not within reach of Dawn's payload capabilities, will allow discrimination between multiple compositional hypotheses. Current and near-term observations by JWST, ALMA, and ground-based optical telescopes can be used to extend Dawn's results and monitor Ceres for activity. In addition, observations of other asteroid groups will mutually support advances in Ceres science. Adaptive optics/JWST observations of Hygiea and other large Ceres-like asteroids will be necessary to test the extent of their similarity to each other and to Ceres.

In addition to the largest asteroids, members of asteroid families should be targeted. Hygiea sits near the edge of a group currently thought to be ejecta from an oblique impact, and while Ceres has no identified family there are arguments that one could exist in particular restricted areas of dynamical space. In both cases, infrared observations would demonstrate whether the dynamical links to Hygiea or Ceres are real. All of this work, and the attendant theoretical work, will require consistent support from R&A programs.

Beyond the astronomical observations, missions are also warranted to these objects. A lander (ideally a rover) on Ceres could measure the geochemistry of its surface and test models of its formation. Techniques being developed hold the promise of in situ radiometric dating of surface minerals, important to determine whether Ceres is still active. Additionally, landers could directly determine whether outgassing is still underway at production rates consistent with observations made by the Herschel Space Observatory. Recognition of Ceres' place in the Solar System menagerie should lead to its inclusion among the Ocean Worlds, with a New Frontiers-level mission concept studied (and ideally advocated) by the next Decadal Survey. Eventually, depending on results from and comparison between Hayabusa-2 and OSIRIS-REx, sample return from Ceres may be deemed particularly scientifically valuable.

The experience learned from Dawn can also be leveraged for missions to Ceres' cousins. Visits to these objects will eventually be necessary to understand the full extent of their similarity. Are they also partially differentiated bodies? Do they also have carbonate-rich bright spots? Rendezvous missions carrying Dawn-like payloads to Hygiea, Patientia, or other cousins of Ceres will allow direct comparison of gravity, morphology, and composition.

Looking beyond the near term, Ceres and the icy asteroids appear to be natural waypoints for ambitious missions to Europa and the icy satellites. Their icy nature, short travel times, and lack of radiation makes them obvious proving grounds for the technology needed to drill on Europa, and a natural next outpost for human exploration beyond Mars. Such missions would not only set the stage for further exploration, but return incomparable datasets to further address the issues mentioned above.

Summary: Over the last decade, we have discovered that Ceres has experienced intense aqueous alteration and partial or full differentiation in its history, it maintains an ice-rich subsurface, and has many ingredients of interest to astrobiologists. We have also learned that several other objects in the asteroid belt are consistent with Ceres within observational uncertainties, with Hygiea (for instance) a compelling match in its 0.5-4 μm spectrum, albedo, size, and density.

With the recognition of Ceres' nature and its importance for understanding Solar System formation, the origin of life, and ongoing geological processes, its further study is more than justified. Along with Ceres itself, significant insight can also be gained by investigating these Ceres-like objects in order to provide context for Ceres itself and for the Ocean Worlds in the outer solar system.