Headline Article

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Volcanism and an Ancient Atmosphere on the Moon

--- Extensive lunar volcanism around 3.5 billion years ago produced a temporary atmosphere on the Moon.

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One of the distinguishing features of the Moon is its flimsy atmosphere, which has a pressure 300 trillion times smaller than Earth's pressure at sea level. The density is so low that gas molecules rarely collide and readily escape into space. Micrometeorites hit the surface at their full cosmic velocities and the solar wind implants hydrogen, helium, carbon, and other elements into the dusty lunar surface. This airless body has been like this for billions of years. However, Debra Needham (NASA Marshall Space Flight Center) and David Kring (Center for Lunar Science and Exploration at the Lunar and Planetary Institute, Houston) show that the Moon probably had a significant atmosphere for about 70 million years during the peak production rate of the lunar maria 3.5 billion years ago. The maria (dark regions that decorate the lunar nearside) are composed of overlapping lava flows. Needham and Kring show that the lavas would have transported sufficient volatiles such as carbon monoxide, sulfur gases, and H_2O to the surface to create an atmosphere. The volcanism would have released about 20 quadrillion kilograms of gases, creating an atmosphere with a pressure 50% higher than in the current Martian atmosphere. Calculations show that the loss rate to space from this atmosphere would have been 10 kilograms per second, implying that it would take about 70 million years to remove this volcanically produced atmosphere.

Reference:

- Needham, D. H. and Kring, D. A. (2017) Lunar Volcanism Produced a Transient Atmosphere Around the Ancient Moon, *Earth and Planetary Science Letters,* v. 478, p. 175-178, doi: 10.1016/j.epsl.2017.09.002. [**article**]
- **PSRDpresents:** Volcanism and an Ancient Atmosphere on the Moon --**Short Slide Summary** (with accompanying notes).

The Airless Moon

The Moon is a barren, airless place. It has no rivers or lakes, trees or grass. Clouds do not decorate the sky. It does not rain. The thin atmosphere does not block cosmic rays and dangerous solar flares, and even tiny, micrometer-sized meteoroids hit the surface at full speed, making microscopic craters in mineral grains. When astronauts kick the loose surface materials (called the regolith), dust does not billow up and slowly fall back, or waft away in the wind; even the tiniest grains fly on ballistic trajectories affected only by their velocities and the pull of the Moon's gravity. It is a stunning, amazing place. "Magnificent desolation," as Buzz Aldrin called it.

There is, however, a tenuous gaseous layer surrounding the Moon. Instruments carried by the Apollo missions detected noble gases, methane, hydrogen, and other gases, but at low concentrations. The pressure is 300 trillion times smaller than Earth's pressure at sea level and has a total mass of only 25,000 kilograms. Each cubic centimeter on the Moon contains 20,000 molecules, compared with 10^{18} molecules (10,000,000,000,000,000,000) for the same volume on Earth. The small number of molecules results in collisions between them being rare, so the lunar "atmosphere" is more accurately called an exosphere. The uppermost region of the Earth's atmosphere, where it grades into the vacuum of space is also an exosphere. The lunar exosphere does not have a lower region of dense atmosphere, so scientists call it a *surface boundary exosphere*, which, of course, requires an abbreviation, SBE. The lunar exosphere is the focus of attention because of a wealth of data from recent missions (**LADEE**, **ARTEMIS**) and because understanding the lunar exosphere will help us understand the exospheres around Mercury and the icy satellites of Jupiter and Saturn.

The Moon has had its SBE for a long time, but did it always have just an exosphere? Could it have had an atmosphere in the past? Debra Needham and David Kring suggest that it did, driven by volatiles released from eruptions of mare basalts.

Lava Gases

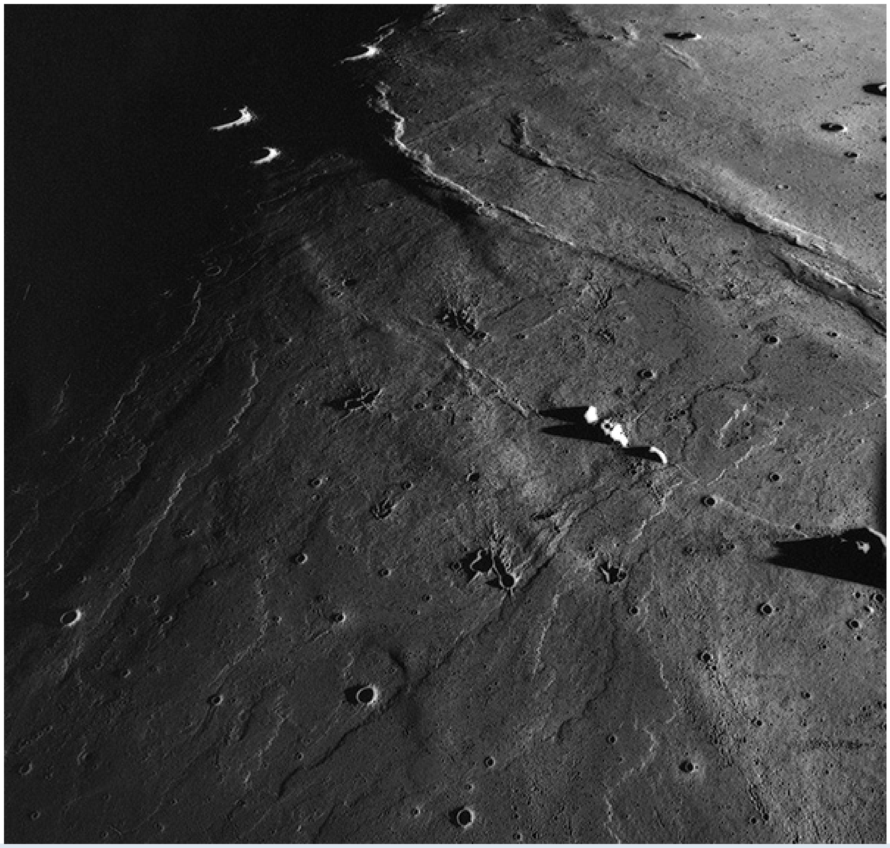
One of life's great pleasures is to see flowing lava. In the case of **pāhoehoe** lava flows, you can get close enough to sample the lava, see it emerge from within the flow to form an intricate ropy surface, and even walk on the dark, quenched surface above a molten interior. And you can smell it. An astringent mix of gases leaks from the lava, sometimes requiring volcanologists to wear gas masks. On Earth, the typical gases are water vapor (H_2O), sulfur gases (SO_2 with some H_2S), carbon dioxide (CO_2), and assorted halogen gases including HCl and HF. SO_2 and HCl often combine with the water vapor to make sulfuric acid and hydrochloric acids, which are dangerous. The ubiquitous presence of noxious fumes proves that volcanologists are very brave. Or reckless.

[LEFT] Volcanologist wearing gas mask while working at Masaya volcano, Nicaragua. **[RIGHT]** Release of gases during eruption along the South East Rift Zone of Kilauea volcano, Hawai'i, USA. Both photographs courtesy of Peter Mouginis-Mark, University of Hawai'i at Mānoa.

The **volatiles** released by lava flows originate in the Earth's interior where high pressure makes them soluble in magma. As magma migrates through the upper mantle and the crust, pressure decreases. At some point, the gases begin to exsolve like carbon dioxide bubbles in a carbonated beverage. Once on the surface as lava, most of the volatile gases form bubbles and leave the lava to become part of the atmosphere. This process is the most efficient way to transport volatiles from the interior to the surface, which is what drove Debra Needham and David Kring to investigate lunar lava flows as a source for atmosphere-building volatiles on the Moon.

Lunar Lava Flows

The lunar **maria** are the dark regions you see when you look at the Moon. They are composed of sequences of lava flows, as shown by orbital photography showing obvious flows and by the textures of samples returned from Apollo landing sites on the maria.



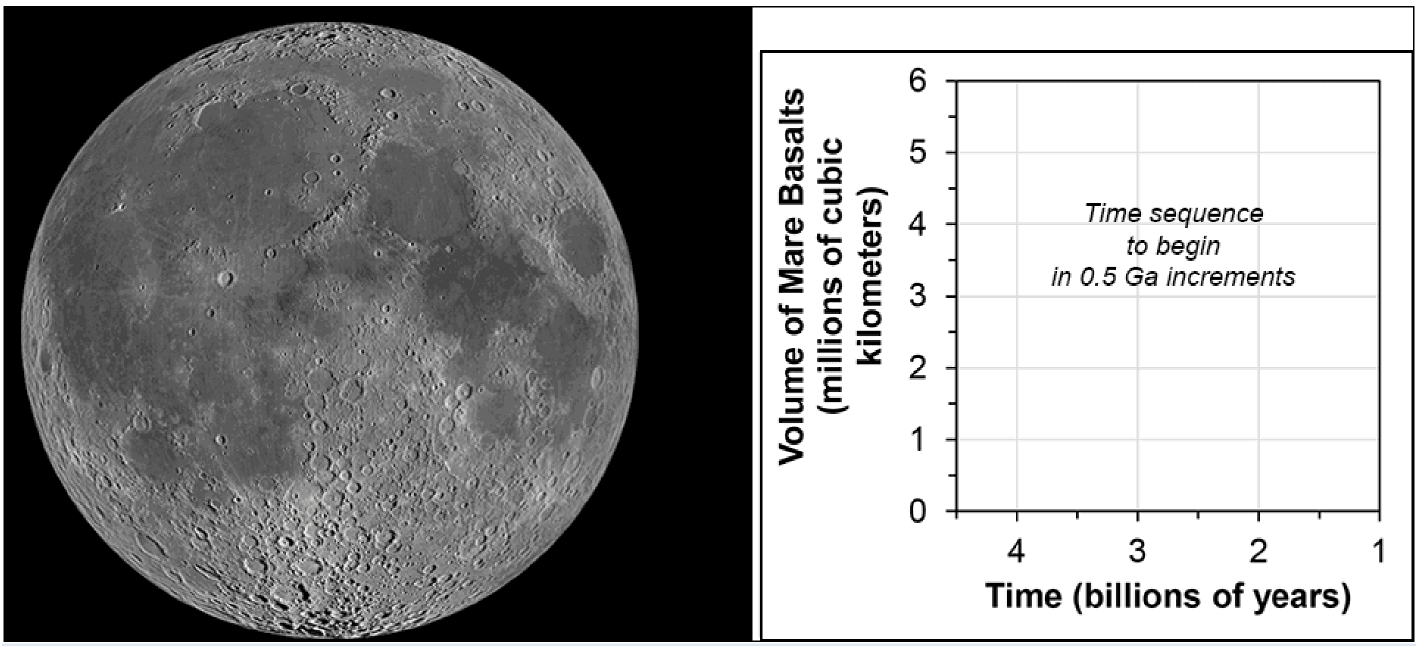
It is easy to see these large flow lobes in Mare Imbrium. The image was taken at a low Sun angle to emphasize topography, which highlights the flow margins. These flows, which reach lengths of a few hundred kilometers, are only about 1.5 billion years old. Their relatively young age allows preservations of the flow boundaries. Older flow margins either are overflowed by younger lava flows or are muted or erased by impacts over billions of years. The important point is that the presence of distinct flows shows that the maria formed by large eruptions of lava. (NASA Apollo metric image.)

Photomicrograph (3 millimeters across) in cross-polarized light of a thin section of lunar rock 12002, an olivine-rich basalt from the Apollo 12 landing site.The bright bluish mineral grains are crystals of olivine, the rest are pyroxene and plagioclase. Some dark areas are ilmenite, an iron-titanium oxide. The rock's texture (the shapes of the crystals and the way they are intergrown) clearly show that it formed in a lava flow, as proven by comparison with terrestrial lava flows and experiments on lunar compositions, thus supporting the photographic evidence shown above.

In one sense, there is not much mare basalt. Basalts compose only about 17% of the lunar surface and make up only 1% of the crust. Nevertheless, as they erupted, whatever gases they contained spewed into the lunar vacuum. The potential for those gases to produce an atmosphere depended on how much gas the lava flows delivered to the lunar surface. In turn, the amount of gas the lavas released depended mostly on the amount of lava that erupted. Needham and Kring needed to know the total volume of mare basalt erupted through time, and the concentrations of volatiles in the lavas.

The first task was to determine the volume of mare basalt that erupted over time. Lunar scientists have done a lot of work on this issue because it is important for understanding how melting varied over time in the mantle, a big deal in understanding planetary geological evolution. It is easy to measure the surface area covered by mare basalt, but trickier to measure the thickness and ages of individual mare basalt units. Fortunately, skilled photo-geologists have measured the areas covered by specific mare basalts. Relative ages have been determined by painstakingly counting the number of craters on specific units identified by composition as determined by spectral properties. Absolute ages have been determined by counting craters on the specific units and relating them to well-established estimates of the number of craters that should have formed in a given time interval. Debra Needham used the detailed flow mapping done by Harry Heisinger (Brown University and now at the University of Münster, Germany) and coworkers.

Determining the thickness of lava flows required using published results from topographic, photographic, and gravitational measurements. The results allow Needham and Kring to derive reasonable estimates of the thicknesses of lavas with the same age inside specific impact basins. A complication is that lava flows often cover pre-existing flows. If one lava flow partially covers an underlying flow, there is no problem as you see both of them. On the other hand, if the most recent flow in a maria completely covers an underlying flow, all we can do is to place a lower limit on the age of hidden, deeper flows. The thicknesses of the buried flows can be estimated from the thickness of the visible flows (they average about 250 meters thick) and the thickness of the entire stack of flows inside a basin (estimated from topographic data and basin geometry).



Time sequence of the eruption of mare basalt lavas, adapted from Figure 1 in Needham and Kring (2017). The maps on the left show in **red** the lava flows emplaced in each given time interval. Pre-existing flows are shown in purple (for those formed before 3.6 billion years [Ga] ago), dark blue (3 billion), blue (2.5 billion), light blue (2 billion), and green (1.5 billion). The graph on the right shows the volume of mare basalts erupted versus time, based on Figure 2a and Table S2 in Needham and Kring's paper. Note the sharp peak in eruptions before 3.0 billion years ago, with most of the action occurring about 3.5 billion years ago.

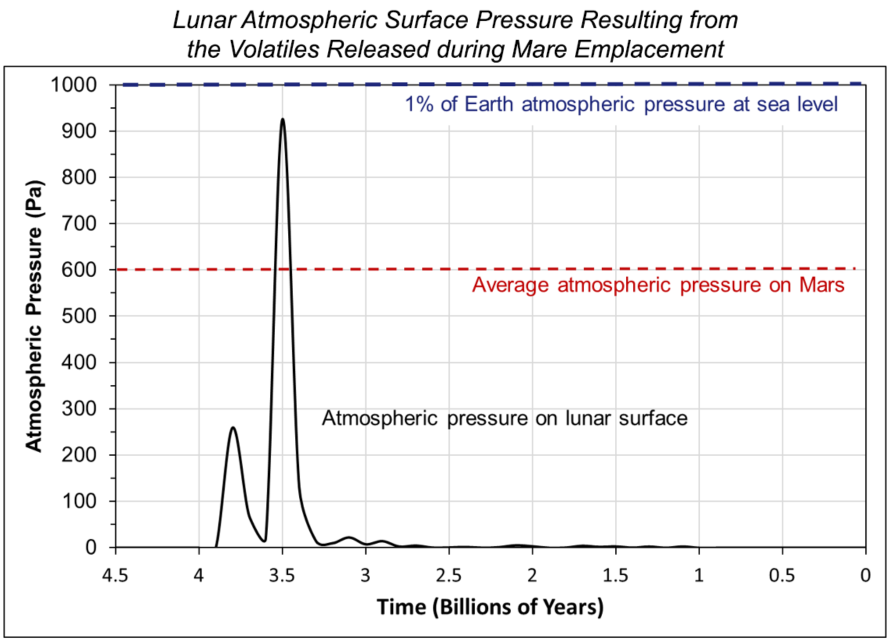
Amount of Volatiles

Determining the amount of volatile species (H_2O, CO, S, etc.) should be simple — just measure how much is in the samples of basalt returned by astronauts. The problem is that the volatile gases escaped during eruption (that's why we call them volatile). However, there is enough remaining in the rocks that lunar geochemists can work backwards by using geochemical savvy and assorted calculations, plus some reasonable assumptions about how much of a given volatile was lost. (Estimates of the percentages of the volatiles loss from a flow range from 90 to 100 %.) The results indicate that each gram of lava releases 80 to 750 parts per million (ppm) of CO, 1.8 to 9 ppm of H_2O, 0.007 to 45 ppm of H_2, and 180 to 540 ppm of S.

This does not sound like it would be enough to make an atmosphere! But at the peak of mare basalt eruptions, around 3.5 billion years ago, 5.4 million cubic kilometers of lava were erupted. Assuming a density appropriate for lunar basalt, 3000 kilograms per cubic meter, the total mass of volatiles released was about 20 quadrillion kilograms (2×10^{16} kg), assuming the maximum concentration of volatiles.

Atmospheric Pressure

Knowing the amount of volatiles discharged into the lunar atmosphere allowed Needham and Kring to calculate the pressure at the surface of the Moon as a function of time. Pressure is the weight of the atmosphere on the surface. Weight is the mass of the atmosphere times the gravitational acceleration (1.62 meters per second per second on the Moon). Using the entire mass as calculated above (2 x 10^{16} kg) and dividing by the surface area of the Moon (37.9 million square kilometers), gives the pressure in **pascals** (Pa). During the peak eruptive period 3.5 billion years ago, the lunar atmospheric surface pressure would have been a bit over 900 Pa. (For reference, 1000 Pa is about 0.01 (1%) the atmospheric pressure on Earth at sea level, see figure below.)



(Needham and Kring, 2017, *EPSL*, Fig. 2c and Table S3, doi: 10.1016/j.epsl.2017.09.002.)

Pressure in pascals vs time, for the maximum volatile release during lava flow emplacement. At the peak of mare basalt volcanic activity at 3.5 billion years ago, the pressure would be higher than the mean pressure on Mars and almost 1% of the atmospheric pressure on Earth's surface at sea level.

Eruptions disgorged enough gas to create an atmosphere around the Moon. In fact, it was shown in 1974 in a fascinating paper by Richard Vondrak (then at Rice University, Houston) that once the atmosphere attains a mass of 100 million kilograms it becomes a true atmosphere in which molecules collide frequently. The gas loss rate would be higher than in an exosphere, but is only 10 kilograms per second. Considering that at the peak of volcanic eruptions the mass of the atmosphere on the Moon would have been about 2 x 10^{16} kilograms, it would take about 70 million years to dissipate. This is a geologically significant time span.

Ancient Water at the Lunar Poles?

Most of the lunar atmosphere would have been composed of carbon monoxide and sulfur, but a hefty mass of water would have been released, too. At the peak of volcanism 3.5 billion years ago, a bit over 10^{14} kilograms of H_2O would have been discharged. The Moon most likely had frigid, permanently shadowed regions (nicknamed PSRs) at both poles, where water could collect and be preserved. If only 0.1% of the water made it to PSRs, it would account for all the water estimated to be in polar regions today. This ancient water from the interior of the Moon might be the best sample of the **isotopic** composition of water inside the Moon.

Debra Needham and David Kring's work points out the importance of taking a global view of water in and on the Moon. It also shows that the present lunar exosphere may not be the permanent state for the Moon. In Rich Vondrak's 1974 paper alluded to above, he explored the effects of adding volatiles to the lunar vacuum, finding that even small amounts lead to loss rates that are so slow that they are negligible over human lifetimes. Vondrak points out that "the present lunar 'vacuum' is a fragile state that should be treated carefully if it is to be preserved or could be modified if so desired."

Additional Resources

Links open in a new window.

- **PSRDpresents:** Volcanism and an Ancient Atmosphere on the Moon -- **Short Slide Summary** (with accompanying notes).

- Hiesinger, H., Jaumann, R., Neukum, G., and Head, J. W. (2000) Ages of Mare Basalts on the Lunar Nearside, *Journal of Geophysical Research-Planets,* v. 105, p. 29239-29275, doi: 10.1029/2000JE001244. [**article**]
- Needham, D. H. and Kring, D. A. (2017) Lunar Volcanism Produced a Transient Atmosphere Around the Ancient Moon, *Earth and Planetary Science Letters,* v. 478, p. 175-178, doi: 10.1016/j.epsl.2017.09.002. [**article**]

- Vondrak, R. R. (1974) Creation of an Artificial Lunar Atmosphere, *Nature,* v. 248, p. 657-659, doi: 10.1038/248657a0. [**article**]

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