Earth and Mars were formed from inner solar system material

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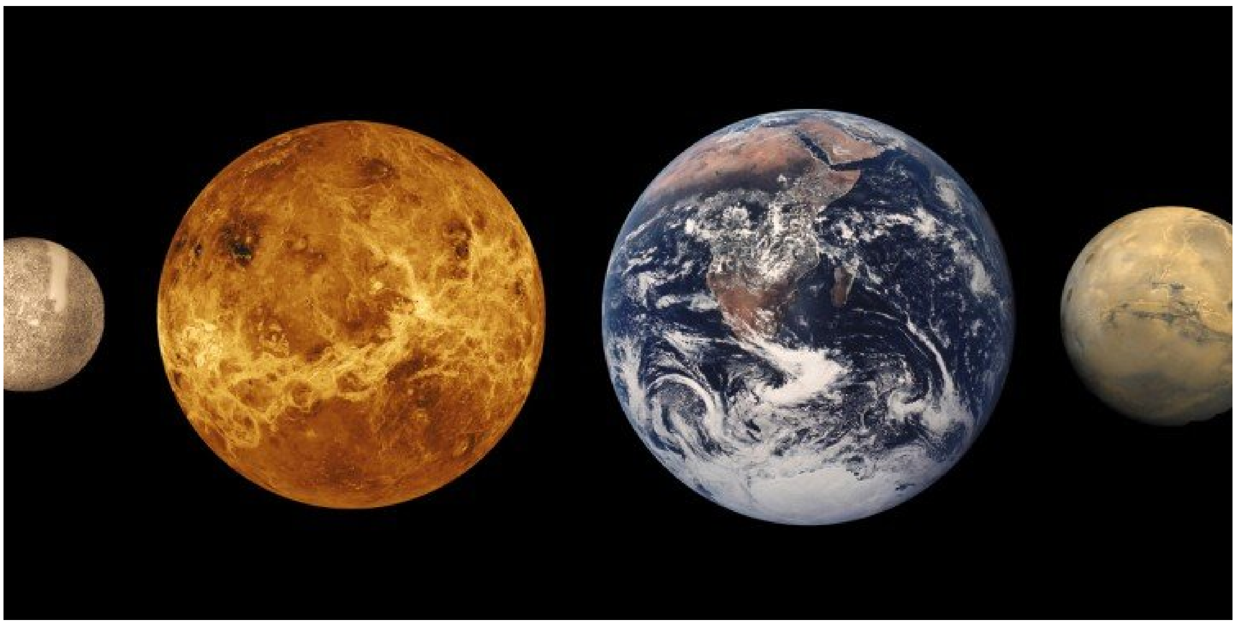


The four terrestrial planets: Mercury, Venus, Earth and Mars. Credit: NASA/Lunar and Planetary Institute

Earth and Mars were formed from material that largely originated in the inner solar system; only a few percent of the building blocks of these two planets originated beyond Jupiter's orbit. A group of researchers led by the University of Münster (Germany) report these findings today in the journal *Science Advances*. They present the most comprehensive comparison to date of the isotopic composition of Earth, Mars and pristine building material from the inner and outer solar system. Some of this material is today still found largely unaltered in meteorites. The results of the study have far-reaching consequences for our understanding of the process that formed the planets Mercury, Venus, Earth, and Mars. The theory postulating that the four rocky planets grew to their present size by accumulating millimeter-sized dust pebbles from the outer solar system is not tenable.

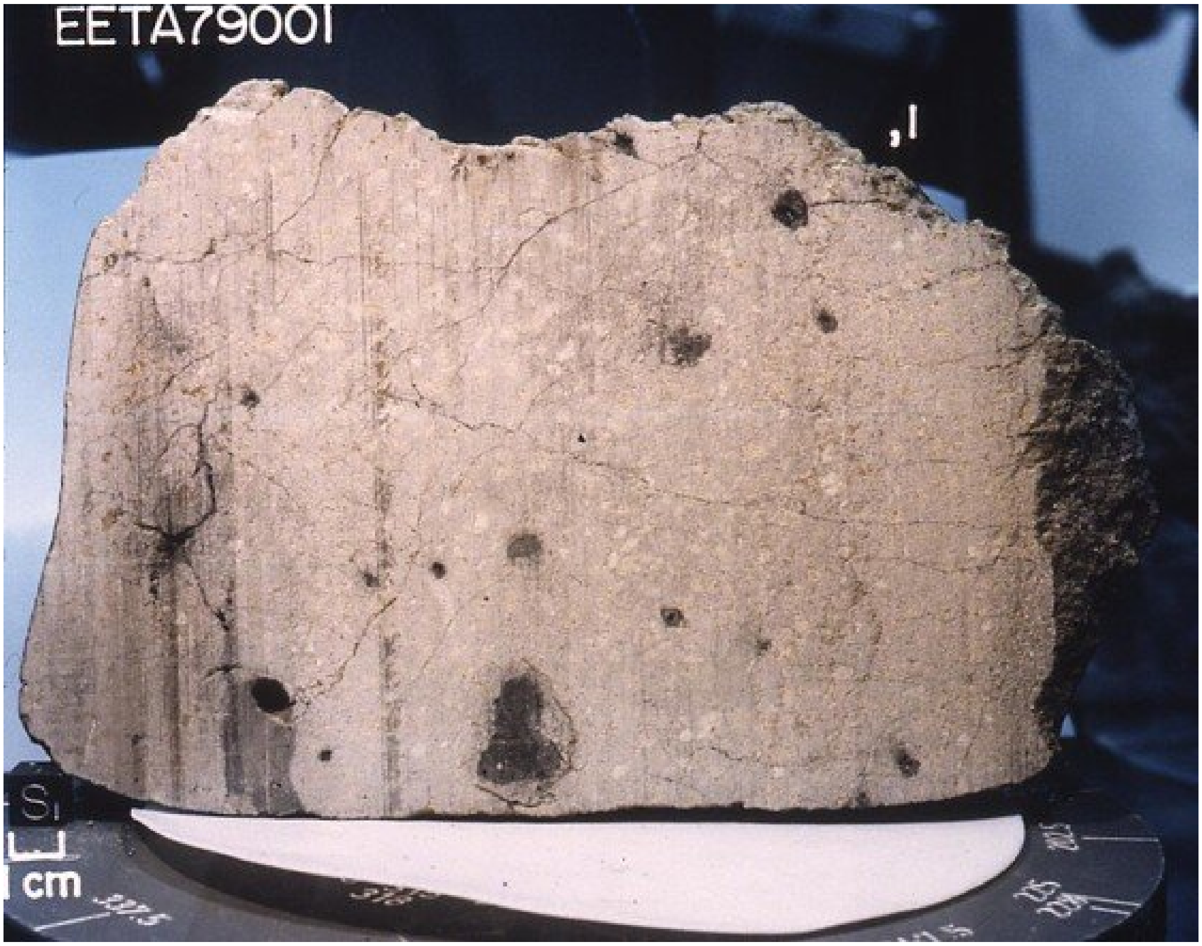
Approximately 4.6 billion years ago, in the early days of our solar system, a disk of dust and gasses orbited the young sun. Two theories describe how, in the course of millions of years, the inner rocky planets formed from this original building material. According to the older theory, the dust in the inner solar system agglomerated to ever larger chunks gradually reaching approximately the size of our moon. Collisions of these planetary embryos finally produced the inner planets Mercury, Venus, Earth and Mars. A newer theory, however, prefers a different growth process: Millimeter-sized dust "pebbles" migrated from the outer solar system towards the sun. On their way, they were accreted onto the planetary embryos of the inner solar system, and step by step, enlarged them to their present size.

Both theories are based on theoretical models and computer simulations aimed at reconstructing the conditions and dynamics in the early solar system; both describe a possible path of planet formation. But which one is right? Which process actually took place? To answer these questions in their current study, researchers from the University of Münster (Germany), the Observatoire de la Cote d'Azur (France), the California Institute of Technology (U.S.), the Natural History Museum Berlin (Germany), and the Free University of Berlin (Germany) determined the exact composition of the rocky planets Earth and Mars. "We wanted to find out whether the building blocks of Earth and Mars originated in the outer or inner solar system," says Dr. Christoph Burkhardt of the University of Münster, the study's first author. To this end, the isotopes of the rare metals titanium, zirconium and molybdenum found in minute traces in the outer, silicate-rich layers of both planets provide crucial clues. Isotopes are different varieties of the same element, which differ only in the weight of their atomic nucleus.

Meteorites as a reference

Scientists assume that in the early solar system these and other metal isotopes were not evenly distributed. Rather, their abundance depended on the distance from the sun. They therefore hold valuable information about where in the early solar system a certain body's building blocks originated.

As a reference for the original isotopic inventory of the outer and inner solar system, the researchers used two types of meteorites. These chunks of rock generally found their way to Earth from the asteroid belt, the region between the orbits of Mars and Jupiter. They are considered to be largely pristine material from the beginnings of the solar system. While so-called carbonaceous chondrites, which can contain up to a few percent carbon, originated beyond Jupiter's orbit and only later relocated to the asteroid belt due to influence of the growing gas giants, their more carbon-depleted cousins, the non-carbonaceous chondrites, are true children of the inner solar system.



The Martian Meteorite Elephant Moraine (EETA) 79001. The scientists examined these and other Martian meteorites in the study. Credit: NASA/JSC

The precise isotopic composition of Earth's accessible outer rock layers and that of both types of meteorites have been studied for some time; however, there have been no comparably comprehensive analyses of Martian rocks. In their current study, the researchers now examined samples from a total of 17 Martian meteorites, which can be assigned to six typical types of Martian rock. In addition, the scientists for the first time investigated the abundances of three different metal isotopes.

The samples of Martian meteorites were first powdered and subjected to complex chemical pretreatment. Using a multicollector plasma mass spectrometer at the Institute of Planetology at the University of Münster, the researchers were then able to detect tiny amounts of titanium, zirconium, and molybdenum isotopes. They then performed computer simulations to calculate the ratio in which building material found today in carbonaceous and non-carbonaceous chondrites must have been incorporated into Earth and Mars in order to reproduce their measured compositions. In doing so, they considered two different phases of accretion to account for the different history of the titanium and zirconium isotopes as well as of the molybdenum isotopes, respectively. Unlike titanium and zirconium, molybdenum accumulates mainly in the metallic planetary core. The tiny amounts still found today in the silicate-rich outer layers can therefore only have been added during the very last phase of the planet's growth.

The researchers' results show that the outer rock layers of Earth and Mars have little in common with the carbonaceous chondrites of the outer solar system. They account for only about four percent of both planets' original building blocks. "If early Earth and Mars had mainly accreted dust grains from the outer solar system, this value should be almost ten times higher," says Prof. Dr. Thorsten Kleine of the University of Münster, who is also director at the Max Planck Institute for solar system Research in Göttingen. "We thus cannot confirm this theory of the formation of the inner planets," he adds.

Lost building material

But the composition of Earth and Mars does not exactly match the material of the non-carbonaceous chondrites either. The computer simulations suggest that another, different kind of building material must also have been in play. "The isotopic composition of this third type of building material as inferred by our computer simulations implies it must have originated in the innermost region of the solar system," explains

Christoph Burkhardt. Since bodies from such close proximity to the sun were almost never scattered into the asteroid belt, this material was almost completely absorbed into the inner planets and thus does not occur in meteorites. "It is, so to speak, 'lost building material' to which we no longer have direct access today," says Thorsten Kleine.

The surprising find does not change the consequences of the study for theory of planet formation. "The fact that Earth and Mars apparently contain mainly material from the inner solar system fits well with planet formation from the collisions of large bodies in the inner solar system," concludes Christoph Burkhardt.

More information: Christoph Burkhardt et al, Terrestrial planet formation from lost inner solar system material, *Science Advances* (2021). DOI: 10.1126/sciadv.abj7601

Provided by University of Münster

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