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Asteroidal impacts and the origin of terrestrial and lunar volatiles

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ABSTRACT

Asteroids impacting the Earth partly volatilize, partly melt (O'Keefe, J.D., Ahrens, T.J. [1977]. Proc. Lunar Sci. Conf. 8, 3357–3374). While metal rapidly segregates out of the melt and sinks into the core, the vaporized material orbits the Earth and eventually rains back onto its surface. The content of the mantle in siderophile elements and their chondritic relative abundances hence is accounted for, not by the impactors themselves, as in the original late-veneer model (Chou, C.L. [1978]. Proc. Lunar Sci. Conf. 9, 219–230; Morgan, J.W. et al. [1981]. Tectonophysics 75, 47–67), but by the vapor resulting from impacts. The impactor's non-siderophile volatiles, notably hydrogen, are added to the mantle and hydrosphere. The addition of late veneer may have lasted for 130 Ma after isolation of the Solar System and probably longer, i.e., well beyond the giant lunar impact. Constraints from the stable isotopes of oxygen and other elements suggest that, contrary to evidence from highly siderophile elements, ~4% of CI chondrites accreted to the Earth. The amount of water added in this way during the waning stages of accretion, and now dissolved in the deep mantle or used to oxidize Fe in the mantle and the core, may correspond to 10–25 times the mass of the present-day ocean. The Moon is at least 100 times more depleted than the Earth in volatile elements with the exception of some isolated domains, such as the mantle source of 74220 pyroclastic glasses, which appear to contain significantly higher concentrations of water and other volatiles.

1. Introduction

It is widely accepted that the Earth is severely depleted in volatile elements with respect to the Sun and carbonaceous chondrites (Anders and Owen, 1977; Palme and O'Neill, 2005). The trend between volatility and depletion is particularly robust for the most typical lithophile elements such as K, Rb, Cl, and Zn. Depletion of volatile elements in the Moon is even stronger (Ganapathy and Anders, 1974), as attested to by the deficit of K and Pb with respect to refractory U, which poses a problem when taking into account recent observations that the lunar mantle contains higher-than-expected amounts of other volatile components, such as water (Hauri et al., 2011; Saal et al., 2008).

There is growing consensus that the Earth accreted in the inner Solar System where temperatures were too high for volatile elements to condense, implying that any volatiles now present in the Earth were delivered subsequently during later stages of terrestrial accretion (Owen and Bar-Nun, 1995). Addition of volatiles from the outer Solar System carried by debris of undifferentiated planetesimals, the so-called late veneer, during the clearing stages of the debris disk, is consistent with current understanding of accretion dynamics (Albarède, 2009; Morbidelli et al., 2000; Robert, 2001). There is, however, no consensus on whether late veneer addition is sufficient to account for the terrestrial abundances of volatile elements (Albarède, 2009; Chou, 1978; Halliday, 2008; Hirschmann and Dasgupta, 2009; Marty and Yokochi, 2006).

How the fraction of a percent of carbonaceous CI chondrites originally deemed to account not only for highly siderophile elements (Chou, 1978) but also possibly for the amount of volatiles in the Earth (Javoy, 1998; Marty and Yokochi, 2006) can be reconciled with evidence from other isotopic systems, which push this proportion to several percent (Lodders, 2000) and even higher (Fitoussi and Bourdon, 2012; Warren, 2011), is unclear. The high end of these estimates corresponds to an amount of volatile-rich material intermediate between the masses of the Moon and Mars. The present work focuses on the process by which water and volatiles

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may have been added to the Earth and the Moon, on how much water and volatiles are still present and in which form, and on the timing and duration of the late veneer stage of accretion.

2. The role of vaporization in establishing planetary inventories

Historically, the concept of late veneer was introduced to resolve conflicting evidence between experiments predicting that highly siderophile elements (HSEs) and, among them, the platinum-group elements (PGEs), should be taken up entirely by the metal phase upon core segregation from the mantle, and the detectable abundances of PGEs and their chondritic relative distribution in the modern mantle (Chou, 1978; Jagoutz, 1979; Morgan et al., 1981). More recently it has become increasingly apparent from the high values of experimental metal/silicate partition coefficients of HSE that their concentrations in the terrestrial mantle cannot have been established by metal/silicate equilibrium, whether metal was emulsified or not (Murthy, 1991, see also Mann et al. (2012) and Walker (2009) and references therein). The excess HSE correspond to 0.4–0.7% of chondritic material, which must have been added sufficiently late in Earth's accretionary history to prevent it from equilibrating with the core.

This estimate of the late veneer proportion, however, neglects both vaporization and metal segregation during impact and therefore underestimates the amount of material added (Fig. 1). The minimum kinetic energy of material impacting the Earth is scaled by the escape velocity (11.2 km s^{-1} = 62.7 MJ kg^{-1}) (Melosh, 1989). For a radial component of impact velocity of 15 km s^{-1} (Chyba, 1991), the liberated energy largely surpasses the vaporization enthalpy of olivine ($\sim$3 MJ kg^{-1} (Ahrens and O'Keefe, 1972)). The energy of the impact is dissipated by shock waves in both the target and the projectile but the distribution of the energy released conditions the fate of the material (O'Keefe and Ahrens, 1977; Tonks and Melosh, 1993). For a random distribution of asteroid velocities, collision is expected to be oblique with a most probable angle of impact of 45° (Pierazzo and Melosh, 2000b). Oblique impacts generate a jet of high-speed, dense, hot vapor (Melosh and Sonett, 1986). Schultz (1996) demonstrated that, because of the friction from high shear stresses developing upon oblique impact, the amount of material vaporized increases when the angle of impact decreases with a maximum at 30°. In an oblique impact, the projectile itself is partly vaporized, partly molten (Pierazzo and Melosh, 2000a). Overall, it may be expected that about 10% of the impactor, even for small objects down to 5 km in size, is volatilized during the original impact (Canup, 2004; Pierazzo and Melosh, 2000a). Part of the vapor produced immediately condenses upon decompression and rains back onto the Earth, while the rest escapes into orbit under the combined effects of pressure gradient and exchange of angular momentum within the different layers of the jet (Stevenson, 1987). To draw an analogy with lunar impact models, the time scale for radiative cooling of the proto-lunar disk is 10^2–10^3 years (Pahlevan and Stevenson, 2007). Meanwhile, the trajectories of the orbiting condensates evolve by momentum exchange, with some material migrating beyond the Roche limit (2.9 times the Earth radius) where it accretes to the Moon, whereas most of the remaining material falls back onto Earth (Canup and Esposito, 1995; Takeda and Ida, 2001).

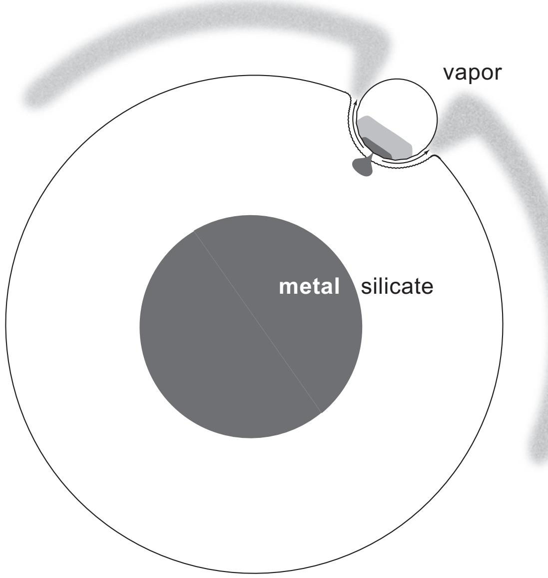

Fig. 1. Impact between a late-veneer asteroid and Earth. The high impact velocity, which must exceed Earth's escape velocity (11 km s^{-1}), liberates enough energy for the impactor and part of the terrestrial mantle to melt and for a fraction of the material to vaporize. Metal (black) separates from the silicate (dark gray) and sinks into the core, while the vapor orbits the Earth until it cools and falls out, thereby modifying the composition of the terrestrial mantle and crust.

A consequence of a high-velocity impact therefore is that the impactor is partly vaporized, with most of the vapor raining back down onto the Earth's surface and further into the terrestrial mantle. Vaporization of the terrestrial mantle itself at the contact with the impactor does not affect terrestrial inventories. If the incoming asteroid is undifferentiated, the impact indiscriminately adds siderophile, lithophile, and volatile elements from the impactor. It has been argued, however, that the heat released by the decay of ^{26}Al and by repeated collisions will lead quickly to the differentiation of most impactors larger than $\sim$30 km (Ricard et al., 2009; Yoshino et al., 2003). Canup's (2004) simulations addressed such a case for the Moon-forming event. It was found that the impactor's core, present as an arm sheared past the target, re-coalesces and re-impacts the planet. To a large extent this new impact is equivalent to downrange ricocheting, which Schultz et al. (2006) demonstrated significantly contributes to the overall vaporization of the impactor.

Meanwhile, the non-vaporized part of the impactor undergoes extensive melting and, if the core is not already differentiated, iron segregates from the silicate. In order to explain the ^{182}Hf–^{182}W observations of the Earth–Moon system, it has been argued that equilibration of the terrestrial mantle with metal from the impactor is incomplete (Dahl and Stevenson, 2010; Kleine et al., 2009; Rudge et al., 2010; Schönbächler et al., 2010). Dahl and Stevenson (2010) ascribed limited exchange to multiple causes: (1) a 'hidden reservoir' effect, which accounts for the lack of contact of the metal with the far side and the solid deep mantle; (2) channeling of coalescing metal diapirs (Golabek et al., 2008); and (3) a 'core crash' effect which reflects the impactor's metal plunging directly through the Earth's mantle into the core as seen in simulations (Canup and Asphaug, 2001).

Whether the impacting asteroids are differentiated or not, decoupling between sinking metal and vapor rain on the planetary surface is expected. Any non-vaporized HSE sink into the terrestrial core and do not show up in the modern mantle inventory. Consequently, since the temperatures reached after impact are high enough to achieve the volatilization of large amounts of material (Canup, 2004; Pahlevan and Stevenson, 2007), HSE abundances in the BSE do not reflect the true proportion of late veneer but mostly its vaporized fraction as condensed in the wake of the impact.

The escape velocity being much smaller on the Moon (2.4 km s^{-1} = 2.9 MJ kg^{-1}) than on Earth (11 km s^{-1}), a much smaller fraction of impactors should hit the Moon at velocities significantly less than that of elastic waves (9 km s^{-1}). A substantial part of the energy released by the impact therefore is allowed to