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Probing space to understand Earth

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Abstract | Progress in the geosciences has often followed the same fundamental paradigm for about two centuries: Earth's present is the key to understanding its past and its future. This concept is at the root of most of what is known about the Earth. Similarly, knowledge of Earth's geological and atmospheric processes can be, and has been, applied when studying the history of other planetary bodies. More recently, however, observations from other planets have fed back into our understanding of Earth. In this Perspective, we argue that many scientific mysteries about the Earth can be solved only by looking beyond it, and describe instances where other bodies, such as Mars, Venus and the Moon, have or could augment our understanding of processes on Earth. Future space missions offer the opportunity to probe the rich diversity of planetary environments and compositions, and further explore how they might serve as analogues, experiments and archives.

Most of what we know about our planet is derived from observations of its present state and inference about its past through the lens of the physical and life sciences. Assuming that the laws of physics and chemistry as we observe them on Earth are valid across the Universe, mechanistic knowledge of Earth's geological and atmospheric processes can be applied to understand the past, present and future of other planetary bodies. Although Galileo arguably pioneered this approach by comparing the Moon's valleys, plains and mountains to those of Earth[1], this scientific endeavour has expanded rapidly in the last century[2–10] (sometimes through trial and error![2]).

In turn, knowledge gained from exploring other planetary bodies can inform us about our own planet. In 1980, R. Sharp remarked that "planetary exploration has proved to be a two-way street"[11], and in the following 40 years, researchers have applied new lessons from throughout the Solar System to studies of Earth. The study of planetary atmospheres, in particular, has led to numerous advances in understanding Earth's atmosphere, including how life might have affected it (originated by Lovelock's classic work on the prospect for life detection on Mars[12]), the physics of nuclear, volcanic and impact winters (motivated by observations of a global dust storm on Mars[13]) and a deeper understanding of the greenhouse effect (aided by application of the radiation-transfer equations to other planets[14]). Since the first confirmed detection of an exoplanet in 1992, exoplanetary science has also provided new insight into the formation of the Solar System and the Earth[15,16]. However, the approach of utilizing other planetary bodies to learn about our own has not permeated all of the Earth sciences equally, and is only starting to make its way into, for example, the mechanics of sedimentary processes.

In this Perspective, we explore how the multitude and variety of planetary bodies within (FIG. 1) and beyond[17,18] (BOX 1) our Solar System present new crucial observations that might be key to resolving some fundamental mysteries about the Earth. There are multiple Earth analogues in the Solar System (and more beyond) that could provide insights into Earth's history and future. Even when planetary bodies are not analogous to Earth, they span a range of sizes, environments and compositions that allow us to approach comparative planetology as a grand, full-scale experiment to systematically develop quantitative models of geological and atmospheric processes that pertain to our understanding of the Earth. Finally, planets, moons and other small bodies might have recorded critical pieces of Earth's history that were not preserved in Earth's geological archive. New data from ongoing, upcoming and future planetary missions and telescopic observations of alien worlds are poised to provide new insights into these planetary bodies and, thus, potentially, Earth.

Planetary bodies as analogues

The Earth has undergone several major transitions throughout its history, including the formation of its core, the onset of its dynamo, the formation and evolution of an early atmosphere, the initiation of plate tectonics and the advent of life. The exploration of our Solar System has revealed a multitude of planetary environments that provide analogues to Earth at various stages of its multifaceted history. As plate tectonics is continuously erasing parts of Earth's geologic record, the surface record of Earth's early history is sparse and highly altered, necessitating a look towards extraterrestrial worlds. In this section, we present four research topics and associated major questions about the Earth that can be addressed by exploiting analogies between early Earth and other planetary bodies.

Core and dynamo formation.

Palaeomagnetic records suggest that the Earth's magnetic field has been continuously active throughout the past 3.5 billion years (Gy) or longer (FIG. 1), with intensities overall comparable to that of the modern-day field throughout most of its history[19,20]. However, models of Earth's thermal evolution suggest that the core is cooling by ~100 K/Gy, such that crystallization of the inner core — which drives the chemical convection in the outer core that produces Earth's magnetic field today — initiated less than 1.5 billion years ago (Gya)[21,22]. Core nucleation ~1.5 Gya is also suggested by an inferred increase in palaeointensity values around that time[20]. As a result, our current understanding of the processes that sustain the Earth's magnetic field is at odds with the palaeomagnetic record. This discrepancy is known as the new core paradox[23,24] and raises the question of how Earth's dynamo could have started so early and still be long-lived. As palaeomagnetic studies of Earth's Hadean

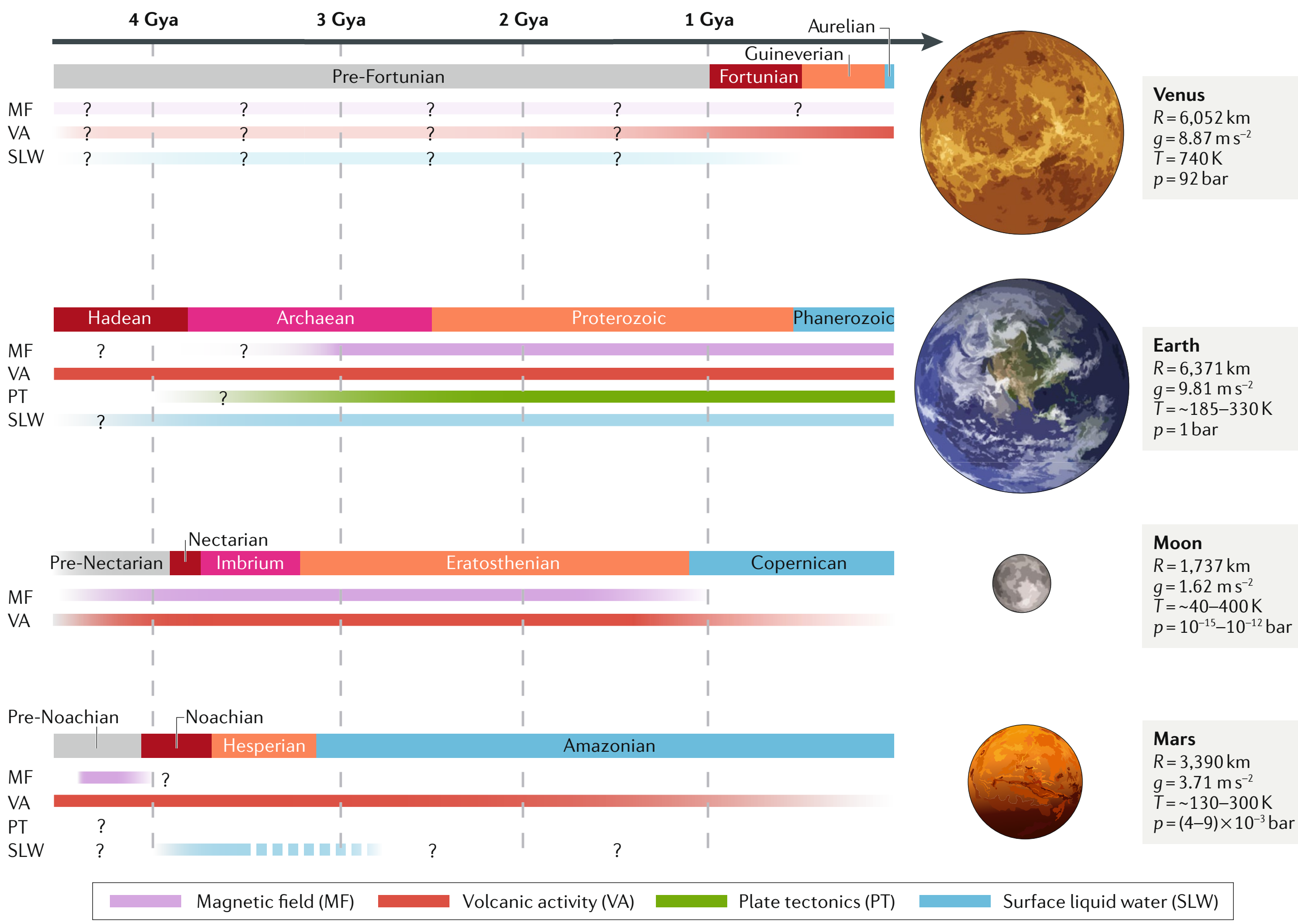


Fig. 1 | **Venus, Earth, the Moon and Mars through time.** Despite being Earth's closest neighbours, Venus, the Moon and Mars display a diverse array of surface conditions today (including surface gravity, *g*; surface temperature, *T*; atmospheric pressure at the surface, *p*; and the presence of liquid water) and size (planetary radii, *R*). Their respective geologic records vary greatly, both in terms of age and magnetic, tectonic and volcanic processes. Displayed here is how a selection of planetary attributes for Venus, Earth, the Moon and Mars evolved through time as inferred from currently available data. Through their similarities and differences, other celestial bodies can be utilized (both in their present state and inferred past) as analogues to ancient, modern and future Earth, as experiments to understand how geological and atmospheric processes operate under conditions that are unachievable on Earth, and as geological archives that hold clues to deciphering Earth's past. Gya, billion years ago.

to Palaeoarchaean eons are ambiguous[25,26], solving the new core paradox may require that we turn towards other worlds.

Exoplanetary magnetic fields have been identified for Jupiter-sized exoplanets orbiting close to their star, called hot Jupiters[27], and it might soon be feasible to detect these fields for smaller, rocky planets. Exoplanetary magnetic fields might, therefore, reveal whether Earth's long-lived dynamo is statistically anomalous[28] and, thus, required special circumstances to form. For example, mechanical mixing of the Earth's core by the Moon-forming impact could have been needed to remove chemical stratification that would have otherwise precluded a dynamo[29], even if the core had a 'hot start' (that is, was initially hot relative to the overlying mantle) and was cooling rapidly enough to drive thermal convection in the absence of adverse chemical gradients.

While Mars, the Moon and Venus (FIG. 1) lack strong intrinsic magnetic fields today, they might teach us about the core-formation processes that enabled Earth's long-lived dynamo and whether those processes are ubiquitous or rare. The well-preserved record of a >4-billion-year-old dynamo on Mars[30] (FIG. 1) is reproduced in models that include a hot start to core formation[31], which supports the hypothesis that a similarly hot start to Earth's core could have driven a Hadean dynamo. Like the Earth, the Moon presents a paradox, as purely thermal core convection is likely insufficient to generate magnetic fields as long-lived or as intense as those inferred from the 4.25 Gy lunar palaeomagnetic record[32] (FIG. 1).

Chemical convection might have increased the longevity and strength of the lunar dynamo[33]. Nevertheless, the identification of a long-lived magnetic field on the Moon motivated preliminary research into dynamos driven by mechanical processes such as librations (the wobbling of an orbiting body as perceived from the orbited body), precession (a change in the direction of a body's axis of rotation) and tides[34]. All of these processes can kinematically sustain a dynamo in simulations[35]. However, further work is needed to fully understand the interplay between turbulence, magnetic fields and the Lorentz force (electromagnetic force) within planetary cores to determine whether mechanically driven flows could present a solution to the new core paradox[23,36].

Unresolved questions about the lunar dynamo also prompted research into dynamos generated within basal magma oceans[37] (layers of molten silicates immediately above the core–mantle boundary), as has been proposed for the early Earth[38–41]. For example, core convection in Earth's Moon may provide insufficient energy to sustain a lunar dynamo for the duration and at the intensities indicated by palaeomagnetic data[42]. Instead, the Moon's dynamo could have been generated for much of its lifetime in a basal magma ocean, where high titanium and iron contents could have bolstered its electrical conductivity[43] to values three orders of magnitude higher than that of olivine melts at lunar mantle conditions[37]. If future studies confirm that liquid silicates have high enough electrical conductivity under basal mantle conditions[44] and, thus, support this method of dynamo generation, there would be a dramatic shift away from conventional thinking that early dynamos must be generated in planetary cores.

The Moon and Mars are too small to have experienced the extreme pressures and temperatures required for chemical processes, such as the precipitation of magnesium oxide or silicon dioxide[45–48], that might have sustained Earth's early magnetic field prior to the crystallization of its inner core. These conditions could have occurred within Venus though, which is Earth's near-twin in size and bulk composition[49,50]. Unveiling the unknown magnetic history of Venus by searching for crustal remanent magnetism could reveal that Earth and Venus had a very similar early history or that stochastic variability during planetary accretion set them on different evolutionary paths from the start[50].

Earth's atmosphere through time. Earth's very first atmosphere likely formed through a number of processes, including magma ocean devolatilization[51] and impact degassing[52]. Models for the growth of Earth's atmosphere thus rely on the composition of the materials present during the time of planet formation, but geological evidence from this era is limited. However, asteroid-derived meteorites that formed at the beginning of the Solar System provide a window into the chemical gradients that existed across the solar nebula during planet formation[53]. Thus, models for the growth and composition of Earth's earliest atmosphere can be developed by using meteorites as proxies for the materials that were delivered to the growing planets during the formation of the Solar System. The bulk and isotopic compositions of the different meteorite groups suggest that a large portion of Earth's volatiles are derived from carbonaceous-chondrite-like material[54]. Accretion of this material appears to have led to the formation of an early steam atmosphere on the Earth, and plausibly on Venus[55].

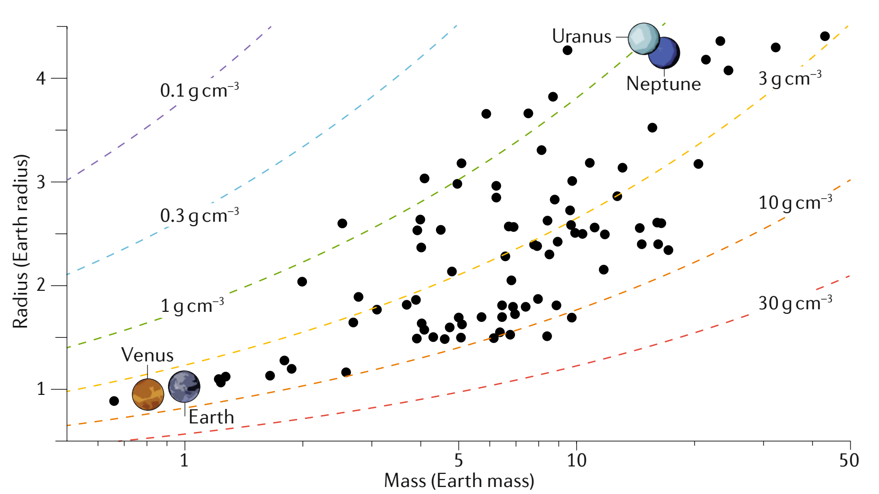
Water acts as a major greenhouse gas and can cause widespread melting of silicates at the surface. As a result, the lifetime of a magma ocean (which can result from giant impacts) can be extended by several orders of magnitude if a massive steam atmosphere is present[56]. This greenhouse warming is more effective for planets receiving higher stellar fluxes. Thus, whereas Earth's magma ocean following the Moon-forming impact might have only lasted 1–5 million years (Myr), a magma ocean could have lasted up to 100 Myr on Venus due to the planet's closer solar orbit[57].

While magma oceans might have only existed in the first ~100 Myr of Solar System history, steam atmospheres and magma oceans from giant impacts could be identifiable in young exoplanetary systems, making it possible to observe some of the fundamental processes that built the Earth into what it is today[58]. In addition, exoplanetary magma oceans could be long-lived on warm-to-hot rocky exoplanets, owing to greenhouse warming from massive atmospheres (potentially as on 55 Cancri e)[59] or extreme solar radiation in the case of plausibly atmosphere-less planets (as on CoRoT-7b and Kepler 10b). Observations of atmospheric signatures from such planets (like the presence of gases composed of silicate material[60,61]) could help us understand the underlying magma oceans. Observations of the effects of magma oceans or steam atmospheres on exoplanets would provide a unique opportunity to constrain atmosphere–interior-exchange models[62] for the early Earth.

Planetary analogues not only speak to Earth's very first atmosphere but also provide insights into Earth's later atmospheric evolution. In one example, studies of the greenhouse and anti-greenhouse effects on Titan[63] led to multiple insights into the mechanisms (such as organic hazes) that could have helped keep Earth warm and shielded the surface from ultraviolet radiation, despite a faint young Sun (FIG. 2) and lack of ozone layer in the Hadean and early Archaean[64–66]. Additionally, the recent realization that Earth's atmospheric N_2 inventory has varied through time[67,68] has inspired modelling of exoplanets with different N_2 inventories. This modelling revealed that exoplanets in the so-called habitable zone of their star (FIG. 2) can build up O_2-dominated atmospheres due to water

Box 1 | **The compositional diversity of detected exoplanets**

Since the first confirmed detection of an exoplanet in 1992, over 4,000 exoplanets have been discovered and confirmed. Many of these planets have masses lower than 50 Earth masses and radii less than 4.5 Earth radii[217] (see the figure). A substantial fraction of observed exoplanets is larger than Uranus-sized or Neptune-sized because they are easier to detect than smaller planets, although many have now been found using newer detection techniques and technology. It is thought that about one in five Sun-like stars host an Earth-like planet in their habitable zone[17] (a problematic term[218] that is usually defined as where liquid water would be thermodynamically stable at the surface of an exact Earth-clone; FIG. 2). Exoplanets with radii smaller than ~1.6 Earth radii are thought to be rocky[219] and those with radii greater than ~4 Earth radii are thought to be ice (like Uranus and Neptune) and gas (like Jupiter and Saturn) giants. However, the bulk composition of planets with intermediate radii (between ~2 and ~4 Earth radii) is more ambiguous, as they could either have rocky and icy cores with thick gaseous envelopes or be water worlds with rocky cores[217]. The wide range in bulk densities of exoplanets smaller than 4 Earth radii (from ~0.5 to ~20 g cm^{-3}) attests to a rich compositional diversity of exoplanets.



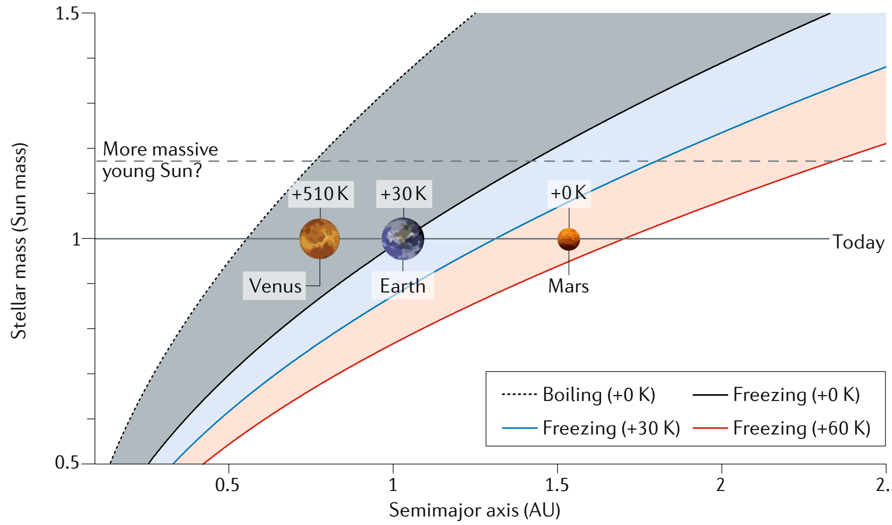


Fig. 2 | **A shifting 'habitable zone' with greenhouse warming and the faint young Sun.** The habitable zone (shaded areas) for a planet with a 1-bar atmosphere, fixed orbital distance around a Sun-like star and fixed albedo (visible reflectivity) shifts when the greenhouse effect is considered (shown here for +0 K, +30 K or +60 K of greenhouse warming). In the absence of atmospheric greenhouse gases (black lines, +0 K), liquid water is predicted to be stable at Venus' orbital radius, whereas only ice would be thermodynamically stable at Earth's and Mars' radii. However, with greenhouse gases, Venus' equilibrium surface temperature is raised by ~510 K and is uninhabitable, whereas greenhouse gases raise Earth's equilibrium surface temperature by ~30 K, making Earth habitable. Approximately 4 billion years ago (Gya), the young Sun is thought to have been less bright, so the outer edge of the habitable zone would have been shifted to smaller orbital radii. Explaining the abundance and sustainability of surface flows on Mars 4 Gya requires the addition of significant greenhouse gases to its atmosphere or that the Sun was once more massive (indicated by the dashed horizontal line).

photolysis when their N_2 levels are low[69–71]. This means that atmospheres with notable O_2 contents can form without biological activity, which has implications for the hunt for life around other stars. Along with palaeopressure and composition proxies for Earth's atmosphere[72,73], this realization is leading to new thinking on Earth's potential rate of oxidation via hydrogen loss in the Archaean[74,75] as a function of its N_2 inventory through time[76,77].

In another example, large volcanic eruptions throughout Earth's history (both explosive and effusive) emitted dust, ash and sulfate aerosols to the atmosphere, triggering major environmental changes and, potentially, mass extinctions[78]. Starting as far back as the 1970s[79,80], studies of sulfate aerosols on Venus[81] and other planets of the Solar System[82] have helped increase our understanding of their climate impact on Earth. This has led to new insights into the possible role of sulfate aerosols in past mass extinctions[83–85] and Snowball-climate transitions[86], and, more controversially, their potential for use in intentional solar-radiation management (solar geoengineering) in the future[87].

Insights into Earth's early stellar-radiation history have been provided by observations of nearby Sun-like stars of varying ages, which have helped to constrain the Sun's bolometric and extreme ultraviolet luminosity evolution[88,89]. Escape of hydrogen and helium from exoplanetary atmospheres has already been inferred from these observations[90,91]. Predictions of atmospheric escape from Earth will be improved by future observations of gas escape from Earth-like planets, which will allow us to validate models of escape from Earth's atmosphere through time. Planetary science is, hence, fundamental to developing a robust understanding of Earth's atmospheric evolution, and the interplay between the two fields is deepening in the modern exoplanet era.

Initiation of plate tectonics. In the absence of substantial geological materials from Earth's early days, understanding how (and when) plate tectonics started is complex[92,93]. A promising approach is to look at Earth's planetary neighbours, which did not develop plate tectonics but may have undergone a similar geodynamic regime as the early Earth. For example, the absence of plate tectonics on Venus and Mars today might, by comparison, provide clues as to how the Earth developed plate tectonics in the past. Venus, which has a younger surface than Earth on average[94] (FIG. 1), could operate in a similar geodynamic regime as an early Earth that featured plume-induced subduction[95]. Enigmatic Venusian tectonic features such as coronae (BOX 2) might provide clues to the initiation of plate tectonics on Earth if they are sites of incipient subduction (as indicated by their morphology and correlations between gravity and topography). Lithospheric conditions for Venus today are similar to those for Archaean Earth, when the mantle was ~200 K hotter and the thermal lithosphere was thinner[96]. Venusian tesserae (BOX 2) have unknown compositions at present but, based on their morphology and surface emissivity[97], they might be analogous to granitic continents on Earth. A felsic composition for tesserae would indicate that they formed in the presence of large volumes of water[98], which would support the hypothesis that the loss of surface water on Venus is responsible for the limited extent of subduction today, whereas long-lived oceans sustain plate tectonics on Earth[93].

Surface processes and geochemical cycles before life. Several planetary bodies of the Solar System display ancient surfaces that predate Earth's oldest rocks. For example, a significant fraction of the Martian surface is older than 3.5 Gy and, thus, formed during Earth's Hadean and Archaean eons (more than 2.5 Gya)[99]. Mars, which experienced significant surface geological activity early in its history (FIG. 1), offers the Solar System's longest known record of geological, hydrological and, possibly, biological processes[100]. Sedimentary rocks observed by the National Aeronautics and Space Administration (NASA) Curiosity rover at Gale crater, for instance, offer a unique window into aeolian[101], fluvial[102] and lacustrine[103,104] processes on Mars at a time when microscopic life is believed to have already evolved on Earth[105,106], but long before macroscopic organisms colonized the Earth's surface.

Life profoundly affects the workings of Earth's surface processes, from rock weathering, soil formation and erosion, to longer-term climate feedbacks that, in turn, control sediment fluxes across Earth's surface[107]. For example, river functioning is intricately tied to vegetation on Earth today[108]. Meandering rivers with muddy floodplains, in particular, are thought to have co-evolved with land plants and to only have become prevalent with the greening of the continents[109,110], but the pre-life fluvial record of Earth is relatively poor[110]. In contrast, the surface of Mars hosts many meandering-river deposits[111,112] dating back to the planet's wet past, offering a unique window into the formation of meandering rivers in the absence of land plants. Understanding Martian river sedimentology will allow us to develop and test new facies models for unvegetated, meandering rivers[113] and quantify the rates of associated processes, such as lateral channel migration[114]. Thus, Martian river deposits might hold the key to interpreting the pre-Silurian rock record of Earth[113], which, in turn, has direct implications for the duration of sediment storage within fluvial floodplains and, therefore, the pace of geochemical cycling and Earth's palaeoclimate[114,115].

Biological cycling dominates the distribution and availability of elements both critical and peripheral to life functions on Earth today, even creating new minerals[116]. In terrestrial conditions, it is extremely difficult to understand the availability of different elements at the time when or before life formed, or to isolate abiotic-element-cycling processes. Samples from small bodies, such as iron meteorites, and Mars could be used to identify and isolate abiotic elemental cycling (such as the Martian phosphorus cycle[117]) from biological effects. Information about extraterrestrial element cycles can then be used to understand the contribution of abiotic cycling on early Earth and the potential availability of key elements when life first arose[118]. Earth-sized and super-Earth-sized planets also provide a wealth of analogues for prebiotic Earth volatile cycles in chemical and mass parameter spaces that are not available in our Solar System[119] (BOX 1). The carbonate–silicate cycle, for instance, is the basis of habitable zone models[120], and statistical tests of these models have been proposed[121] that would evaluate the validity of geological controls on atmospheric CO_2 by comparing measurements of its atmospheric abundance in a large sample of planets with model predictions. Such tests must await the next generation of space telescopes (such as the Large Ultraviolet Optical Infrared Surveyor, or LUVOIR, and the Habitable Exoplanet Observatory, or HabEx), which may be capable of making these measurements for small, cool habitable-zone worlds.

Planetary bodies as experiments

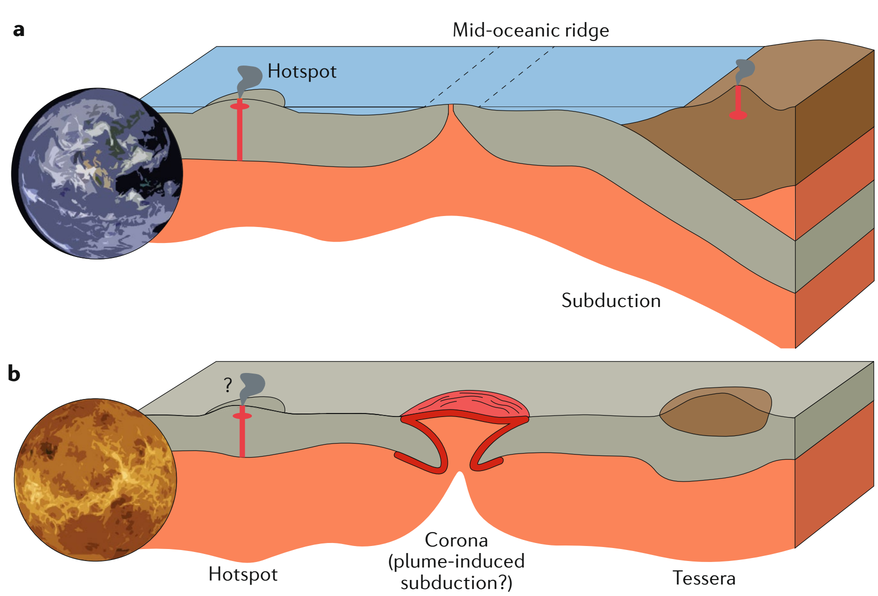
Developing complex geological and atmospheric models requires knowledge or estimation of all possible controlling factors, either through laboratory and field-based experiments or observations. However, it is often not possible to test all controlling factors on Earth and, as a result, the predictive power of our models is often hindered by our inability to account for unknowns. Owing to their diverse physical and chemical characteristics, planetary bodies can serve as full-scale experiments, allowing us to probe parts of parameter spaces that are unachievable on Earth and refine our mechanistic understanding of geological and atmospheric processes (BOX 3). Here, we present three research topics with associated major questions regarding the geological and atmospheric processes that can be tackled by utilizing the diversity of the planetary bodies in our Solar System (FIGS 1,3) and beyond (BOX 1).

Tectonic regimes. Earth, the only planet in the Solar System that clearly exhibits plate tectonics, has abundant water in its crust and upper mantle[122]. Hydration of Earth's asthenosphere, in particular, is thought to have played an important role in the onset of plate tectonics[123]. For example, hydration could lead to weakening and cooling of the lithosphere, which would facilitate convection, lithospheric failure and subduction[124]. However, this paradigm was questioned recently[125]. Observations from planets of different sizes, water contents and water distributions (FIG. 1) will, therefore, aid understanding of the precise mechanisms by which water contributes to plate tectonics.

Venus is similar in size to Earth but is water-poor near the surface[122,126,127] and shows no evidence of plate tectonics. Mars is, conversely, much smaller than Earth and has (or had) water in its interior and at its surface (FIG. 1), but it too has no known plate tectonics[122]. It is, thus, possible that larger planets retain higher concentrations of water in their upper mantles (as opposed to being more evenly distributed throughout the entire mantle) as an outcome of magma-ocean solidification and overturn, and that this internal water distribution increases the likelihood that Earth-sized planets develop plate tectonics[128]. On Earth, plate tectonics is sustained by the subduction of surface water back into the upper mantle, but this process

Box 2 | **The Venusian mystery**

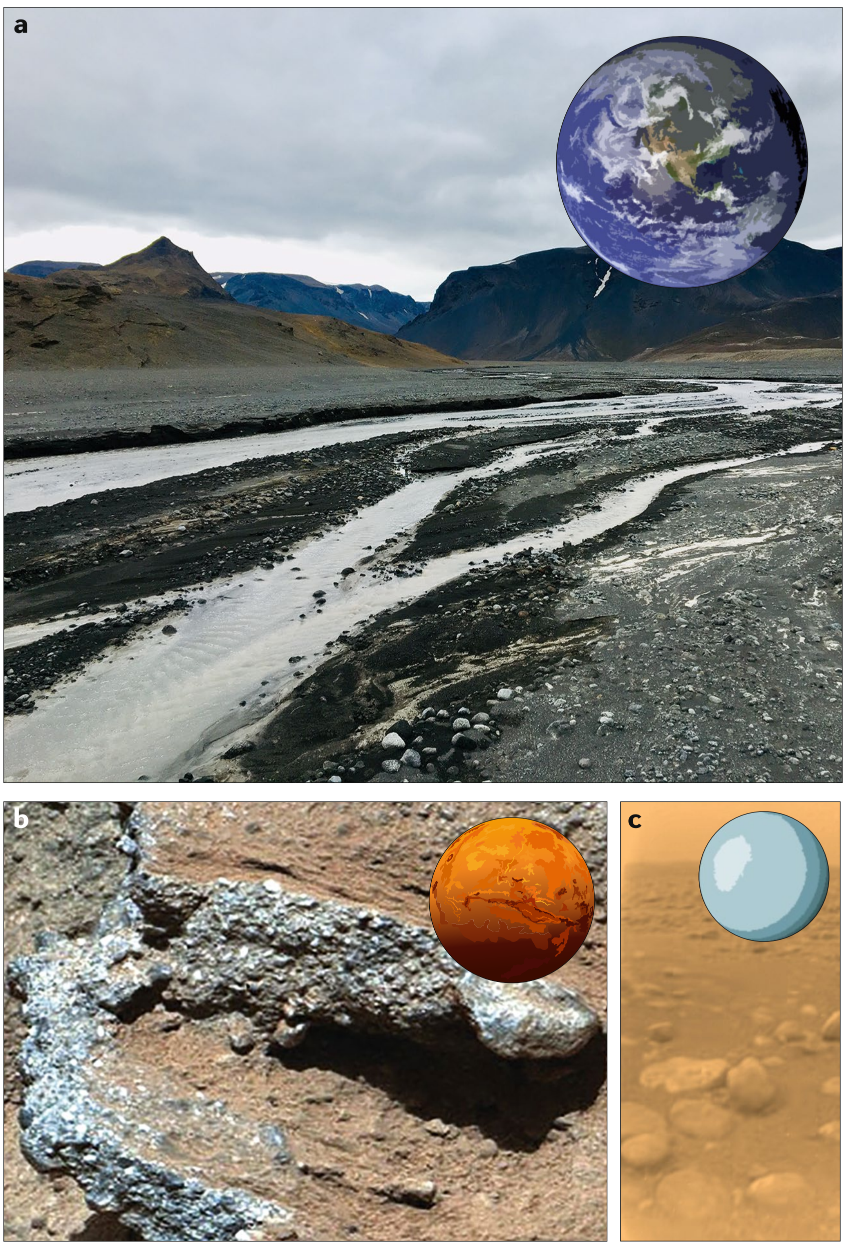
In many respects, Venus is Earth's misunderstood twin. Its hellish, thick CO_2 atmosphere is almost impenetrable at visible and infrared wavelengths, and, as a result, many first-order questions about the history of Venus are still unanswered. For example, has Venus ever hosted a dynamo-generated magnetic field[50]? The surface of Venus is young (<1 billion years on average), could possess present-day volcanic activity[220] and displays unique tectonic features, such as coronae ('oval-shaped features', often with concentric fractures) and tesserae (heavily deformed terrains with high topography and high radar backscatter). Coronae could form when plumes of hot mantle material rise and form a crustal dome, which then collapses, leaving a crown-like imprint on the surface. Alternatively, some coronae could be the surface expression of plume-induced subduction[96] (see the figure) or delamination. Tesserae, in contrast, have tantalizing features resembling felsic highlands[97], possibly analogous to Earth's continents. Contrary to models of planet-wide resurfacing followed by quiescence[221], studies of impact craters[222], coronae[96], hotspot analogues[223] and volcanic outgassing[224] point to steady geologic activity and volcanism on Venus that continues today. The Venusian mystery extends into the atmosphere, where the high deuterium-to-hydrogen ratio signals that water, perhaps an ocean's worth, has been lost to space[225].



Box 3 | **Planetary surfaces within the Solar System**

Planetary bodies within our Solar System are all shaped by processes that are governed by the same fundamental laws of physics. For example, winds redistribute regolith almost universally across the Solar System, from the Venusian surface under a thick atmosphere[226], to Earth's and Mars' deserts, to the hydrocarbon-sand seas of Titan[227], to surfaces underlying the rarified atmosphere of Pluto[140] or even to the 67P/Churyumov–Gerasimenko comet[143]. On all of these surfaces, windblown grains organize into migrating bedforms (including ripples and dunes) that respond to changes in atmospheric conditions and record critical information about the environment in which they formed.

Liquid flows also play or played a significant role in shaping the surfaces of, for example, Earth, Mars and Titan. Water is responsible for the transport of silicate grains across the surfaces of Earth (as seen in a gravel-bedded stream in Iceland, shown in panel **a** of the figure) and Mars (as seen from the deposits of a gravel-bedded stream observed by NASA's Curiosity rover in Gale crater, Mars[102], shown in panel **b**). In contrast, flows of liquid methane and ethane carve river channels and transport sediments made of solid water ice on Titan (as shown in panel **c**, depicting a dry riverbed observed by the European Space Agency's Huygens lander on Titan). Because bedforms are ubiquitous throughout planetary landscapes and form in concert with environmental fluids, they offer a unique opportunity to test our mechanistic understanding of sedimentary processes.



Part **b** of figure credited to NASA/JPL-Caltech/MSSS and part **c** to ESA/NASA/JPL/University of Arizona.

cannot occur on Venus because its crust is dry. It is possible that Earth and Venus had similar initial water contents and internal distributions, but Venus was later dehydrated (perhaps by impacts or hydrodynamic escape that was exacerbated by Venus' closer proximity to the Sun[129,130]). The hypothesis that larger rocky planets are more likely to have water in their upper mantles could be tested in the future by measuring the water content of mantle-derived materials from Mars, such as lherzolites and other peridotites. These water contents could be compared with both terrestrial values[123] and results from thermal models for planetary interiors that systematically investigate the effect of variable initial water distributions and concentrations.

Some models[131] suggest that the current tectonic regime of exoplanets can, in principle, be determined from their surface temperature (calculated after measuring bulk atmospheric properties) and size. Definitive atmospheric (or other) signatures of plate tectonics have not yet been identified. However, the presence of liquid surface water, which is possibly detectable through surface glint[132], would be indicative of surface temperatures that support the formation of long-lived discrete plates. Since no other planet is currently known to operate in a plate-tectonic regime, observations that indicate its occurrence on another planet would help to constrain the driving forces behind plate tectonics and potentially inform our understanding of when and how it began on the Earth.

Runaway-greenhouse atmospheres. The presence of a global surface ocean on Earth sets the Blue Marble apart from the other planetary bodies of the Solar System (FIG. 1). Indeed, Earth is the only planet in the Solar System that is able to stably host liquid water at its surface today (FIG. 2). However, it is unknown what will happen to the Earth's oceans and habitability as thermonuclear fusion continues to brighten the ageing Sun. Venus' runaway-greenhouse hypothesis[14] is a classic example of how another planet can serve as a full-scale experiment for understanding Earth's possible future. In this scenario, as the young Sun became brighter, a critical luminosity threshold was eventually reached, where Venus' surface rapidly became hotter and water vapour accumulated in the atmosphere. The resulting greenhouse effect caused a runaway increase in surface temperatures that ultimately evaporated any oceans, and, subsequently, nearly all of Venus' hydrogen was lost to space[14]. Although Earth today is still believed to be safe from such a catastrophic transition, Venus' atmospheric evolution provides a sobering perspective on how much climate can change with only small changes in external forcing.

Observations from Earth-like low-mass planets that are close to their host star (such as GJ1132b[62] and the TRAPPIST-1 system[133,134]) could help to guide our understanding of the runaway-greenhouse phenomenon. A better understanding of the runaway-greenhouse effect, likely through a dialogue between new observations of Venus and exoplanets[135], will be key to testing whether Earth's habitable conditions are common and understanding how our Sun impacts Earth's habitability. For instance, this research might confirm whether plate tectonics played a critical role in maintaining the long-term habitability of Earth as the Sun brightened[120]. The carbonate–silicate cycle has provided a pathway through which CO_2 could be extracted from the atmosphere and stored in rocks as insolation rose in response to the brightening Sun. If widespread among exoplanets, such feedbacks would effectively stabilize planets against runaway processes related to the evolution of their own stellar hosts[136].

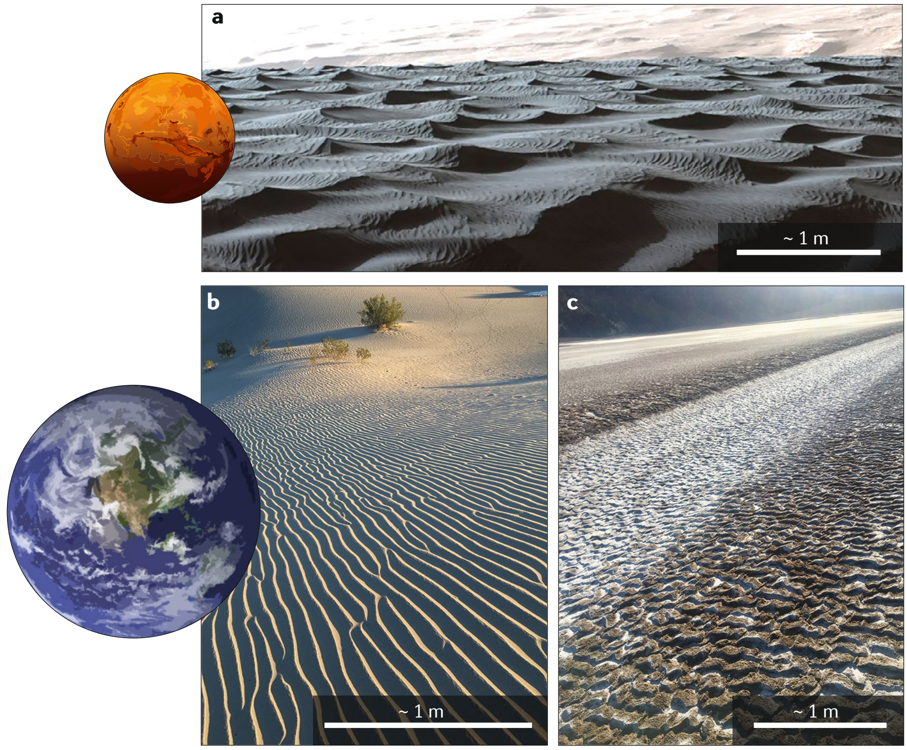


Fig. 3 | **Large wind ripples on Mars: an experiment that challenges our understanding of aeolian ripple formation, and a likely analogue to terrestrial current ripples. a** | Two scales of aeolian ripples (decimetre and metre) atop a basaltic sand dune within the Bagnold dune field of Gale crater, Mars. **b** | Decimetre-scale aeolian ripples in the Mesquite Flat sand dunes, Death Valley, California, USA. **c** | Decimetre-scale current ripples on the dry bed of the Amargosa River, Death Valley, California, USA. Part **a** credited to NASA/JPL-Caltech/MSSS.

Bedforms and sediment transport. Bedforms, such as ripples and dunes, are found throughout the Solar System and are created when a fluid flows over a granular bed, such as water on sand and gravels[137], winds on sand[138], hydrocarbon flows on water-ice grains[139], winds on methane-ice grains[140] or even thermal winds on cometary regolith[141] (FIG. 3; BOX 3). Bedforms represent prime palaeoenvironmental indicators on Earth because they are formed in concert with environmental flows and are preserved in the rock record. However, their use as an indicator requires a quantitative mechanistic understanding of their formation. Our current understanding of bedform-formation processes, which is primarily based on terrestrial observations, can be tested using the extraterrestrial bedforms within our Solar System[138,140–143].

Metre-scale ripples formed by winds in fine sand, for example, appear to be common on Mars but are nowhere to be found on Earth[138,144,145] (FIG. 3). Their identification challenges state-of-the-art models, calling for a reappraisal of the underlying ripple-formation mechanics[138]. Several new models have been proposed to explain the large Martian ripples[138,146,147], leading to new insights in the formation of both fluvial[147,148] and aeolian[138,146,147] bedforms with direct applications to terrestrial environments and their sedimentary record. These applications include the formulation of a new palaeoenvironmental technique to reconstruct flow characteristics from stratigraphy[148] and the reappraisal of the conditions required to initiate sand transport.

For example, until recently, it was assumed that a relatively high threshold wind speed[149] was required to initiate the saltation (or hopping) of sand grains on Mars. Missions to the Martian surface, though, have revealed that winds rarely exceed that minimum wind speed[150–152]. Nevertheless, active sand transport has been observed globally on Mars from orbiter-based imagery[153,154] and locally by rovers[155–157], challenging our Earth-based understanding of windblown-sand fluxes. To solve this apparent contradiction, new quantitative models that account for the detailed physics of grain-to-grain collisions, grain splash and sporadic saltation clusters have been developed and suggest a greatly decreased (maybe up to about an order of magnitude lower, depending on grain size) threshold wind speed to sustain and even initiate sand transport[149,158–160]. Furthermore, owing to the virtual absence of chemical weathering today, Mars offers an exotic picture of mineral sorting during transport, providing critical insights into how mafic and felsic phases partition along transport pathways due to, for example, crystal size, mineral density and grain shape[161–165].

Space as an archive

Between the transformation of the early Earth by the Moon-forming impact, the alteration of Earth's surface by the hydrosphere and atmosphere, and continuous recycling by tectonics, key pieces of Earth's history have gone missing from the geologic record. Here, we argue that some of these pieces were not completely lost and can be found by looking towards space. We illustrate how space exploration could help us to reconstruct or infer parts of Earth's lost archive through three example research topics and associated questions about Earth's history.

Building Earth. It is likely that the Earth formed in a similar cosmic environment to the thousands of exoplanets known to date (BOX 1). Specifically, a gaseous protoplanetary disc would have persisted for 1–10 Myr, followed by a period lasting roughly

100 Myr characterized by giant impacts between planetary embryos within a gas-free environment. Only by observing young analogues of our Sun can important details of these early phases be deduced. For example, young gaseous discs are often permeated with gaps and rings, likely caused by the existence of forming planets[166]. Together, discoveries of giant planets occupying extremely close-in orbits, planetary chains in orbital resonance (in which orbital periods are close to integer ratios) and gaps in circumstellar discs are strong indicators that planets undergo significant radial migration during the gaseous protoplanetary disc stage. Later, during the gas-free disc stage, the four giant planets in our solar system potentially migrated in their orbits as they gravitationally interacted with solids left over from the planet-building process[16]. For example, a period of migration (first inwards, then outwards) has been proposed for Jupiter, in which its early path sculpted the inner Solar System and hindered the growth of Mars[167]. Additionally, young Solar analogues reveal strong magnetic fields and rapid (1–10 days) rotation rates, which expel the disc gas closest to the star during the first 10 Myr and drive a strong Solar wind during the subsequent 100 Myr, a period of time during which the Earth was still forming. The influence of these winds in the early Solar System remains mysterious and could have included an outwards motion of planetary building blocks from the now empty region interior to Mercury's orbit[168] and atmospheric erosion in close-in planetary atmospheres[169].

Meteorites have long been used to infer the primordial history of the Solar System and the Earth[54,170–178]. Other examples of possible cosmic archives relevant to Earth's history come from exoplanetary debris. Spectral observations of these objects (as can be found around white dwarf stars[179] or even within our own Solar System[180]) reveal that exoplanetary rocky materials are, overall, similar in chemical composition to those of Earth[181], suggesting that the Earth did not experience a fundamentally different chemical evolution than these objects. Perhaps even more directly, observations of protoplanetary discs will help us answer key questions about the materials that went into forming Earth. For example, Earth is substantially depleted in carbon and nitrogen relative to the interstellar medium (the background material and radiation in a galaxy)[182]. The only way to understand this depletion is through understanding the chemistry of protoplanetary discs. With the advent of large ground-based telescopes such as the Vera C. Rubin Observatory (previously the Large Synoptic Survey Telescope, or LSST) and the Atacama Large Millimeter/submillimeter Array (ALMA), more observations of exoplanetary debris[183] and protoplanetary discs[166] might disclose new clues about the building blocks of our planet.

The lunar archive. The Moon is an archive of some of Earth's early processing, as its highlands have not been significantly modified since the Moon's formation. For example, lunar samples from the Apollo missions have been used to date Earth's core formation by comparing the Hf-W isotopic compositions of the Earth and Moon[184]. Lunar crustal zircons have also constrained the timing of the giant Moon-forming impact to about 4.51 Gya and subsequent lunar magma-ocean crystallization[185,186]. The magma ocean would have solidified over ~10 Myr, although tidal heating from Earth likely caused the melting and recrystallization of portions of the lunar crust for an additional ~200 Myr[187].

In addition, characterizing Earth's bombardment history[188] is critical to understanding the surface environment of Hadean Earth[189]. Based on lunar rocks, it was proposed that the Moon recorded a spike in cratering approximately 3.9 Gya — a hypothesis that came to be known as the Late Heavy Bombardment[190]. However, this hypothesized cratering-rate spike has recently been widely challenged, as this interpretation could be the result of sampling biases[191]. Regardless, because the Moon shares its circumstellar orbit with Earth, it offers a unique record of the impact history at Earth's orbital radius that is not preserved on Earth itself. Resolving the bombardment history of Earth, therefore, will likely require that we look towards the Moon and other celestial bodies, such as meteorites.

Finally, in addition to its cratering record, the Moon might carry yet another record of Earth's early days in the form of meteorites that came from Earth. A potential Earth meteorite was recently identified in Apollo 14 samples[192]. If a terrestrial origin is confirmed, this rock offers a truly unique window into the Hadean and Archaean Earth.

A faint young Sun. It is believed that, about 4 Gya, the young Sun was only 70–75% as bright as today[193], leading to an apparent faint young Sun paradox[194]: under a dimmer Sun, how could liquid water have been stable at the surface of Earth and Mars (FIG. 2)? This problem can be resolved, in principle, if greenhouse gases like CO_2, CH_4, NH_3 or H_2 were present in Earth's early atmosphere[64,195–197]. Nevertheless, the paradox itself rests upon numerous assumptions regarding the early Earth and its geologic record. For example, potential biases could exist in the abiotic deposition of sedimentary records (such as carbonates) that make the early Earth appear warmer than it truly was[198]. Moreover, the paradox could, in principle, be solved without a substantially enhanced greenhouse effect if the Sun was once more massive[199]. For the young Sun to have been more massive, the magnitude of the ancient Sun's winds would have been required to far exceed that of its current winds. Whereas measured mass-loss rates by Sun-like stars confirm that wind magnitudes are generally greater in younger stars, the Sun's ancient winds would need to be anomalously strong to entirely solve the faint young Sun paradox[200].

Avenues to test the massive young Sun hypothesis are few, owing to the inherent difficulty of measuring the Sun's historical mass. Helioseismology (the study of the Sun's interior through its oscillations), for example, has been used to investigate the problem but has not been able to confirm or refute a large mass loss[201,202]. Another way to test this hypothesis would be to constrain the early Solar magnetic field from meteorites[203], although extracting a signal from the early Sun is greatly complicated by any remanent magnetism from an intrinsic dynamo of the meteorite's parent body[204].

Despite these difficulties, modelling of the whole Solar System has shown that, throughout solar mass loss, there is a linear relationship between the Sun's mass and the frequency of orbital oscillations associated with the modern Milankovitch frequency of ~405,000 years[205,206]. A promising direct test of the massive young Sun hypothesis will be to constrain the variation of the Milankovitch frequencies through time using observations of old, pristine banded sediments. Mars, in particular, is an ideal target to test this idea, as its sedimentary record is longer than Earth's and it has thick sequences of quasiperiodically layered sediments at its surface that might reflect an astronomical forcing[207,208]. The feasibility of measuring the signals on Mars will strongly depend upon the chronometers that will be sent to the planet in the future and, perhaps more critically, on the success of sample return to Earth[209]. Proposed atmospheric compositions thought to be characteristic of the early Earth hinge critically upon

Solar insolation[197]. Thus, testing the massive young Sun hypothesis would help us understand the conditions under which Earth's earliest life forms emerged.

Outlook

The dialogue between the Earth and planetary sciences is at the root of many recent advances and discoveries. An important aspect of this dialogue — what space can teach us about our own planet — will likely yield even more exciting results and surprises about the Earth in the future.

Several advances are foreseeable in the short-to-medium term. For example, numerical modelling of mantle evolution within planets could test how different initial conditions (such as water content and distribution) affect a planet's tectonic regime and can readily provide insights into the initiation of plate tectonics on Earth. Furthermore, detections of exoplanetary magnetic fields via radio, far-ultraviolet auroral or H_3^+ infrared auroral emissions are now within reach[27] and will eventually enable statistical studies of dynamos in terrestrial planets. Observations of exoplanetary magnetic fields could reveal correlations between magnetic field strength or lifetime and planetary attributes such as size, atmospheric mass or rotation rate.

In addition to modelling and statistical studies, telescopic observations could soon provide clues about our planet's infancy. For instance, under the classic Moon-forming-giant-impact model[210], the incredibly close agreement between the oxygen isotopes of the Earth and Moon requires the impactor to have had nearly identical oxygen isotopic composition to the proto-Earth. Although not impossible, the low likelihood of such a scenario has led to the revision of the classic giant-impact hypothesis and to the proposal that the Moon formed in a synestia (a rapidly spinning, non-hydrostatic body of vaporized rock)[211]. Telescopic observations of giant impacts in other planetary systems, which are technologically achievable today, would confirm that they are a common process and could, by analogy, support the giant-impact hypothesis. The planned James Webb Space Telescope will enable the observation of much older star systems than its predecessors[212] and should provide a wealth of new data on planetary formation that can directly augment our understanding of Earth's birth. The Parker Solar Probe (launched in 2018) could also help us understand Earth in its infancy by measuring solar energetic particles, allowing deeper insight into how they have affected the inner planets[213].

Planned space missions will also provide a wealth of new data that will directly feed back into our understanding of the Earth. NASA's and the European Space Agency's (ESA) next Mars rovers will investigate ancient surface and subsurface aqueous environments. These rovers should provide new data on geological processes in the absence of macroscopic life that will inform our understanding of Precambrian Earth. The Mars 2020 rover, in particular, will acquire a series of samples to be returned to Earth through a Mars sample-return mission orchestrated by NASA and the ESA. These samples could provide critical constraints on the timing and magnitude of Solar System events that directly impacted Earth's history, including, possibly, the origins of life[118,209]. NASA's Psyche orbiter will launch in 2022 to explore the metal-rich 16 Psyche asteroid, seeking to answer fundamental questions about planetary cores and possibly offering our first direct look at a protoplanetary core fragment. NASA's Dragonfly mission will send a small rotorcraft to Titan in 2026, which, upon arrival in 2034, will explore what might constitute an atmospheric analogue for the early Earth and offer a glimpse into Earth-like sedimentary processes operating in a world dominated by water ice, nitrogen and hydrocarbons.

Looking further into the future, several fundamental questions could be readily addressed by exploration missions. The NASA-led Artemis programme intends to send a crewed mission to the Moon's south pole within a decade. The crew will collect lunar rocks from a location that is far from the near-equatorial Apollo landing sites and return them to Earth, where they will undergo a new generation of laboratory analyses that will provide insight into the chemical and physical heterogeneity of the lunar crust and, for example, allow us to test the Late-Heavy-Bombardment hypothesis. Measurements of water content within extraterrestrial materials that contain components derived from upper mantles, which could be collected by lunar and Mars sample-return missions, would provide quantitative constraints to models of plate-tectonics initiation.

Additionally, in situ palaeomagnetic studies and observations of remanent crustal magnetism on the Moon and other planetary bodies by rovers or through low-altitude-flight measurements would inform us on the occurrence and longevity of planetary dynamos and, thus, on how Earth has protected its life forms from dangerous solar winds and cosmic rays for billions of years. Although some crustal palaeomagnetic data exist for the Moon, Mars and Mercury, their coverage and spatial resolution do not permit the timing and duration of their respective dynamos to be inferred. A return to the Moon, such as through the Artemis programme, will enable the collection of oriented samples that will leverage accurate determinations of the ancient lunar magnetic-field structure[214].

In contrast to the Moon, Mars and Mercury, no palaeomagnetic data from Venus have been acquired to date. In addition to constraining Venus' magnetic past and core history, a robotic mission to Venus could determine the extent of its similarity to the early Earth. Compositional measurements of the Venusian surface and atmosphere would help determine whether it ever hosted a surface-water ocean, providing direct clues to Earth's response to a brightening Sun. More measurements of noble-gas isotopic ratios in the Venusian atmosphere are, in principle, straightforward and would teach us about atmospheric accretion and loss processes[215,216]. High-resolution geophysical investigations of Venus' elastic thickness and heat flow would highlight potential differences with the Earth's lithosphere and inform our understanding of Earth's geodynamic past.

We will likely never know everything about Earth and its history, but a complete understanding of the Earth system will require that we explore the totality of Earth's environments, from its core outwards. As one of the last largely unexplored terrestrial environments, the oceans are often referred to as Earth's final frontier, but this vision relies on the assumption that only Earth can teach us about the Earth. Rather, we argue that Earth's final frontier is much vaster than its oceans — space could be the key to solving fundamental mysteries about our own planet. Space exploration, however, is a laborious endeavour, and even the most mundane tasks conducted by geoscientists on Earth will likely prove to be complex when performed on another planet. Thus, a continued effort in advancing exploration technology, as well as a robust planetary exploration programme, will be instrumental to gaining further extraterrestrial insights about Earth.

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