

CAN COLLAPSE OF A VOLCANICALLY-INDUCED LUNAR ATMOSPHERE DELIVER VOLATILES TO PERMANENTLY SHADOWED REGIONS?

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Introduction: Volcanic outgassing is one possible source of the volatiles currently observed in the lunar permanently shadowed regions (PSR). Such outgassing during the peak of lunar volcanic activity ~3.5 Ga could have produced transient tenuous collisional atmospheres [1]. These would efficiently transport volatiles [2] from the outgassing sites to the polar regions where they could be stored indefinitely in the polar cold traps. Though the amount of thus transported water is large, most of it would be deposited outside of PSRs. To be preserved the water would need to migrate to PSRs by successive sublimations and condensations. A short-lived atmosphere may not allow enough time for this and most of the deposited water would eventually be lost to space. While the short lifetime of a volcanically-induced lunar atmosphere may thus pose a problem for the efficient deposition of volatiles in PSRs, in some cases it may also provide a solution to it. The lifespan of a CO₂-dominated lunar atmosphere is mainly determined by its condensation at the surface, rather than escape to space. This condensation will predominantly happen in the PSRs. The condensing CO₂ will also deposit all other volatiles contained in the atmosphere, providing a robust mechanism for targeted delivery of volatiles (in particular, H₂O) to PSRs. In this work, we investigate mechanisms of condensation (and possible atmospheric collapse) of a CO₂-dominated atmosphere on the Moon and estimate its efficiency in delivering water to PSRs.

Methods: We use the ROCKE-3D [3] planetary general circulation model (GCM) to study a collapsing volcanically-induced lunar atmosphere via a 1 microbar dry CO₂ atmosphere at zero obliquity. The general setup of our paleo-Moon model is described in [4]. PSRs are treated as patches of ground receiving zero solar radiation, but which exchange energy with the atmosphere through sensible heat flux and thermal radiation. The condensation of CO₂ is not simulated explicitly. Instead, we conduct our simulations in the absence of condensation, and then compute the condensation flux from the energy balance. Namely, in the areas where the ground temperature drops below the condensation point, we assume that in the real world it would stay at the condensation temperature and the latent heat from condensing CO₂ will provide the

necessary heat to keep the model in radiative balance. This gives the condensation flux

$$F = \sigma (T_c^4 - T_g^4)/L$$

where T_c is condensation temperature, T_g is ground temperature, σ is Stefan-Boltzmann constant and L is the latent heat of CO₂ condensation. Here T_c is computed based on simulated surface pressure.

For a comparatively “moist” volcanic outgassing, the relative humidity (RH) would increase as the air parcel moves towards the pole, and is likely to reach 100% RH in polar regions (we typically observe such behavior in our “moist” outgassing experiments [2]). So, to compute the amount of water delivered to PSRs by condensing CO₂, we assumed that the amount of water in the lower atmosphere above the PSRs was at saturation level (computed according to lower atmospheric temperature).

Results: In our simulations, the surface pressure was ~1 microbar, with slight deviation due to topography and meteorological conditions. This kept the CO₂ condensation temperature in the range 104 K to 106 K. Figure 1 shows the ambient ground temperature (outside of PSRs) and the temperature inside the PSRs. One can see that all areas outside of the PSRs were too warm to condense the CO₂, while most areas inside the PSRs did condense it. Figure 2 (top) shows the CO₂ condensation flux per unit area. One can see that this flux increases as one gets closer to the poles. This is a result of both lower ground temperatures and higher concentration of PSRs. Figure 2 (bottom) shows the corresponding H₂O flux to PSRs. Interestingly, here the highest flux is reached slightly away from the poles. This is due to the fact that very cold atmospheric temperature at the poles keeps atmospheric water concentration there very low.

The CO₂ condensation flux integrated over the entire surface is 3.5×10^5 kg/s. It is interesting to compare it to the outgassing rate in the major volcanic eruption known as Cobra Head suggested by Head et al [5]: 9.3×10^5 kg/s. Our number is ~3 times smaller, so the atmosphere would accumulate, but most likely it would collapse rather quickly after the eruption finishes, probably on a timescale of ~1 year. One should also mention that the atmosphere is still likely to accumulate even for smaller eruptions, because a thinner

atmosphere would have lower condensation temperature and, hence, lower condensation rate.

The corresponding integrated H₂O deposition flux is 1×10^3 kg/s. If we assume the duration of the volcanic eruption ~ 150 days [5], that would result in average ice deposition in PSRs ~ 0.25 mm H₂O equivalent per eruption, but due to the non-uniformity of this distribution some PSRs could get as much as ~ 2.2 mm H₂O equivalent per eruption.

The estimate for the H₂O deposition rate was made with the assumption that the eruption is “moist” (i.e., that it at least provides enough water to keep the lower atmosphere in polar regions saturated). The amount of outgassed H₂O in excess of this minimum will not increase this deposition flux and is likely to just precipitate over larger areas. One should also mention that this estimate is very sensitive to the atmospheric conditions at the poles. A sensitivity test we did for the obliquity 2° case gave the H₂O deposition flux 1.3×10^3 kg/s. The flux is higher due to warmer atmospheric temperatures at the poles in this case.

The volatile delivery process which we described here would load PSRs with a large amount of CO₂ which is not currently observed. We argue that being more “volatile” than H₂O it is more likely to be lost to space due to some persistent perturbation (e.g., impact gardening), but this topic requires further investigation.

Conclusions: A tenuous lunar CO₂ atmosphere in a zero obliquity case is likely to collapse quickly (on a timescale ~ 1 year) due to CO₂ condensation in PSRs. A collapsing atmosphere can bring other volatiles (such as water) to PSRs and efficiently deposit them there. The efficiency of such volatile deposition depends on meteorological conditions, but even if this flux is smaller than typical atmospheric transport to polar regions, the fact that it delivers volatiles directly to PSRs makes it an important potential source of currently observed lunar volatiles.

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References: [1] Stern S. A. (1999) *Rev. Geophys.*, 37, 453–492, [2] Aleinov I. et al. (2022) *LPSC 2022*, Abstract #1784, [3] Way M. J. et al. (2017) *ApJS*, 231, 12, [4] Aleinov I. et al. (2019) *GRL*, 46, 5107–5116. [5] Head J. W. et al. (2020) *GRL*, 47, e2020GL089509.

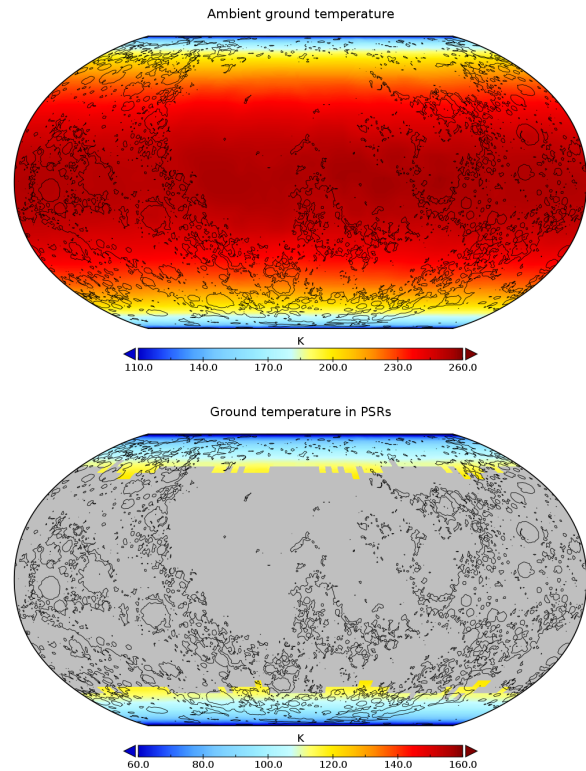


Figure 1. Ambient and PSR ground temperature.

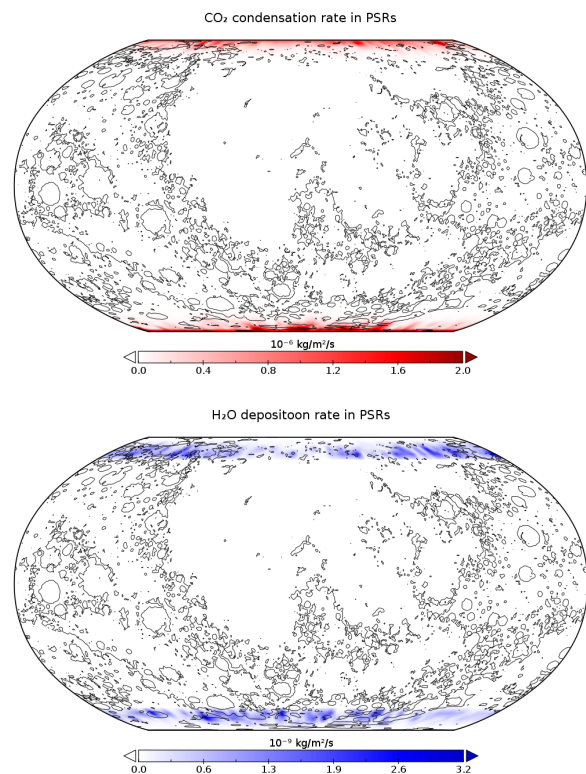


Figure 2. CO₂ and H₂O deposition flux to PSRs.