The Properties of the Moon's Ancient Maria-Outgassed Atmosphere. I. Aleinov[1,7], M. J. Way[2,9], C. Harman[3,8], K. Tsigaridis[4,7], E. T. Wolf[5] and G. Gronoff[6,10], [1]NASA Goddard Institute for Space Studies, New York, NY, 10025, USA (igor.aleinov@nasa.gov), [2](michael.way@nasa.gov), [3](chester.e.harman@nasa.gov), [4](kostas.tsigaridis@columbia.edu), [5]University of Colorado, Boulder, USA (eric.wolf@colorado.edu), [6] Science Directorate, Chemistry and Dynamics Branch, NASA Langley Research Center, Hampton, VA, USA, [7]Center for Climate Systems Research, Columbia University, New York, NY 10025, USA, [8]Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY 10025, USA, [9]Theoretical Astrophysics, Department of Physics & Astronomy, Uppsala University, Uppsala SE-75120, Sweden, [10]SSAI, Hampton, VA, USA

Introduction: Recent observational discoveries in the field of lunar volatiles raise the question of their origin and potential current distribution. The volcanic outgassing from lunar maria is one of the possible sources of these volatiles (together with solar wind and impactors), so understanding the outgassing, transport and capture of these volatiles in polar regions is crucial for understanding lunar volatile history and their current distribution.

The fact that volcanic outgassing from the maria could produce a very thin (~10^{-8} bars) short-lived transient atmosphere was well known for some time [1], but recent research by Needham and Kring [2] suggested that ~3.5 Giga-years ago (Gya) a much thicker atmosphere could have formed due to intensive volcanic outgassing from the maria, which at its peak could reach a pressure of ~10^{-2} bar and could survive for millions of years.

In our work we attempt to estimate the stability of such an atmosphere with respect to atmospheric escape and its possible collapse due to freezing-out in cold regions. We study the dynamics of such an atmosphere as applicable to transport and evolution of the outgassed volatiles.

Methods: To study the outgassed lunar atmosphere we use the ROCKE-3D [3] planetary 3-D General Circulation Model. We configure our model to conditions 3.5 Gya. For insolation we use solar constant 0.75 of modern value and spectrum from 2.9 Gya. For orbital parameters we set the distance from the Earth to 0.75 of modern value and assume zero obliquity with respect to normal to the ecliptic. Since we investigate the period after the Late Heavy Bombardment, we assume that the Moon's surface hasn't changed significantly since then and use modern observational data for surface topography, albedo and the distribution of permanently shadowed regions. Our model uses a 4^ox5^o spatial resolution and 40 vertical layers for the atmosphere.

For chemical composition of the atmosphere we use data provided by Needham and Kring [2], who list CO, H_2O, H_2 and S as the major outgassed species. We assume that H_2 easily escapes to space and S condenses quickly at the surface, so we don't include them in our current simulations. Depending on atmospheric temperature and abundance of H_2O, CO can react with it, producing CO_2. We use our 0-D chemistry model to determine conditions which would favor such a conversion to a CO_2 atmosphere. In our simulations we investigate both limiting cases of a pure CO and a pure CO_2 atmosphere. We also consider a completely dry atmosphere and an atmosphere that was initialized with 0.005 kg/kg H_2O (which is close to the ratio provided in [2]).

We made thermal escape estimates for our major atmospheric species and made an attempt to estimate non-thermal escape (though, this problem is significantly more difficult). Our numbers are slightly higher than the ones used in [2], but in general are of the same order. So, with the assumption that outgassing rates of [2] hold, we ran simulations for a range of atmospheric pressures between 10^{-3} and 10^{-2} bar.

Results: We present results for the set of simulations, as described above. As atmospheric thickness decreases, so do atmospheric and ground temperatures, which is expected due to the greenhouse effect. The lowest mean bulk atmospheric temperature in our experiments was 211 K (in case of a 10^{-3} bar CO_2+H_2O atmosphere), which is still above our estimated threshold for CO to CO_2 conversion. So, provided one has a sufficient supply of H_2O, one can expect the atmosphere to be CO_2-dominated. In case of the total absence of H_2O, of particular interest are experiments with a pure CO atmosphere. The atmosphere in these experiments is much warmer, due to its inability to emit to space the heat obtained by turbulent transport from the surface. Such an atmosphere would be a more efficient conductor of volatiles.

Ground temperature at the poles in most experiments was below the condensation point of CO_2. As a result a pure CO_2 atmosphere of 2.5x10^{-3} bar or lower is prone to collapse. This effect could be mitigated if the 3.5 Gya Moon had a substantial obliquity (as it prevents atmospheric collapse on modern Mars). Considering the uncertainty in orbital parameters 3.5 Gya, this is a possibility.

References: [1] Stern S. A. (1999) *Rev. of Geophysics, 37*, 453-492. [2] Needham D. H. and Kring D. A. (2017) *Earth and Planetary Sci. Lett., 478*, 175-178. [3] Way, M.J. et al. (2017) *ApJS, 231*, 12.