

Water on the Moon

Linda T. Elkins-Tanton

The Moon is not wet like Earth, and it doesn't have frozen icecaps like those on Mars. But it might be just a tiny bit damp, both inside and on its surface.

Lindy Elkins-Tanton is an associate professor of geology at the Massachusetts Institute of Technology in Cambridge.

The Moon was long thought to be completely dry. With only a few exceptions, lunar rocks brought back by the Apollo astronauts were dry. In contrast, almost all Earth rocks contain hydrous minerals that incorporate water as building blocks of their crystal structures. Moreover, almost all lunar samples include iron metal, whose presence indicates a lack of available oxygen, which would oxidize the iron as it does on Earth. And not just water, but all volatile elements—those that condense at temperatures less than about 700 K—are depleted in lunar samples. Together, the above observations led scientists to estimate that the Moon formed with something like 1 part per billion by mass (ppbm) of water.

The Moon's dryness is naturally explained if the satellite was created from a disk of superheated rock fluidized when a Mars-sized protoplanet crashed into the young Earth. In the immediate aftermath of impact, during which there was neither significant pressure nor shielding magnetism, the solar wind likely transported water or hydroxyl floating free in space away from the accreting lunar materials.

Since the Moon formed, however, its surface has experienced about 4.5 billion years of impact by solar wind, comets, and meteoroids and may also have received volatiles released during the Moon's approximately 2 billion years of active volcanism. For years, scientists have suggested that water frost could have accumulated in permanently shadowed craters at the lunar poles. Now two new sets of observations, one from the lunar surface and one from the lunar interior, are changing our view of how dry is dry. The observations appear to be clear and reproducible, but their interpretations are currently the subject of hot debate.

Are we really talking about water?

A water molecule is made from two hydrogen atoms and an oxygen atom. Hydrogen is famously mobile and can even have its electron stripped and wander around as a proton. Water, then, is a bit of a moving target. Take off one hydrogen and it becomes the hydroxyl molecule.

On the lunar surface, water and hydroxyl can bind loosely via weak van der Waals forces onto the surfaces of cold minerals or by stronger covalent bonds onto crystal defects of grain boundaries. Solar wind can deliver protons that react with surface materials to become hydrogen atoms. The neutral atoms can then bind to oxygen in mineral surfaces and become hydroxyls and perhaps water that are released at high temperatures. Ice can be delivered by cometary impacts and gradually migrate to cold craters, where it is trapped. In addition, water or hydroxyl incorporated into the crystal structures of solidifying minerals can be held in place over geologic times.

A touch of frost on the lunar surface

In the past two years, six space missions have detected water or its constituents on the lunar surface. First, instruments on three orbiter missions—*Chandrayaan-1*, *Cassini*, and *EPOXI*—measured levels of water, hydroxyl, or hydrogen on the Moon's surface. Later, the *Lunar Prospector* reported water on the surface. Most recently, the *Lunar Crater Observation and Sensing Satellite* (LCROSS) sent a spent Centaur rocket crashing into the Cabeus crater at the Moon's south pole. Both water vapor and ice were detected in the impact plume by LCROSS instruments and those aboard the *Lunar Reconnaissance Orbiter*. A rush of data has now confirmed the decades-old hypothesis that the Moon's surface contains water.

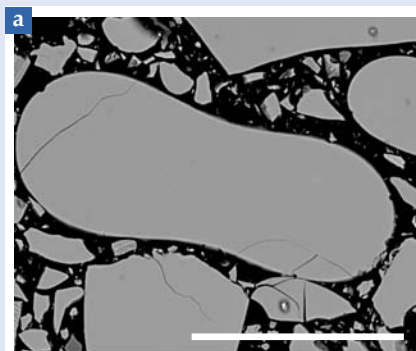
Spectral measurements from both *Chandrayaan-1* and *EPOXI* showed water or hydroxyl over the whole lunar surface during parts of the day. The signal was strongest nearer the poles and in deep, permanently shadowed craters. In the course of a day, the signal was lost and then recovered. That oscillation indicates to many of the *Chandrayaan-1* and *EPOXI* scientists that the water and hydroxyl are created by the solar wind, as described above. Indeed, the instruments aboard the two craft were sensitive to only the top few millimeters of the lunar surface, the layer most sensitive to solar radiation.

The *Lunar Prospector*, on the other hand, measured hydrogen directly to a depth of about 50 cm. Its data indicate water-ice contents of as much as 4%, an astonishing total, but one in agreement with the results from the LCROSS impact plume. Further, the *Lunar Prospector* data show that at the depths studied, hydrogen is present in both illuminated and shadowed areas of the crater where LCROSS struck. That deeper layer of water ice may have been delivered by cometary impacts or degassed from the lunar interior to be preserved in the cold lunar soil.

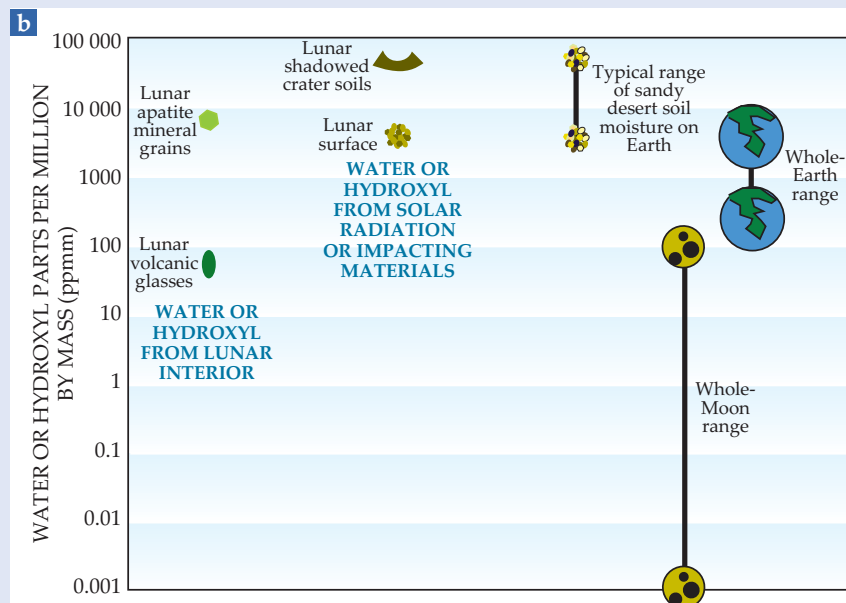
A drop of water in the lunar interior

Closer to home, laboratory scientists interested in the origins of the Moon and its history of volcanism have been making new measurements on samples from the Apollo missions. Any water measured inside minerals could be linked directly to water from the lunar interior, and thus to the bulk composition with which the Moon formed after a giant impactor blasted Earth.

The conversion of the impactor's kinetic energy to heat was sufficient to melt the material that formed the Moon and, to some depth, even Earth; the result was magma oceans on both bodies. As the lunar magma ocean solidified, any water in it fit into defects in solidifying minerals, degassed into space or the growing crust, or remained in residual liquids that solidified at the end of the magma ocean solidification.



Observations of lunar water. (a) This photomicrograph shows volcanic glass beads obtained from lunar soils collected by the *Apollo 15* astronauts. The beads contain as much as 46 parts per million by mass of water and provide evidence that the Moon accreted with at least some water. The scale bar is 100 μm across. **(b)** Water has also been observed on the lunar surface and in craters. This chart indicates high-end estimates for the water or hydroxyl content of various lunar materials and compares them to lunar and terrestrial benchmarks.



stage. Later, regions in the lunar interior partially melted, and the resulting magma erupted onto the surface. Any traces of water contained in that magma may have come from the melting source region inside the Moon and may constitute proof that the Moon accreted with some water.

Lunar volcanic glass beads such as shown in the figure were produced in volcanic fountains 3–4 billion years ago and contain as much as 46 parts per million by mass (ppmm) of water. The water content is highest in the center of the beads and declines toward the surface, a distribution suggesting that the whole bead originally had a higher water content and that water diffused out over time. If water had been added to the volcanic glass bead from the lunar surface environment, concentrations would be higher at the rim of the bead. The volcanic magmas, therefore, started with at least some water in them.

Other studies have found that individual apatite grains, tiny late-crystallizing minerals in lunar igneous rocks, contain as much as 7000 ppmm of hydroxyl. As magma cools, the first minerals to solidify accept only a tiny fraction of water into their crystal structures. The remaining water is concentrated in the residual magma, so the final dregs of magma to solidify contain the highest percentage of water. Apatite is among the last minerals to form, and thus it crystallizes from the most water-rich magma.

Many questions remain: What percentage of the source region melted to make the magma? To what extent did the magma solidify before apatite formed? Could the magma have been enriched with water on its way to the surface, rather than having acquired all its water from the melting source region? In any case, meticulous measurements indicate that water in the bulk Moon may range from ten to hundreds of ppmm, well more than the once-accepted 1-ppbm value.

One more measurement has been made, though, that casts some doubt. Lunar rocks contain a far wider range of chlorine isotopic ratios ($^{35}\text{Cl}/^{37}\text{Cl}$) than is found on Earth. Chlorine bonding to such metals as iron and zinc is thought to create the unearthy fractionations measured. But chlorine and metal bonds occur only at very low hydrogen content,

and therefore at very low water content. For chlorine to bond with metals instead of with hydrogen, the hydrogen content of the Moon must be 10^{-5} to 10^{-4} times that of Earth. The researchers conclude that the Moon's mantle has a hydrogen content around 10 ppbm—the comparable value on Earth is about 260 ppbm—which pushes the initial water content of the Moon back closer to 1 ppbm.

Can we drink it?

The amount of water in the lunar interior is almost certainly too tiny for explorers to mine for drinking. It makes a big difference, though, in our understanding of planetary formation and evolution—even a few parts per million by mass of water or hydroxyl in the solid rocky interior of a planet lowers the interior's viscosity and melting temperature, alterations that encourage volcanism and possibly help to explain some lunar observations.

Surface water is another matter. The observations made for the Moon will change the way scientists interpret remote sensing data for other bodies. And if some cold traps do contain 4% or more of water, they actually may be minable for use by lunar visitors—they could get water from a stone.

Additional resources

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- NASA's Lunar and Planetary Science website, <http://nssdc.gsfc.nasa.gov/planetary>.