ENTROPY GAIN FOR SHOCK-HEATED FORSTERITE: IMPLICATIONS FOR ATMOSPHERIC BLOW-OFF ON THE EARLY EARTH AND VENUS

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Introduction: Impact-induced silicate vapor clouds should play important roles in a number of geologic events [e.g., 1-4]. In this study, we focus on atmospheric blow-off due to an expanding silicate vapor plume on rocky planets.

The physical consequence of atmospheric blow-off is as follows. When hypervelocity impacts occur, impactor and target surfaces suffer from intense irreversible heating, i.e., $dE = u_p^2/2 \sim v_{impact}^2/8$. Then, shock-heated materials including both impactor and target surfaces expand into ambient atmosphere along with isentrope. When the shock-heated materials reach the liquid-vapor phase boundary, a phase separation from a super critical fluid to the mixture of gas and melt droplets occurs. Internal energy of the silicate vapor is converted to the kinetic energy, that is, the expansion energy during isentropic release. The expanding silicate vapor accelerate an ambient atmosphere via momentum transfer. A part of accelerated atmosphere with higher velocities than the escape velocity of the host planet escapes into the space. Hence, the quantification of the amount of silicate vapor and its expansion energy are essential to discuss the atmospheric evolution of rocky planets. However, although there are a number of analytical [e.g., 4] and numerical studies [e.g., 5] for atmospheric blow-off, large ambiguities in the estimation of the amount of escaped atmosphere still remain. This is probably because the reliable Hugoniot curves of silicates on an entropy-pressure (*S-P*) plane at >10 km/s impacts have not been obtained and, as a result, the shock-induced entropy, which controls both the amount of silicate vapor and the final expansion energy, is quite uncertain.

In this study, we investigated the *S-P* Hugoniot curve of forsterite up to 800 GPa using the laser shock technique [e.g., 6]. Then, the results were applied to the atmospheric blow-off on the early Earth.

Laser shock experiments: We carried out laser shock experiments at GEKKO XII-HIPER facility of Institute of Laser Engineering of Osaka University.

The experimental condition and procedure are basically the same as our previous studies [7, 8]. Targets have three layers: 20 μm of plastic ablator, 40μm of Al plate, and 50 μm of forsterite (Mg_2SiO_4). A velocity interfelrometer, VISAR, was newly used with the streaked spectrometer used in our previous studies. The optical signal from the shock front in the targets could be observed from the rear surface of the forsterite samples because it is transparent.

Experimental results: We captured time-resolved optical signal using the streaked spectrometer and the VISAR, including emission spectra from shock-heated forsterite and a fringe shift due to the movement of the shock front. Fig. 1 shows an example of raw data. The shock incidence into the forsterite from the Al driver and the shock breakout at the rear surface were cleary detected. We used the signal during the shock propagation. Peak shock temperatures were evaluated by Planck function fitting. Peak shock pressures were calculated using the obtained shock velocity and the Rankine-Hugoniot equations. The u_p-V_s relation for forsterite up to ~1 TPa was also obtained using a quartz pressure standard by ourselves [9]. Fig. 2a shows the peak shock temperatures as a function of the peak shock pressures. For comparison, the M-ANEOS prediction [10] is also plotted in the figure. Although error evaluations are still ongoing, the uncertainties in the temperatures and the pressures are roughly 20% and 10 %, respectively. The high optical reflectivity (~30 %) of the shock front was observed by the VISAR, suggesting that shock-induced ionization occurs as well as quartz [6], MgO[11], and enstatite[12].

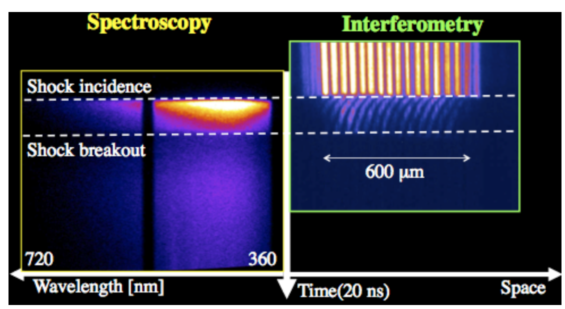

Fig. 1. An example of law data.

The *S-P* Hugoniot curve for forsterite: We construct the *S-P* Hugoniot curve for forsterite using a semi-analytic formula [13]. The melting entropy is roughly estimated based on the difference of irreversible energy gain between the Hugoniot curves for solid and liquid [14]. Fig. 2b shows the *S-P* Hugoniot curve for forsterite and quartz. The M-ANEOS predictions are also plotted. Note that our result including the melting entropy for quartz is consistent with the recent Hugoniot curve by [15]. The shock-induced entropy for forsterite is much higher than M-ANEOS prediction because of following two reasons. First, M-ANEOS is constructed based on an extrapolation of the u_p-V_s relation obtained by the gas-gun. The compressivity of forsterite at >350 GPa is higher than the extrapolation [9]. Second, M-ANEOS does not include the entropy increases due to melting, dissociation, and ionization under high pressure conditions [e.g., 8, 15].

Discussion & Conclusions: Here, we apply the *S-P* Hugoniot curves to the atmospheric blow-off. The degree of vaporization ϕ during isentropic release can be calculated using the lever rule [e.g., 16]. The final expansion energy $E_{expansion}$ is given by ~ $\phi M_{projectile} v_{impact}^2/4$. We assume that the internal energy for an expanding gas is completely converted to its expansion energy and that the mass of a silicate vapor is twice of $\phi M_{projectile}$, i.e., the same mass of target surface also vaporizes. In this formulation, the effect of exothermic heat to a gas phase due to condensation is included (this effect is neglected in the previous studies). Note that $E_{expansion}$ is expressed in the previous studies [e.g., 4] as $2M_{projectile}(v_{impact}^2/8 - H_{vap})$, where H_{vap} is vaporization enthalpy for silicate. Fig. 3a shows $E_{expansion}$ normalized with the impactor kinetic energy as a function of impact velocity.

Based on the above results and the size and velocity distributions [17, 18] of impactors at the heavy bombardment period, we construct a stochastic atmospheric evolution model for early Earth. We employ "the sector blow-off model" [4] to investigate the eroded mass from planetary atmosphere. Although the treatment of hydrodynamic motion is too simplified, the model can express the energy transfer from impact to atmospheric blow-off without any uncertainties in the EOS at off-Hugoniot. In addition, this model can approximately treat the inhomogeneous energy transfer as a function of the zenith angle due to an atmospheric structure under a hydrostatic equilibrium. The cumulative mass and the maximum size of impactors are given by [17]. Planetary mass and radius are set to the values for the current Earth. The initial atmospheric pressure $P_{initial}$ and atmospheric scale height H are free parameters. Note that we used the expansion energy for quartz because it can be calculated with a high accuracy at this stage of the research. Fig. 3b shows the results of the Monte Carlo runs, which is the probability of complete atmospheric lost as a function of $P_{initial}$. If $P_{initial}$ is smaller than ~10^6 Pa, the pre-existing atmosphere is like to be completely lost during the heavy bombardment period. This result suggests that Venus has not been experienced the complete atmospheric lost at the heavy bombardment period due to the protection by a thick steam atmosphere [19]. In contrast, the pre-existing atmosphere on Earth may be completely blown off because there were no thick H_2O, CO_2, and H_2 atmosphere on Earth due to condensation into the ocean, carbonate formtion, and hydrodynamic escape. The pressure due to the residual of pre-existing atmosphere originated from the solar nebula is too low (< the obtained threshold pressure, ~10^6 Pa) to prevent the atmosphere on Earth from the blow-off during the heavy bombardment period. This difference is qualitatively consistent with the noble gas amount in the current Earth and Venus.

References: [1] Ćuk & Stewart, *Science*, **338**, 1047, 2012. [2] Mukhin et al., *Nature*, **340**, 46, 1989. [3] Johnson & Melosh, *Nature*, **785**, 75, 2012. [4] Vickery & Melosh, *GSA special paper*, **247**, 289, 1990. [5] Shuvalov, *MAPS*, **44**, 1095, 2009 [6] Hicks et al., *PRL*, **97**, 025502, 2006. [7] Kurosawa et al., *17th SCCM*, **1426**, 855, 2012. [8] Kurosawa et al., *JGR*, 117, E04007, 2012. [9] Sekine et al., *in prep*. [10] Melosh, pers. comm. [11] McWilliams et al., *Science*, **338**, 1330, 2012. [12] Spaulding et al., *PRL*, **108**, 065701, 2012. [13] Sugita et al., *17th SCCM*, **1426**, 895, 2012. [14] Luo et al., *JGR*, **109**, B05205, 2004. [15] Kraus et al., *JGR*, 117, E09009, 2012. [16] Kurosawa et al., *EPSL*, **337-338**, 68, 2012. [17] Bottke et al., *Science*, **330**, 1627, 2010. [18] Chyba, *Icarus*, **92**, 217, 1991. [19] Liu, *EPSL*, **227**, 179, 2004.

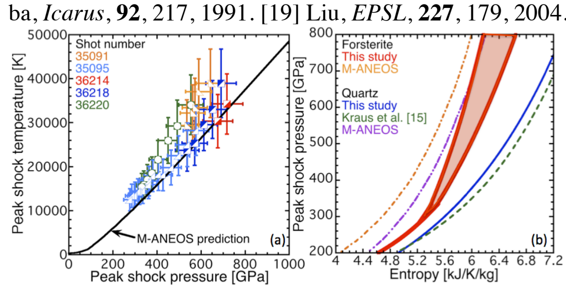

Fig. 2. (a) The peak shock temperatures as a function of the peak shock pressures. (b) The *S-P* Hugoniot curves for forsterite and quartz.

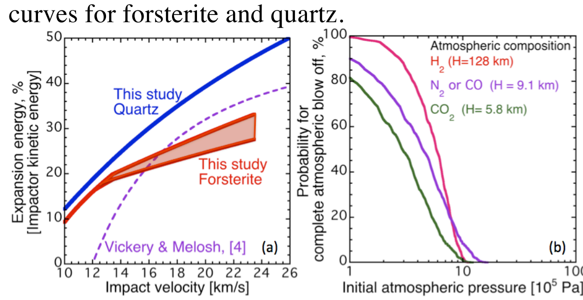

Fig. 3. (a) $E_{expansion}$ normalized with the impactor kinetic energy as a function of impact velocity. Note that the degree of vaporization at the ambient pressure of 10^5 Pa was used in the calculation. (b) The probability for complete atmospheric lost at the heavy bombardment period as a function of $P_{initial}$.