DOES LASER ABLATION VAPOR SIMULATE IMPACT VAPOR? S. Sugita[1], T. Kadono[2], S. Ohno[1], K. Hamano[1], and T. Matsui[1], [1]Univ. of Tokyo, Dept. of Earth Planet. Sci. (Hongo, Bunkyo-ku, Tokyo 113-0033, JAPAN, sugita@eps.s.u-tokyo.ac.jp.), [2]IFREE, JAMSTEC (Yokosuka, Kanagawa 273-0061, JAPAN).

Introduction: Many laser experiments have been done to simulate hypervelocity impact vaporization [e.g., 1- 5]. Laser simulation has a number of advantages. It can create high-temperature plumes with high repeatability and a high repetition cycle at a relatively low cost. Furthermore, because laser light can penetrate through a glass window (if chosen properly), the target material and vaporization products have virtually no risk of contamination. This is an ideal condition for a chemical analysis.

However, there is a critical disadvantage in laser simulation; we do not know if a laser irradiation really simulates a hypervelocity impact. The purpose of this study is to address this problem quantitatively.

Similarities and Differences: Vapor plumes generated by both laser and hypervelocity impact have very high initial temperatures and pressures. However, there are significant differences, too. First, impact heating is purely thermal, and condition immediately after shock heating is considered to be in thermal equilibrium. However, laser plume may not be in thermal equilibrium, particularly when a UV laser is used. Photonic energy tends to excite certain transitions preferentially and create disequilibrium. Nevertheless, if the initial plume density and mass are large, such disequilibrium is compensated before it expands significantly.

Second, laser produces a much lower pressures than an impact. An impact vapor plume whose peak-shock temperature is 10^4 K goes through a very different adiabatic decompression path that a laser plume with the initial temperature of 10^4 K does. This difference in thermodynamic path comes from that in entropy. The former vapor has much higher entropy than that of the latter. However, if the entropies of a laser-induced vapor and that of an impact vapor are matched, their adiabatic decompression paths coincide.

Thus, the key for laser simulation of impact vaporization phenomena is to match the entropies of the two kinds of vapor. In the following, we discuss a method to match the entropies of laser- and impact-induced vapor plumes.

Entropy of Impact-Induced Vapor: The increase in entropy due to hypervelocity impact can be calculated by Rankine-Hugoniot relations and thermodynamic relations. Here, we assume a linear velocity relation, which holds for a variety of materials over a wide range of impact velocity [e.g., 6]:

$$V_s = C_o + s\,U_p, \qquad (1)$$

where V_s, C_o, U_p, and s are shock velocity, bulk sound velocity, particle velocity, and a constant, respectively. Using equation (1), the differential form of Rankine-Hugoniot relations, and thermodynamic relations, we obtain:

$$\frac{dS}{dU_p} = \frac{sU_p^2}{T\left(C_o + sU_p\right)} \qquad (2)$$

$$\frac{dT}{dU_p} = \frac{C_o\Gamma_o T}{\left(C_o + sU_p\right)^2} + \frac{1}{C_v}\frac{sU_p^2}{C_o + sU_p} \qquad (3)$$

where S, T, Γ_o, and C_v are entropy, temperature, Grüneisen parameter, and constant-volume heat capacity, respectively. Heat capacity and Grüneisen parameter are functions of temperature T and density ρ [7,8]:

$$C_v = C_{vo} + \beta_o T\left(\frac{\rho}{\rho_o}\right)^{-\frac{2}{3}} \qquad (4)$$

$$\Gamma\rho = \Gamma_o\rho_o = \text{const.} \qquad (5)$$

The second term in equation (4) is the contribution of electron energy and becomes important at higher temperatures. The constant β_o is theoretically given by

$$\beta_0 = \frac{4\pi^4}{\left(3\pi^2\right)^{2/3}}\frac{k^2 m_e}{h^2}N_e^{1/3}\rho_o^{-2/3} \qquad (6)$$

and experimentally measured to be on the order of 10^{-2} J/kg/K^2 for metals [7]. Here, k, h, m_e, and N_e are Boltzmann constant, Planck constant, electron mass, and the number of free electrons per a unit mass, respectively. The equations (2) through (5) can be solved numerically to yield T and S as functions of U_p.

Rankine-Hugoniot relations and equation (1) also provide the relation between pressure P and particle velocity U_p:

$$P = U_p(C_o + sU_p)\rho_o. \qquad (7)$$

We use parameters for basaltic materials [9] and a relation between Γ_o and s [8]:

$$\Gamma_o = 2s - 1 \qquad (8)$$

The specific values used for the calculation is given in Table 1. The results of the calculations are shown in Figures 1 and 2.

Entropy of Laser Ablation Vapor: The initial pressure and temperature of laser ablation vapor are given by the following semi-empirical formulae [10]:

$$P = 2\times10^{-4}A^{1/8}\Psi^{9/16}I^{3/4}\left(\lambda\sqrt{\tau}\right)^{-1/4}\ \text{(Pa)} \qquad (9)$$

where

$$\Psi = A\left[Z^2(Z+1)\right]^{-1/3} \Big/ 2 \qquad (10)$$

and

$$T = 3\times 10^3 A^{1/8}(Z+1)^{-5/8} Z^{3/4}\left(I\lambda\sqrt{\tau}\right)^{1/2} \text{(K)}. \qquad (11)$$

Here, A, Z, I, λ, and τ are ion mass number, ion valence, laser intensity (W/m^2), laser wavelength (m), and laser pulse duration (sec), respectively. It is noted here that the formulae do not hold for laser intensity lower than 10^{12} W/m^2 [10]. The P-T relation given by equations (9) and (11) is shown in Figure 1. The laser condition used here is that for a typical Q-switched Nd:YAG laser (λ = 1.06x10^{-6} m, τ = 15x10^{-9} sec), and the plasma parameters, A and Z, are assumed to be 20 and 1, respectively.

Using the temperature and pressure, we can calculate the entropy ΔS of the laser ablation plume as

$$\Delta S = C_p \ln\frac{T_b}{T_o} + \frac{H_{vap}}{T_b} + \frac{\gamma}{\gamma-1}\frac{R}{\mu}\ln\left[\frac{T}{T_b}\left(\frac{P}{P_o}\right)^{-\frac{\gamma-1}{\gamma}}\right], \qquad (12)$$

where C_p, H_{vap}, T_b, R, γ, μ, T_o, and P_o are the constant-pressure heat capacity (1.46 kJ/K/kg), the heat of vaporization (13.5 MJ/kg), vaporization temperature (3000 K), gas constant, the ratio of specific heats of vapor, molecular weight (0.02 kg/mol), reference temperature (300 K) and reference pressure (1 bar), respectively. Although the above laser formulae are based on metals and hydrocarbons [10], spectroscopic observation of laser plumes by a Nd:YAG laser show that T and P given by equation (11) and (12) predicts plumes condition for a non-metallic inorganic matter [11]. The entropy values for typical laser intensities found in the literature are shown in Figure 2.

Discussion and Conclusion: Although there is substantial uncertainty in the entropy estimates, the entropy estimate with β_o=0.01predicts an almost identical result by an independent analysis of a laser plume using a 1-D hydrocode and Tillotson EOS [4]. This supports the validity of the approach in this study.

Furthermore, the results obtained in this study lead us to a couple of important conclusions. First, typical laser irradiation intensities (10^{12} – 10^{14} W/m^2) achieve very high entropies, which correspond to extremely high impact velocities (50 – 100 km/s). Thus laser ablation vapor may simulate impact vapor produced by collision of long-period comets.

However, typical Q-switched Nd:YAG laser cannot create ablation vapor at irradiation intensity lower than 10^{12} W/m^2 because interaction between laser light and solids becomes very inefficient. Laser light merely reflect on and/or transmits through the target solid. Thus, vaporization phenomena at typical asteroidal impact velocities (11 – 25 km/s) on Earth is difficult to simulate with a typical Nd:YAG laser.

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Table 1. Physical properties of basalt [7, 12].

ρ_o	C_o	s	C_{vo}	Γ_o	β_o
3.6x10^3	3.1x10^3	1.3	1.46x10^3	1.6	0.01
kg/m^3	m/s		J/K/kg		J/K^2/kg

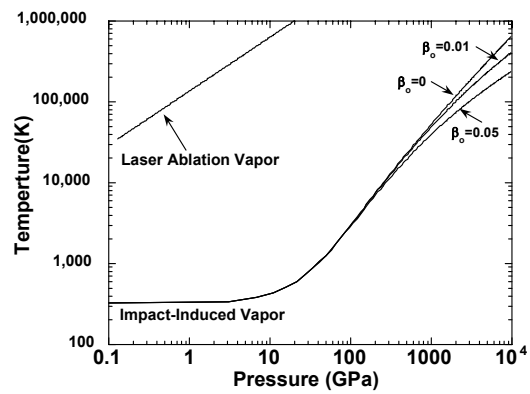

Figure 1. P-T diagram for laser- and impact-induced vapor. Note that the temperature of laser-induced vapor is much higher than that of impact-induced vapor at the same pressure. Different values of β_o used in the calculation are shown in the figure.

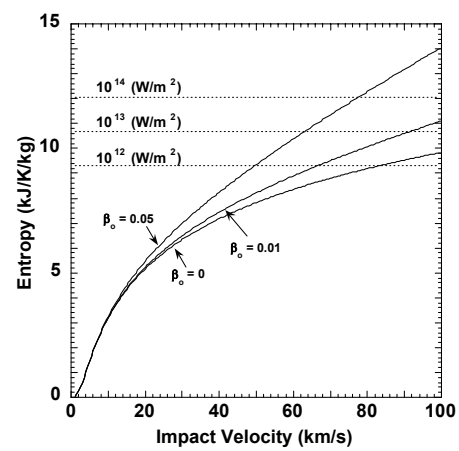

Figure 2. Entropies of laser- and impact-induced vapor as function of impact velocity. The impact velocity is assumed to be $2U_p$ (i.e., collision between two basaltic bodies). The three curves in the figure show the effect of β_o, coefficient for the electron energy. Note that entropy depends on β_o much more strongly than peak-shock temperature is (see, Figure 1). Horizontal dashed lines are entropies produced by laser irradiation. The irradiation energy densities are given in the figure.