A NEW METHOD TO MEASURE THE PRESSURE OF IMPACT-INDUCED VAPOR CLOUDS.

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Introduction: Impact vaporization process may have played an important role in the formation and evolution of the atmospheres and oceans of planets e.g.[1,2] and have had significant consequences to planets' surface environment e.g.[3,4]. Although a mechanical aspect of this process has been investigated extensively, its chemical aspect has not been studied to a great depth. One of the reasons for this is that there has been no method to measure the pressure of an impact vapor cloud in a laboratory. Temperature, line-of-sight column density, the degree of ionization, and chemical composition can be measured by existing methods [5], but a thermodynamic state of a vapor cloud cannot be determined only from these parameters. For complete thermodynamic description of a vapor cloud, measurement of pressure is indispensable. In this study, we propose a method of pressure measurement using spectral broadening and examine its feasibility.

Laser Experiments: We used a high-energy pulse laser (Nd:YAG, 1064 nm) to simulate the impact vaporization process. In order to observe hydrogen emission lines, we used a hydrous mineral, Gypsum ($CaSO_4 \cdot 2H_2O$), as the target. The YAG laser was irradiated vertically on the target in a vacuum chamber filled with Ar at 40 torr. The laser beam, with pulse energy of 240 mJ and pulse duration of 15 ns, was focused with a quartz lens to a 0.7 mm-diameter spot. The impact flash from a resulting vapor cloud is observed with a high-speed spectrometer (focal length = 30 cm). The exposure is triggered by a photodiode, which is placed near the irradiation point. Spectroscopic measurements were made for a variety of exposure times. The wavelength range in this study was from 420 nm to 680 nm. We observed a significant line broadening of hydrogen emission line (Fig. 1).

Spectral Analysis: Any spectral line is observed with a finite spectral width, partly due to the finite resolution of the spectrometer and partly due to its intrinsic line width. The intrinsic spectral line broadening has two components: Doppler broadening and collision broadening. Doppler broadening is due to the thermal motion of the light-emitting atoms or ions. The resulting line profile at a frequency is Gaussian.The line width of the Gaussian breadth Δw_d of Doppler broadening is given by

$$\Delta w_d = \left(\omega_0/c\right)\left(2kT/M_A\right)^{1/2} \qquad (1)$$

where ω_0, c, k, T and M_A are a frequency which corresponds to the transition frequency, light speed, Boltzmann constant, temperature and a mass of the light-emitting atom, respectively e.g.[6].

Collision broadening is caused by typically collisions between light emitter and their neighboring particles. The resulting line profile is typically Lorentzian:

$$L(\omega) = \frac{\Gamma}{2\pi}\frac{1}{(\omega-\omega_0)^2+\Gamma^2/4} \qquad (2)$$

where Γ is a constant.

Theoretical studies indicate that hydrogen lines are very sensitive to Stark broadening, which is a kind of collision broadening e.g.[7]. In particular, the Balmer-α line of hydrogen is the most prominent and not severely influenced by self-absorption. We estimated the maximum Full Width at Half Maximum (FWHM) of Doppler broadening of the Balmer-α line under our experimental condition. It is so small compared to the observed line width that we can neglect Doppler breadth. Thus we can assume that the broadening of the Balmer-α line is mainly caused by collision broadening and that the "true" spectrum of the spectral line profile is Lorentzian. However, observed spectrum is also contributed by the instrumental function of our spectrometer system (Fig. 2). Consequently, we need to deconvolute the observed line profiles to obtain the FWHM of the Lorentzian.

Collision broadening is divided into two types: Vander Waals broadening and Stark broadening. In highly dissociated plasmas, Stark broadening is usually much larger than others. Especially electrons, which have a Coulomb force, can interact with emitters from a dis-tance and have an extremely high collision frequency because of its high translational velocity. Consequently, we can assume that the spectral broadening mainly depends on electron number density not ions e.g.[6]. We used the theoretical estimate of Stark profile by Griem[7] and plotted the values of the FWHM of the Balmer-α line of hydrogen (Hα:656.28nm) at different temperatures as a function of n. Under our experiment conditions, the effect of temperature is negligible. We approximated the FWHM was a function only of n[m^3]:

$$\Delta w_{FWHM}\,[nm] = 6.30\times10^{-16}\, n^{2/3}. \qquad (3)$$

This allows estimating n of the vapor cloud from the measured Δw_{FWHM}.

Temperature in the vapor cloud was determined by the method developed by Sugita et al. [5] using relative intensities of spectral lines from the same species of atoms. We assumed that atoms in a vapor cloud are in a thermal equilibrium. In this study, we measured temperature from intensities of emission lines of both hydrogen and calcium.

Using the electron number density and temperature measured above, we can obtain the pressure of the vapor cloud. We assume that Gypsum is completely dissociated and the atoms contained in Gypsum exist as singly-charged ions. From the equation of state of an ideal gas, pressure is estimated.

Results and Discussion: We measured the temperature of the vapor cloud as a function of time. Temperature decreases as the vapor cloud expands.

The line profile is sharper after the effect of the instrument function of the spectrometer is removed (Fig. 2). Using the relationship (Eq. (3)) in the previous section, we obtained n. n has a very clear correlation with time (Fig. 3).

From the electron density and temperature, we estimated the pressure as a function of time as well. Since the spectral data were observed in an early stage of vapor expansion, we can assume that the expansion is adiabatic. Then, we can obtain the ratio γ of specific heats of the vapor, using the Poisson's equation as 1.31±0.05. Both theoretical calculations and field observations of atomic explosion indicate that it is generally about 1.1-1.3 e.g.[8]. Thus our experimental result is consistent with the theoretical prediction. This supports that the method used in this study provides an accurate pressure measurement.

We estimated the initial pressure of the observed laser-induced vapor cloud from our spectral data and compared it with a calculation from an empirical formula [9]. This empirical formula predicts that the initial temperature and pressure under our laser condition are 2.2×10^5 K and 1.6×10^4 bar, respectively. We use the predicted initial temperature is given by this calculated value and estimate the initial pressure from the temperature-pressure relation obtained from our data, and the ratio of specific heats obtained from them. The estimated initial pressure is 2.4×10^4 bar, and it agrees with the prediction very well.

The above two examples of comparison strongly suggest that the method using spectral line broadening serves as an accurate pressure measurement method.

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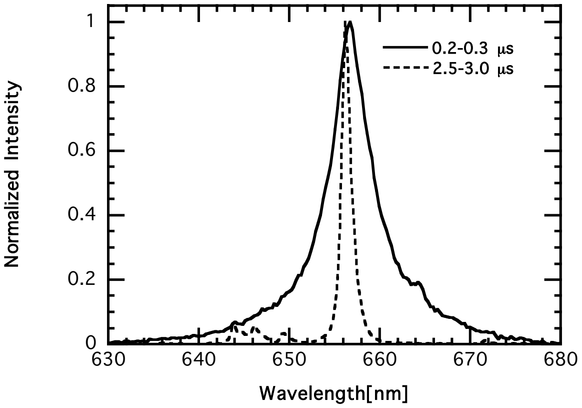

Figure 1. Comparison of spectral profiles of H_α emission line (656.28nm) observed in 0.2-0.3μs and 2.5-3.0μs of exposure times after laser irradiation. Each profile is normalized with its peak value. The FWHM of the observed line decreases rapidly. The slight difference in the wavelength positions of the two line peaks may be caused by Stark shift.

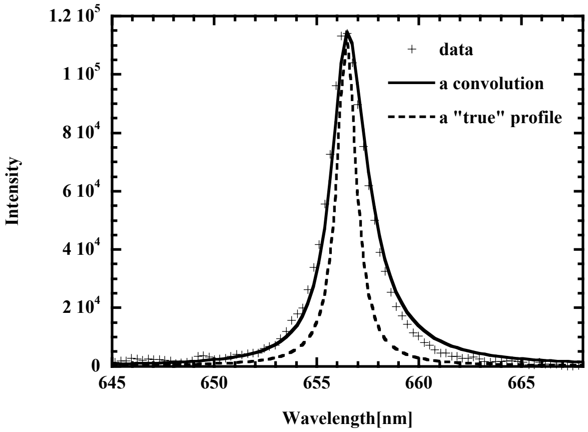

Figure 2. A fitted line profile of H_α as a convolution of Lorentzian and an instrumental function (solid line) with data (crosses), and a deconvoluted, “true” line profile (dot line).

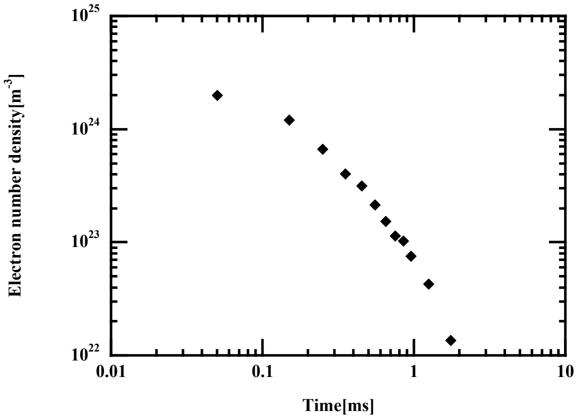

Figure 3. Electron number density of the vapor cloud as a function of time.