BORN OF DUST

TEXT: THORSTEN DAMBECK AND TOBIAS BEUCHERT

Life on Earth, as we know it today, exists thanks to many coincidences – and the planet Jupiter. Its weighty role in the Solar System is one aspect of its turbulent history, a subject Thorsten Kleine and Joanna Drążkowska investigate using meteorites and computer simulations at the Max Planck Institute for Solar System Research in Göttingen.

On September 12, 2019, eyewitnesses experienced a celestial spectacle: shortly before 3 PM, a fireball streaked across the sky in Central Europe. The meteor even caused rolling thunder in some places. Photos and videos documented the event, and newspapers and TV stations reported on it. And so it was no surprise when someone gardening in Flensburg recovered a conspicuous gray rock in the shape of a golf ball the following day. This is currently the only known fragment of the "Flensburg meteorite." The cosmic discovery in North Germany may seem spectacular, but meteorite finds are hardly rare. "In collections around the world there are more than 70,000 rocks that fell from the sky at one time or another," explains Kleine. Since 2021, he has served as a Director at the Max Planck Institute for Solar System Research, where he heads the Planetary Science Department.

Meteorites are fragments of objects such as asteroids, which today orbit the Sun in a belt between Mars and Jupiter. Apart from these small objects, there are two types of planets in the Solar System. Rocky planets orbit the Sun at close range and are called terrestrial planets. They have relatively low masses, but high densities. They are Mercury, Venus, Earth, and Mars. The second type comprises the gas and ice giants that orbit the Sun beyond the orbit of Mars. They are divided into two groups: the gas giants Jupiter and Saturn, located beyond Mars, and the ice giants Uranus and Neptune, situated far from the Sun on the edge of the Solar System. The terms gas and ice giant do not refer to the condition of the planets today, but to how they formed. The mixture of hydrogen and helium that accumulated around the planets as they grew was purely gaseous at this stage. Because of their tremendous weight and the high pressure of the accumulated gases, the hydrogen and helium liquefied in the lower layers of the gas giants while remaining gaseous in the outer atmosphere. Uranus and Neptune differ from the gas giants in that they took on additional frozen water, methane, and ammonia as they formed. These elements remain inside the planets even today, mainly in liquid form.

But how did the planets form in our cosmic homeland, the Solar System? In the classical collision model, still widely accepted today, the planets formed via "oligarchic growth" in a disk of gas and dust around the newborn Sun known as the "protoplanetary disk." The dust then consolidated into increasingly larger conglomerates until "planetesimals" formed. These early protoplanetary bodies resembled modern-day asteroids. Subsequent collisions caused bodies to grow to the size of, say, our Moon or the moons of Mars. Researchers believe that even more violent collisions between these planetary embryos resulted in the planets we know today.

Kleine's team is testing this hypothesis in the lab with the aid of meteorites, rocks that fell to Earth like the one in Flensburg. "Meteorites contain evidence indicating where they formed, how they developed, and how old they are," says Kleine. Meteorites are the oldest known rocks, making them approximately as old as the Solar System itself. They are the remnants of the materials from which the planets formed. Consequently, when researchers analyze meteorites, they are travelling back in time and gaining an indirect view of the formation of the Solar System. By analyzing meteorites, they learn how the building material of the early Solar System was distributed. This knowledge then helps them determine where the planets formed – the first step in reconstructing their history.

SUMMARY

Our planets formed approximately 4.6 billion years ago from a disk of gas and dust around the newborn Sun.

New analyses of meteorites, as indicators of time of origin, and computer simulations of processes in the disk explain how the planets could have formed from gas and dust.

The gas planets came into being when granular material (pebbles) flowed in from the outer Solar System and clumped together to form solid cores. The cores then attracted hydrogen and helium, the planets' main building materials.

Jupiter's gravity prevents Earth from being bombarded with asteroids. This created the conditions under which life could develop here.

Kleine and his team searched for a property that would reveal which part of the protoplanetary disk a meteorite originates from. A criterion like this should function like a human fingerprint, which remains unchanged throughout a person's life. The chemical composition of the meteorites alone – that is, the frequency of elements such as iron, silicon, and oxygen – gives only a vague indication of where the celestial body came from, because the elements in the early disk were thoroughly mixed.

However, Kleine discovered that the isotopic ratios of elements such as iron, molybdenum, and chromium are suitable indicators of the place of origin. Isotopes are variants of the same chemical element with slightly different masses. It appears that the isotopes of these elements were not evenly distributed in the molecular cloud from which our Sun and the protoplanetary disk, and later the planets themselves, emerged. On the contrary, even then there must have been differences in isotopic ratios,

PHOTO: SWEN PFORTNER FOR MPG

A selection from the meteorite collection of the Max Planck Institute for Solar System Research: the largest of the objects measures more than 20 centimeters. The majority belong to the most common class of rock meteorite, consisting mainly of silicates. In the bottom center is a section cut from one such meteorite. The section on the right comes from an iron-nickel meteorite like the one depicted in the upper left.

> **“In collections worldwide, there are more than 70,000 rocks that fell from the sky.”**
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> *THORSTEN KLEINE*

correlating to the distance from the center of the cloud. The nascent planetary bodies consequently formed from building material with different isotopic compositions, depending on whether the material accreted near to or far from the Sun. Billions of years later, the isotopes can still be read as clues to the early distribution of the planetary building material. “The ratio of a given isotope is an excellent marker for distinguishing between meteorites based on where they came from,” Kleine explains. There are two groups of meteorites: non-carbonaceous and carbonaceous. They emerged from two different reservoirs in the early gas and dust disk of the embryonic Solar System: non-carbonaceous meteorites from the inner part of the disk and carbonaceous from the outer. They are called this for historical reasons, and unlike what the names suggest, they have nothing to do with how much carbon a rock contains. “Isotopes of molybdenum were the first that enabled us to prove the split into two reservoirs. The two different groups of meteorites clearly existed from the very beginning,” says Kleine. When analyzing samples at the Max Planck Institute for Solar System Research, the re-

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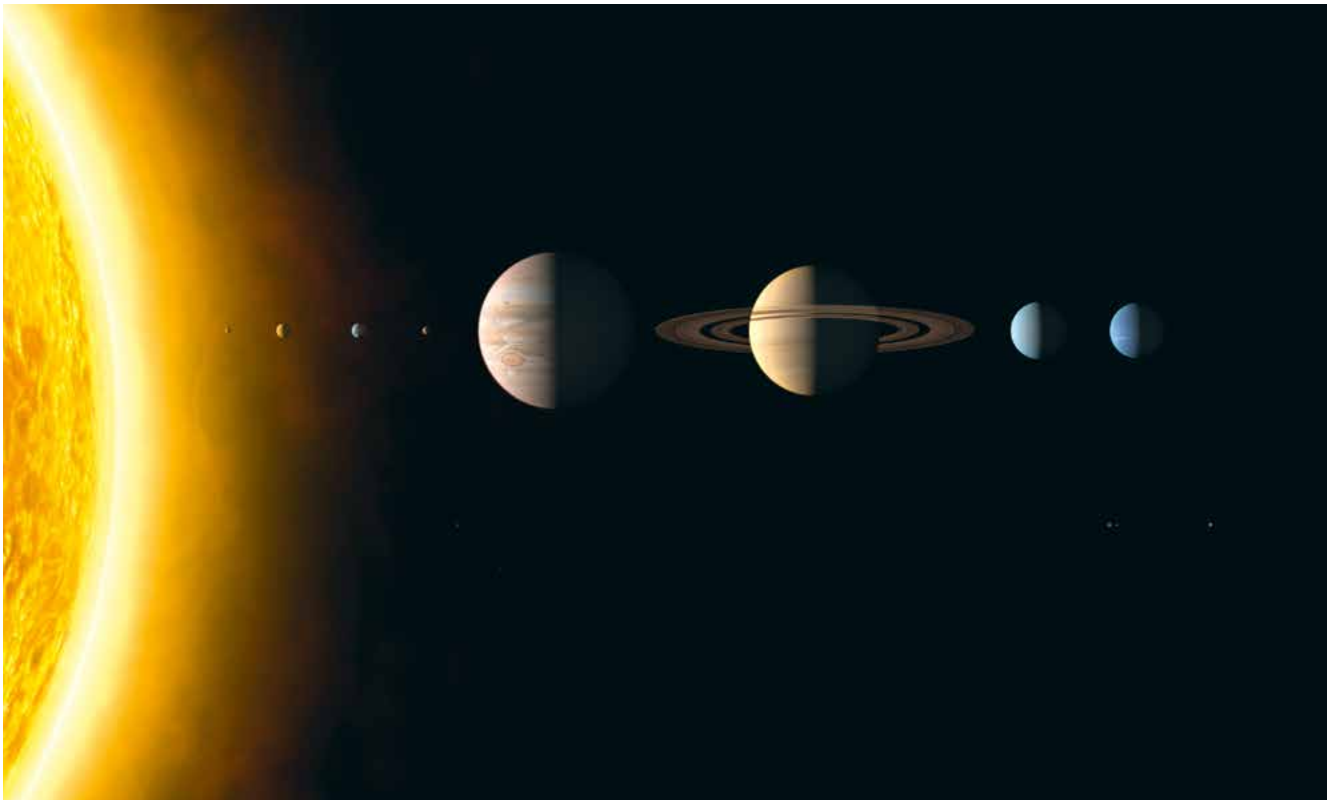

IMAGE: THE INTERNATIONAL ASTRONOMICAL UNION/MARTIN KORNMESSER

All in a row: the planets of our Solar System shown correctly in terms of relative sizes, but not at the correct distances from the Sun. From left to right: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune.

searchers have to work under highly sterile conditions to exclude the possibility of contaminating the rock samples, which would throw off the measurements. They start by pulverizing the samples, which they then subject to chemical preparation, sometimes for weeks at a time. Next, they use highly precise mass spectrometers the size of a compact car to determine differences in the proportions of isotopes in the samples to a high degree of precision.

One question, two theories

When the isotopic ratios in meteorite samples of known origin in the protoplanetary disk are compared with the ratios in planetary rocks, it becomes possible to speculate where the planet's building material might have originated. Until recently, there was no reason to doubt the classical collision model as an explanation of how planets formed in the early Solar System. However, new insights into the outer gas giants have caused the foundations of this model to crumble, helped in part by research from Joanna Drążkowska, a group leader at the Max Planck Institute for Solar System Research. Whereas Kleine prepares direct messengers from the nascent Solar System for painstaking study in the lab, Drążkowska takes a different approach to deciphering the history of our planetary system. The goal of her working group is to create a computer simulation of the initial clumping of dust in the flat disk of matter around the young Sun. “We want to decipher the fundamental principles of early planet formation. Most other models leave out this initial stage,” explains Drążkowska. She places particular emphasis on the growth of Jupiter, a gas giant and the bigwig among our planets. Although Jupiter consists largely of hydrogen and helium, its interior is presumed to contain a solid core weighing between ten and twenty Earth masses. This is also the mass required for a body to have enough gravity to bind gas to itself from the protoplanetary disk in the early days of the Solar System. According to computer models, however, Jupiter's core must have formed relatively quickly, in the first few million years, in order to attract enough of the surrounding gas before it could be distributed elsewhere. In the classical planetary growth model, it would have taken too long for Jupiter's core to form, because the collisions of large celestial bodies postulated in the model were relatively rare. Therefore, another growth mechanism must be found.

A new theory could explain the rapid formation of Jupiter's core. It holds that small clumps of cosmic dust coming primarily from cold regions far from the Sun contributed to the growth. In scientific jargon, they are called "pebbles." Due to friction and collisions within the original gas and dust disk, they lost the energy that kept them orbiting the Sun. As a result, they wandered towards the central star and ran into already formed planetesimals, which grew very quickly by accreting vast numbers of these pebbles. "Today everyone agrees with the pebble model as far as the cores of gas and ice giants are concerned," says Kleine. However, the question quickly arises whether the material used to form Earth and Mars was delivered from regions far from the Sun and whether the current conception of classical, oligarchic growth has been rendered fully obsolete.

To answer the question, Kleine and an international team led by Christoph Burkhardt, which is also part of the Max Planck Institute for Solar System Research, conducted in-depth studies of 17 fragments of the red planet and material from the Earth's crust. The researchers compared this planetary material with samples from meteorites known to have come from the outer Solar System. To this end, they analyzed the isotopic evidence of three rare metals: titanium, zirconium, and molybdenum. Their findings confirm the original assumption that Earth and Mars have little in common with material from the outer Solar System; only around four percent originates from there. "The values would have to be almost ten times higher if the predecessors to Earth and Mars actually accreted grains of dust from the outer Solar System," says Kleine. Both planets were formed of materials delivered from very close by – from the inner Solar System. The classical model of oligarchic growth still works very well in explaining the formation of the terrestrial planets.

Messengers from afar

However, not everything that roves around the inner Solar System originated from there. An international research team of which Kleine is a member studied crumbly sample material brought to Earth from the asteroid Ryugu by the Japanese probe Hayabusa 2 in December 2020. Ryugu is a fragment in the form of a double pyramid and measures around one kilometer in diameter. Today it is found in an orbit close to the Sun, much like Earth. The sample consisted of only 5.4 grams of material, but that was enough to determine where Ryugu originally came from. To this end, the team compared the sample with

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Research up close: astronomer Joanna Drążkowska discusses the details of her models with the team (left). Thorsten Kleine analyzes meteorites in the lab under highly sterile conditions using cutting-edge technology (right).

PHOTOS: SWEN PFÖRTNER FOR MPG

several meteorites whose isotopic signatures were known, and whose place of origin in the early protoplanetary disk could therefore be determined. The ratios of Ryugu's iron isotopes resembled those of a class of rare meteorites, the carbonaceous meteorites, which originated from the outer Solar System. Ryugu is therefore a wanderer whose journey to the inner Solar System began once upon a time far from the Sun. Studies such as these lead to speculation that material from the outer Solar System definitely found a way into the vicinity of Earth and Mars.

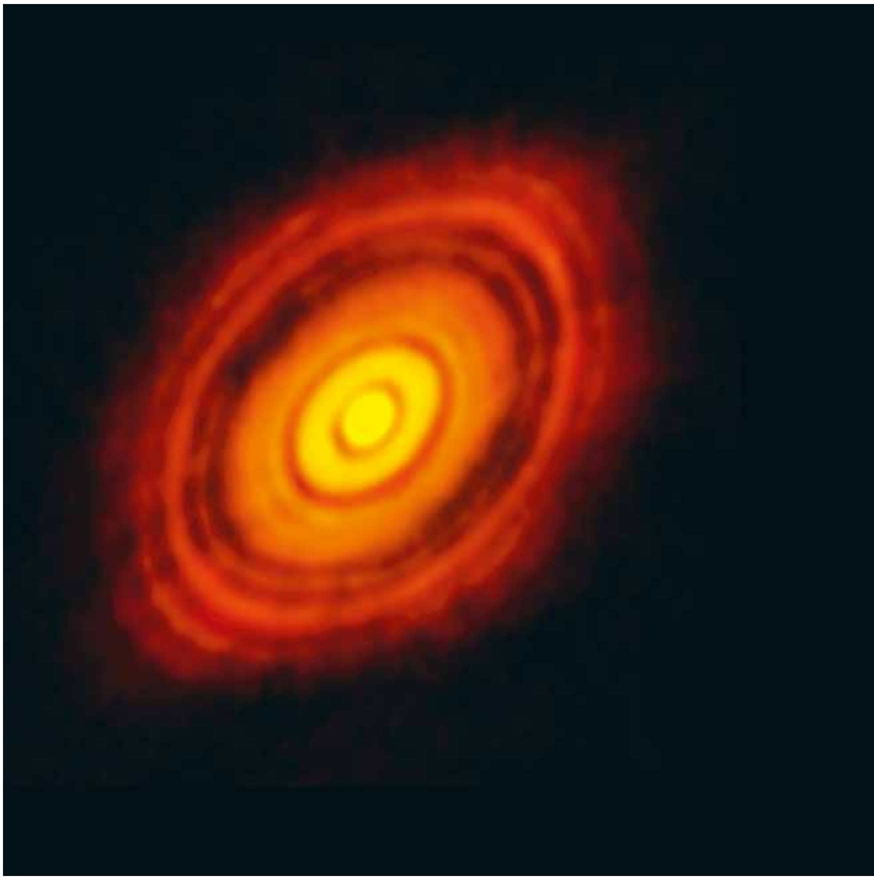
It all comes down to Jupiter

Investigations of relics from the early days of our Solar System by her colleague Kleine are an important component of Drążkowska's computer simulations. They are indispensable in seeking to understand the formation of gas giants, whose rocky cores are buried deep beneath impenetrable layers and cannot be probed directly. She calculates that for Jupiter to grow, there had to be a lot of dust, or more exactly a dust-to-gas ratio of around one to one. As she later discovered, this special condition was met at what is termed the ice line. At that distance from the Sun, water froze into ice, and today Jupiter can in fact be found near that conceptual line. "At the ice line, the dust concentration was high enough for pebbles to combine quickly and effectively into planetesimals," reports Drążkowska.

Kleine, Drążkowska, and their teams quickly realized why the two groups of meteorites did not mix in the inner and outer protoplanetary disk of the early Solar System. The planet Jupiter formed during the first million years by accreting large amounts of dust and gas flowing towards the Sun from the outer Solar System. "Jupiter played a central role in the formation of our Solar System," says Kleine. Its enormous mass prevented the building material from mixing, resulting in a mass-starved inner Solar System. Even today, Jupiter makes a major contribution to the emergence of higher life on Earth by forming a natural barrier against bombardment from the outside. This lowers the probability of asteroids striking Earth and causing mass extinctions, as happened with the dinosaurs. "What is more, without Jupiter the Earth would be a super-Earth with more than ten times its current mass," says Kleine. And life on such a massive planet would look completely different from life on Earth, to say the least. Jupiter's role in limiting the influx of planetary building material also explains why it took the Earth almost 150 million years to reach its current mass. Without the influx of pebbles, the inner terrestrial planets grew relatively slowly in situ through collisions with bodies ranging in size from the Moon to Mars in line with the classical theory.

Nor is this view disproved in any way by Ryugu, which formed in the outer Solar System and today resides in the vicinity of the inner planets. Like most asteroids, it wandered to its current position relatively recently due to gravitational interactions between various bodies in the Solar System. The interplay of forces dominated by Jupiter now holds the asteroids – remnants of early planetary formation which act as a sort of quarry for meteorites – in a belt between Mars and Jupiter.

Planetary formation before our eyes: this image from the Alma telescope shows a dust disk surrounding the young star HL Tauri, where planets might already exist. The dark rings could indicate young planets accumulating dust on their path around the star.



According to Drążkowska, however, we are still far from fully understanding how the planets formed in our Solar System or other planetary systems in the Milky Way. “A comprehensive and detailed model combining all the stages and processes of planet formation is still lacking,” she says. This makes her even more eager to subject her computer simulations to a reality check that extends beyond the direct sampling of our Solar System. Because the fundamental processes of planet formation presumably follow the same physical principles in the entire Milky Way, Drążkowska turns her eyes to the night sky.

> **“Jupiter’s core must have formed relatively quickly within the first few million years.”**
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> *JOANNA DRĄŻKOWSKA*

Modern telescopes provide views of very different planetary systems both young and old at various distances from our homeland. Some, like our Solar System, are at an early stage of around 4.6 billion years. Astronomers obtained the first evidence of one such youthful system in the 1990s in the Orion nebula. This active birthplace of new stars and new planetary systems can be admired with binoculars mainly in the winter months in Germany. Photos from the Hubble Space Telescope led to the discovery of several unusual-looking stars. Against the background of the dimly lit sky, their light spots seemed to indicate two dark bulges at the sides. These turned out to be the first photographs of gas and dust disks, providing a glimpse of the arena where planets are born. Many more planetary cradles have been discovered since then. The best tool for this purpose is the Alma telescope (Atacama Large Millimeter/Submillimeter Array) in Chile, which captures short radio waves and depicts the dust disks in hitherto unattainable detail. The images of many of these disks reveal gaps that could be caused by young planets.

Specially optimized telescopes can also detect other planetary systems that are already fully developed. In 1995, the first extrasolar planet was discovered orbiting a star in the constellation Pegasus over 51 light years from Earth. A flood of similar discoveries has followed since then, with astronomers finding more than 5,000 of these exoplanet systems. The characteristics of some systems seem exotic. Their architecture seems twisted compared to our Solar System, with the largest gas planets located unusually close to the central star. According to Kleine, this can already be explained by the fact that it is especially difficult to observe planetary systems similar to our Solar System with telescopes, mainly because terrestrial planets are much smaller, weigh far less, and reflect far less light than their big brothers and sisters, the gas and ice giants. In Drążkowska’s view, observations of other planetary systems are still an excellent source of insights into the formation and development of our planetary system.

While Kleine’s research differs from Drążkowska’s in many details, both ask the same big question: how did the many known planetary systems form throughout the Milky Way? How did the Earth, the only place in the universe known to contain life, come into being? Analyses of meteorite rocks and computer simulations of physical formation processes do not simply help us gain a better understanding of the history of our cosmic homeland; they also help us understand why the Earth developed conditions so favorable to life.

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GLOSSARY

ISOTOPES
are variants of the same chemical element with slightly different masses due to variations in the number of neutrons in the atomic nuclei. The number of protons, and hence the charge of the atom, stays the same.

PROTOPLANETARY DISKS
are flat streams of gas and dust around young, newborn stars in which planets form.

PEBBLES
are pebble-like dust aggregates measuring between a millimeter and a centimeter that wander from the exterior of the protoplanetary disk to the interior. They serve as the building material for the solid cores of external gas and ice giants.

IMAGE: ALMA (ESO/NAOJ/NRAO)