PLANETARY SCIENCE

Traveling to the origins of the Solar System

Asteroid data from the Hayabusa2 mission support collisional evolution of a pristine body

By **Gerhard Wurm**

In December 2014, the Japanese spacecraft Hayabusa2 began its more than 2 billion miles journey to rendezvous and land on a rocky body with a diameter of no more than a kilometer. It arrived in June 2018, and on pages 272, 268, and 252 of this issue, the first observations of Hayabusa2's remote sensing instruments are reported by Kitazato *et al.* (*1*), Watanabe *et al.* (*2*), and Sugita *et al.* (*3*), respectively. Designed to probe the geology, morphology, and composition of the asteroid, this mission will help clarify the formation of the solar system 4.5 billion years ago (see the figure).

Viewed on a larger cosmic scale, Earth's planetary system is not the only one in the galaxy. Extrasolar planets orbiting other stars are detected regularly now. Recently, a planet barely emerging from its birthplace was imaged sculpturing the remains of the flat disk of gas and dust in which it formed (*4*). Protoplanetary disks of gas and dust can develop rings and gaps (*5*), and the early shaping of planetary systems often leaves behind belts of smaller bodies. Earth's solar system harbors two such belts. At the outer perimeter is the Edgeworth-Kuiper belt. Situated beyond Neptune, it is considered the reservoir of cold, icy, short-period comets (those orbiting the Sun in less than 200 years). The European Rosetta mission was the first spacecraft to rendezvous and land on a comet (Churyumov-Gerasimenko) from this belt, carrying a suite of instruments to do a similar survey (*6*). Planet formation in these cold regions—beyond what is known as the snowline—strongly depends on the existence of water ice. The condensating of water to ice makes it easier for giant planets such as Jupiter to form because there are more solids available to initiate the growth.

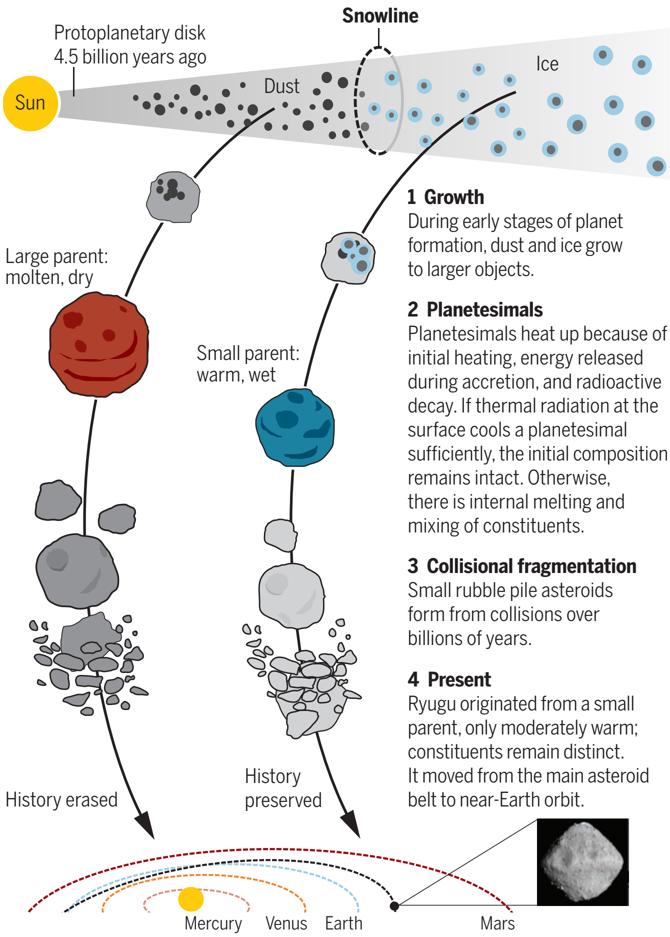
The other belt in Earth's solar system—the asteroid belt—is a ring of small bodies situated just inside of Jupiter's orbit. The inhabitants of this belt, between Mars and Jupiter, feel the gravitational presence of Jupiter. This region is too warm for water ice to persist, and low ambient pressure makes water only stable in the gas phase. However, as the temperature varied with the evolution of the protoplanetary disk early on, the outer edge of the asteroid belt could have reached up to, or slightly beyond, the snowline. If so, some water might have made it into the minerals of these asteroids. Therefore, the asteroid belt links different aspects and regions of planet formation, and as part of the inner Solar System, might provide details about the formation of Earth.

The objects within the asteroid belt never became full-size planets. These asteroids are not the remains of only a single planet that was destroyed. The asteroid belt was, and is, dominated by collisions, but it began with many larger parent bodies (*7*). NASA's DAWN spacecraft mission studied two of the larger existing dwarf planets in this belt, Ceres and Vesta (*8*). Even though these large objects may be favorable targets for exploratory probes, their (almost) spherical shape implies that they melted inside. Because of a decreasing surface to mass ratio with size, large bodies do not cool efficiently through thermal radiation. Thus, the continuous build up of internal heat provided by radioactive decay, can cause internal melting; Dwarf planets could not avoid that. As a consequence, once the melting temperature of metal (iron) was reached, it unmixed from other materials and sedimented to the center, forming a core.

By contrast, somewhat smaller bodies might heat up only moderately and escape melting. In this case, most of the original constituents and their composition remain intact. Studying these objects, therefore, gives an account of the conditions during planet formation. The study of meteorites has provided a glimpse at the origins of the Solar System. The class of meteorites known as carbonaceous chondrites is considered to originate from asteroids that heated up only moderately. They are among the most primordial samples of the Solar System known. For example, they have provided the best age determination of the Solar System and provide a record of evolutionary sequence during the first 10 million years of planet formation. However, although observed meteorite falls can be traced back to the asteroid belt, and even though the comparison between visual spectra from asteroids and meteorites suggests possible relations, the Hayabusa2 mission now provides a firm connection between an asteroid and carbonaceous

A well-preserved witness

Data collected by Hayabusa2 on the geology, morphology, and composition of the asteroid Ryugu provide a glimpse of the early formation of the solar system.



1 Growth
During early stages of planet formation, dust and ice grow to larger objects.

2 Planetesimals
Planetesimals heat up because of initial heating, energy released during accretion, and radioactive decay. If thermal radiation at the surface cools a planetesimal sufficiently, the initial composition remains intact. Otherwise, there is internal melting and mixing of constituents.

3 Collisional fragmentation
Small rubble pile asteroids form from collisions over billions of years.

4 Present
Ryugu originated from a small parent, only moderately warm; constituents remain distinct. It moved from the main asteroid belt to near-Earth orbit.

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chondrites. Now that Hayabusa2 has landed on Ryugu, there is the prospect of sampling the planetesimal's material in situ. Luckily, collisions and planetary gravity scattered Ryugu from the main belt of asteroids and made it a near-Earth object, which is much easier to reach, orbiting the sun at approximately the same distance as Earth.

Kitazato *et al.* report on spatially resolved near infrared spectra of the surface of Ryugu. These spectra are sensitive to the minerals composing the asteroid. The spectral data are rich in hydroxyl groups (OH), implying that water was present in the past, and likely lead to an aqueous alteration of what probably were dry minerals before. Some degree of thermal- or shock-induced metamorphosis also can be deduced from the data. This all implies that the asteroid's material might have started cold but was subject to some energy input. This notion is complemented by the imaging of Ryugu's surface by Watanabe *et al.* which implies that the asteroid was not small when it was created. It is thought that after large minor planets initially grew, the Solar System became quite destructive. Small asteroids are presumed to be the rubble piles formed after collisions of larger asteroids, which are often referred to as parent bodies. Watanabe *et al.* confirm this history of Ryugu. To round out the story, Sugita *et al.* report that the surface of the asteroid is rather young on the basis of geomorphological features. For example, the small number of craters identified is indicative of the time interval that its surface was subjected to impacts. In addition, Sugita *et al.* report a very low albedo—that is, the asteroid's surface reflects a small amount of the incoming radiation and absorbs the rest. This finding is consistent with moderate thermal-processed material at the surface, resembling the properties of carbonaceous chondrites.

The remote sensing instruments are not the only instruments on board Hayabusa2. The MASCOT lander was successfully released in October, touching down on the asteroid's surface (*9*). The next step is to bring back a sample from this object, which might now be considered one of the most precious time capsules of the solar system. ■

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CHEMISTRY

Toward fire safety without chemical risk

Use of halogenated flame retardants continues despite health and environmental concerns

By **Jacob de Boer**[1] *and* **Heather M. Stapleton**[2]

Halogenated flame retardants are used widely in consumer products such as carpets, textiles, and electronics to reduce the risk of fire. It has been known for more than 20 years that these compounds can leach into the environment, with particularly high concentrations recorded in fish and marine mammals. Concerns have also been raised about carcinogenic and endocrine-disrupting effects in humans. Some brominated flame retardants—in particular, polybrominated diphenyl ether (PBDE) commercial mixtures and hexabromocyclododecane (HBCD)—have been banned or phased out in some jurisdictions, and the possible use of alternative flame retardants has been investigated. Yet, over the past 20 years, global production of flame retardants has continued to rise without a decrease in halogenated flame retardant production. It is time for a critical evaluation of flame retardant use.

In the late 1980s, scientists began to develop analytical methods and gather the first screening data on flame retardants in the environment in Europe, Japan, and North America. Concern among environmental scientists rose when Norén and Meyronité reported rising concentrations of PBDEs in human milk (*1*) and de Boer *et al.* detected PBDEs in sperm whales stranded in the Netherlands (*2*). Soon after, more studies documented increasing PBDE trends in fish, sediment profiles, sewage sludge, aquatic birds, and human tissues (*3*).

Intensive discussions between scientists, regulatory authorities, and the international bromine industry, represented by the Bromine Science and Environmental Forum, followed but did not lead to reductions in the global use of halogenated flame retardants. Instead, repeated regrettable substitutions were made, in which one halogenated flame retardant was phased out and replaced by another halogenated flame retardant, for which less information on exposure pathways and potential environmental and health effects was available (*4*, *5*). All substitutes showed harmful effects, although these effects were sometimes slightly different from those of the compounds they had replaced.

In the meantime, a suite of other halogenated flame retardants was introduced; about 75 different brominated flame retardants are on the market, and many of them have been detected in the environment (*6*). For each of these compounds, scant information was available on their environmental behavior at the time of introduction, because years of research are needed to collect information and support a thorough risk assessment. Such risk assessments have been carried out in the past for single compounds or for well-defined mixtures but are much more difficult to conduct when the effects of multiple substances are cumulative (*7*).

Even after a detailed risk assessment of the flame retardant tris-(1,3-dichloro-2-propyl)phosphate (TDCIPP) found it to present a potential risk for children (*8*), the compound was not taken from the market but only voluntarily removed from children's pajamas. More than three decades later, this same chemical became a popular replacement for pentabromodiphenyl ether (PentaBDE) in U.S. furniture, including baby and juvenile furniture (*9*).

Recent research has drawn attention to human exposure to flame retardants in indoor environments such as homes, with children receiving greater exposure than adults (*6*). Furniture and electronics appear to be substantial sources of flame retardants in indoor dust and air, as well as in cars (*6*). Scientists are now increasingly investigating the importance of dermal absorption and inhalation as primary uptake routes compared with diet.

POLICY AND REGULATIONS

The European Union (EU) issued bans on the production and use of PBDEs and HBCD starting in 2002. More recently, several frameworks and directives have been developed in Europe, including the Registration,

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