What Makes a Habitable Planet?

Space missions help answer one of humanity’s most profound questions: Are we alone in the universe? To begin to understand what makes a planet habitable, and thus where to look for life both within and outside of Earth’s solar system, scientists need to understand what in planetary formation and what in its subsequent evolution combine to produce a habitable planet.

Many things may help to make a habitable planet. However, to whittle these variables down to one, habitability in this piece is defined as the existence of liquid water. Atmospheres and crusts are the easiest parts of a planet to observe, and scientists use these observations to determine if a planet might have held liquid water in the past (as with Mars) or might hold liquid water in the present (e.g., by measuring the atmospheres of exoplanets).

These observations raise key questions about the evolution of the solar system: What makes the other rocky planets different from the Earth? Why does Earth have a lot of liquid water while the others have little or none? Answering these questions involves a close look at what makes the presence of life-sustaining liquid water possible on a planet.

Sources of Water

For a planet to have water, two criteria must be met: It must accrete with or later obtain water, and it must have a heat source sufficient to keep some of that water liquid.

Simulations of initial planetary formation agree that substantial radial mixing occurs during initial accretion—the gravitationally driven merging of planetesimals and planetary embryos that produces bodies as diverse as the terrestrial planets contain volatile-rich material. During this process, the accretion of a planet produces enough water and other volatiles to form an atmosphere and crusts that are differentiated; none have a crust with the bulk composition of the body. Even the Moon is thought to have a differentiated crust, as indicated by its high bulk density and large iron core.

Some astronomers have hypothesized that the Moon may have formed from a disk of material that accreted around a planet that never formed. However, simulations of this process suggest that the Moon is more likely to have formed from a disk of material that accreted around a planet that never formed. The Moon is thought to be composed of a mixture of materials that accreted from the disk of material that was left over after the formation of the Earth.

Judging the Water Content of a Planet’s Interior From Its Crust

Larger solid bodies all have either icy or rocky crusts that are differentiated; none have a crust with the bulk composition of the body. Immediately upon return of the first Apollo samples in 1970, both Wood et al. [1970] and Smith et al. [1970] proposed that its strange, almost pure plagioclase crust was formed by flotation from a magma ocean. Here is a third kind of crust—an ancient crust formed by differential density of minerals in a solidifying planet.

Thanks to those crustal samples, scientists long believed that the Moon was completely dry because no hydrated minerals could be detected in them at the time [see, e.g., Epstein and Taylor, 1970]. The Moon is therefore the test object of whether large rocky bodies can retain water in their interiors during energetic accretion events. The formation of the Moon from a disk of superheated rock fluidized by the last giant accretionary impact to the young Earth [Cameron and Ward, 1976; Canup, 2004; Hartman and Davis, 1975] was thought to explain its dryness. Without significant pressure or shielding magnetism, water or hydroxyl floating free in space in the fluidized disk produced by the giant impact was likely lost by transport in the solar wind.
Recently, however, water or hydroxyl in concentrations similar to some terrestrial mantle rocks have been found in some lunar accessory minerals and in microscopic melt inclusions in other minerals [Hauri et al., 2001; McCubbin et al., 2010; Saal et al., 2008]. These volcanic materials came from deep inside the Moon, and thus, the water they contain had been retained since accretion. Therefore, the energy of giant accretionary impacts does not fully dry the accreting material.

Further, the new measurements of sulfur and potassium on the surface of Mercury made by the Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) mission imply that Mercury began with a volatile inventory (possibly including some water) and was not fully devolatilized by any later process, including the hypothesized giant impact that may have stripped its mantle and left it with a core so much larger, proportionally, than those of the other rocky planets [Peplowski et al., 2011; Solomon, 2009]. Either Mercury’s remaining mantle retained volatiles despite a giant impact or impacts, or the volatile-bearing material partially reaccreted following each impact. If Mercury began with and retained volatiles, then the argument that all rocky planets begin with volatiles is strengthened.

If volatiles are delivered to all rocky planets during accretion and are not entirely removed by the energy of giant accretionary impacts, then the initial habitability of a young planet may be set by degassing of a magma ocean. During magma ocean solidification, some volatiles are partitioned into the solidifying mantle, but the majority are expelled late in solidification into a dense superheated atmosphere. Models predict that cooling of the atmosphere can result in liquid water oceans within 10 or tens of millions of years based only upon the initial bulk composition of volatiles, with no later additions [Elkins-Tanton, 2011]. Even a relatively dry initial magma ocean will produce a water ocean on the planet’s surface; a bulk silicate composition with just 100 to 500 parts per million of water will degas, upon cooling, sufficient water to produce an ocean [Abe and Matsui, 1986; Matsui and Abe, 1986].

The terrestrial planets, then, may be hypothesized to begin with a dense degassed atmosphere, which has been radically altered or stripped away by the age of the solar system. All rocky worlds should start with water oceans, but only those with the right distance to their star, a sufficiently large mass, and a shielding magnetic field may keep them [Elkins-Tanton, 2011].

Venus provides an excellent study case for the retention of atmospheres and water: The planet likely started with an ocean but lost it. Its mass allows it to retain the heavier, carbon- and sulfur-based molecules [Donahue et al., 1982]. Heavy carbon dioxide, in particular, is more effectively bound by the planet’s gravity and remains as the major atmospheric component on Venus, making surface temperatures hot enough to vaporize liquid water. Water gas is easily dissociated into oxygen and hydrogen, and in the absence of a magnetic field, hydrogen is easily lost from the top of the atmosphere. Why did Venus’s carbon end up as a greenhouse atmosphere, where Earth’s carbon is mainly bound into rocks? With its unmistakable cautionary tale for our own planet, Venus is a body crying out for further exploration.

Mars has been proved repeatedly to have had flowing liquid surface water in its past [e.g., Carr, 1987] and to have periodic seeps of some briny liquid in the present [McEwen et al., 2011]. Mars had only a short-lived magnetic field, originally detected by the Mars Global Surveyor mission [Acuna et al., 1999], to protect its atmosphere from stripping, and its mass is too small to bind a significant atmosphere through gravity. Thus, though nature gave Mars a habitable surface for some period of time, later evolution has removed it.

A Temporary Habitability

Though water likely was added to every planet’s surface through the tail of accretion that continues to the present day, all indications are that the rocky planets obtained the majority of their water through primary accretion. The planetesimals and planetary embryos collided together, melted, cooled, and breathed out atmospheres and oceans onto the surfaces of the young planets. The planet needed to be large enough to hold on to that atmosphere with gravity and needed to have a magnetic field strong enough to prevent water molecules in the atmosphere from being stripped away.

Further, and critically, these requirements for habitability demonstrate that it is temporary. No planet remains in any state forever; rather, it experiences continuous evolution of bulk chemistry, geophysics, and solar radiation. Without a magnetic field, would the Earth lose its water and become Venus? With less mass, would it be Mars? Yet Mars was once and may still be habitable in specific places—its habitability has shrunk over time. Even Venus may once have been habitable. Furthermore, someday the Earth will not be, if only by dehydration from the eventual swelling death of our star.

Pursuing the questions of habitability requires investigating the icy satellites, the subsurface of the Earth, and the surface of Venus and meaningfully approaching sample return from Mars. With a strong grounding in understanding the planets of our solar system, scientists can make better hypotheses about the conditions and structure of exoplanets. Science edges closer and closer to understanding how life originates and where else it can be found, but answers, as always, yield new questions, requiring continuing exploration in and outside of the solar system.

References


—LINDA T. ELKINS-TANTON, Department of Terrestrial Magnetism, Carnegie Institution, Washington D. C.; E-mail: ltelkins@dtm.ciw.edu