IMPACT GENERATED VAPOR PLUMES AFTER DISPERSAL OF THE SOLAR NEBULA.

E. J. Davies[1], P. J. Carter[1], M. S. Duncan[1], S. Root[2], D. K. Spaulding[1], R. G. Kraus[3], S. T. Stewart[1], S. B. Jacobsen[4]. [1]Department of Earth and Planetary Sciences, U. California, Davis, CA (ejdavies@ucdavis.edu), [2]Sandia National Laboratories, [3]Lawrence Livermore National Laboratory, [4]Department of Earth and Planetary Science, Harvard University.

Introduction: Collisions during planet formation can have a significant effect on the thermal and geochemical evolution of the growing Earth. Ref [1] shows that high-velocity impacts are common in energetic scenarios of planet formation such as the Grand Tack. However, the thermo-physics controlling the geochemical evolution induced by hypervelocity impacts is poorly understood. While impacts are capable of melting and vaporizing silicates, we do not understand the cumulative magnitude of the physical and chemical effects from these phase changes.

Moderately volatile elements (MVEs), such as potassium (K), sodium (Na), and rubidium (Rb), are defined as elements with 50% condensation temperatures between 650 K and 1300 K. Planets and meteorites in our solar system have different abundances of MVEs, with differentiated bodies typically being more depleted relative to undifferentiated bodies. The origin of this pattern is widely debated, and there are many proposed mechanisms [2]. However, whatever the mechanism, it cannot lead to significant isotopic fractionation [2, 3].

In this work, we use the experimentally constrained vaporization and melting criteria for forsterite, quartz, ice, and iron from [4]. *N*-body planet formation models [1, 5] demonstrate that the impact velocities necessary for vaporization are readily achieved during planet formation. Here, we introduce a mechanism for impact-induced separation of MVEs in planetary building blocks.

Thermodynamic Path: Figure 1 shows a schematic of the thermodynamic path of a parcel of shocked material. The shock wave increases the pressure, temperature, and entropy. The shocked parcel decompresses isentropically via a rarefaction wave down to the ambient pressure of the surroundings. In the nebula, this is similar to the triple point pressure for silicates, ~5 Pa [6, 7]. However, after the nebula disperses, a vaporizing parcel will decompress isentropically to below triple point pressures, initiating the condensation of solids.

The vaporizing parcel initially expands as a mixed phase system with liquid and vapor in equilibrium. The onset of vaporization is accompanied by many orders of magnitude increase in volume (see Fig. 2 in [4]). The optically-thick vapor plume cools radiatively from a relatively thin photosphere. Thus, initially the main body of the vapor plume is adiabatic. Bulk radiative cooling (which reduces the specific entropy of the mixture) is delayed until the plume expands in volume sufficiently to become optically thin. At that point, the vapor condenses as dust and the liquid droplets will begin to freeze. Separation of the condensed and vapor components in the expanding plume does not occur until the vapor pressures in the plume become negligible.

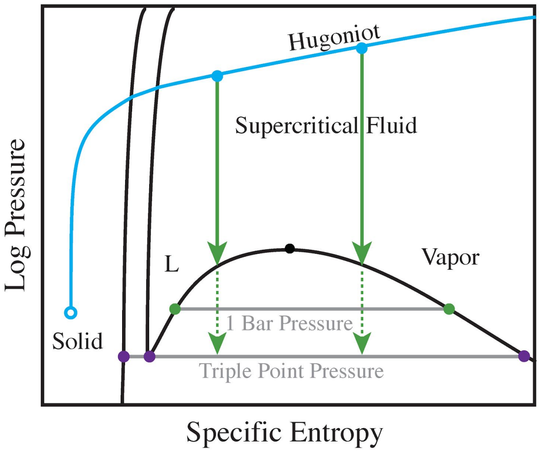

Fig. 1: Schematic of a generalized single component phase diagram. The solid, liquid (L), and vapor phase boundaries (black lines) are shown, along with the critical point (black point), triple point (purple points), and 1 bar pressure (green points). The blue curve is the Hugoniot, the locus of possible shock states. Green lines show the decompression along isentropes from specific shock states (blue points), dashed lines follow bulk decompression through the vapor dome. The mass fraction of each phase is given by the lever rule. The triple point pressure of silicates is similar to the fiducial pressure of the solar nebula at 1 AU, about 10^{-4} bar.

Implications: Here, we introduce a new conceptual model for separation of volatile and refractory components in vaporized silicate materials ejected after the dispersal of the nebula (Fig. 2). The outcome of vaporizing collisions in the presence of the nebular gas is discussed in [8].

Shock-induced vaporization is different than vaporization by heating under quasi-static conditions. Because the shock and rarefaction waves impart momentum, vaporization during decompression from a shock state imposes a specific direction and magnitude to the material velocity that affects the subsequent dynamics of the system. Thus, vapor does not immediately separate from the liquid droplets in the ejecta. Instead, the liquid-vapor mixture initially decompresses and expands together. Following an energetic impact, depending on the impact velocity, the ejecta is either initially dominated by vapor (high entropy, high impact velocity V_i), or melt (low entropy, low impact velocity V_i). In the high entropy case, melt droplets condense from the vapor, and in the low entropy case, bubbles form in the melt. In both cases, the vapor expands rapidly, dominating the volume of the ejecta. Final decompressed volumes are at least 10^7 times greater than the pre-shocked volumes when the final vapor fraction is ~10 wt% [4]. In either case, there is chemical exchange between within the mixture of silicate melt and vapor during decompression. As the system decompresses, the temperature is buffered by the silicate phase boundaries, and MVEs will prefer the vapor phase. During adiabatic expansion into vacuum, the pressure eventually drops below the triple point of silicates and the melt will begin to freeze. Once the system becomes optically thin, the vapor cools radiatively, condensing as dust or aerosols and onto all available surfaces, comparatively enriching the smallest particles in MVEs, due to the surface area to volume ratios. The smallest particles tend to separate from larger particles due to processes that affect dust more efficiently. These processes include to Poynting-Robertson drag (into the sun) and radiation pressure (away from the sun).

Based on the large number of vaporizing collisions that occur after nebula dispersal found in [1], we propose that size-separation of MVEs in vaporized ejecta was a major process during terrestrial planet formation and should be investigated to estimate the cumulative effects on the composition of the final bodies.

Acknowledgments: Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. Prepared by LLNL under Contract DE-AC52-07NA27344.

References: [1] Carter P. J. et al. (2019) *LPSC **50***, 1246. [2] Davis A. M. (2006) *MESS II*, **1**: 295-307. [3] Humayun M. & Clayton R. N. (1995) *GCA* **59.10**: 2131-2148. [4] Davies E. J. et al. (2019) *LPSC **50***, 1257. [5] Carter P. J. et al. (2015), *ApJ* **813**, 72. [6] Mysen B. O. & Kushiro I, (1988) *AM* **73**, no. 1-2: 1-19. [7] Nagahara H. et al. (1994) *GCA* **58.8**: 1951-1963. [8] Stewart S. T. et al. (2019) *LPSC **50***, 1250.

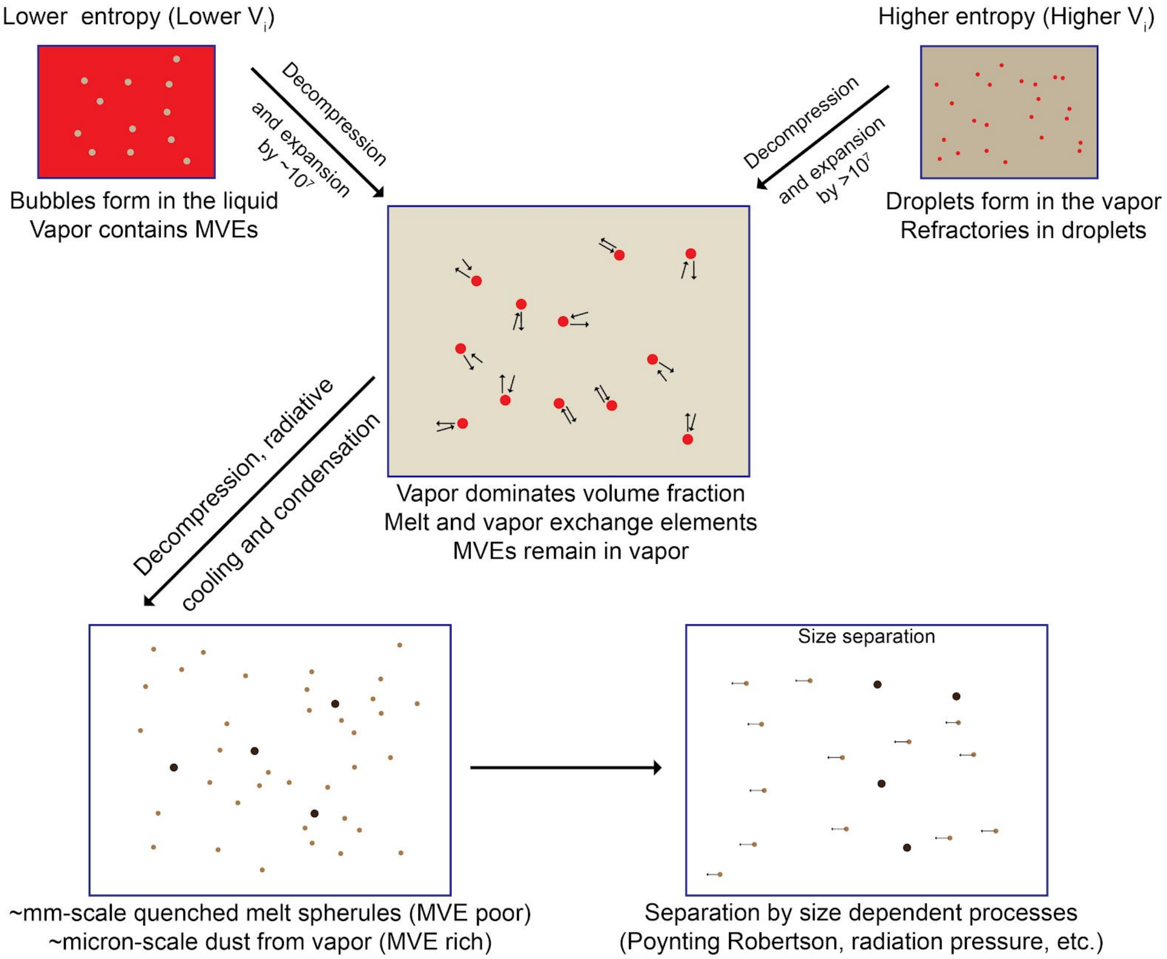

Fig. 2: Schematic evolution of a high/low entropy vapor plume of silicates into vacuum.