THE ROLE OF THE TRANSIENT VOLCANICALLY-INDUCED LUNAR ATMOSPHERE IN TRANSPORT AND DEPOSITION OF POLAR VOLATILES.

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Introduction: Early in its history, the Moon had periods of active volcanic activity, which could have released substantial amounts of volatiles through the outgassing from the erupted lava. While their total amount and release rates are still poorly constrained, some estimates suggest that if preserved they could have accounted for all currently observed lunar volatiles [1]. However, the actual preservation of these volatiles depends largely on their ability to reach the polar cold traps before they escape to space. While such migration could happen by means of ballistic hopping, the presence of even a tenuous atmosphere would significantly boost such transport by conducting the volatiles with atmospheric currents and protecting them from photodestruction by solar radiation.

The possibility that major volcanic eruptions on the Moon could produce a tenuous transient atmosphere was been suggested for a long time [2], but the density and longevity of such an atmosphere is still debated. The ability of such an atmosphere to accumulate to a substantial density would depend on competition of volcanic outgassing and atmospheric escape. This would require volcanic events that are sufficiently strong and frequent, so that the atmosphere would not escape completely between eruptions. Needham and Kring [3] suggested that most of the eruptions during the peak of lunar volcanic activity ~3.5 Ga happened in a short period of time, in which case the atmosphere could accumulate to the level of ~10 mb and could persist for the period of ~70 million years. However, Head et al. [4] argue for longer intervals between the eruptions. In this case, the atmosphere is unlikely to accumulate more than a few microbars, and would persist for less than several tens of thousands of years after each major eruption. In either case, such a volcanically-induced atmosphere would be collisional and would promote the transport of volatiles to the poles.

Another important factor that would have an effect on transport and deposition of volatiles are the orbital properties of the Moon during the period in question. While our understanding of tidal dissipation allows us to estimate the Earth-Moon distance reasonably well, the Moon's obliquity is less well constrained. At this stage of its evolution the Moon just passed the Cassini state transition which could cause its obliquity to become as high as 50°.

Here, we study the ability of the tenuous transient lunar atmosphere to transport volatiles. We investigate the sensitivity of the transport efficiency to the thickness of the atmosphere and to the variations in the Moon's obliquity.

Methods: For simulations of the ancient volcanically outgassed lunar atmosphere we use the ROCKE-3D [5] planetary 3-D General Circulation Model. For the discretization of the atmosphere the model uses a Cartesian grid with a 4° × 5° horizontal resolution and 40 vertical layers. The boundary at the top of the atmosphere was set to ~10^{-4} of the surface pressure. To represent conditions 3.5 Ga, we set the solar constant to 0.75 of the modern value and used the solar spectrum from 2.9 Ga. The distance from Earth was set to 0.75 of modern value, which corresponds to a lunar rotational period ~17.7 modern Earth days. We assume that the Moon's surface didn't change significantly since the era of the Late Heavy Bombardment. Hence, we use modern observed data for the topography, the albedo and the distribution of permanently shadowed regions.

While outgassed species reported by Needham and Kring [3] are CO, H_2O, H_2 and S, in our previous study [6], we conclude that H_2 and S will not stay long in the atmosphere, and for our simulated climatological conditions CO is likely to convert to CO_2. For the experiments presented in this research we initialized the atmosphere to pure CO_2 with a trace amount of water (0.005 kg/kg).

Experiments: To study the capability of the transient lunar atmosphere to transport volatiles (in our case water), we simulate a single major eruption event according to [7]. We set a 250 km × 250 km outgassing region in the middle of Mare Imbrium. The duration of the eruption event was 100 days and the H_2O outgassing rate was set to 3×10^4 kg/s (which assumes 1000 ppmw H_2O in lava). We assumed that at the time of the eruption the transient atmosphere was already present (induced by previous eruptions). In each experiment we first ran the model until such a background atmosphere reached an equilibrium and then initiated the eruption. We then followed the fate of the injected volatiles for several years after the eruption.

We performed two sets of experiments. In one we used background atmospheres with 10, 2.5, 1 and 0.1 mb surface pressures and zero obliquity. In the second set of experiments, we used 1 mb background atmosphere and 0°, 8° and 25° obliquity.

Results: Figure 1 shows the total deposition flux of water at the polar regions (either above 68 °N or below 68 °S) over the period of 3 years after the onset of the eruption for four experiments with different surface pressures of the background atmospheres. *Surprisingly, in our experiments thinner atmospheres delivered the water more efficiently.* This may be the result of the fact that the saturation level of thinner atmospheres was higher, which resulted in a more efficient precipitation. The more flat signal for the case of the 10 mb atmosphere could be a result of higher water holding capacity of a thick atmosphere and the presence of sufficient amounts of background water, so that the added water was at the scale of the internal variability of the system. Nevertheless, the signal is still positive, and the water is delivered to the polar regions, just at a lower rate.

Figure 2 presents similar results from the experiments with several obliquities. The results are more intuitive here. Lower obliquity leads to higher volatile delivery rates. This is a result of colder poles promoting a stronger Hadley cell and a more efficient precipitation in polar regions. The delivery rate is still strong for 8° obliquity, but for 25° it becomes weaker with periods of seasonal removal of volatiles. Note that for 25° obliquity there would be no PSRs and the poles would probably be too warm to preserve volatiles for geological time scales.

Our results allow us to conjecture that for low obliquities even extremely thin volcanically-induced atmospheres can effectively transport volatiles to the poles. Current limitations of our model do not allow us to simulate atmospheres thinner than 0.1 mb, but work is underway to extend it to much lower pressures. This will allow us to test the validity of our conjecture.

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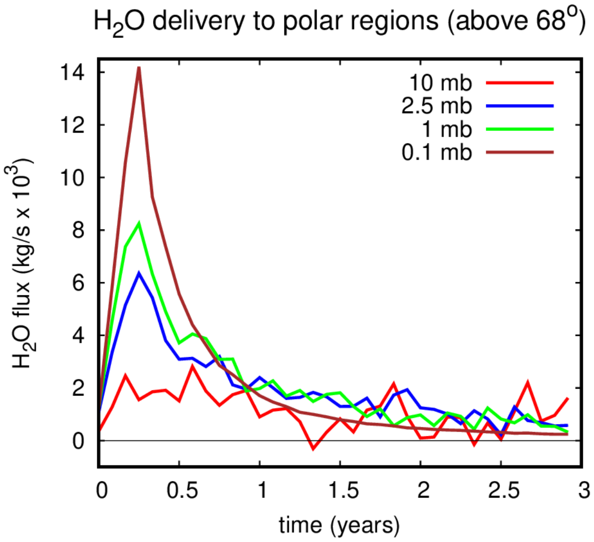

Figure 1. Water deposition flux at the poles for 10, 2.5, 1 and 0.1 mb atmospheres.

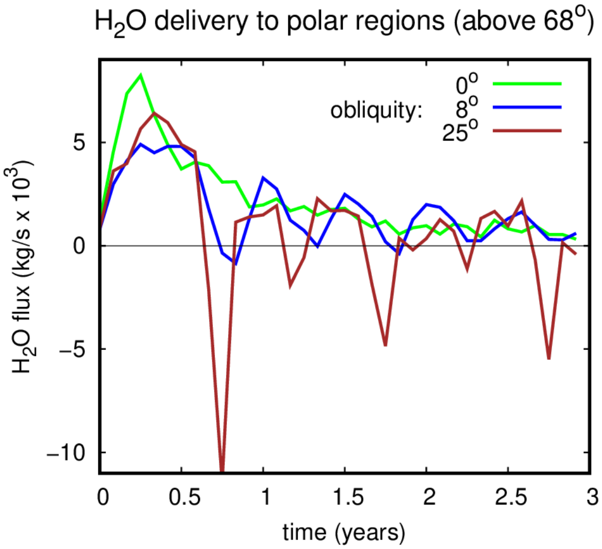

Figure 2. Water deposition flux at the poles for 0°, 8° and 25° obliquity.