WHAT CONTROLS THE INTENSITY OF IMPACT-INDUCED LUMINESCENCE? S. Sugita[1], P.H. Schultz[2], and S. Hasegawa[3], [1]Univ. of Tokyo, Dept. of Complexity Sci. and Eng. (Hongo, Bunkyo-ku, Tokyo 113-0033, JAPAN, sugita@eps.u-tokyo.ac.jp.), [2]Brown Univ., Dept. of Geol. Sci. (Providence, RI 02912, USA.), JAXA/ISAS (Yoshinodai, Sagamihara, Kanagawa, 229-8510, JAPAN).

Introduction: The intensity of optical emission during hypervelocity impacts is proportional to impact velocity raised to a power, the value of which varies from 4 to 8, depending on impacting materials [e.g., 1,2,3,4]. It is not yet well understood, however, what controls this power-law exponent value. Nevertheless, the exponent value is required for predicting the intensity of optical emissions from hypervelocity impacts. Such a prediction is particularly relevant when a Discovery-class mission, *Deep Impact*, produces a collision between a metallic projectile and a comet in July 2005.

One reason why the basic mechanism controlling the emission intensity has not been understood is the absence of spectroscopic observation with high time resolution and wavelength resolution. Time-integrated and/or spectrally integrated spectra are difficult to interpret. Here we report a series of impact experiments in order to obtain emission spectra of hypervelocity impacts with high resolution in both time and wavelength.

Impact Experiments: The experiments ware carried out at NASA Ames Vertical Gun Range (AVGR) with impact velocities ranging from 2 to 5.5 km/s by Cu projectiles. The impact angle was fixed at 45° as representative of the most probable impact angle. Two spectrometers with ICCD cameras are used. The details of the spectrometer system are given by Sugita et al. [5]. We focused on the earliest component of the impact-induced luminescence, which contains the most intense atomic emission without a strong blackbody. The exposure time of the spectrometers were set to be 0.5 – 2.5 μs after the first contact of impact. This generally corresponds to the jetting phase of impacts [5, 6].

Experimental Results: Little emission occurs at velocities lower than 2 km/s. Above 2 km/s, CaO molecular bands, Na atomic lines, and Cu atomic lines appear, but there is no observable Ca line. As impact velocity increases, a number of Ca atomic lines start to appear. The relative intensities of Ca with respect to Na and CaO increase strongly with increasing velocity. At the maximum impact velocity (5.5 km/s) in this study, the emission spectrum is dominated by Ca and Cu atomic lines.The emission intensity integrated over the entire observed wavelength range (435 – 650 nm) follows a power-law function of impact velocity well (Fig. 1) with the best-fit exponent of 5.1. The intensities of individual emission lines as a function of impact velocity also are also well represented by power-law functions, but the power-law exponents vary over a wide range (2.1 – 9.1). This large range in power-law exponents is consistent with the drastic change in spectral content as a function of impact velocity: transition from prevalent CaO bands and Na D lines at lower velocities to Ca and Cu lines at high impact velocities. The power-law exponents also correlate with the excitation energy of the electronic transition associated with the emission lines.

Such results are consistent with the radiation theory of high-temperature gas [e.g., 7] and the increase in vapor temperature [6]. The intensity of a line emission from neutral atoms is given by

$$P_{nm} = h\nu_{nm} A_{nm} \frac{g_n}{g_o} \exp\left(-\frac{E_n}{kT}\right) N_o^{(o)} \qquad (1)$$

where h, ν_{nm}, A_{nm}, g, E_n, k, T, and $N_o^{(o)}$ are Planck constant, photon frequency, statistical weight, transition probability, upper-state excitation energy, Boltzmann constant, temperature, and the number of ground-state neutral atoms. Using Taylor's expansion, we can obtain the logarithmic derivative $d\ln P_{nm}/d\ln V_{im}$ of emission intensity (i.e., local power-law exponent) [5],

$$\frac{d\ln P_{nm}}{d\ln V_{im}} = \frac{E_n}{kT_o} \frac{d\ln T}{d\ln V_{im}}. \qquad (2)$$

There is a good correlation between the logarithmic derivative of emission intensity predicted by equation (2) and the observed exponents (Fig. 3a). However, there is also a significant discrepancy between predicted emission intensities based on excitation energy and those observed. More specifically, observed exponent values for Ca and Na emission lines are much lower than prediction. Thus, there must be some process(es) controlling the intensity of light emission other than electronic excitation (i.e., Boltzmann distribution).

Theoretical Model: In order to understand the discrepancy between the observed power-law exponents and those predicted by equation (2), we conducted a plasma model calculation. A model calculation needs to consider chemical equilibrium among different molecular and atomic species, electronic equilibrium among different excitation levels in atoms, and ionization equilibrium. The contributions of these factors to the logarithmic derivative of emission intensity are given by the following equation.

$$\frac{d\ln P_{nm}}{d\ln V_{im}} = \left(\frac{E_n}{kT} + \frac{d\ln\left(N_o^{(o)}/N_{tot}\right)}{d\ln T}\right)_{T_o} \frac{d\ln T}{d\ln V_{im}} + \frac{d\ln N_{tot}}{d\ln V_{im}} \qquad (3)$$

A separate model calculation is needed in order to assess each factor. First, the chemical equilibrium was calculated with the Lewis Thermodynamic code [8]. Second, the electronic equilibrium among different excitation levels can be given as a partition function.

Although the partition function of an atom is generally very complex, simple formulae by Gray [9] provide a good approximation. Third, the ionization equilibrium was calculated with Saha's equation.

Calculation Results and Discussion: The chemical equilibrium calculation indicates that most Ca, Na, and Cu stay in the atomic states during the observed conditions of impact jetting. Thus, the effect of the variation in molecule/atom ratio on the intensity of atomic emission is not significant.

The model calculation indicates that the effect of the partition function is significant, but its contribution to the logarithmic derivative $d\ln P_{nm}/d\ln V_{im}$ is only 0.5 to 1. This is not sufficient to account for the large discrepancy between the data and the prediction.

The effect of ionization, however, is very large. The plasma calculation indicates that the emission intensities of atoms (e.g., Ca and Na) with low ionization energies are reduced significantly at high temperatures, whereas those atoms with high ionization energy are not [5].

When these calculation results are incorporated into equation (3), we obtain the results shown in Fig. 3b. Corrected estimates for power-law exponents predict observed power-law exponents with significantly higher accuracy (Fig. 3b). The large difference between Cu and Ca (also Na) results from the difference in ionization energy. The small ionization energies of Ca and Na lead to the large reduction in emission intensity at high impact velocities.

One implication inferred from this result is that the Cu is a very efficient element to produce the initial impact flash because it has both high ionization and low excitation energies for major emission lines. Combined with its high impact impedance and rarity in natural environment, this spectroscopic property makes Cu an excellent projectile material for probing an unknown planetary body.

Conclusions: The intensity of optical emission is strongly controlled by electronic excitation and ionization. The former controls the relative intensity ratio among emission lines from the same atom, and the latter controls the intensity ratio of emission lines between different atoms. Such fundamental understanding of impact plasma process will help us predict the intensity of early-stage optical emissions from the *Deep Impact* collision with Comet 9/P Tempel 1.

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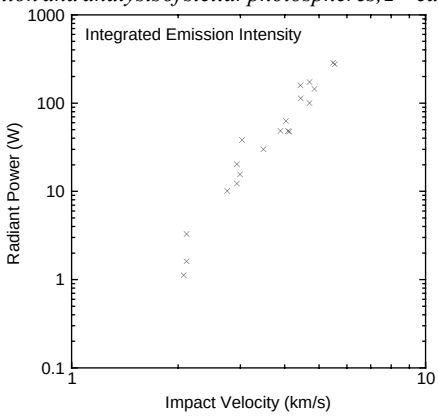

Figure 1. Wavelength-integrated emission intensity of hypervelocity impacts between spherical copper projectiles and polycrystalline dolomite targets as a function of impact velocity. The projectile diameter, impact angle, and exposure time are 3.2 mm, 45°, and 0.5 – 2.5 μs from the first contact of impact, respectively. The total emission intensities observed over a wavelength ranges (435 – 650 nm) are shown. The average radiant power (W) is given by the total emission intensity (J) observed by spectrometers divided by the exposure time (i.e., 2 μs).

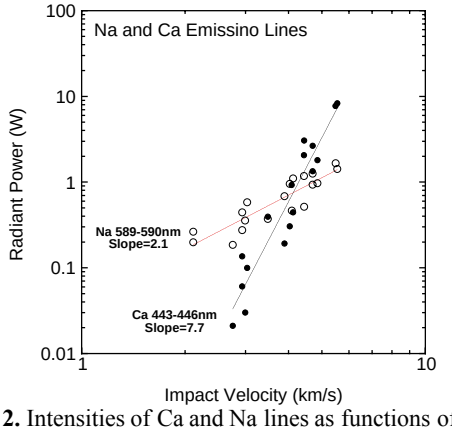

Figure 2. Intensities of Ca and Na lines as functions of impact velocity. The best-fit lines and their slopes are also shown.

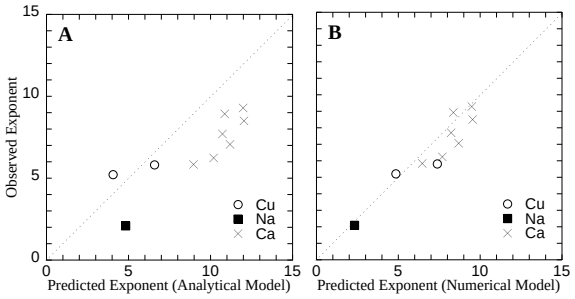

Figure 3. Comparison between observed and theoretically predicted power-law exponents of the intensities of atomic emission lines. (A) The analytical model considers only electronic excitation (i.e., equation (2)). (B) The numerical model incorporates electronic excitation, ionization, partition function, and increase in vapor mass.