SPECTROSCOPIC OBSERVATION OF ATMOSPHERIC INTERACTION OF IMPACT VAPOR CLOUDS.

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Abstract: A series of laboratory experiments were conducted to observe atmospheric interaction of impact vapor clouds using molecular emission spectroscopy. A spectral form inversion method is used to derive the temperature of the molecular radiation source. The results of the experiments are compared with a number of models of radiation source mechanisms. Temporal variation and ambient pressure dependence of radiation temperature as well as other observation indicate that the dominant source of molecular emission in the impact vapor clouds produced in the laboratory is ablation gas from the surface of fine-grain fragments of impactors rather than impact vapor generated by direct shock heating of an impactor.

Introduction: Interaction between an atmosphere and impact-induced vapor clouds has significant importance in geology of planets. Emplacement of run-out flows around Venus craters may be controlled by atmospheric deceleration of impact vapor clouds [1,2]. Environmental damage by terrestrial impacts may be augmented by atmospheric interaction and radiation of impact vapor clouds [3]. Significant amount of atmosphere may have been lost by impact erosion on a planet with a thin atmosphere such as Mars [4].

Despite of rapid progress of hydrocode calculation in recent years, there are still many factors not considered in theoretical calculations such as radiation efficiencies of impact vapor and effects of small fragments and melt droplets in vapor clouds. Laboratory experiments show that the radiation intensity is greatly enhanced at higher pressure [5]. But the mechanism of this intensity enhancement has not been studied. The main question of this study is: Can classical hydrodynamic processes such as adiabatic expansion and shock formation explain radiation phenomena of real impact vapor clouds generated in a laboratory? If not, what is the process controlling the radiation under ambient atmosphere?

Experiments: The impact experiments were conducted at NASA Ames Vertical Gun Range. The spectroscopic instruments are the same as our previous experiments [6,7]. Polycarbonate (Lexan) projectiles and liquid water target are used to enhance vaporization efficiency and reduce the abundance of fine-grain fragments in the resulting impact vapor clouds. The ambient air pressure is from 1.3kPa to 13kPa. Air and argon gas were used in the lowest pressure cases and the higher pressure cases, respectively. The impact angle and velocity of are 30° from the horizontal and 5.7-6.1km/s, respectively. Strong Swan band emission of C_2 molecules was observed in all the impacts as well as significant blackbody radiation. The band heads of Δv_{vib}=+1 around 440-480nm were chosen for quantitative analyses. An advantage of this molecular emission hands is that reliable temperature measurements can be achieved with spectral band width much narrower than a calcium atomic emission technique [6,7].

Analyses: Swan band emission is caused by an electronic transition from $C^1\Pi_g$ to $A^1\Pi_u$ of C_2 molecules [8]. Because the energy levels of both upper state and the lower state of an electronic transition are influenced by vibrational and rotational states of molecules, the molecular emission does not form a single line spectrum but rather a series of rotational lines clustered around vibrational band heads [9]. Although the spectral structure of such molecular band emission is complex, its radiation intensity distribution is well described by quantum theory [10]. With such theory, we synthesized a number of emission spectra taking account of all the rotational lines with effects of Doppler/Lorentz broadening and self-absorption. Then the synthetic spectra is compared with actual observations to obtain radiation source temperature using a spectral form inversion method.

Results: Swan band emission spectra obtained in the experiments were successfully reproduced by theoretical synthetics (Fig. 1). The optimum temperatures to minimize the difference between observation and synthetics as a function of ambient pressure and time are shown in Figure 2. At higher ambient pressure, temperature is initially higher but decreases more rapidly with time. Although quantitative values were not obtained, the total intensity of both Swan band emission and blackbody radiation increase rapidly with ambient pressures. The duration of strong molecular emission of C_2 produced by Lexan impact in an atmosphere is much longer than Ca atomic emission and CaO molecular emission by quartz impacts into dolomite blocks at much lower atmosphere [7]. Although the accuracy is limited owing to a narrow spectral coverage, the blackbody radiation temperatures are roughly comparable to the C_2 emission. Emission of some other carbon compound such as CH and CN are observed, but emission lines/bands from argon gas, air, or water were not observed in an experiment with a wide spectral coverage (380-650nm). Thus the radiation source is high-temperature polycarbonate gas coming from impactors.

Radiation Source Mechanism: What is the process to generate the high-temperature carbon-rich gas from the a solid Lexan impactor? The first alternative of the radiating gas is decompressed impact vapor generated by shock heating of projectile during the impact. One-dimensional hydrocode calculations, however, show that the temperatures of carbon-rich vapor produced by a Lexan impact into water rapidly decreases to temperatures nearly an order of magnitude lower than observed. This is inconsistent with the long duration of strong radiation of C_2 molecules with high temperature.

Another possibility is re-heating of such decompressed impact vapor by thermal conduction from surrounding high-temperature air. As high-pressure impact vapor expands adiabatically, a shock front forms in the surrounding air. This shock compresses the air and raises its temperature extremely high. The air temperature can exceed 10,000K. Because the high-temperature air and decompressed impact vapor is in direct contact at the material interface, there should be significant conduction from air to impact vapor.

This may contribute to production of high-temperature impact vapor. Rankine-Hugoniot relation, however, indicates that air with a lower initial pressure attains higher temperature at the same shock pressure, and thermodynamics shows that the amount of heat which thermal conduction carries within a gas medium does not depend on pressure. Thus this model predicts higher temperature carbon-rich gas at lower ambient pressures and approximately the same amount of radiation intensity at different ambient pressures. These predictions do not agree with the observations.

The numerical calculation also shows that a shock front does not form in the expanding vapor cloud until very late stage because the pressure in the cloud is much greater than the surrounding air. Thus the temperature of a vapor cloud monotonically decreases during the decompression stage. This situation is not different even when an impact vapor cloud has a very large translation downrange velocity (~3km/s).

The last alternative for radiation source is high-temperature carbon-rich vapor ablated from high-speed and fine-grain fragments in impact vapor clouds. With this process, higher ambient pressure increases the rate of heat supply to the surface of fine grain fragments, thereby enhancing both temperature and total radiation intensity. Flight speed of small fragments is also a controlling factor of ablation temperature [11]. The more rapid decrease in radiation temperature at higher ambient pressure is consistent with deceleration process of small fragment by air drag. The strong blackbody radiation with high temperature supports the presence of highly-heated fine particles in vapor clouds. A simple ablation model of polycarbonate fragments indicates that such high-temperature ablation may be controlled by non-equilibrium vaporization processes.

Geological Implications: The results of the experiments and analyses have several important implications to planetary geology. First, intense ablation from fine-grain fragments in an impact vapor cloud may contribute to augmentation of vapor/melt mass. Ablation may be a very efficient process to convert high-speed solid fragments to vapor/melt. Such "secondary" vapor/melt production may be significant in oblique impacts on a planet with a thick atmosphere such as Venus. Another important factor is the temperature structure within an impact vapor cloud. Contrary to our intuitive expectations, highest temperature does not occur in impact vapor due to shock heating but rather in the ablation gas layer around colder solid/melt particles. Because such high-temperature zone is chemically very reactive, ablation processes may be important in chemical reaction within an impact vapor cloud. Third, disequilibrium process occurring around small particles will be important in radiational process during large-scale impact events. Formation of fine-grain fragments/droplets is controlled by microscopic processes such as shock comminution or surface tension. Thus the size of the smallest particles, which has the highest ablation efficiency owing to its high surface area ratio, may not be larger at planetary scales than at laboratory scales. Then radiation from planetary-scale impact vapor clouds may also be largely enhanced by ablation gas from such small particles.

References: [1] Schultz, P.H., *JGR*, *97*, 16,183-16,248, 1992; [2] Sugita S. and P.H. Schultz, *LPSC XXVII*, 1287-1288 1996; [3] Schultz, P.H. and S. D'Hondt, *Geology*, *24*, 963-967, 1996; [4] e.g., Melosh, H.J. and A.M. Vickery, *Nature*, *338*, 487-489, 1989; [5] Gehring, J.W. and R.L. Warnica, *Proc. 6th Hypervelocity Impact Symp., 2*, 627-682, 1963; [6] Sugita et al., *LPSC XXVIII*, 1393-1394, 1997; [7] Sugita et al., *JGR*, submitted, 1997; [8] e.g., Martin, M*., J. Photochem. Photobiol. A: Chem*., *66*, 263-289, 1992; [9] e.g., Herzberg, G*., Molecular Spectra and Molecular Structure. I. Spectra of Diatomic Molecules, 2nd ed*.,, pp. 658 1950; [10] e.g., Arnold, J.O. et al., *J. Quant. Spectrosc. Radiat. Transfer*, *9*, 775-798, 1969; [11] Penner, S.S. and D.B. Olfe, *Radiation and Reentry*, pp. 493, 1968

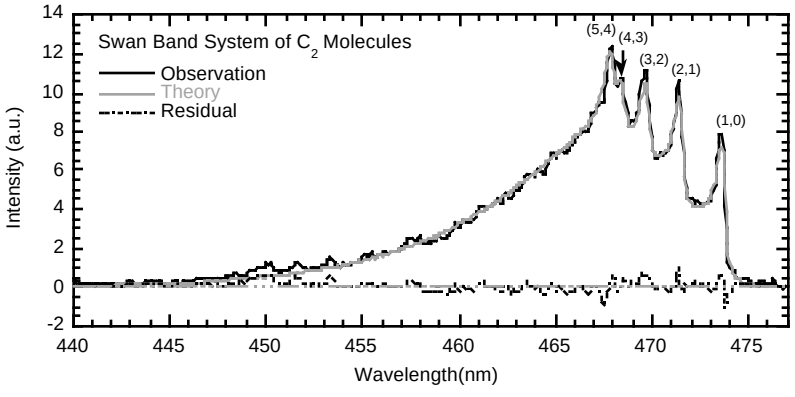

Figure 1. Comparison between observed emission spectrum and optimum theoretical synthetics. The synthetics is optimized for both temperature and optical thickness. The residual is 6.2 % of observed radiation intensity. The emission spectrum was observed in an impact of Lexan projectile into liquid water target with velocity of 6.07 km/s and angle of 30° measured from the horizontal in 13.4 kPa of argon atmosphere. The exposure time is from 1 to 9 μs after the impact. The vibrational quantum numbers of electron transitions are indicated in the diagram. Note that the observed spectrum is subtracted with blackbody radiation contribution.

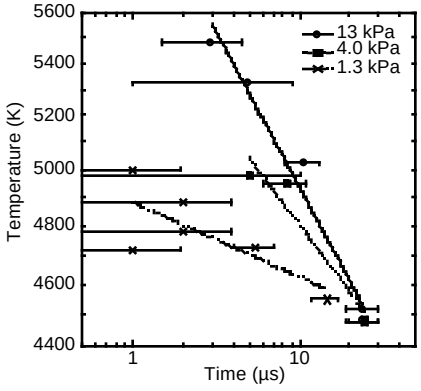

Figure 2. Temperature of C_2 radiation source as a function of ambient pressure and time. The ambient pressure is shown in the upper corner of the diagram. The horizontal bars indicate exposure time. The best fit power-law functions are also shown.