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A model of the primordial lunar atmosphere

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ABSTRACT

We create the first quantitative model for the early lunar atmosphere, coupled with a magma ocean crystallization model. Immediately after formation, the moon's surface was subject to a radiative environment that included contributions from the early Sun, a post-impact Earth that radiated like a mid-type M dwarf star, and a cooling global magma ocean. This radiative environment resulted in a largely Earth-side atmosphere on the Moon, ranging from $\sim 10^4$ to $\sim 10^2$ pascals, composed of heavy volatiles (Na and SiO). This atmosphere persisted through lid formation and was additionally characterized by supersonic winds that transported significant quantities of moderate volatiles and likely generated magma ocean waves. The existence of this atmosphere may have influenced the distribution of some moderate volatiles and created temperature asymmetries which influenced ocean flow and cooling. Such asymmetries may characterize young, tidally locked rocky bodies with global magma oceans and subject to intense irradiation.

1. Introduction

The Moon is an important and relatively observationally accessible marker of solar system history. Evidence obtained from study of the lunar surface has yielded insight into numerous physical processes that have transformed the planets over the history of the solar system (Heiken et al., 1991; Keller and McKay, 1997; Stöffler and Ryder, 2001). Consequently, interpretation of the evolution of the lunar interior and surface helps to inform understanding of the environment the Earth evolved in. Critical to the interpretation is tracing the history of the surface right from the initial formation of the Moon to the present day.

Petrological evidence supports the theory that the early lunar surface was very different from the solid, crater marked version observed today. Instead, the Moon was believed to have been covered by a deep global magma ocean immediately after its formation (Yamamoto et al., 2012). This magma ocean is believed to be a consequence of the relatively quick accretion of the Moon after its formation from a collision between the Earth and a planetary sized impactor (Canup, 2004; Barr, 2016). After formation, the magma ocean cooled and solidified to ∼70–80% in less than 1000 yrs, leading to the eventual flotation of plagioclase rockbergs (Longhi, 1977) that would form a floatation lid. The initial radiative environment of the Moon's surface was likely to have an additional consequence often not associated with the Moon – the creation of an early atmosphere.

While today the Moon possesses a rarefied exosphere composed largely of Argon, Helium and Neon (Elphic et al., 2016), previous work has recognized that at earlier times, the Moon likely possessed denser atmospheres (Stern, 1999). These atmospheres are proposed to have been a result of the vapor pressure equilibrium that likely existed above the exposed magma on the surface. However, several studies have also recognized that an immediately post-collision Earth may have been hot enough to induce a temperature asymmetry on the Moon (Wasson and Warren, 1980; Stern, 1999; Roy et al., 2014), and that the radiative contribution from the glowing Earth may have served as an additional energy source for vaporization of surface magma. This additional radiation source and the potential that it may have induced asymmetries on the early Moon may have had some important consequences for surface evolution.

However, to date there is no model which looks at spatially resolved atmospheric-surface conditions on the Moon prior to and during plagioclase lid formation. Here we discuss results of the first spatially resolved surface model for the early Moon, one that couples an atmosphere model to a Lunar Magma Ocean (LMO) crystallization model. We use an atmosphere model originally developed to explore the meteorology of Io (Ingersoll et al., 1985) in conjunction with a LMO crystallization model that yields crystallization timescales for the LMO and surface temperatures as the magma evolves (Elkins-Tanton et al., 2011). Our model includes radiative contributions from a cooling lunar magma ocean, the Earth

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immediately after the Moon forming impact and the early Sun. The following two sections describe the details of the atmosphere and magma ocean crystallization models and how they were linked. The results of the model are then given in the next section. Finally, we conclude with a section discussing potential implications of the results and consideration of alternate Moon formation and evolution models.

2. Atmospheric model details

Our atmosphere model is a one dimensional vertically integrated model, solving a system of equations for conservation of mass, momentum and energy. The structure of our model is the atmospheric model described in Ingersoll et al. (1985). This model solves for the atmospheric pressure, temperature and velocity (at the base of the atmosphere) as a function of the angular distance away from the substellar point (the form of the conservation equations used are given in Ingersoll et al., 1985). The equations used for the model are given in the Supplementary Material.

Values in the equations for the mass per atom, m, as well as C_p are taken for the expected dominant constituent in the atmosphere (which in most cases is sodium). The choice for a single constituent atmospheric model is based upon expected vaporization pressures for a Bulk Silicate Earth (BSE) (Miguel et al., 2011). The choice of a BSE composition versus a Lunar Primitive Upper Mantle (LPUM) (Longhi, 2006) or Taylor Whole Moon (TWM) (Taylor, 1982) composition was made in order to remain agnostic about potential mechanisms for moderate volatile loss – in particular to avoid the assumption that all or most of the apparent moderate volatile depletion occurred during formation (particularly given evidence of potential increased CME activity and incidence early in the Sun's history). These vaporization pressures are calculated using the MAGMA code (Fegley and Cameron, 1987; Schaefer and Fegley, 2004), which calculates the equilibrium between the melt and vapor in a magma exposed at temperatures higher than 1000 K for Al, Ca, Fe, K, Mg, Na, O, Si, Ti and their compounds. Vaporization pressures as a function of temperature were fit to the Clausius Clapeyron form. For equilibrium temperatures up to nearly 3500 K, the vapor pressure of the dominant constituent is nearly an order of magnitude greater than the next most significant constituent. This justifies our assumption of a single species atmosphere.

These vapor pressure curves can be used to extract the constants used in our vapor pressure equations. Since sodium was the dominant constituent for most models, we explicitly state any models where there was a different dominant atmospheric constituent. The only case where multiple components were summed was at the point immediately after formation, when SiO was a major component. In this case we summed the partial pressures to find an overall pressures and restricted motion to the slower of the two velocity profiles. To determine dynamic viscosity we used Sutherland's formula. We use the values (see Supplemental Information) listed in Castan and Menou (2011) for the equation (it is important to note that Sutherland's formula is only valid to about 555 K, but simulations we ran show that our results are not highly sensitive to small extrapolated temperature appropriate variations).

The radiative environment of the early Moon controls the surface temperature for the atmospheric model. Inputs for the surface temperature included the radiative contribution of the early Sun, the Earth immediately post-Moon formation impact, and the surface temperature of the Lunar Magma Ocean. The farside temperature and spatially uniform contribution of the Sun's radiation we used corresponded to a solar flux ∼70% of the present day value. The spatially uniform contribution of solar flux is a simplification since the rotation of the Moon would lead to a diurnal cycle. However, given the short rotation timescales for a tidally locked early Moon (∼0.3–0.75 Earth days) and the relatively small relative contribution of the Sun compared to the Earth at the Moon (about an order of magnitude less), such an approximation is a reasonable first order simplification. Given the relative magnitudes of the two fluxes, a diurnally varying Solar flux is unlikely to change the overall atmospheric profiles significantly. It would most likely create a time varying asymmetry in the extent of the atmosphere and wind magnitudes on the two sides of the sub-Earth point.

The contribution of the radiation due to a hot Early Earth is obtained by taking radiating temperature values given in Zahnle et al. (2007, 2015). Moon formation simulations that indicate high outer layer temperatures for the Earth after the collision underpin the prediction of high radiating temperatures for the Earth used in this study. The steep drop in radiating temperature, particularly as the Earth may develop a steam atmosphere, occurs after the time period corresponding to lid formation on the Moon. Earth radiating temperatures (surface temperatures are much higher) used as inputs for the three times the models were output for were 2500, 2450 and 2300 K.

Radiative input from Earth was attenuated as a function of angle of incidence by including a disk approximated angular size of the Earth as observed on the lunar surface. We model the Earth's radiative contribution to the Moon using a lambertian profile used in Castan and Menou (2011) (with a sub-Earth temperature calculated for an albedo of 0.3, which we consider conservative given the low albedo of the similarly hot 55 Cnc e Demory et al., 2016) and extending it to the total Earth illuminated portion of the Moon, which is limited by the effective angular size of the Earth in the Moon's sky. This is done by using this temperature profile for $0 \leq \theta \leq 90$ and mapping that temperature profile to $0 \leq \theta \leq 90 + 0.5\theta_*$, where θ_* is the approximate angular size of the Earth as seen from the sub-Earth point of the Moon and is given by $\theta_* = 2\arctan(R_*/a)$, where a is the Moon's orbital distance. The orbital separation of the early Moon (which is expected to be tidally locked $\leq \sim$100 days) from the Earth is derived from equation 1 of Wasson and Warren (1980) but cases are also tested for slower and faster migration (with similar overall results – see 5.4).

Intuitively, this roughly takes into account the penumbra effect of illumination due to the angular size of the Earth by treating the Earth as a continuum of point sources that consequently illuminate slightly shifted portions of the Earth-side. This is an approximation as it ignores the overlap of illumination between those adjacent points, but it still provides a very similar temperature model to those used in analogous work (Castan and Menou, 2011; Léger et al., 2011) (differences in the illuminated portion of the tests we ran for planets used in those studies are less than half a degree).

Finally, the last input for surface temperature is the top of the LMO temperature. This temperature is conservatively assumed to be liquidus for the evolving magma (ignoring contributions such as radiogenic heating). We use the magma crystallization model in the following section to model the evolution of the magma and the consequent top of the LMO temperature. A rough estimate of the total net heat loss from the Moon over time can be approximated using the change in temperature of the evolving magma summed with the latent heat lost due to crystallization.

There are several details which are not considered in our atmosphere-magma ocean model. All of these have been neglected due to what is either their relatively minimal effect on the bulk surface properties or in order to remain as conservative as possible regarding the radiative inputs to the atmosphere. The atmosphere model neglects the effect of rotation as a first approximation. While Rossby numbers are larger but on the order of unity and rotation may be useful to model in the future, rotation terms are unlikely to effect the qualitative results of the model as it pertains to this study. We do not include absorption or scattering effects of the two atmospheric constituents in the model, Na and