PRESSURE MEASUREMENTS OF SELF-LUMINOUS ROCK VAPORS USING ATOMIC LINE BROADENING K. Kurosawa1,2 and S. Sugita1,1 Graduate school of Frontier Sci., Univ. of Tokyo (Kashiwa, Chiba 277-8561, JAPAN, kurosawa@astrobio.k.u-tokyo.ac.jp), 2Japan Soc. for the Promo. Sci. (Chiyoda-ku, Tokyo, JAPAN).

Summary: We present a new pressure measurement method for high-temperature rock vapor plumes using spectral line broadening. This method may serve as a powerful tool for the understanding of post-impact chemistry.

Introduction: Generation of impact-induced vapor clouds may have played important roles in the origin of the atmosphere and ocean [e.g., 1], prebiotic organic synthesis [2], and global mass extinction, such as the K/Pg event [e.g., 3]. However, thermodynamic and chemical evolution of the vapor clouds has been poorly understood because there is no reliable pressure measurement method for high-temperature rock vapors.

Self-luminous plasmas radiate light energy as emission lines due to electronic transitions between the upper and lower states of atoms/ions. A number of emission lines from impact-induced vapor clouds are observed at laboratory-scale velocities (<6.5 km/s) [e.g., 4]. In general, line width has been considered as a good indicator of the particle number density of the plasma. In this study, we present the framework of pressure measurements for self-luminous rock plasmas based on spectral line broadening [5]. Then, we applied the proposed method to rock plasma, which is approximated well as an ideal gas as the first step of research development.

Principles of pressure measurements: If radiating atoms/ions interact with other particles, the wave function of an electron in the upper state of an atom/ion is disturbed. Then, the emission lines resulting from electronic transitions from the upper state to lower states are broadened, yielding a Lorentzian. The line width resulting from such interactions is expected to correlate with the perturber number density in the plasma. Thus, this process is called “pressure broadening” [e.g., 6]. The perturbation is proportional to the inverse power $p$ of the distance to the perturber. Pressure broadening is classified into four types by the dependence on $p$: (a) $p = 2$, the linear Stark effect; (b) $p = 3$, resonance interaction; (c) $p = 4$, the quadratic Stark effect; and (d) $p = 6$, van der Waals interaction. Under the “nearest-neighbor approximation,” whereby only interaction with the closest particle is considered, the relations between full width at half maximum (FWHM) by each broadening and perturber density can be expressed analytically [e.g., 6]. We discussed spectral line broadening in detail in [5].

The quadratic Stark ($p = 4$) and the van der Waals ($p = 6$) broadening are suitable for pressure measurements because these occur for all emission lines from atoms/ions. The perturber of the quadratic Stark effect and of the van der Waals interaction are electron and neutral atoms, respectively. Based on the relationship between FWHM and perturber number density and spectroscopic constants of atomic emission lines of Fe atom at 381.58 nm, quadratic Stark broadening is the dominant broadening mechanism if the degree of ionization exceeds 1%. The van der Waals broadening should be considered if the degree of ionization is less than 1% [5]. Thus, taking into account the appropriate broadening mechanisms, it is possible to accurately measure the electron/neutral atom number density in vapor clouds. Then, we can calculate the pressure of the self-luminous plasma using an equation of state (EOS) based on ionization/chemical equilibrium.

Experiments: We conducted laser ablation experiments with Hematite ($\text{Fe}_2\text{O}_3$) targets to assess the validity of the proposed method. Spectroscopic observations of laser-induced hematite plasma were carried out to measure temporal change in the pressure and temperature of the vapors. The experimental system consisted of three components: an Nd:YAG laser, a vacuum chamber, and an optical spectrometer (Acton, SpectraPro 2750 connected with Roper Scientific, PI-MAX). The laser wavelength was 1064 nm and the pulse width was 13 ns. We obtained emission light from the entire laser-induced high-temperature vapor using a focusing lens installed in front of an optical fiber. The field of view (FOV) was ~20 mm in diameter. We conducted calibration experiments for both wavelength and irradiance with an Hg lamp and NIST-traceable standard light source (Oriel Corporation, Model 63355).

We investigated the time evolution of the temperature and pressure of the laser-induced vapor cloud, gradually varying the gate delay and exposure time. The laser-beam diameter and intensity were fixed at $0.5 \text{ mm}$ and $1.5 \times 10^{10} \text{ W cm}^{-2}$, respectively. The total pressure in the chamber was fixed at $10^2 \text{ Pa}$ of air.

To increase the S/N ratio, we averaged 300 spectra measured under the same conditions. During the experiment, the target was moved in both the X and Y directions to irradiate the laser beam on a fresh surface of the target. Figure 1 shows the photograph of a laser-induced vapor cloud in the vacuum chamber.

Experimental results: The main results of this study are the time evolution of the pressure and temperature of the laser-induced hematite plasma. Figure 2 shows the emission spectra with 2 time windows. All emission lines are Fe. First, we measured the tempera-
ture, $T$, of the vapor using relative intensity ratio (i.e., the Boltzmann-plot method [e.g., 4, 6]). Next, we spectrally fitted the atomic line profile of Fe 381.58 nm to obtain the FWHM due to pressure broadening. The laser-induced hematite vapor is expected to be highly ionized because the obtained temperatures are significantly high (8000-14000 K). Thus, we considered instrumental, Doppler, and the quadratic Stark broadening to measure the electron number density, $n_e$, of the vapor clouds. Then, we calculate the total particle number density based on the obtained $T$ and $n_e$ under ionization equilibrium. Consequently, we calculate the pressure, $P$, with the ideal gas EOS. Figure 3 shows the time evolution of the $P$ and $T$ of laser-induced vapor clouds.

**Validity of the method:** In general, laser-induced vapor clouds expand adiabatically and hemispherically [e.g., 7]. We conducted a spherically symmetric one-dimensional hydrocode calculation to compare with the experimental results. The numerical code simulates the expansion of a laser-induced vapor cloud into ambient air ($10^2$ Pa). The ideal gas EOS was used as the equations of state for the vapor cloud and ambient air. Note that we treated the ratio of specific heats, $\gamma$, as a linear function of internal energy in the calculation because $\gamma$ strongly depends on $T$. Figure 3 also shows the irradiance-weighted values of $P$ and $T$ obtained with the hydrocode calculation. The experimental values and numerical results are in good agreement, strongly suggesting that our method provides the pressure of high-temperature rock vapor plumes accurately.

**Discussion & Conclusions:** There are three advantages of the proposed method in planetary application because the method is applicable to all the atomic/ionic emission lines whose spectroscopic parameters have been measured. First, the proposed method is applicable to emission lines with low upper-energy levels. Thus, this method is likely to be applicable to actual impact experiments, where emission lines with high upper-energy levels have very low light levels. Second, this method simplifies the simultaneous measurement of the $P$ and $T$ of vapor clouds, which is important for impact experiments because it is difficult to perform repeated experiments under the same conditions. Third, the proposed method is applicable to Fe atomic lines. Because both meteoritic materials and planetary crusts are generally Fe-rich, this method is expected to work well if actual planetary materials (e.g., meteorites) are used as targets in laser/impact experiments.

Our spectroscopic method is expected to be used without any modification when impact-induced vapor clouds behave an ideal gas (e.g., later stage of expansion). If the degree of ionization is lower than 1% due to its lower temperature, we can obtain the total number density of the vapor clouds with van der Waals broadening. Our method provides a complete thermodynamic description of vapor clouds at late stage evolution. If the method is combined with chemical analyses, such as Time-of-flight mass spectrometry [e.g., 8], we could estimate chemical kinetics parameters at a variety of pressures and temperatures. Thus, the proposed method may provide significant insights into post-impact chemistry.