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Volatile retention from cometary impacts on the Moon

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ABSTRACT

Impacts of comets and asteroids play an important role in volatile delivery on the Moon. We use a novel method for tracking vapor masses that reach escape velocity in hydrocode simulations of cometary impacts to explore the effects of volatile retention. We model impacts on the Moon to find the mass of vapor plume gravitationally trapped on the Moon as a function of impact velocity. We apply this result to the impactor velocity distribution and find that the total impactor mass retained on the Moon is approximately 6.5% of the impactor mass flux. Making reasonable assumptions about water content of comets and the comet size–frequency distribution, we derive a water flux for the Moon. After accounting for migration and stability of water ice at the poles, we estimate a total 1.3×10^8–4.3×10^9 metric tons of water is delivered to the Moon and remains stable at the poles over 1 Ga. A factor of 30 uncertainty in the estimated cometary impact flux is primarily responsible for this large range of values. The calculated mass of water is sufficient to account for the neutron fluxes poleward of 75° observed by Lunar Prospector. A similar analysis for water delivery to the Moon via asteroid impacts shows that asteroids provide six times more water mass via impacts than comets.

1. Introduction

Spectroscopic observations of the lunar surface by the Chandrayaan-1, Cassini, and Deep Impact spacecraft show unequivocally that water ice or hydroxyl is present on the surface of the Moon (Pieters et al., 2009; Clark, 2009; Sunshine et al., 2009), but the existence of buried water ice at the poles remains controversial. The presence of water on the Moon was first posited in the early stages of lunar exploration and was predicted to lie within the permanently shadowed regions at the lunar poles (e.g. Watson et al., 1961). However, the 3.0 μm hydration feature observed independently by Pieters et al. (2009), Clark (2009), and Sunshine et al. (2009) was found at a range of latitudes and within sunlit regions. Because the hydration feature is associated with the top few millimeters of the lunar surface, Pieters et al. (2009) favor surficial formation mechanisms for the water ice or hydroxyl.

In contrast to the hydration feature observed on the lunar surface, high counts of fast and epithermal neutrons measured by Lunar Prospector sample hydrogen buried up to 1 m at the lunar poles (Feldman et al., 2001). These fluxes, elevated at the poles relative to the equator, indicate abundances of hydrogen within the top 10 g cm^{-2} of the lunar regolith (Feldman et al., 2000). Although the Lunar Prospector data was taken at low spatial resolution, pix-on image reconstruction of devolved Lunar Prospector data shows the hydrogen signature is localized in the permanently shadowed regions at the lunar poles (Eke et al., 2009).

Many emplacement mechanisms have been hypothesized for the Lunar Prospector hydrogen signatures and the spectroscopic hydration feature, including: reaction of solar hydrogen released in solar flares (Crider and Vondrak, 2000), reaction of solar wind protons with oxygen-bearing minerals in the lunar regolith (Pieters et al., 2009; Sunshine et al., 2009; Clark, 2009), and recent impact of a comet or asteroid onto the lunar surface (Shevchenko, 1999; Klumov and Berezhnoi, 2002; Pieters et al., 2009; Clark, 2009). Cocks et al. (2002) show that water adsorbed in the lunar regolith can shelter a modest reservoir. A surficial solar wind reaction mechanism is favored for the formation of the global hydration feature, but this model for water and hydroxyl formation has not been quantified. Feldman et al. (2000, 2001) argue that the large, more deeply buried hydrogen abundances responsible for the neutron fluxes observed at the poles are higher than the supply of hydrogen from solar wind and conclude that water ice is responsible for the neutron fluxes observed. Based on assumptions about the depth of burial of the frozen water and the area of the permanently shadowed regions, Feldman et al. (2000, 2001) estimate a maximum $2.1 \pm 1.3 \times 10^9$ metric tons of water ice at both poles.

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In this paper, we test the hypothesis that comets deliver water ice to the Moon and supply enough hydrogen to the lunar poles to account for the Lunar Prospector neutron flux measurements. We model the fractional mass of cometary material that remains gravitationally trapped on the Moon during and after impact. We apply this velocity-dependent function to the velocity distribution of comets impacting the Moon inferred from observations of cometary orbits, and integrate over an extrapolated impact flux. This gives us the total mass of water delivered to the Moon over a 1 Ga period, the timescale over which ice is stable against impact gardening at a depth of 1 m at the lunar poles (Crider and Vondrak, 2003). We conclude that approximately 6.5% of the total cometary impactor mass becomes gravitationally trapped on the Moon during impact integrated over all expected impactor masses and velocities. We compare our water fluxes to estimates of water ice at the poles from Lunar Prospector hydrogen abundances, for which cometary and asteroidal origins are favored. Uncertainty in our estimate of water delivered is largely due to diverse estimates for the comet impact flux; for nominal values we find that cometary impacts deliver enough water to account for the mass of hydrogen observed by Lunar Prospector. We end with a discussion of the effects of oblique impacts and porosity to water retention rates, and an estimate of asteroidal contributions to water on the Moon.

2. Analytical models and benchmarks

Volatile retention during comet impacts has been investigated both numerically, using computer hydrocodes, and analytically in a number of studies.

2.1. Analytical model of an expanding hemispherical vapor plume

The gravitational retention of volatiles during and after an impact is modeled analytically as a sudden expansion of an ideal gas vapor cloud into a vacuum (Zel'dovich and Raizer, 1966). This analytical technique is commonly applied to impact vapor plumes without consideration of complicated plume geometries or complex equations of state (e.g. Melosh, 1989; Vickery and Melosh, 1990; Zahnle, 1990; Moses et al., 1999). In this study, we test the analytical approximation detailed in Moses et al. (1999) against our numerical simulations, which produce non-hemispherical plume geometries and which use an accurate equation of state for water. We use the Moses et al. (1999) model as a fiducial benchmark for our hydrocode impact simulation results.

In estimating water delivery to Mercury by comets, asteroids, and interplanetary dust particles, Moses et al. (1999) develop the approximation of an expanding hemispherical vapor plume for the case of an impact induced vapor plume on a terrestrial body. They assume the vapor plume is an ideal gas mixture of projectile and target material with an initial uniform density ϱ_0, uniform pressure p_0, and with a hemispherical volume defined by an initial radius R_0. The plume is initially at rest, and at time $t = 0$ the cloud begins expanding into the vacuum. When the radius R is much larger than R_0, the velocity of the flow becomes linearly dependent on radius within the plume and the plume is assumed to be well-mixed (Zel'dovich and Raizer, 1966). The maximum velocity of the plume is:

$$u_{max} = \frac{2}{\gamma - 1}[\gamma(\gamma - 1)\varepsilon_0]^{\frac{1}{2}} \quad (1)$$

where ε_0 is the internal energy per unit mass of the plume and γ, the adiabatic index, is the ratio of the specific heats of the gas (Moses et al., 1999).

The density of the expanding plume does not have a unique solution, but using symmetry arguments and the solution to the analytically solvable one-dimensional problem, Zel'dovich and Raizer (1966) and Moses et al. (1999) among others (e.g. Vickery and Melosh, 1990; Zahnle, 1990) assume the following density distribution for the three-dimensional plume:

$$\varrho(r) = \frac{AM_{tot}}{R^3}\left(1 - \frac{r^2}{R^2}\right)^{\alpha}, \quad \alpha = \frac{5 + \gamma}{2(\gamma - 1)} \quad (2)$$

where $R(t)$ is the radius of the plume $R = u_{max}t$, and A is a dimensionless constant defined such that the density function multiplied by the volume of the plume and integrated over all radii equals the total mass of the plume. The density equation is more easily integrated when α is an integer, and $\gamma = 9/7$ has been used as a reasonable value for high-velocity impacts into silicates (Melosh and Vickery, 1989; Zahnle, 1990; Moses et al., 1999) and is close to the adiabatic index of H_2O at high temperature. Using $\gamma = 9/7$, the exponent α equals 11, and the constant $A = 15.39$.

The total mass of the impactor that remains gravitationally bound to the planet is then:

$$M_{v<v_{esc}} = \frac{AM_{tot}}{R^3}\int_0^{r_{esc}}\left(1 - \frac{r^2}{R^2}\right)^{\alpha} 2\pi r^2\, dr \quad (3)$$

(Moses et al., 1999). This is integrated from $r = 0$ to r_{esc}, which is the radius within the plume at which the material in the plume is moving faster than escape velocity. Thus $r_{esc} = Rv_{esc}/u_{max}$, where v_{esc} is the escape velocity of the planet. The integral describing the gravitational mass retained is simplified and restated as the fractional mass of the impactor that remains bound to the planet after impact:

$$\frac{M_{v<v_{esc}}}{M_{tot}} = 2\pi A\int_0^{q'}\left(1 - q^2\right)^{\alpha} q^2\, dq \quad (4)$$

when $q = r/R$ and $q' = v_{esc}/u_{max}$.

The internal energy of the vapor plume is dependent on the latent energies of the target and projectile materials, the partitioning of the impact energy into internal and kinetic energies of the projectile and target, and the fraction of the vapor plume that is composed of projectile and target materials. The analytical model assumes the resultant plume is well-mixed and composed of equal parts of target and projectile by mass (Melosh, 1989; Moses et al., 1999). The energy partitioning, and therefore the internal energy of the plume, is also strongly dependent on impact angle, although these relationships are not well understood. Although we only model impacts at normal incidence, in the discussion of the effects of impact angle we assume a $\sin^2\theta$ dependence on angle, where θ is the impact angle measured from the horizontal (Vickery and Melosh, 1990). The internal energy of the plume is

$$\varepsilon_0 = 0.139 v_i^2 \sin^2\theta - \frac{1}{2}(L_{target} + L_{proj}) \quad (5)$$

where the factor of 0.139 reflects the impedance mismatch between the solid ice projectile and the silicate target (Vickery and Melosh, 1990). We model the comets as solid ice spheres, so $L_{proj} = L_{ice} = 3000$ kJ kg^{-1} and $L_{target} = L_{basalt} = 1300$ kJ kg^{-1}. Note that the analytical model assumes a simple equation of state and constant molecular mass.

2.2. Tracking volatile retention in hydrocode models with tracer particles

Lagrangian tracer particles are commonly used in Eulerian hydrocode models of impacts to track the movement of target, projectile, and atmospheric masses. Pierazzo and Chyba (2002) model comet impacts on Europa, whose surface gravity is about 20% less than that of the Moon, and estimate the fractional cometary mass