The oddballs of the solar system

Small bodies orbiting the Sun are either comets or asteroids – for many years, this was the official line in textbooks. At the **Max Planck Institute for Solar System Research** in Goettingen, **Jessica Agarwal** is studying "active asteroids", small solar system bodies that don't quite fit into the traditional categories.

TEXT **THORSTEN DAMBECK**

Those who cast their gaze to the night sky in the Advent season between December 4 and 14 can hope for a special gift: shooting stars. If you extend the trails of light backwards, the meteors appear to be coming from the constellation Gemini, and they are therefore known as the Geminids. These shooting stars are made up of tiny grains of cosmic dust, and Earth is in precisely the right position every Advent for this dust to burn up in its atmosphere. When it does, it produces the fleeting bursts of light that will make a secret wish come true, as popular belief would have it.

Taking a more rational view, astronomers have long known the origin of the dust. It comes from Phaethon, an asteroid identified in 1983 that orbits the Sun on an elongated elliptical path. In the course of each orbit, its distance from the Sun varies considerably – every 1.4 years, Phaethon approaches the Sun to a distance of 0.14 astronomical units (AU), or around 20 million kilometers. At this point, the temperature on the surface of the body, which is just five kilometers wide, rises to over 700 degrees centigrade, and the radiation pressure from the intensive sunlight can catapult tiny dust particles off the surface and out into space.

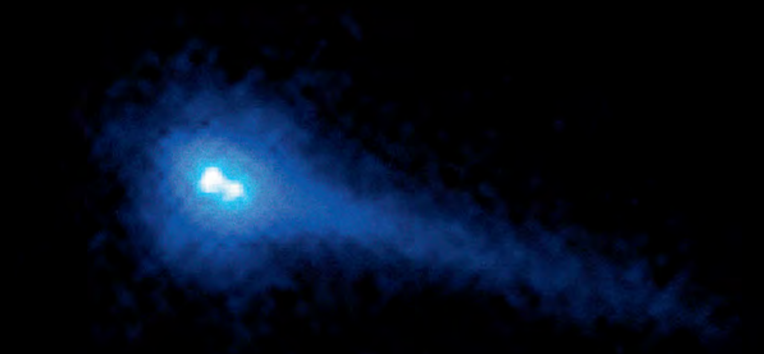
MOST ASTEROIDS ORBIT IN THE MAIN BELT

"It's highly unusual for an asteroid to be the source of a meteor stream," says Jessica Agarwal of the Max Planck Institute for Solar System Research. "Normally, meteor streams come from comets." The latter have been known about since ancient times and can sometimes produce impressive tails of gas and dust when they are close to the Sun. Then, the spectacular goings-on in the night sky even become a talking point among the general public. The dust that comets release into space is swept away by sublimating ice and is the origin of the periodic meteor streams. At any rate, that is what has long been taught in textbooks.

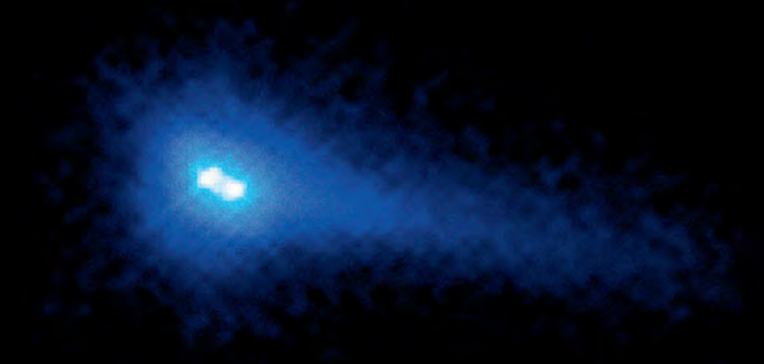
Phaethon is different: although it too emits dust, it does so in the absence of ice. Asteroids have only been known about for around 200 years. The first example, Ceres, was their largest representative for a long time but is now considered a dwarf planet (see box on page 51). These objects have since been cataloged in their hundreds of thousands, with most of them orbiting the Sun in what astronomers call the *main belt*. This lies between the two large planets Mars and Jupiter. >

An optical illusion! This sequence of images from the *Hubble* Space Telescope shows that the asteroid 288P consists of two parts orbiting one another. In addition, the celestial body exhibits the key characteristics of a comet – a coma, which envelops the two nuclei, and a dust tail.

Photos: NASA, ESA, and J. Agarwal (Max Planck Institute for Solar System Research)



August 22, 2016



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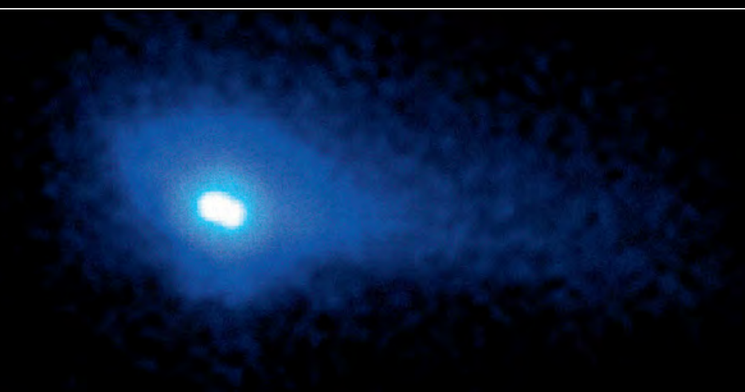

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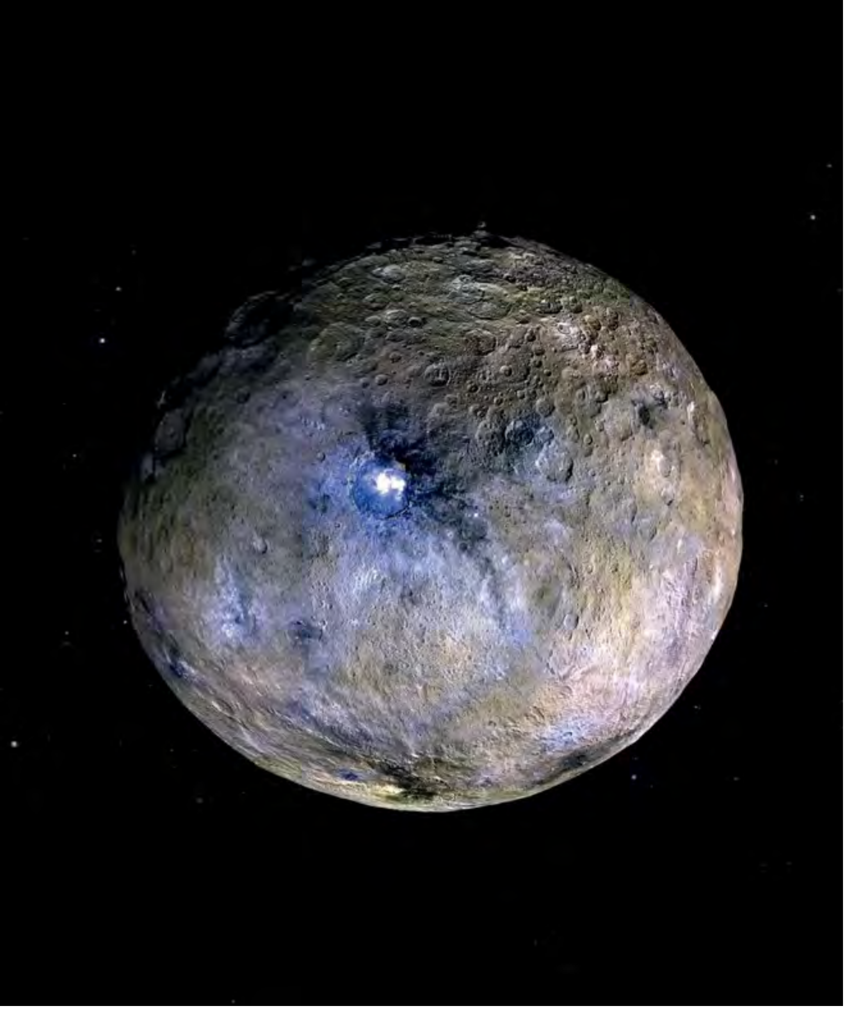
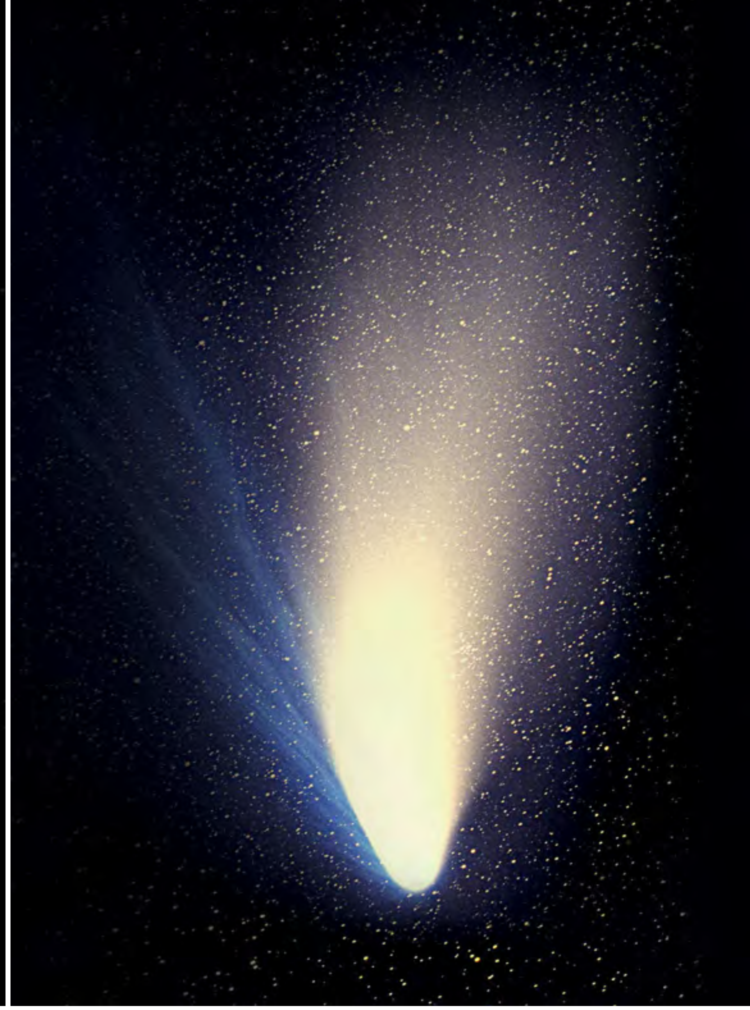




Cosmic odd and ends: the dwarf planet Ceres (left) is an asteroid, whereas Hale Bopp belongs to the family of comets. Until a few years ago, astronomers drew a clear distinction between the two classes because of their different features, but the boundaries are becoming increasingly blurred.

Asteroids and comets – Jessica Agarwal knows her way around both fields, as well as the boundary region between them: “We conduct research at the interface between astronomy and geophysics,” says the Goettingen-based astronomer, whose work examines physical processes that can have a profound effect on these small celestial bodies. One focus of the scientist’s work is an even more elusive subgroup of the minor planets: the so-called active asteroids. Phaethon belongs to this particular group of oddballs, whose common feature is that they can emit dust. A paper published in 2015 already included 18 such specimens, most of which are only a few kilometers in size, with the notable examples of Scheila and Ceres, which have estimated diameters of 113 and 975 kilometers respectively.

Asteroids become smaller and smaller due to collisions with other small bodies in what Agarwal compares to a grinding process. One example is the collision that struck the object P/2010 A2 and which the researchers dated back to the year 2009. The following year, they observed the developing tail of P/2010 A2 for five months using the *Hubble* Space Telescope. It turned out that it was different from a normal comet’s tail because, since comets emit gas and dust almost continuously while they are near the Sun, they usually have a fan-shaped tail.

A UNIQUE X-SHAPED STRUCTURE IN THE DUST TAIL

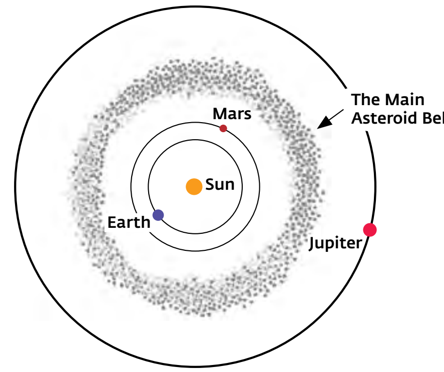
In contrast, the linear tail of P/2010 A2 suggested that it was formed by a single, brief event. On the first detailed *Hubble* photos, the researchers noticed a spot of light and estimated the diameter of the corresponding object to be around 120 meters. “The nucleus almost seemed to be detached from the dust cloud,” says Agarwal, who at that time was still analyzing the images at the ESA’s research center in Noordwijk, the Netherlands. The experts interpreted the spot of light to be a large fragment from an asteroid collision. An X-shaped structure in the dust tail, directly behind the fragment, makes this asteroid a unique specimen.

Some of the active asteroids are also referred to as *main-belt comets*. In their case, the astronomers suspect that the dust emission is driven by water ice or other volatile substances that sublimate and sweep near-surface dust particles away in the process, as happens in comets. One example of this group of objects is 288P, which follows an elliptical path in the outer main belt and takes 5.3 years to complete a full orbit of the Sun.

This minor planet has only been known about since 2006, after the Spacewatch telescope in Kitt Peak National Observatory, Arizona, discovered a small, weak spot of light; this telescope is specially designed for small solar system bodies. Just five years later, the object was observed during several months of activity close the Sun. The photos clearly showed a short dust tail pointing away from the Sun and an approximately six-times-longer trail running along its direction of motion. Even at that time, the long period of activity pointed to the sublimation of ice as the driving force for dust emission.

September 2016 offered especially favorable conditions for observing 288P, which came as close as 1.45 AU to Earth, providing a great opportunity for Jessica Agarwal and her colleagues to unravel further secrets about their object of study. High-resolution photos taken by the *Hubble* Space Telescope now clarified what previous images had only hinted at: 288P is binary! In other words, it consists of two separate components of roughly the same size, which orbit about their common center of gravity; both have a diameter of around 1.8 kilometers. The striking thing is their relatively large separation of approximately 100 kilometers.

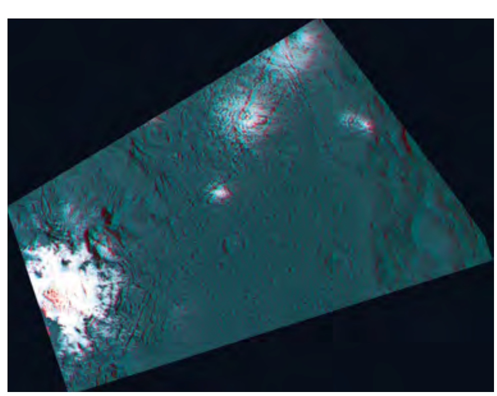
The active binary asteroid is a good example of how these bodies can turn out to be fascinating objects. They allow researchers to study – live, so to speak – the processes of change they are undergoing. 288P probably originates from a collision that long ago destroyed a precursor body with a diameter of around 10 kilometers. That instant, some 7.5 million years ago, marked the birth of not only 288P but also a whole family of asteroids. At least eleven members of this group have already been identified, with their similar orbits around the Sun betraying their common origin. Astronomically speaking, it is a very young family. A second collision at a later stage might then have split 288P into two fragments. Or it might already have been a binary object when it emerged from its violent birth. "Neither option can be ruled out," says Jessica Agarwal. "We don't know exactly what happened." >



Rich source: most asteroids orbit the Sun on trajectories between the planets Mars and Jupiter, in what is known as the main belt.

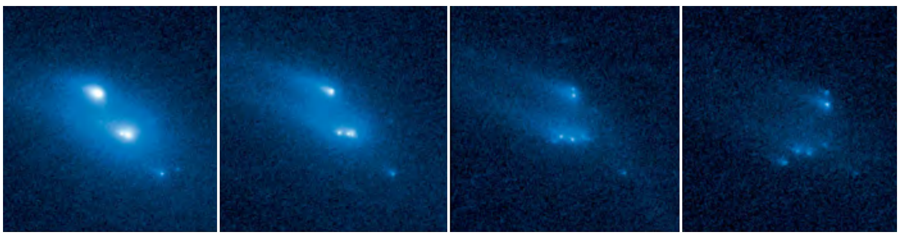
AN ACTIVE GIANT

On the scale of the entire solar system, Ceres is only a dwarf, with an average diameter of 975 kilometers and just 0.28% of the mass of the lightest planet, Mercury. However, it is a giant among the active asteroids, most of which are just a few kilometers in diameter. Since June 2018, the space probe *Dawn* has been orbiting Ceres on a new, highly elliptical path. At points, this NASA probe is only around 35 kilometers from the surface, bringing *Dawn* closer than ever to its object of study since its arrival in March 2015. From this short distance, it has now been able to take detailed photos, some of them with ten times better resolution, of the 90-kilometer-wide Occator crater (see image), providing the best view yet of the ominous bright spots that *Dawn* had previously discovered there.



In the middle of this impact crater is a depression with a strikingly bright, asymmetric hilltop rising from its center – this is the scene of past cryovolcanic activity. Scientists from the Max Planck Institute for Solar System Research have discovered that salt solutions escaped from this location until well into recent geological history. When the water evaporated, it left behind light-colored deposits that spectroscopic measurements have identified as sodium carbonate. Further bright spots in the eastern part of the crater are probably also points at which a water/salt mixture came to the surface. Several current studies suggest that the crust of Ceres contains large quantities of water ice. It is likely that a steady stream of smaller meteorite impacts and landslides uncover deposits of ice, which then evaporate. This creates an extremely thin atmosphere of water vapor, or "exosphere".

Graphic: designergold based on a draft from the MPC; photo: NASA/JPL-Caltech/UCLA/MPS/DLR/IDA



Total disintegration: the asteroid P/2013 R3 practically crumbled before the astronomers' eyes. Presumably, the object was once a loose agglomeration of large lumps of rock. In the end, it disappeared from the scene entirely and has never been seen again.

There is, however, another plausible scenario. Small celestial objects can also be torn apart by centrifugal forces, in other words, when they rotate too quickly around their own axis. Such events, which have already been known to occur in comets for some time, also affect asteroids – and a drama of this kind can be triggered by various causes. "For example, if there are patches of ice near the surface, then the recoil from the subliming gas could produce a jet-like effect that speeds up rotation relatively quickly – until it exceeds a critical level that the body can no longer withstand," says Agarwal.

Therefore, the asteroid could break up after just a few thousand years. The latest analyses suggest that this "jet engine" effect tore 288P apart through precisely such a process of escalating rotation. This effect may also have played an important role in the development of the mutual orbit, causing the two components to move further and further apart until they ultimately reached the large separation seen today – which allowed *Hubble* to reveal the binary nature of 288P in the first place.

Experts also know of another process that can alter a body's rotation: over long periods of time, the so-called YORP effect can cause the rotation of a small, irregularly shaped celestial body to speed up – simply due to illumination with sunlight and the re-radiation of heat – until the centrifugal forces eventually tear the body apart (see box below). Another variant, known as the binary YORP effect, can bring the components of a binary system back together again – or move them further and further apart.

A particularly dramatic example of this led to the fragmentation of the asteroid P/2013 R3, as witnessed by David Jewitt of the University of California in Los Angeles along with Jessica Agarwal and other colleagues in 2014. The researchers had an almost live view as the asteroid fell victim to its own rapid rotation, which was probably caused by the YORP effect: at least ten fragments have been identified, the largest of which has a radius of less than 200 meters. This was accompanied by a cloud of dust and debris, whose mass the researchers have estimated at 100,000 tonnes.

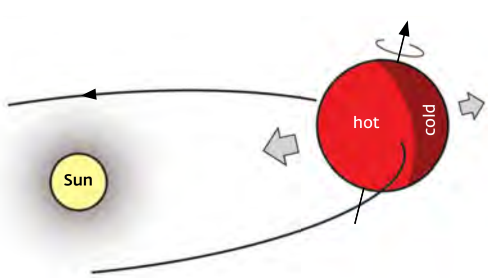
Photos taken by *Hubble* and the Keck telescope, on Hawaii, can be used to extrapolate the trajectories of the individual fragments. This indicates that the asteroid began breaking up in several stages between February and September 2013 – just a few months before it was discovered. P/2013 R3 was probably nothing more than an agglomeration of dust and large lumps of rock, loosely held together by the body's weak gravitational pull to form what is known as a rubble pile asteroid.

As the celestial body released large quantities of dust, thereby producing a distinct tail, the researchers first mistakenly classified it as a comet. Could the

SHREDDED ASTEROIDS

The YORP effect is a gradual alteration of the rotation state of small celestial bodies, such as asteroids, under the influence of sunlight. It occurs when thermal radiation is emitted from the body directionally, producing a continuous torque. This can alter the spatial position of the body's axis of rotation, which then aligns parallel, perpendicular, or antiparallel to its orbital plane. In addition, the effect can cause deceleration or acceleration of the asteroid's rotation (see image).

The effect was first demonstrated in 2007 by studying the asteroids YORP and Apollo. Evidently, the rotation of the active asteroid P/2013 R3 was accelerated by the YORP effect to such an extent that it broke up into at least ten fragments due to the resulting centrifugal forces. The name of the effect is an acronym of the first letters in the surnames of the researchers **Y**arkovsky, **O**'Keefe, **R**adzievskii, and **P**addack.



Photos: NASA/ESA/D. Jewitt (UCLA) (top); graphic: designergold based on a draft from the MPG asteroid also have been destroyed by an impact? Agarwal thinks this is unlikely because, as she explains, the speed of the fragments is far too slow to have resulted from a collision. Likewise, "jet effects" due to the sublimation of frozen substances – above all water ice – are highly unlikely, as there was no indication whatsoever of prolonged sublimation-driven dust activity.

VANISHED NEVER TO BE SEEN AGAIN

When studying active asteroids, you always have to be prepared for surprises. "P/2013 R3 disintegrated, disappeared, and has never reappeared since. The object P/2016 G1 was obviously just a dust cloud, or at any rate the nucleus was too small to be visible. P/2013 P5, on the other hand, exhibited nine highly individual dust tails," says Jessica Agarwal. This booming area of research has also drawn the attention of the space agencies. In January 2018, for example, the ESA considered launching a mission to several active small solar system bodies, although initially this was merely a theoretical study. The Japanese space agency, JAXA, has made more progress: with the *Destiny+* space probe, it is planning to venture forth to the source of the Geminid stream – that is, to Phaethon – with a launch planned for 2022.

Four years later, if everything goes to plan, a dust detector on board the probe could be inspecting the raw material that brings shooting stars to Earth's sky each December; the instrument is being developed at the University of Stuttgart. But Phaethon has a volatile nature, with active phases also followed by long periods of relative tranquility. If Jessica Agarwal could wish for a target object for a space probe, her choice would be a different one, however: "288P! It shows comet-like activity, and the large separation between its components is unique. That would be my favorite." ◂

An eye for the unusual: Jessica Agarwal from the Max Planck Institute for Solar System Research in Goettingen dedicates her time to studying active asteroids. These celestial bodies have special characteristics, such as being made up of multiple nuclei or outwardly resembling a comet.

Photo: Ronald Schmidt/AFWK

SUMMARY

- **In recent years, researchers have discovered that there is no clear dividing line between tail-forming comets and asteroids.**
- **A group of transition objects in the planetary system are referred to as active asteroids because they can release dust and form tails.**
- **Asteroids have also been discovered that consist of a binary body.**
- **Some asteroids seem to consist only of a dust cloud, while others break up before researchers' eyes.**

GLOSSARY

Astronomical unit: One astronomical unit (AU) is the average distance between Earth and the Sun and is equal to 149.57 million kilometers.

Cryovolcanism: A form of volcanism in which volcanoes do not eject hot lava, as on Earth, but rather methane, carbon dioxide, water, or ammonia. These substances are present in a frozen state inside a planet or moon.

Sublimation: On Earth, substances such as water pass from the solid state to the liquid state and then into the gaseous state. When one of these phases is skipped and a substance passes directly from the solid to the gaseous state, the process is known as sublimation.