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Transport of water in a transient impact-generated lunar atmosphere

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ABSTRACT

In recent decades, several missions have detected signs of water and other volatiles in cold, permanently shadowed craters near the lunar poles. Observations suggest that some of these volatiles could have been delivered by comet impacts and therefore, understanding the impact delivery mechanism becomes key to explaining the origin and distribution of lunar water. During impact, the constituent ices of a comet nucleus vaporize; a significant part of this vapor remains gravitationally bound to the Moon, transforming the tenuous, collisionless lunar exosphere into a collisionally thick, transient atmosphere. Here, we use numerical simulations to investigate the physical processes governing volatile transport in the transient atmosphere generated after a comet impact, with a focus on how these processes influence the accumulation of water in polar cold traps. It is observed that the transient atmosphere maintains a certain characteristic structure for at least several Earth days after impact, during which time volatile transport occurs primarily through low-altitude winds that sweep over the lunar day-side. Meanwhile, reconvergence of vapor antipodal to the point of impact results in preferential redistribution of water in the vicinity of the antipode. Due to the quantity of vapor that remains gravitationally bound, the atmosphere is sufficiently dense that lower layers are shielded from photodestruction, prolonging the lifetime of water molecules and allowing greater amounts of water to reach cold traps. Short-term ice deposition patterns are markedly non-uniform and the variations that arise in simulated volatile abundance between different cold traps could potentially explain variations that have been observed through remote sensing.

1. Introduction

Over the years, a number of missions have observed signs of water and other volatiles in permanently shadowed craters ('cold traps') near the lunar poles (Feldman et al., 2000; Spudis et al., 2010; Colaprete et al., 2010; Gladstone et al., 2012). Due to the almost perpendicular orientation of the Moon's spin axis relative to the ecliptic, parts of the interiors of these craters have not seen sunlight for billions of years (Arnold, 1979) and have temperatures so low that a variety of volatile compounds, notably water, can remain stable at the surface and shallow sub-surface over geological time scales (Watson et al., 1961; Paige et al., 2010).

Water can reach the lunar surface in several ways; it can be degassed from the lunar interior, generated in situ by solar wind bombardment of the regolith or delivered by impacts of volatile-bearing bodies ranging in size from micrometeoroids to comets (Arnold, 1979; Morgan and Shemansky, 1991). Numerical models (Butler, 1997; Crider and Vondrak, 2000, 2002) suggest that some of the water supplied by these sources can subsequently migrate to polar cold traps. Several groups, most recently Miller et al. (2014), Zuber et al. (2012) and Neish et al. (2011), have used remote sensing data to derive constraints on the abundance and distribution of cold-trapped volatiles, but significant uncertainties remain regarding the nature and amount of water present. In this context, understanding source and delivery mechanisms becomes key to interpreting observations and to understanding the lunar volatile inventory.

Comet impacts are a delivery mechanism of particular interest. The LCROSS mission led to the detection of not only H_2O, but also CH_4, NH_3 and other compounds commonly found in comets, at the Cabeus cold trap (Colaprete et al., 2010). More recently, Miller et al. (2014) revisited neutron spectroscopy data from the Lunar Prospector mission and identified isolated sub-surface hydrogen signatures at some cold traps – the absence of a corresponding surficial signature suggesting delivery of the detected hydrogen (possibly water) by some ancient, episodic source. Lastly, it has been observed that water ice, if present, appears to be heterogeneously

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distributed between cold traps, with some regions of permanent shadow lacking signs of water (Mitrofanov et al., 2010; Gladstone et al., 2012). These differences could partly be due to local variations in topography and thermal history (Siegler et al., 2011; Schorghofer and Taylor, 2007), but it could also be the case that certain delivery mechanisms, such as comet impacts, distribute volatiles non-uniformly between cold traps, further contributing to the heterogeneity of the signatures observed. Other delivery mechanisms, such as the cold-trapping of solar wind-generated volatiles, rely on collisionless migration of molecules to the poles, which should lead to uniform filling of cold traps, since the average ballistic hop distance is larger than typical cold trap dimensions (Watson et al., 1961).

Modeling comets as a source of lunar water is a complex problem. During impact, a cometary nucleus is subject to extreme pressures and temperatures, more than sufficient to completely vaporize constituent ices (Pierazzo and Melosh, 2000). Much of this vapor escapes lunar gravity within seconds, but a significant part remains gravitationally bound and can linger for months (Stewart et al., 2011) in the form of a transient atmosphere. The primary challenge in modeling this atmosphere lies in the fact that the sheer quantity of volatiles delivered by a comet impact significantly changes the way in which volatile transport takes place. Usually, the Moon's surface-bound exosphere is so tenuous, with surface densities $O(10^{10})$ molecules/m^3, that molecules rarely encounter each other, and can be assumed to migrate across the lunar surface through collisionless, ballistic hops (Stern, 1999; Cook et al., 2013). However, after a large-scale impact, the atmosphere can become sufficiently dense that gas dynamic processes are governed by collisions between molecules – these interactions are then no longer negligible. Moreover, in a sufficiently dense atmosphere, water vapor may be partially shielded from photodestruction (Arnold, 1979), the primary loss process. Shielding and other physical processes that become important in an impact-generated atmosphere – such as photochemical reactions (Berezhnoi and Klumov, 2000) and radiative heat transfer – can play a key role in determining the abundance and distribution of cold-trapped species.

Several prior investigations have focused on transport of volatiles in the collisionless limit – a valid approximation when the source of volatiles does not alter the tenuous nature of the lunar exosphere. For instance, Butler (1997) and Crider and Vondrak (2000, 2002) have used Monte Carlo methods to model the transport of solar wind-generated hydrogen and water to polar cold traps, tracking the migration of molecules from a globally distributed surficial source, through collisionless hops, until capture or photodestruction. Considering volatile-rich impacts as another source, Berezhnoi and Klumov (1998) estimated the amount of water that could be delivered by a comet to polar cold traps, based on an analytical approximation of how much impact-generated vapor would remain gravitationally bound given comet size, density and impact velocity. More recently, Ong et al. (2010) addressed this question in greater detail, using hydrocode simulations to study the dependence of volatile retention on impact velocity by tracking the fraction of non-escaping projectile material for a series of vertical impacts at different velocities. Determining the gravitationally bound fraction of impact-generated vapor under various impact parameters is an important step toward understanding the cometary contribution to the lunar volatile inventory, but how and how much of the gravitationally bound vapor ultimately reaches a cold trap is determined by the loss rate and gas dynamics of volatile transport in a collisionally thick, temporally evolving atmosphere.

Most previous studies have not explicitly addressed the qualitatively different nature of volatile transport in an impact-generated atmosphere. Berezhnoi and Klumov (1998) estimated that almost all gravitationally bound vapor would condense into cold traps, while Ong et al. (2010) applied the result of Butler (1997) to project that 20% of the gravitationally bound vapor would migrate to cold traps. Both of these approaches assumed diffusive transport of water vapor and neglected any shielding of lower layers of the atmosphere from photodestruction. Stewart et al. (2011) developed the approach adopted in this work and used the SOVA hydrocode and the Direct Simulation Monte Carlo (DSMC) method to simulate an oblique comet impact and to track the deposition of impact-generated water vapor in cold traps over the course of months (i.e. several lunar days). The hybrid SOVA–DSMC method accounts for the collisional character of the transient atmosphere and, although some simplifications were introduced, Stewart et al.'s (2011) work represents the most detailed treatment of post-impact gas dynamics to date.

The primary objective of Stewart et al. (2011) was to determine how much water from the simulated comet impact was transported to polar cold traps. Here, we focus on understanding post-impact volatile transport processes in more depth – characterizing the structure of the transient atmosphere generated by a large-scale impact on an otherwise virtually airless body and analyzing the implications of such an atmosphere for the transport and deposition of water at lunar cold traps. The Stewart et al. (2011) code has been modified to account for additional physical processes of significance; specifically, radiative cooling of water vapor and shielding of lower layers of the atmosphere from dissociating ultraviolet radiation.

In the sections that follow, we describe the numerical method used and then discuss results obtained for the evolution of a transient, impact-generated lunar atmosphere over the course of several Earth days after impact, focusing on characteristic atmospheric structures, their influence on the transport and deposition of water, and relation to remote sensing observations.

2. Numerical method

Stewart et al. (2011) provide a detailed description of the numerical method used in this work. Here, we briefly review the method and then discuss modifications that have been made to the physical model in order to simulate post-impact gas dynamics more accurately. We retain the hybrid SOVA–DSMC approach of Stewart et al. (2011), reviewed below.

To start with, the SOVA hydrocode (Shuvalov, 1999) is used to simulate the immediate physics of a comet impact: the phase changes that occur in both target and projectile due to the passage of successive compression and rarefaction waves, and the resultant hydrodynamic flow of molten and vaporized target and projectile material. The simulations discussed here consider a comet that impacts the Moon at 30 km/s and at an angle of 60° (measured from the horizontal). The lunar surface is assigned the material properties of dunite, and the comet is modeled as a sphere of pure water ice, 2 km in diameter.

Hydrocodes use a continuum description of material behavior, which is accurate when modeling the initially dense plume of impact-generated vapor. However, as the plume expands into a near vacuum background, it undergoes rapid rarefaction and transitions from a dense, continuum regime close to the point of impact to collisionless at the outermost fringes of the expanding cloud. Due to the ultimately non-continuum behavior of the impact-generated vapor, the SOVA simulations are limited to a hemispherical domain extending out to 20 km from the point of impact. Subsequent modeling of impact-generated water vapor is carried out using the Direct Simulation Monte Carlo (DSMC) method (Bird, 1994). Although the impact-generated plume consists of both water vapor and vaporized or molten rock, in this