New research provides possible insights into the formation of Earth

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A new study, conducted by scientists at The University of New Mexico, found ancient, primordial helium-3 leaking from the Earth's core, suggesting the planet formed inside a solar nebula, stirring further debate among scientists.

Each year, about 2 kg of the rare isotope gas helium-3 escapes from

Earth's interior, mostly along the mid-ocean ridge system, a range of underwater volcanos around the globe. Helium-3 is primordial, created shortly after the Big Bang and acquired from the solar nebula as the Earth formed. Geochemical evidence indicates the Earth has deep reservoirs of helium-3, but their locations and abundances are uncertain.

Earth's inventory of helium consists of two stable isotopes, the more abundant helium-4, and the rare helium-3. Unlike terrestrial helium-4, which is mainly produced by the decay of uranium and thorium, terrestrial helium-3 is largely of primordial origin, synthesized in the aftermath of the Big Bang and incorporated into the Earth primarily during its formation.

Now, scientist models of volatile exchange during Earth's formation and evolution implicate the metallic core as a leaky reservoir that supplies the rest of the Earth with helium-3. The results also suggest that other volatiles may be leaking from the core into the mantle. Helium-3 originates primarily in nebulae, an enormous cloud of dust and other basic elements such as hydrogen and other ionized gases. As one of the earliest elements produced in the universe, most helium-3 was created during the initial stages of the Big Bang.

"Helium-3 was synthesized very early in the history of the universe, very early, meaning within a few seconds of the big bang," said Peter Olson, a UNM geophysicist and lead author of the paper, "Primordial Helium-3 Exchange Between Earth's Core and Mantle," published recently in American Geophysical Union journal *Geochemistry, Geophysics, Geosystems*. "This study helps identify the core as the source of the leak rather than the mantle. It's 13 plus billion years old and is measured to come out of the earth's interior and the place where it apparently is leaking at the fastest rate is the Mid Ocean Ridge spreading centers. These are the plate boundaries where new ocean crust is being created.

"Two things are important even though it's a small amount. First of all, it didn't get there recently. It's a primordial element and some of the places from which it is leaking are related to the core. For example, the source of the lavas that make up Hawaii and Iceland are thought to be derived from plumes that rise through the mantle from the core-mantle boundary region. The helium loss from the earth is global. It's not just in a few places. It is concentrated in spreading centers at the mid-ocean ridges. These spreading centers are global, covering the entire Earth. Helium is found leaking out of other environments as well. So, it's global and it comes from deep in the earth and those are two inferences, which are really solid, I think."

The study, which also involved Zach Sharp, a UNM geochemist in the Department of Earth and Planetary Sciences, involved two aspects as part of the modeling process—first, how helium-3 got into the deep earth to begin with, the acquisition process, and second, how it gets out. Previous studies have shown how helium-3 gets in, but none have done both, acquiring helium-3 and the process for getting it out. Both are fundamentally different mechanisms and occur at different time scales in earth's history.

"The acquisition process, or the gas that makes up the solar system, is actually the gas that makes up the Sun, Jupiter and Saturn and is about 15 percent helium," said Olson. "It's the second-most abundant element in those bodies (after hydrogen), which makes it the second-most abundant element in the solar system. The obvious way to incorporate a lot of helium-3 into the earth is to build the earth while the solar nebula was in place surrounding it. When the Earth was enveloped in nebular gas, and if the surface of the earth is molten, then the gas can dissolve into the molten Earth as it forms because gases readily dissolve into melts."

"There are lots of small comets or small little pebbles we call snowballs within the solar nebula that will fall slowly towards the Sun simply because of the gravitation of the attraction of the Sun," Sharp said. "That's a physical certainty—it must happen. Now, if you have planetary bodies that are not yet fully grown, and you have the pebbles coming in towards the sun, then a significant fraction of the 'pebbles are going to be gravitationally captured by the growing Earth. You can make in 2 million years, something the size of Earth by this process, whereas previous models required more like 10 million years to make an Earth-sized body."

The scientists used a model that consisted of a nebular atmosphere made from the same composition as the solar nebula, and ingassing of this material into the molten which provided the environment needed to partition the helium from the mantle and the core.

"You find out very quickly that the surface would be so hot under those conditions that it would be a magma ocean, just the environment where you could dissolve loss of helium," said Olson. "That gets the helium into the earth, but not into the core, for that, you have to dissolve it into the iron that forms the core. There have been lab measurements that measure the solubility of helium in free metals, like molten iron. This gave us an estimate of how much helium you could dissolve into the core as the Earth formed. That's the modeling process for the first step, which told us that you get one or more petagrams (1,000,000,000,000,000 grams) of helium-3 into the core that way."

"It's very nice where we're going with this. The question is" 'how do we get so much helium into the mantle'? This was always a problem that was never fully addressed," said Sharp. "It was like, yeah, it's in there, and maybe it came from these late comets or asteroids, but the problem is helium is not dense. It wants to 'float' at the surface. It's like taking a beach ball and trying to push it down to the bottom of a swimming pool. It's going to pop back up. How can you get helium all the way down to the deep mantle? It's really a problem.

"It's generally not discussed in the case of the idea of nebular ingassing, but 15 percent of the nebula is helium. Most of the rest is hydrogen, so there we go, that's the bulk of the nebular gas. If you've got this high pressure, just like the CO_2 dissolving into your water in a can of soda, the helium will dissolve all the way down to the interior of the planet."

The second step in the process is tricky because you have to deplete the mantle of helium-3 before it will start leaking out of the core. Numerous studies have assumed that helium was lost from the mantle as the Earth solidified after the "Giant Impact." The Giant Impact is the presumed formation of the Moon during a collision between the proto-Earth and a large planet equivalent in size to Mars.

"The Giant Impact was such a disruptive event that the Earth's mantle would've lost a lot of its gases, including its helium three. That's a critical step because otherwise, the core won't leak helium," said Olson. "Once those two were in place, the process for leaking that we modeled was just an ordinary diffusion plus convection in the earth mantle, which drives plate tectonics. That would transport mantle material down to the core-mantle boundary where it would entrain helium-3 from the core and transport it back up to the surface at the ocean ridges and volcanic hotspots, and maybe the Rio Grande Rift here in New Mexico for example."

"The amount of helium leaking is somewhere in the neighborhood of four pounds a year, maybe enough to fill 50 balloons depending on the size of the balloons," said Sharp. "It's not much, but the fact that it continues to come out of the earth all the time with the idea that the core being an important source is all viable. No one cares about a little bit of helium leaking out of the Earth into space, but we think it's a fingerprint for important early events in our planet's history. It's evidence that the nebular ingassing idea is valid. If the helium was delivered later by asteroids and comets slamming into the Earth millions of years after the Earth formed, we would not expect to see so much helium in the deep mantle and core. It is in essence, a proxy for delivery of life-giving water to Earth. It provides a mechanism for making a habitable planet."

More information: Peter L. Olson et al, Primordial Helium-3 Exchange Between Earth's Core and Mantle, *Geochemistry, Geophysics, Geosystems* (2022). DOI: 10.1029/2021GC009985

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