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Big realities for small bodies

The importance of small bodies in Solar System studies is not proportional to their size. Due to their variety of types, scope, and link to Solar System formation, they are one of the most active fields in planetary science.

In 2019, Richard Binzel wrote in our pages that, despite their lack of majestic landscapes compared to Solar System planets, small bodies "loom large" in space exploration programmes. That Comment was written in the wake of the arrival of the OSIRIS-REx and Hayabusa2 spacecraft at their respective near-Earth asteroids, Bennu and Ryugu, and a couple of years after NASA had selected two asteroidal missions at once, Lucy and Psyche, for its Discovery programme. Since then, the community interest in small bodies has only grown, and they loom larger than ever: not only have both OSIRIS-REx and Hayabusa2 brought back their regolith samples to Earth and both NASA missions have been launched successfully, but we reached further milestones such as the successful planetary defence-oriented Double Asteroid Redirection Test (DART) mission that changed the orbital properties of the asteroid moonlet Dimorphos. More recently, China has launched its own mission that will rendezvous with both an asteroid and a comet, and multi-telescope campaigns are undergoing to observe the recently discovered interstellar object 3I/ATLAS at unprecedented detail. This quick snapshot of activities showcases one of the reasons for the popularity of minor bodies: their extreme diversity encompasses a vast array of scientific questions and interests. This issue of *Nature Astronomy* presents a few examples of this activity.

The main asteroid belt between Mars and Jupiter has a privileged space in minor bodies studies as it contains more than 99% of Solar System asteroids. It is also where the majority of meteorites falling on Earth come from, so it has a direct influence on our planet's evolution. We know now that the belt's asteroids come from a variety of sources and have been implanted from different Solar System locations, but the belt is a dynamically chaotic place and reconstructing its history is a complicated affair. Marine Ciocco and colleagues, using meteoritic data, show the complexity of this process by retracing the collisional history of the asteroids linked to the most common type of meteorites, the L chondrites. L chondrites fell en masse on Earth around 466 million years ago — possibly influencing the biological diversification of the Middle Ordovician period — and researchers attribute this sudden influx to the catastrophic disruption of the L chondrites parent body in the main belt a few million years before that. According to Ciocco and colleagues, this breakup is only one — and not even the last — of a long series that can be traced back in time to 4.4 billion years ago, not long after the formation of the Solar System. Each collision in the chain generated its own asteroid family, meaning that such families are not fully independent but part of the same very ramified genealogical tree.

In a similar spirit, but using dynamical modelling rather than meteoritic tools, Sarah Anderson and co-authors look at the origin and history of the progenitors of carbonaceous chondrite meteorites, focusing on the CM and CI sub-types. There is consensus that carbonaceous asteroids come from the outer Solar System, but Anderson and co-authors show that the finer details provide hidden information, with the parent bodies of these two sub-types implanted in the belt from different places (the Saturn formation region for the CM-types and beyond Uranus for the CIs) and at different times, following two different upheavals of the outer Solar System triggered by the giant planets' migration. CM and CI chondrites thus provide fingerprints for the gas profile of the protoplanetary disk at the time of their formation. Both Ciocco and colleagues and Anderson and co-authors highlight the connection between small bodies and planetary formation, by providing constraints that help define and refine planetary formation and evolution models.

Small bodies have a direct impact on Earth's history, and possibly on the development of life, too. One of the most discussed questions is where Earth's water comes from. Anderson and co-authors show that only CM chondrites and their related water content could efficiently deliver water to Earth, making them the main exogenous water source. Comets are also often indicated as such a source. Martin Cordiner and colleagues observe both water and singly-deuterated water (HDO) with ALMA to confirm that comet 12P/Pons–Brooks's D/H ratio is consistent with that measured in terrestrial oceans, suggesting an Oort cloud contribution to some of Earth's water. Margot Leemker and co-workers come to a similar conclusion via a different means and for a different protoplanetary system: by calculating the D/H ratio in doubly-deuterated water (D_2O) in the V883 Ori disk, they find again cometary values and suggest that inner terrestrial planets (Earth included) could inherit some of their water in pristine form directly from the protosolar/stellar nebula.

Small bodies will continue to shine in the future, considering the wealth of new information we are going to receive. The Vera Rubin telescope is expected to discover millions of new small bodies of all kinds (including 5–50 interstellar objects) in the first two years of observations, and test runs of the instrument support these optimistic projections. Lucy will have its first flyby of Trojan asteroids in 2027 and will continue until 2033, whereas Psyche will arrive at its namesake target in 2029. That year there will surely be a surge of public interest in asteroids: the Earth-grazing flyby of asteroid Apophis at barely 40,000 km of altitude (one tenth of the Earth–Moon distance) will be observed by 2 billion people and at least a couple of dedicated missions, and will renew the attention on planetary defence. By that time, the Japanese DESTINY+ should be travelling towards Phaethon, the active asteroid source of the Geminid meteor shower, and the Emirates should have launched their ambitious new mission which aims to visit seven main belt asteroids by 2034. The Emirates mission is also the first to explicitly include a mention of future asteroid resource utilization, hinting tantalizingly at a new era for small bodies still very far away but not out of the picture anymore.

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