News & views

Planetary science

Earth's molten youth had long-lasting consequences

Sean N. Raymond

A model shows that key physical properties of our planet, from the density of its iron core to its water, could have been set by interactions between a magma ocean and an early hydrogen atmosphere that was lost to space. **See p.306**

Among Earth's many mysteries, two are particularly puzzling for planetary scientists: the origin of its water, and the fact that its core is less dense than it should be, given that it is made mainly of metallic iron. On page 306, Young *et al.*[1] show that interactions between a young proto-Earth and its atmosphere might explain both in one fell swoop, and also account for the oxidation state of Earth's mantle.

Understanding Earth's composition first requires an explanation of how planets form – a process that begins with a giant gaseous disk surrounding a star. Although Earth's atmosphere is now just a thin shell, astronomical observations suggest that rocky planets such as Earth are bathed in gas during their early years[2]. These observations show that planet-forming disks around young stars comprise roughly 99% hydrogen and helium gas, with dust containing other elements, such as silicon, carbon and oxygen, accounting for the remaining 1%.

The standard model suggests that gas drives large dust particles to aggregate into mountain-sized solids called planetesimals[3]. Protoplanets come next: these are the building blocks of rocky planets, and those that formed Earth are thought to have had masses that were roughly between those of the Moon and Mars (around 1–10% of Earth's mass)[4]. The gaseous disk around the Sun evaporated a few million years after protoplanet formation[5]. The planets of the Solar System then formed through a series of collisions between these protoplanets, which were drawn together by long-range gravitational interactions[6,7].

For decades, the idea has been that Earth's water came from the impacts of water-rich asteroids[8,9]. Young and colleagues suggest that the water might have had a different origin. And the strength of their model lies in the fact that it simultaneously explains why Earth's iron core is less dense than pure iron owing to the incorporation of light elements. As a bonus, the model shows how iron oxide could have been incorporated into Earth's silicate mantle, and is consistent with its oxidation state.

The authors' idea is that at least one of Earth's protoplanets grew faster than previously thought. By doing so, the protoplanet accrued enough mass – and therefore sufficient gravity – to retain a large hydrogen atmosphere while it was still in a molten state (Fig. 1). When protoplanets first form, they are exceedingly hot, with molten surfaces covered with magma. A small protoplanet the size of Mars can keep its atmosphere from flying off into space only if it's had a chance to cool down and solidify[10]. By contrast, a protoplanet with a mass more than 0.2–0.3 times that of Earth could maintain a long-lived atmosphere before solidifying, enabling this atmosphere to interact with the magma ocean[1,10].

By revising the idea that Earth's largest protoplanets were as small as Mars, Young *et al.* have proposed a way in which hydrogen gas could have mixed into Earth's mantle before it solidified, affecting the entire planet through convection. This suggests that gaseous hydrogen is the light element responsible for the low density of Earth's core. The authors' calculations are also consistent with the oxidation state of Earth's mantle, as well as with evidence that gas from the disk made its way into Earth's protoplanets while they were being formed[11].

An intriguing implication of Young and co-workers' model is that Earth's water could have been a by-product of the incorporation of hydrogen into metallic iron and of the oxidation of hydrogen in the primordial atmosphere. This oxidation could have been triggered by partial evaporation of a silicate mantle at its interface with hydrogen gas.

The authors focused on a test case that involves a hydrogen atmosphere with 0.2% the mass of Earth enveloping a protoplanet with

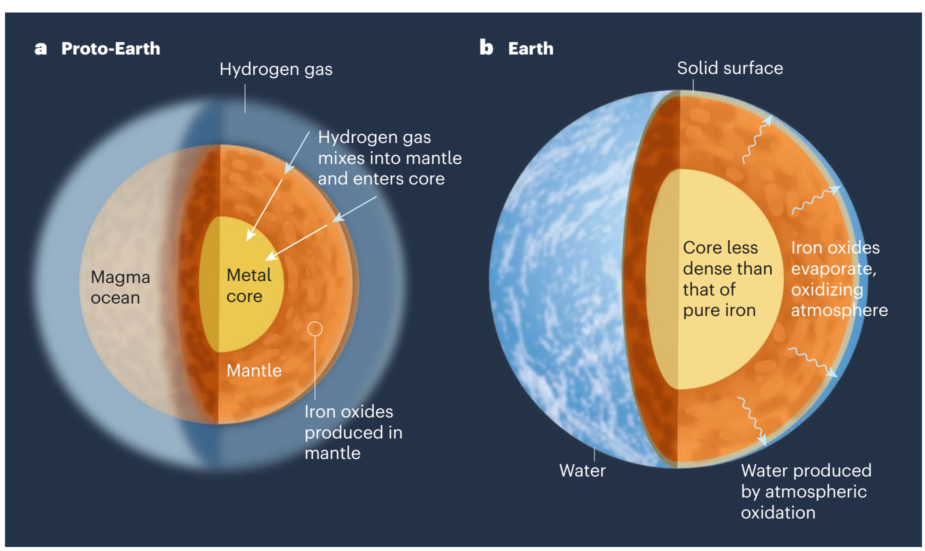

Figure 1 | Interactions between a magma ocean and an early hydrogen atmosphere. Earth's protoplanets are often thought to have had the mass of Mars or smaller[6]. **a**, Young *et al.*[1] propose that one protoplanet was 0.2–0.3 Earth masses and had sufficient gravity to retain a hydrogen atmosphere that would have interacted with the magma ocean on its surface. Hydrogen gas could have mixed into Earth's mantle before it solidified, leading to the production of iron oxide, and also entered its metallic core. **b**, Incorporation of hydrogen into the core and the oxidation of hydrogen in the atmosphere (triggered by evaporation of oxides in the mantle) could have led to the production of a large fraction of Earth's water.

half the mass of Earth. In addition to matching the core's density and the mantle's oxidation state, their calculations produced one to three 'oceans' of water, where one ocean is the total amount of water on Earth's surface[12]. Although the authors modelled this proto-Earth only, its water (and other chemical signatures) would have been inherited by Earth during the collisions that led to its growth.

The theory that Earth's water came from asteroid impacts is supported by the fact that hydrogen isotopes in Earth's water are a near-match for those of meteorites called carbonaceous chondrites, which come from the outer asteroid belt[12]. However, a study published in 2020 revealed that the meteorites most closely resembling Earth's precursor planetesimals, known as enstatite chondrites, also match Earth's hydrogen isotopes – and contain more water than previously thought[13].

When elements such as zinc and nitrogen are included, the isotopic content of Earth's volatile components (including water) is consistent with a simple mixture in which around 70% of volatiles are made of enstatite-chondrite-like material and 30% are carbonaceous-chondrite-like material[14]. But carbonaceous chondrites have a higher volatile content than do enstatites[13], so this mixture would result in carbonaceous chondrites making up only roughly 5% of Earth's mass.

Young and colleagues' model suggests that the isotopic signature of water could have evolved through various reactions, including through oxidation of the hydrogen atmosphere[15]. In their scenario, atmosphere-sourced water would make up the 70% assumed to derive from enstatite chondrites, which would require the water to have the same isotopic content as these chondrites. This might seem like too much of a cosmic coincidence, but the authors show that this scenario is nonetheless plausible.

Young and colleagues' study highlights the potential importance of interactions between the atmosphere and a magma ocean on a planetary scale. The sequence of events put forward by the authors is so intuitive that one might wonder whether it is, in fact, generic. And if the authors' model can also be applied to the known exoplanets, there is hope that it could be tested.

Of course, it's worth keeping in mind that other solutions already exist for each of the problems that the authors attempt to solve. Enstatite chondrite meteorites on their own have enough water to explain Earth's oceans despite originating in parent bodies much too small to have hydrogen-rich atmospheres over magma oceans[12]. Nonetheless, one strength of Young and colleagues' model is that it links together all three issues.

Yet the comprehensive nature of the authors' model might prove to be a weakness. For instance, evidence that hydrogen is not the light element responsible for the density deficit would compromise the model, as would a revision to the critical protoplanet mass required for a long-lived magma ocean. Despite these uncertainties, the authors have demonstrated that early interactions between magma oceans and atmospheres represent a key ingredient in future models of how Earth was shaped.

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Engineering

Swift progress for robots over complex terrain

Chen Li & Feifei Qian

A four-legged robot has learnt to run on sand at a faster pace than humans jog on solid ground. With low energy use and few failures, this rapid robot shows the value of combining data-driven learning with accurate, yet simple, models.

Anyone who has walked along a sandy beach knows how hard it is to move on sand. Like other granular materials, including mud and snow[1], sand yields and flows under the feet until they sink deep enough, and then it stops flowing and provides a stable foothold. In addition, sand doesn't spring back after impact, and the weight it can support before giving way depends on how wet and tightly packed it is, thus changing how much our foot sinks in and slips as we walk[1]. These complexities complicate the task of controlling a robot so that it can run on sand. However, writing in *Science Robotics*, Choi *et al.*[2] have succeeded in doing so, enabling a four-legged robot to be fast, robust and energetically efficient on sand.

Legged robots have, for several decades, been able to run on solid ground[3–5], and some robots that are small enough to fit in the palm of the hand have even done so on uniform sand in the laboratory[6]. Larger legged robots can walk slowly on natural granular materials[7,8], but researchers have struggled to control legged robots such that they match an animal's running pace on sand. Choi *et al.* managed this feat – achieving a top running speed of 3.03 metres per second – by integrating three approaches.

First, they used reinforcement learning[8] to train their robot to maximize its running speed and minimize how often it fails and the energy it expends. To do so, they first applied a technique called privileged learning, which is akin to training a teacher so that they can teach a student efficiently[9]. A simulated robot – the teacher – first trains itself to identify optimal control strategies by learning from a very large data set, which takes a long time. The student – the real robot – then benefits from what the teacher has already learnt, and can use partial, noisy data to quickly shift between control strategies. In the authors' case, the teacher learnt how to run under different sandy conditions in simulations, so that the student could adapt as it ran across real sand.

Second, to bridge the gap between simulation and reality, Choi *et al.* trained their robot teacher by simulating sand with highly variable physical properties and load-bearing abilities, similar to those found in nature (dry to wet, loosely to tightly packed). This is important because machine-vision systems, which are designed to see and interpret the world as eyes do, cannot reliably estimate the physical properties of a challenging terrain. For example, machine-vision systems might erroneously