A revealing last glance at Ceres

Before its demise, the Dawn spacecraft performed a series of low passes over the bright spots of dwarf planet Ceres. These high-resolution data highlight the nature of Ceres as an active ocean world with unique characteristics.

The launch window for spacecraft towards Mars, which repeats at a cadence of 26 months, has become one of the most reliable appointments in space exploration. Since 1988, only two (1994 and 2009) have passed without a spacecraft launch, and with eight currently operational missions, Mars is by far the most crowded body in the Solar System. Remarkably, the 2020 launch window, which saw three spacecraft leaving for the red planet, marked the arrival of two newcomers: China, an established Moon explorer, sent Tianwen-1, an ambitious combination of orbiter, lander and rover, and the United Arab Emirates launched the Hope orbiter, their first planetary mission ever. Slowly but surely, the Martian exploration is opening up beyond the usual suspects, though we are still far from a 'democratization' of Martian space.

We celebrated the Martian season last month by publishing two Mission Controls related to these new actors, and for more about NASA's Perseverance rover, Emily Lakdawalla has written on the science that can be done at the landing sites of the NASA and ESA rovers (the latter, meanwhile, has been delayed to the next launch window, in 2022). This issue of *Nature Astronomy* moves a bit farther from the Sun to the only dwarf planet in the inner Solar System: Ceres. NASA's Dawn mission arrived at Ceres in 2015 and, while still in orbit, stopped operating in October 2018 due to lack of fuel. In a similar fashion to Cassini, Dawn planned its own 'Grand Finale' during the second extended mission (XM2) phase, with a series of low-passing orbits — the closest one a mere 35 km above the surface — that could study Ceres at unprecedented resolution.

When it came to choosing the location that would most benefit from such a unique perspective, it could not have been anything other than the Occator crater. Occator is the location that turned Ceres from a relatively placid (albeit large and ice-rich) asteroid into an overnight sensation with the unexpected discovery of large bright spots — faculae — that stand out strikingly against the dark greyness of the surface. Made up of a mixture of salty brines, the faculae offered a different vision of Ceres as an active world for most of its history, a vision reinforced by the presence of cryovolcanoes of different ages scattered across the surface. Given that Occator formed only about 22 million years ago, the presence of such bright spots indicates very recent activity. The idea of Ceres as a relict ocean world started to take shape. And an ocean world in the asteroid belt was not expected. Ocean worlds, with the obvious exception of Earth, are mostly associated with the outer Solar System. Ceres, in addition, does not have a favourable configuration to host an ocean: there is no possibility of tidal heating like the moons of the giant planets, it is too far from the Sun, and it is rather small to have sufficient radioactive materials to keep an ocean liquid for the whole of Ceres's history.

Dawn's XM2 phase was planned to answer a series of open questions about Ceres's interior and activity that needed specifically high-resolution data, and to remove ambiguities connected to the formation of the faculae. The first results from Dawn's XM2 are presented here in a series of seven papers spanning three journals: *Nature Astronomy*, *Nature Geoscience* and *Nature Communications*. In this way, each paper is published in its most suitable venue, and at the same time it is clearly shown as part of a whole through a dedicated webpage. Following in the steps of last year's publication of the first results from the OSIRIS-REx mission to asteroid Bennu, the Dawn XM2 series reaffirms the commitment of the Nature Research group to highlighting important events in astronomy and planetary science through the publication of a full package of related scientific papers.

And the results from Dawn are indeed well worth highlighting. As Julie Castillo-Rogez and Marc Rayman show in their summary, this series of papers marks yet another shift in our vision of Ceres: from a relict ocean world to an active one. The discovery of a particular salt, hydrohalite, and its higher concentration at the centre of the biggest facula, is proof that the briny liquid material is still coming up from the interior, as hydrohalite dehydrates in less than 100 years if left undisturbed. This means that the impact that created Occator had both short- and long-term consequences, mobilizing deeper-seated brines that are still active today. Thanks to the close pass of Dawn's XM2, the story of the crater from its formation until today can be reconstructed with precision, showing repeated events associated with cryovolcanism. This picture of a porous and possibly brine-filled interior is confirmed by high-resolution gravity data. Ceres can then be added to the rather short list of bodies for which we know the interior structure at high resolution, and the only ocean world to date (bar Earth).

Interestingly enough, the ensemble of these data indicates that Ceres's internal ocean does not seem to be like the others we are used to. It is much more full of rocks and non-icy materials than, say, the liquid bodies within Europa or Enceladus. This result reveals the astonishing diversity of possible ocean worlds in our Solar System, and surely the missions coming in the next decade (and beyond) that target ocean worlds will provide many further surprises.

When we mention an ocean we can't avoid thinking about its potential habitability. Each ocean world has astrobiological potential, but it is not yet clear whether the potential can be translated into possibility. For Ceres, we will probably need a follow-up mission. And the search for life is what ultimately ties icy world Ceres with our neighbour Mars. Mars has always been a candidate in the search for past (and extant) life, and the new and upcoming Martian missions are becoming increasingly astrobiologically oriented. At both Mars and ocean worlds like Ceres, we are preparing, with very concrete steps, to tackle one of humanity's biggest questions. ❐

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