IN SITU TEMPERATURE MEASUREMENTS OF IMPACT-INDUCED VAPOR CLOUDS WITH A SPECTROSCOPIC METHOD

S. Sugita, P. H. Schultz, Brown University, Providence, RI; M. A. Adams, Jet Propulsion Laboratory, Pasadena, CA

Abstract: Vapor production during a hypervelocity impact has significant geologic implications. But the details of its mechanism are not fully understood yet. Particularly, energy partitioning to an impact vapor cloud during an oblique impact has just started to be understood [1]. Here we present a spectroscopic method to measure directly the evolving temperatures of impact vapor and to assess the effects of impact angle. This spectroscopic approach can be also applied to impact flash spectroscopy proposed for near future planetary missions [2].

Introduction: Numerical calculations have shown that planetary scale hypervelocity impacts produce large amount of impact vapor [3]. But homogeneous shock heating is typically considered as the only energy coupling process; however, other physical processes such as shear heating [1] and microscopic localized heating [4] may play important roles. This neglect is mostly due to the physical complexity of these processes and scarcity of experimental data. Thus direct temperature measurements of impact vapor due to various conditions of hypervelocity impacts will greatly benefit our understanding of these processes.

A more direct implication to planetary science may be the evolution of planetary atmospheres. Although it is established that impact degassing occurs in volatile-rich impacts [5], the temperature of the resulting vapor cloud is not known. But whether the degassed volatile will stay on the planet or escape from it critically depends on temperature if the planet has relatively small gravity and atmospheric mass because the expansion velocity of impact vapor is controlled by its initial temperature or specific energy [1, 6].

Measuring the temperature of an impact vapor cloud, however, is very difficult. First, the generation and evolution of an impact vapor cloud in a laboratory is an extremely transient phenomenon. High-speed imaging reveals that the time scale is on the order of microseconds [1]. This time constraint excludes virtually all but optical methods. Second, a gas body does not emit black body radiation but emits line/band spectrum radiation, unless the optical thickness of the body is much larger than unity over a wide spectral range [7]. Laboratory experiments have confirmed that both atomic lines and molecular band emissions are observed in an impact flash [1, 2, 8]. Hence, identification and quantification of the evolving gaseous line emissions require both high spectral resolution and wide spectral coverage.

Theory: Intensity, I_{kn}, of atomic emission due to electronic transition from an upper energy level, n, to a lower level, k, is given by

$$I_{kn} = \frac{h\nu_{kn}}{4\pi} A_{kn} N_o g_n e^{-\frac{E_n}{KT}} / Z(T) \qquad (1)$$

where h, ν_{kn}, A_{kn}, N_o, g_n, E_n, K, T, and Z are Planck constant, the frequency of photons, Einstein coefficient, number of atoms, the statistical weight of upper energy level, the energy level of upper state electrons, Boltzmann constant, temperature, and the partition function of atoms [9]. This expression clearly indicates that the emission intensity is a function of both atomic abundance, N_o, and temperature, T, in a vapor cloud. In other words, temperature is necessary in order to obtain information on elemental abundance in a vapor cloud from atomic emission intensity.

When another line emission from a different electronic transition (n' to k') of the same atoms is available, one can eliminate the partition function, $Z(T)$, by taking the ratio of equation (1) because atoms in thermal equilibrium share the same partition function. Then a straightforward formulation yields

$$T_n - T_{n'} = -T\left(\ln \hat{I}_{kn} - \ln \hat{I}_{k'n'}\right), \qquad (2)$$

where T_n and $\hat{I}_{kn}$ are the excitation temperature of an upper state of atoms and normalized emission intensity respectively, and defined as:

$$\hat{I}_{kn} \equiv 4\pi\, I_{kn} / h\nu_{kn} A_{kn} g_n \qquad (3)$$

$$T_n \equiv E_n / K. \qquad (4)$$

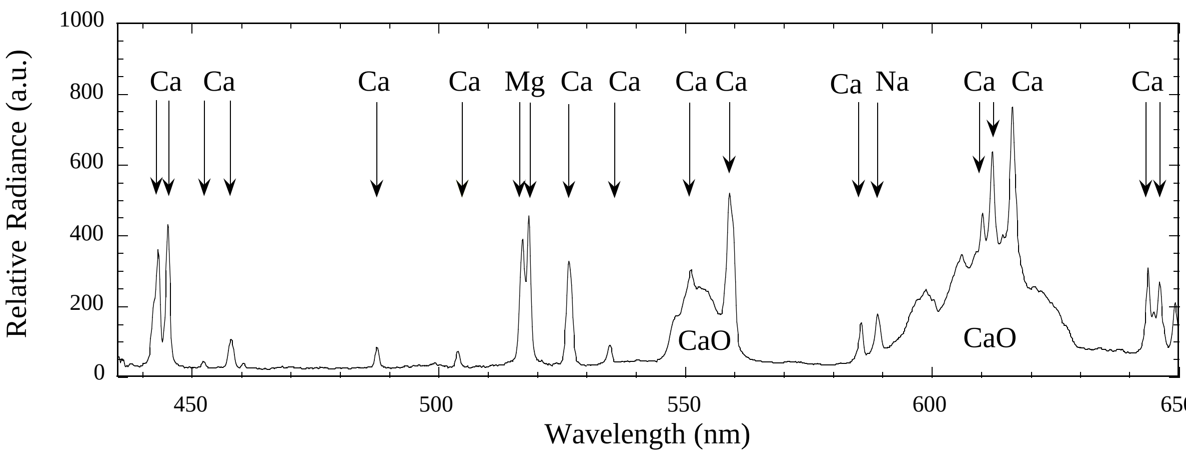
Equation (2) indicates that the temperature of vapor can be obtained as the slope of a semi-log plot of excitation temperature and normalized emission intensity. This method has been used in various scientific fields such as plasma spectroscopy [10] and lightning study [11].

Experiments and Results: To obtain high-speed response and high spectral resolution, Oriel Corporation's Gated Intensified CCD cameras and imaging spectrographs are used. The spectral resolution is up to 0.1 nm. The detector heads are sensitive over the spectral range of 200-900 nm. The minimum exposure time is 5 ns. The impact experiments were conducted at Ames Vertical Gun Range .

To unambiguously interpret the spectral signals, we maximized the photonic output from the target and minimize that from the projectiles by using easily vaporizable dolomite as target material and chemically very stable quartz as projectile material. Fig. 1 shows the emission spectrum of a vapor cloud due to impact with velocity of 5.3 km/s. The impact angle is 60° from the horizontal. The dominance of atomic and molecular emission over the thermal background indicates that the vapor cloud is dominated by gas phase rather than melt or solid phase. The atomic species and excitation temperature of each line emission were identified, and its normalized intensity was measured. Because the emission spectrum has many calcium atomic lines from various energy states (i.e., excitation temperatures), it can define a slope temperature based on equation (1). Fig. 2 shows a linear relation between the logarithm of normalized intensity of calcium emission and excitation temperatures. The linear regression slope of the plot gives the temperature of the vapor cloud: 6000±800 K. Most of the error is caused by uncertainty in Einstein coefficients of calcium atoms. Similar analysis was done for a 30° impact with the same velocity and obtained temperature of 4200±700 K. It appears that a shallower angle impact yields lower vapor temperature. This is consistent with shock heating theory and other laboratory results [1]. More data are required, however, before a more definitive correlation can be made. Nevertheless, we can demonstrate the viability of the approach.

References

[1] Schultz, P.H., *JGR*, *101*, 21117-21136, 1996; [2] Schultz, P.H. et al., *LPSC*, *XXVII*, 1149-1150, 1996; [3] e.g., O'Keefe, J.D. and T. J. Ahrens, *Proc. 8th LPSC*, 3357-374, 1977; [4] Kondo, K. and T.J. Ahrens, *Phys. Chim. Miner.*, *9*, 173-181, 1983; [5] e.g., Lange, M.A. and T. J. Ahrens, *Proc. 13th LPSC*, *JGR*, *87*, A451-456, 1982; [6] Melosh, H.J. and A.M. Vickery, *Nature*, *338*, 487-489, 1989; [7] e.g., Zel'dovich, Y.B. and Y.P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*, Academic Press, 1967; [8] Gehring, J.W. and R.L. Warnica, *Proc. 6th Hypervelocity Impact Symp.*, *2*, 627-682, 1963; [9] Canon, C.J., *The transport of spectral line radiation*, Cambridge Univ. Press, 1985; [10] Griem, H.R., *Plasma Spectroscopy*, McGraw-Hill, 1964; [11] Uman, M. A., *Lightning*, Dover Press, 1984



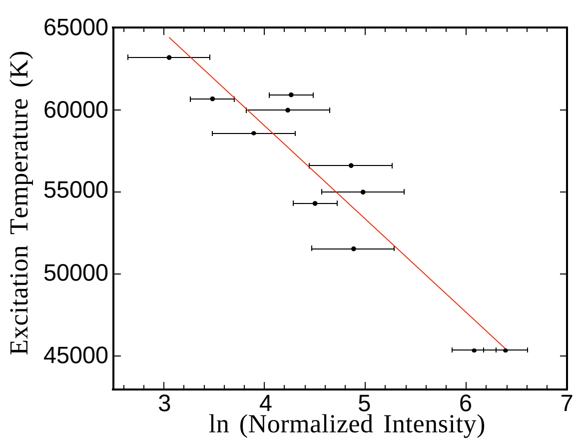


Fig. 1 Emission spectrum of a vapor cloud produced by an impact of a quartz projectile into a dolomite block target with the velocity of 5.3 km/s and impact angle of 60° from the horizontal. The diameter of the spherical impactor is 6.3 mm. The atoms of line emission and molecules of band emission are indicated in the diagram.

Fig. 2 Normalized intensity of line emission as a function of excitation temperature of the upper levels of the electron transitions. The error bars show uncertainties in Einstein coefficients of calcium atoms and do not include measurement errors. The slope of the regression line gives the temperature of vapor cloud. The impact condition are the same as in Fig. 1.