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Geochimica et Cosmochimica Acta 173 (2016) 50–63

Geochimica et Cosmochimica Acta

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# Silicate impact-vapor condensate on the Moon: Theoretical estimates versus geochemical data

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Received 26 February 2015; accepted in revised form 9 October 2015; available online 27 October 2015

**Abstract**

We numerically simulated the impacts of asteroids and comets on the Moon in order to calculate the amount of condensate that can be formed after the impacts and compare the results with data for lunar samples. Using available equations of state for quartz and dunite, we have determined pressure and density behind shock waves in these materials for particle velocities from 4 to 20 km/s and obtained release adiabats from various points on the Hugoniot curves to very low pressures. For shock waves with particle velocities behind the front below 8 km/s the release adiabats intersect the liquid branch of the two-phase curve and, during the following expansion, the liquid material vaporizes and does not condense, forming a two-phase mixture of melt and vapor. The condensate can appear during expansion of material compressed by a shock with higher (>8 km/s) velocities. Using our hydrocode SOVA, we have conducted numerical simulations of the impacts of spherical quartz, dunite, and water–ice projectiles into targets of the same materials. Impact velocities were 15–25 km/s for stony projectiles and 20–70 km/s for icy impactors, and impact angles were 45°and 90° to the target surface. Along with the masses of condensates we calculated the masses of vaporized and melted material. Upon the impact of a projectile consisting of dunite into a target of quartz at a speed of 20 km/s at an angle of 45°, vaporized and melted masses of the target are equal to 1.6 and 11 in units of projectile mass, respectively, and the mass of condensate is 0.19. Vaporized and condensed masses of the projectile are 0.16 and 0.02, more than 80% of the projectile mass is melted. The calculated ratio of vaporized to melted mass proved to be on the order of 0.1. However, we calculated that, at impact velocities below 20 km/s, the condensate mass is only a small fraction of the vaporized and melted masses and, consequently, the major part of vapor disperses in vacuum in the form of separate molecules or molecular clusters. At an impact velocity of 15 km/s, the abundance of silicate condensates relative to melt is 0.001–0.0001, in agreement with data from lunar samples. Should the observed condensate abundances be representative, the velocities of major asteroid impacts on the Moon could not substantially exceed 20 km/s. Comet impacts at the same velocities produce much smaller amounts of vapor condensate because the low densities of cometary material induce lower shock pressures in the target.


## 1. INTRODUCTION

A high-speed impact of an asteroid or a comet on the Moon can vaporize a mass of target rocks comparable to the mass of the projectile. After such an impact, the vapor expands, forming a vapor plume, and, when it cools and reaches the liquid–vapor coexistence curve, liquid spherules can condense from the vapor. Ejecta layers bearing condensate spherules have been found on the Earth along with melt droplet spherules (Johnson and Melosh, 2012a,b), but impact-vapor condensate is extremely rare among the lunar samples (Warren, 2008). The current average impact velocities on the Moon and Earth differ only slightly (Ivanov, 2008), and the main distinction between the

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http://dx.doi.org/10.1016/j.gca.2015.10.019
0016-7037/

impacts on these objects is probably that the vapor plume expands into the atmosphere on the Earth and into vacuum on the Moon.

Studies of lunar samples have shown presence of high-alumina silica-poor spheroids termed HASP (Naney et al., 1976). It is most likely that this type of material, found in many Apollo lunar soils and breccias, formed as a result of impact-induced vaporization (Delano et al., 1981; Keller and McKay, 1992; Papike et al., 1997). Investigation of a sample 14076 from Apollo 14 (Warren, 2008) has shown that the regolith breccia contains, along with HASP material of evaporation-residue origin, a small amount of complementary condensates, named GASP (gas-associated spheroidal precipitates). Images of HASP and GASP sheroids are shown in the papers by Warren et al. (2005) and Warren (2008). $SiO_2$-rich GASP material is depleted in the same refractory major oxides ($Al_2O_3$ and CaO) that are in excess in HASP. GASP was found to be in two forms: as glassy or fine grained, quenched-melt spheroids, less than 5 μm across, and as quenched, textured clasts up to 200 μm in size. GASP spheroids and clasts are composed mainly of $SiO_2 + MgO + FeO$, however, they are highly diverse in the ratios of these constituents. Compositionally the spheroids vary from a nearly pure $SiO_2$ (termed SiGASP) to a type rich in FeO (FeGASP) (Warren, 2008).

The composition of GASP is incompatible with both igneous and impact-melt origins, and, as has been shown by Warren (2008), GASP undoubtedly originated from liquid-condensate droplets. Submicrometer-sized spheroidal condensates, about an order of magnitude smaller in diameter than the GASP spherules, had been detected in lunar soil (an Apollo 16 sample) earlier by Keller and McKay (1992). This type of material was called VRAP (volatile-rich, alumina-poor) because of high concentrations of $K_2O$ and $Na_2O$. VRAP can be considered as a smaller equivalent of GASP. Nanometer-scale particles probably of condensation origin have been also found in the Apollo 15 and 17 samples (Yakovlev et al., 2008). The distinctive composition of GASP and VRAP permits them to be easily identified; but most lunar samples contain very little of this material.

Warren et al. (2008) estimated from lunar sample observations that lunar condensate constitutes less than 0.0001 of the megaregolith. Assuming, following Warren et al. (2008), that approximately half of the lunar megaregolith, by mass, consists of impact-melt breccia, within which slightly more than half represents impact melt, we obtain that the condensate is less than 0.0004 times as abundant as melted material. The scarcity of VRAP and GASP spherules is a mystery, because impact-melt breccia is a typical component of the lunar crust and regolith, and current impact velocities on the Moon, with an average value 17.5 km/s (Ivanov, 2008), seem to be sufficient to vaporize an appreciable amount of lunar material in comparison to melt. Assuming that the impacts generally produce vapor along with melt in a roughly 1:9 mass ratio, Warren (2008) and Warren et al. (2008) considered this discrepancy as an enigmatic characteristic of the sampled lunar regolith (a lunar impact-vapor paradox). The observed abundance of lunar condensate appears to be lower by at least 2 orders of magnitude than predicted on the basis of the calculated amount of produced vapor.

The mass of impact vapor has been calculated in several works we review below. Hydrodynamic simulations of impacts (gabbroic anorthosite objects into a gabbroic anorthosite target) by O'Keefe and Ahrens (1977a, 1982) gave a mass ratio of vapor to melt about 1/10 only for impact velocities greater or equal to 30 km/s. The vaporized mass decreased steeply at lower velocities and at 15 km/s was negligible or not resolved in simulations. O'Keefe and Ahrens used Tillotson's equation of state (Tillotson, 1962) for gabbroic anorthosite which is not quite correct at phase transitions (Melosh, 1989).

Pierazzo and Melosh (1999) calculated the vapor and melt masses in simulations of the Chicxulub impact event, assuming that the target consists of a 100 m deep shallow sea, a 2.9-km thick sedimentary layer (calcite), and a 30-km thick continental crust (granite). They used the SESAME (1983) equations of state for calcite and granite and the ANEOS equation of state (Thompson and Lauson, 1972) for water. After the impact of a 10-km-diameter dunite spherical body at 20 km/s, the mass ratio of crustal vapor to melt was found to be about 0.04 for a vertical impact and about 0.02 for an impact angle of 45°.

In numerical simulations of the Ries crater's formation (Pierazzo et al., 2001), it was assumed that a stony (dunite) projectile 1.6 km in diameter struck the Earth's surface at 15 km/s and at an angle of 45° from the surface. The target consisted of a 600 m thick sedimentary layer (30 m of quartzite, 150 m of calcite, and 420 m of quartzite) and a granitic crystalline basement. Using ANEOS equations of state, the authors found that the mass ratio of vaporized quartzite to completely melted quartzite was about 0.3 for the upper layer and about 0.1 for the lower layer.

Another numerical simulation of the Chicxulub impact event (Artemieva and Morgan, 2009) assumed a layer of calcite 3 km thick, 30 km of crystalline granitic basement, and a dunite mantle. A ratio of vaporized to melted volume of the granitic basement was found to be about 0.1 for 18 km/s impacts at angles of 45° and 90°, and around 0.05 for a 36 km/s impact at 45°. Notice that the updated version of the ANEOS equation of state (Melosh, 2007), which takes a liquid/vapor phase transition, molecular clusters in the vapor, and a high-pressure phase transformation into account, gives bigger masses of vapor for a given shock compression than the previous versions. This suggests that the vapor production in preceding works, including (Artemieva and Morgan, 2009), was underestimated, probably by a factor of two (Artemieva et al., 2013).

Except for the works of O'Keefe and Ahrens (1977a, 1982), who used Tillotson's equation of state, inappropriate for vaporization, the calculated ratio of impact vapor to melt after impacts at 15–20 km/s (0.02–0.3) exceeded the proportion of GASP-like material observed within the lunar highland regolith by two orders of magnitude. Several explanations were suggested. First, condensation of the vapor plume may be inefficient or, as Warren et al. (2008) cautioned, the inventory of condensates in 14076 may be unrepresentative and/or incomplete. Most lunar condensate