Interactions between impact-induced vapor clouds and the ambient atmosphere:
1. Spectroscopic observations using diatomic molecular emission

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The importance of interactions between impact-induced vapor clouds and an ambient atmosphere has been widely recognized, and theoretical approaches have provided significant insights. Few experiments, however, have been done to observe directly the energy partitioning during the interactions between impact vapor clouds and the ambient atmosphere. The present study attempts to understand the difference between actual and theoretical model impact vapor clouds produced under an atmosphere. A series of hypervelocity impact experiments was conducted using a spectroscopic measurement method. Plastic (polycarbonate) impactors allowed simulating vaporization phenomena associated with natural impactors (e.g., silicates and metals) at high impact velocities into water. Water as the target material served to suppress the effect of fine-grained fragments from the target. Emission spectra of the leading part of downrange-moving impact vapor clouds were captured with high-speed spectrometers as a function of time for various ambient pressures. The emission spectra exhibit strong molecular bands from carbon compounds as well as blackbody continuum radiation. In order to estimate the temperature of the radiation source, we carried out a spectral-form inversion analysis based on diatomic emission theory. Obtained molecular radiation temperatures range from 4500 K to 5500 K with relatively high accuracy (~2%) and place a number of well-defined constraints for the radiation source. A simple theoretical model that is often assumed for an impact-induced vapor cloud, however, does not readily satisfy the constraints. This strongly suggests that real impact-induced vapor clouds may be more complex than previously thought.


1. Introduction

Understanding the interaction between an impact-induced vapor cloud and an atmosphere has a number of important consequences. First, run-out flows around Venus craters may be controlled by such interactions. Both their unique occurrence on Venus and exotic morphologies can be explained if impact-vapor condensates contribute to flow generation [Schultz, 1992; Sugita and Schultz, 2002]. Atmospheric deceleration of the downrange-moving vapor clouds controls the downrange offset of the source regions of run-out flows, and condensation from this cloud may comprise much of the run-out material [Schultz, 1992; Sugita and Schultz, 2002]. Second, shock interaction between impact vapor clouds and atmosphere may produce a large amount of thermodynamically metastable chemical compounds, such as simple organic molecules in the early Earth atmosphere [e.g., Fegley et al., 1986; McKay and Borucki, 1997], nitrogen oxides in the modern atmosphere [e.g., Zahnle, 1990], and N$_2$ in the Titan atmosphere [McKay et al., 1988]. Third, the expansion of high-energy impact vapor clouds on planets and satellites during the late-stage heavy bombardment period has been proposed to...
cause significant atmospheric escape [e.g., Walker, 1986, Melosh and Vickery, 1989].

[1] However, experimental validation on this process has not been done in detail previously. Does existing theory predict the actual process adequately? If not, what is the cause of the discrepancy? The goal of this study is to understand the difference between actual and theoretical impact vapor clouds. Theoretical studies usually assume that the vapor occurs as a pure gas phase, and often treat vapor clouds as ideal-gas bodies. If actual impact vapor clouds differ from conventional theoretical models, how does the difference affect our previous inferences? To address this question, we observed interactions between impact vapor and the ambient atmosphere at the NASA Ames Vertical Gun Range (AVGR) using the high-speed spectroscopic approach described previously [Sugita et al., 1998; Sugita and Schultz, 1999].

[4] It is important to note that an impact-induced vapor cloud is not a single uniform entity but rather a chemically and thermally heterogeneous entity with multiple components each having different momentum, energy, and mass [Schultz, 1996]. Among the multiple components of an impact vapor cloud, this study focuses on the downrange-moving component, which is the same component studied by Sugita and Schultz [2002]. Since this component is driven mainly by the impactor [Schultz, 1996], observing its evolution is also very important in studying the fate of an impactor [e.g., Schultz and Sugita, 1994].

[5] Laboratory impact experiments are limited in velocity. Plastic impactors, however, have a heat of vaporization much smaller than that of silicates and metals. Dimensional analysis by Schmidt et al. [1995] indicates that an impactor with a low heat of vaporization at a low impact velocity should simulate vaporization phenomena of an impactor with a high heat of vaporization at a high impact velocity. The radiation spectrum of such plastic impacts, however, is dominated by molecular band emission of carbon compounds. Because molecular emission spectra are much more complex than atomic line emission spectra, the spectroscopic methods previously used [Sugita et al., 1998; Sugita and Schultz, 1999] need to be extended.

[6] There have been extensive efforts made to obtain quantitative thermodynamic information based on the spectral pattern of molecular emission from high temperature gas. A standard approach is to calculate a synthetic spectrum of given molecular species at different temperatures and optical thicknesses and to compare them with an observed spectrum [e.g., Whiting et al., 1967; Arnold, 1968; Arnold et al., 1969]. This approach, however, does not allow precise comparison between a theoretical spectrum and observation; nor does it allow an error assessment. Another approach uses different narrow bands of a molecular spectrum and compares the relative intensities [e.g., Abhilasha and Thareja, 1993; Park et al., 1998]. This provides direct temperature measurements. Nevertheless, such an approach requires high spectral resolution and high signal-to-noise (S/N) ratio. These requirements are not yet compatible with impact flash spectroscopy. Impact flash lasts for a very short period of time, and it is extremely time-consuming to reproduce the same condition of hypervelocity impacts. Thus techniques that are usually used to increase the S/N ratio without reducing spectral resolution (such as taking longer exposure time and averaging many spectra taken under the same condition, i.e., “stacking”) are not practical here. Consequently, obtaining emission spectra of hypervelocity impacts with a very high resolution and a high S/N ratio is difficult. Such challenges lead to a third approach: spectral form inversion. Spectral form inversion iteratively compares a theoretical spectrum and an observed spectrum while gradually changing controlling parameters. When the difference between the two spectra is minimized, the calculation ceases and yields the optimum parameter set. Because this approach takes advantage of the whole structure of a molecular emission band, it can achieve very accurate determination of temperature at a relatively low spectral resolution.

[7] Here, it is worthwhile noting that the use of molecular emission spectra in analysis of impact-induced luminescence demonstrated in this study widens the range of the application of impact-flash spectroscopy greatly. For example, higher-velocity impacts may generate silicate vapor including a variety of diatomic oxide molecules, such as SiO, MgO, FeO, and AlO. But these oxides may not atomize even at high temperatures because their dissociation energy is very high. Even if they do dissociate and emit atomic lines, the number of emission lines is sometimes so limited that they may not yield accurate temperature estimates. Diatomic molecules, however, provide complex enough spectral patterns that temperature can be measured with a high accuracy.

[8] Another example is measurement of volatile elements, such as C, N, O, and H. These are very important elements in understanding the origin and evolution of an atmosphere and an ocean. They are also the main constituents of life. The behavior of these volatile elements upon impact vaporization is of great importance. However, energy levels for the lowest excitation state of these atoms are very high [e.g., Reader et al., 1980]. Thus, despite the ease of evaporation, they do not necessarily emit strong atomic line emission in the range of temperatures produced in hypervelocity impacts in a laboratory. Furthermore, diatomic molecules made of these elements, such as C2, O2, N2, H2, CO, CN, CH, NO, OH, and NH, are well characterized by both theory [e.g., Herzberg, 1950] and experiments [e.g., Pearse and Gaydon, 1976; Huber and Herzberg, 1979]. Consequently, use of molecular emissions of these elements provides an alternative thermometer.

2. Experimental Conditions

[9] Impact experiments were conducted at the AVGR with polycarbonate material (General Electric, Lexan) impactors. Among a variety of plastic materials, Lexan was chosen as previous experience demonstrated that it provides high launching reliability at high impact velocities. In fact, the repeatability in impact velocity in a series of experiments with Lexan impactors in this study was as small as about 3%, i.e., 5.9 ± 0.2 km/s. Liquid water was used as target material in order to minimize the contribution of fine-grained impact debris from the target. The impact angle was fixed at 30° from the horizontal throughout this study. The relatively low impact angle is suitable for observing a downrange-moving impactor-derived vapor cloud because it separates well from other components of a vapor cloud at this angle [Schultz, 1996].
Ambient pressure varied from 0.013 bar (10 torr) to 0.13 bar (100 torr). Gas species in the ambient atmosphere, however, introduces a new variable. At a low ambient pressure (0.013 bar), air was used as an ambient atmosphere. Since the vapor pressure (0.012 bar at 10°C) of liquid water is close to the total ambient pressure, the ambient atmosphere should be dominated by water vapor. At higher atmospheric pressures, however, air cannot be used because it would introduce potential risk for safety. Because the two-stage light gas gun at the AVGR uses hydrogen in the second-stage pressure chamber, the presence of a large amount of oxygen inside the impact chamber needs to be avoided. For higher pressures of ambient atmospheres, we introduced argon gas into the impact chamber after evacuating air in the impact chamber down to about 0.013 bar (10 torr). The freezing and boiling of water below this pressure precludes complete evacuation of air. Consequently, in the higher-pressure cases (0.13 bar and 0.04 bar), the ambient atmosphere predominantly consists of argon gas with minor amount of water vapor and air. To assess the effect of different atmospheric gas, helium gas was also used to purge residual air from the impact chamber for an experiment.

Two spectrometers capture the emission spectra of the leading part of downrange-moving vapor clouds. The spectrometer system used in this study is described by Sugita et al. [1998]. Viewing geometry in this study is also similar, wherein the two spectrometers view down on the impact site through a window on the top of the impact chamber. Here, however, the two spectrometers observe different positions in the impact chamber at different times. This strategy allows observation of a given vapor cloud at different stages of its evolution as it moves downrange.

The diameter of the field of view (FOV) of the spectrometers is approximately 5 cm at the target plane. This is significantly smaller than the size of self-luminous vapor cloud produced in the experiments (Figure 1). It is possible that the spectrometers receive stray lights from a part of a vapor cloud other than its leading edge because there may be reflection on the floor and the walls of the impact chamber. The contribution of such spurious light, however, is very small. We used a dark chamber floor and covered the chamber walls with black cloth in order to minimize reflection. The high-speed photographic observation (e.g., Figure 1) indicates that the leading edge exhibits the highest luminosity within a vapor cloud. Furthermore, when a spectrometer measures the chamber floor a few centimeters in front of the leading edge of an impact vapor cloud, the observed spectral intensity is less than 1/100 of the spectrum of the leading part of a vapor cloud.

Although impact flash spectra from Lexan impacts show many bands of emission of a variety of carbon compounds, we focused on a part of Swan-band emission of $C_2$ molecules at 450–475 nm. There are several reasons for this choice. First, Swan-band emission is one of the

Figure 1. (opposite) High-speed photographs of a Lexan into liquid water within a 0.13 bar of argon atmosphere. The impact velocity and angle are 6.07 km/s and 30° from the horizontal, respectively. Time after the impact is indicated in the figure.
strongest emission bands in the observed spectra of experimental impacts. This enhances the signal-to-noise (S/N) ratio of spectral data. Second, since $C_2$ is one of the most studied diatomic molecules, its fundamental spectroscopic constants such as electronic moment of transition, Franck-Condon factors, and H"{o}nl-London factors are well established (see Appendix A). This allows accurate calculation of synthetic emission spectra. Third, the particular cluster of emission bands at 450–470 nm exhibits many band heads in a spectrogram with a moderate spectral resolution. The relative height of well-resolved band heads provides accurate vibrational temperatures [e.g., Park et al., 1998]. Fourth, the spectral coverage required for the particular emission bands is narrow. It is less than a fourth of that required for Ca and Cu atomic lines used by Sugita et al. [1998] and Sugita and Schultz [1999].

3. Analysis

[14] Synthetic spectrograms are calculated in order to extract information on temperature of the impact vapor clouds from observed emission spectra. There are three steps in such calculations. The first step is to calculate a “source” spectrum, i.e., emission intensity per a unit mass of $C_2$ molecules. This step considers all the rotational lines and the effects of line broadening, but neglects self-absorption (i.e., optically thin approximation). The second step calculates the effect of self-absorption. The third step assesses the effect of the finite spectral resolution of spectrometers. A spectrogram obtained in the first step is called “source spectrum” and is denoted here by $E_s$. The calculation procedure of a source spectrum is given in Appendix A. A spectrogram calculated in the second step is a “true spectrum” observed by an ideal spectrometer with an infinitely high spectral resolution. Because a real spectrometer has a finite spectral resolution, the “true spectrum” needs to be convoluted with the instrument function of the spectrometer. The result of the synthetic calculation can then be compared with experimental results. Then the optimum temperature that minimizes the difference between an experimental spectrum and a theoretical spectrum is sought.

[15] A source spectrum $E_s$ given in Appendix A is a spectrum emitted from an optically thin radiation source. In reality, however, the source spectrum is altered by the effect of self-absorption because a radiation source has finite optical thickness. The radiance $I$ after self-absorption is given by

$$I(\lambda) = B_T(\lambda) \left[ 1 - \exp \left( \frac{E_s(\lambda) l}{B_T(\lambda)} \right) \right] \left( \text{W/m}^2/\text{nm}/\text{sr} \right) \tag{1}$$

where $B_T$ and $l$ are the blackbody radiation function (i.e., Planck function) at temperature $T$ and the thickness of radiation source along the line of sight, respectively [e.g., Arnold et al., 1969]. The Planck function is given by

$$B_T = \frac{2hc^2}{\lambda^5} \exp\left( \frac{hc}{\lambda kT} \right) - 1 \left( \text{W/m}^2/\text{nm}/\text{sr} \right). \tag{2}$$

Equation (1) assumes that the radiation source is homogeneous and is in thermal equilibrium. Incident radiation from outside the radiation source is also assumed to be negligible. Since radiation sources produced by hypervelocity impacts are not expected to be homogeneous, equation (1) does not apply in a strict sense. Nevertheless, it should give a first-order estimate of the spectral characteristics of a radiation source.

[16] Spectral radiance $I$ given by equation (1) is often called a “true spectrum.” This spectrum represents what an ideal spectrometer with infinitesimal spectral resolution would observe. The effect of finite spectral resolution of the spectrometer needs to be introduced in order to convert a “true spectrum” into a “synthetic spectrum” that can be compared directly with an observed spectrum. A synthetic spectrum $I_{syn}$ is given by a convolution of a true spectrum and the instrument function $\Psi$ ($\text{nm}^{-1}$) of a spectrograph [e.g., Seshadri and Jones, 1963]:

$$I_{syn}(\lambda) = \int_{-\infty}^{\infty} I(\lambda + \Delta\lambda) \Psi(\Delta\lambda)d\Delta\lambda/W/\text{m}^2/\text{nm}/\text{sr}. \tag{3}$$

The integral over infinity in equation (3) can be approximated with that over a relatively narrow wavelength range because the instrument function $\Psi$ converges to zero very quickly as the absolute value of $\Delta\lambda$ increases. Since the spectral resolution of the spectrometers used in this study (FWHM ~ 0.4 nm) is much larger than the width of a typical atomic line, line profiles of an atomic emission line from a mercury-argon lamp (Oriel Corporation, 6035 Hg(Ar) Lamp) captured by the spectrometers provide the instrument functions. The instrument function was measured each time the configuration of the spectrometers was changed.

[17] The last difference between synthetic and observed spectra is the background continuum. Planck function fits the continuum radiation well and is subtracted from the observed spectrum before comparing with theoretical synthetics.

[18] The spectral pattern of theoretical synthetics is controlled by temperature $T$, column density $N_J$ ($\text{cm}^{-2}$) of $C_2$ molecules, and the ratio $\alpha$ of Lorentz/Doppler broadening ratio. For different values of these controlling parameters, a synthetic spectrum is calculated and compared with an observed spectrum. The degree of similarity is assessed with the square mean $Er$ of the difference defined as

$$Er = \frac{\int [I_{syn}(\lambda) - I_{obs}(\lambda)]^2d\lambda}{\int[I_{obs}(\lambda)]^2d\lambda}, \tag{4}$$

where $I_{obs}$ is an observed spectrum. The combination of parameters that minimizes the error $Er$ is considered to be the optimum condition to describe an observed emission spectrum.

4. Experimental Results

[19] Figure 1 shows high-speed photographs of a self-luminous vapor cloud induced by a Lexan projectile impacting obliquely a water target. In the first frame before the impact in Figure 1, a self-luminous wake induced by shock interaction between the projectile and the atmosphere is recorded. Upon the impact, an intense self-luminous vapor cloud is generated and moves downrange rapidly. The vapor...
cloud continues to move downrange and expands laterally very rapidly. The basic process recorded in the photographs is further underscores results of impact vaporization experiments under different conditions [Schultz, 1996].

[20] The field of views and exposure times of spectrometers were prescribed to capture the emission spectra of the leading edge of a downrange-moving vapor cloud. In the first set of the experiments, we took rather long exposure times and wide spectral ranges to survey what molecules and atoms are present in the vapor clouds. Second, we observed emission spectra with much shorter exposure times and a narrower spectral range for detailed analysis using the C$_2$ Swan band emission.

4.1. Spectral Content

[21] Strong emission bands from several carbon compounds, such as C$_2$, CH, and CN are observed in the spectral range between 400–650 nm with lower dispersion configurations of the spectrometers (Figure 2). No water-derived compounds such as OH, however, were spectrally observed, although strong OH bands are located in a much shorter wavelength range than the current coverage [e.g., Pearse and Gaydon, 1976]. Further, no spectral signature of either air (e.g., O, N, O$_2$, N$_2$, NO, etc.) nor argon gas was identified. In one of the experiments with a relatively high ambient pressure (0.13 bar) of an argon atmosphere, two spectrometers covered the spectral range between 405 and 440 nm, where argon atoms have very strong emission lines [e.g., Reader et al., 1980]. Still, only the CN band emission was observed in this spectral range (Figure 2). Thus the dominant radiation source of the observed emission is a high-temperature carbon-rich gas. This radiation source cannot be the shock-heated ambient atmospheric gas or the vaporized water. The vapor must originate from the Lexan projectile.

4.2. Molecular Temperature

[22] In order to capture the spectral pattern of C$_2$ Swan-band emission accurately with $\Delta \nu = +1$, a higher dispersion...
configuration was used in most of the impact experiments in this study. The spectral resolution (FWHM) of the configuration is about 0.4 nm, with a spectral coverage from 440–475 nm. Obtained spectra are analyzed with the inversion method described above. Comparison between an observed spectrum of Swan-band emission and theoretical synthetics with different controlling parameters is shown in Figure 3. When too low a temperature is used for a synthetic calculation, the intensities of band heads at longer wavelengths (471.5 nm and 473.7 nm) become too high, whereas those at shorter wavelengths (467.8 nm and 468.5 nm) become too low (Figure 3a). The intensity of the tail part of emission bands extending from around 445 nm to 467 nm is too low in a synthetic spectrum with too low a temperature (Figure 3a). When too high a temperature is used, the opposite occurs (Figure 3b). Only when an optimum temperature is chosen, can the pattern of intensity be reproduced correctly (Figure 3c). Note that the intensity scale for a synthetic spectrum is adjusted such that the mean square difference $E_r$ with the observation may be minimized.

When too large a value of column density of $C_2$ molecules is used, a synthetic spectrum with the optimum temperature fails to resemble the observed spectrum (Figure 3d). A large column density enhances the effect of self-absorption, thereby reducing the intensities of band heads relative to the tail. Self-absorption is more effective in the band heads at 467.8 nm and 468.5 nm than in other bands because the band heads represent the densest population of rotational lines. This reduces the intensities of these band heads relative to the others. When too low a
value of column density is used, the opposite occurs (Figure 3e). Consequently, the effect of self-absorption is similar to that of temperature, and these two effects are often difficult to resolve. The exact ratio of changes due to temperature and self-absorption, however, are different, and a quantitative analysis can determine simultaneously the optimum values of both temperature and column density. Figure 3c reveals that the square mean error for a very small value of column density (Figure 3e) is not much larger than that for the optimum case. This is because the effect of self-absorption for the optimum condition (Figure 3c) is already small enough that the synthetic spectrum is not very different from the source spectrum. The radiance $I$ including the effect of self-absorption becomes proportional to a source spectrum $E_s$ when column density is small (see equation (21)). Thus a column density smaller than the optimum condition does not change the spectral pattern significantly. Consequently, the lower limit of the column density of $C_2$ molecules is not well constrained in this case.

Figure 4. Contour map of the square mean error of synthetic spectra as a function of both temperature and the column density of $C_2$ molecules. The observed spectrum shown in Figure 3 is used here for the analysis. The minimum error is given by 4500 K of temperature and 0.6 $\mu$mol/cm$^2$ of column density of $C_2$ molecules. Although this error analysis assumes the ratio of line broadening factor $\alpha$ of 3, the optimum temperature and column density has little dependence on $\alpha$. Note that there are so many contour lines in the figure that they appear as bands of color in the parameter regions far from the optimum condition.

respectively. Although the calculation is only for a single value of the line-broadening ratio $\alpha$ of 3, the optimum temperature and column density of $C_2$ molecules depend little on $\alpha$. The optimum temperature and column density for each emission spectrum in this study are obtained by an exhaustive search of the parameter space for the global minimum of $Er$.

[25] The analysis of a $C_2$ molecular spectrum does not give a direct assessment of the total column density of a high-temperature impact vapor cloud (i.e., including all the other molecules). For example, an impact vapor cloud with larger amount of $C_2$ molecules can have a small total mass, or an impact vapor cloud with weak $C_2$ emission may contain a large amount of other molecules that do not emit strong light. Furthermore, estimated column densities of $C_2$ molecules have relatively large uncertainties as discussed above. Consequently, the column density of $C_2$ molecules in emission is not used for the interpretation of the physical condition of the observed emission in this study.

[26] A summary of temperature derived from $C_2$ molecular emissions is given in Figure 5. From the scatter in Figure 5, uncertainty in the temperature determination can be estimated. There are several pairs and a group of measurements with practically identical experimental conditions: measurements under 0.013 bar (10 torr) of atmosphere with exposure times of 0–2 $\mu$s, 0–4 $\mu$s, and 4–7 $\mu$s, and measurements under 0.13 bar (100 torr) of atmosphere with exposure times of between about 20 and 30 $\mu$s. The relative difference in estimated temperature within these pairs and a group is generally about 100 K or less. An

Figure 5. Temperature of $C_2$ molecular radiation as a function of both time and ambient atmospheric pressure. A horizontal bar indicates exposure time. Ambient pressures are indicated in the figure. The ambient gases used for the experiments are a dominant amount of argon and minor amounts of air and water vapor in both 0.13 bar and 0.04 bar cases, and air-water vapor mixture in the 0.013 bar cases. Impact velocities are $5.9 \pm 0.2$ km/s, and impact angle is $30^\circ$ for the horizontal.
exception is the early time exposure (0–2 μs) under 0.013 bar (10 torr) of atmosphere, in which exceptionally low radiation intensity reduced the S/N ratio down to as small as about 3 (i.e., optimum $E_r \sim 30\%$). Because the other spectra have much higher intensity and smaller mean square error (i.e., minimum $E_r \leq 10\%$), uncertainty in temperature is expected to be about 100 K (~2%). Consequently, the variation in temperature as a function of both atmospheric pressure and time observed in Figure 5 is statistically significant.

There are several important features in the observed temperatures. First, they are very high (4500–5500 K). Such temperatures are almost as high as jetting temperatures produced by quartz impacting solid dolomite blocks, i.e., 4000–6000 K [Sugita et al., 1998]. Second, the vapor temperature decreases monotonically with time. Third, the initial temperature is higher at higher atmospheric pressures. And fourth, the rate of temperature decay is greater at higher atmospheric pressures.

### 4.3. Radiation Intensity and Blackbody Radiation

As described by Sugita et al. [1998], the spectrometer system in this study provides high accuracy for relative intensities but has significant uncertainty in absolute intensity calibration. The difference in radiation intensity for higher ambient pressures, however, was so large that the gain of the spectrometers needed to be reduced by an order of magnitude. The tentative estimate for the absolute radiation power as a function of time and atmospheric pressure shown in Figure 6 also indicates that the radiation intensity is higher at higher-pressure experiments (i.e., 0.04 bar and 0.13 bar). Thus the enhanced radiation intensity at higher atmospheric pressures is real, despite uncertainty in absolute calibration in the spectrometer system.

The temporal variation of radiation power also shows a characteristic trend. Radiation power increases during early stages of the evolution of impact vapor clouds and decreases subsequently (Figure 6). This trend is observed at all the atmospheric pressure used in this study, although the timing of the increase and decrease varies. The reproducibility of this phenomenon eliminates the possibility that it may result from some measurement error such as a problem in pointing of the foreoptics of the spectrometers and uncertainty in absolute intensity calibration of the spectrometers.

Strong blackbody radiation was observed in every spectrogram. The intensity of the blackbody radiation is comparable to that of molecular emission (Figure 2). This differs from impacts of quartz projectiles into dolomite targets at much lower ambient pressures (0.5–1 mb) [Sugita et al., 1998]. At low ambient pressures, the intensity of blackbody radiation is initially very low but subsequently increases. Although a blackbody temperature can be estimated by spectral fitting with a Planck function, the narrow wavelength coverage ($\Delta \lambda \sim 30$ nm) precludes precise determination of temperature. The resulting estimate indicates, nevertheless, blackbody temperatures roughly comparable to those determined from $C_2$ molecular emission (i.e., 4500–5500 K). This is also different from experiments under lower pressures (0.5–1 mb) with quartz projectiles and dolomite targets that yielded the blackbody temperatures significantly lower than those estimated from atomic emission [Sugita et al., 1998].

### 5. Discussion

The results obtained in the spectroscopic observation provide rather strict constraints on the mechanism of radiation from impact-induced vapor clouds rapidly moving/expanding in a thick atmosphere. When the radiation mechanism is modeled, it needs to account for the observational constraints: enhanced radiation intensity at higher ambient pressures, strong blackbody radiation with temperatures comparable to the molecular temperatures, and the temperature history of molecular radiation.

A simple theoretical model that is often assumed for an impact-induced vapor cloud, however, does not readily
satisfy these constraints. If the spectrally observed impact vapor in this study is a direct product of the initial shock heating due to collision of a high-speed projectile with the target, its initial temperature should not depend on the ambient pressure significantly. The ambient atmosphere does not influence the initial shock heating because the ambient pressure is smaller than the peak shock pressure induced by the collision between a projectile and a target by many orders of magnitude. Furthermore, if the rate of decrease in vapor temperature is controlled by the adiabatic expansion of the impact vapor cloud, temperature should decrease more slowly under a higher ambient pressure. These expectations are inconsistent with the observational constraints obtained in this study. This strongly suggests that the radiation mechanism in a hypervelocity impact under a thick ambient atmosphere may be much more complex than such a simple model. Nevertheless, resolution of this problem requires very extensive theoretical calculations. This is beyond the scope of this study and is explored in a separate contribution [Sugita and Schultz, 2003], which is referenced as Paper 2. Comparison between the observational constraints obtained in this study and the theoretical calculations by Paper 2 indicates that the observed high-temperature radiation could not come from either the impact-induced vapor or the shock front between impact vapor and the ambient atmosphere. Rather, it comes from ablation vapor generated on the surface of small, high-speed fragments of the projectile entrained in the impact vapor cloud.

6. Conclusions

A series of impact experiments with polycarbonate projectiles and liquid-water target are conducted under varying atmospheric pressures. High-speed spectrometers focused on the leading part of downrange-moving vapor clouds, which are mainly derived from ricocheted projectile debris, revealed both strong molecular band emission of carbon compounds and blackbody background.

In order to analyze the molecular band emission quantitatively, we used a spectral inversion calculation. Results of the calculation provided highly accurate temperatures with an error of about 100 K (or 2%) for most of the obtained emission spectra. The results also provided several well-defined constraints on the possible source of the observed molecular radiation:

1. The temperature of molecular radiation is extremely high, ranging from 4500 K to 5500 K.
2. Initial radiation temperature is higher at high ambient pressures.
3. Radiation temperature decreases more rapidly at higher ambient pressures.
4. Radiation intensity is higher at higher ambient pressures.
5. Radiation power increases in the first few to twenty microseconds but subsequently decreases.
6. The intensities of molecular band emission and blackbody continuum are comparable in the all observed spectra.
7. Although the estimated blackbody radiation temperatures have uncertainty, they are roughly comparable to molecular radiation temperatures.

These experimental constraints provide a basis for modeling the mechanism of radiation from a downrange-moving vapor cloud within a thick atmosphere. A simple theoretical model that is often assumed for an impact-induced vapor cloud, however, does not readily satisfy the constraints. This strongly suggests that real impact-induced vapor clouds may be more complex than previously thought.

Appendix A: Calculation of Source Spectrum of C₂ Molecules

Although molecular band emission appears to be spectrally continuous, it consists of numerous individual emission lines [e.g., Herzberg, 1950]. The wavelength or wave number of each rotational line of a molecular band emission is calculated from the difference in two rotational energy levels. The wave number ν of a rotational line is given by

\[ \nu = T_e' - T_e'' + G'(v') - G''(v'') + F'(J') - F''(J'') \] (A1)

where the variables in equation (A1) are the energy level of an electronic state at the equilibrium position \( T_e \), vibrational energy \( G \), rotational energy \( F \), vibrational quantum number \( v \), and total rotational quantum number \( J \). A single prime and a double prime denote the upper and the lower states of an electronic transition of molecules, respectively. Note that the energies \( T_e, G, \) and \( F \) are in the unit of wave number \( (\text{cm}^{-1}) \).

The vibrational energy \( G(v) \) is approximated as

\[ G(v) = \omega_v \left( v + \frac{1}{2} \right) - \omega_v^2 \left( v + \frac{1}{2} \right)^2 + \omega_v^3 \left( v + \frac{1}{2} \right)^3 \] (A2)

where \( \omega_v, \omega_v^2, \) and \( \omega_v^3 \) are vibrational constants obtained from spectroscopic experiments. Because the wavelength shift due to spin splitting is very small for Swan-band emission [Herzberg, 1950; Arnold, 1968; Arnold et al., 1969], the spin splitting is ignored in the calculation. The effective line wavelength of a triplet transition in Swan band is calculated with rotational energy approximated as

\[ F(J) = F(K) = B_v[K(K+1) + 4Z_2] - D_v\left(K + \frac{1}{2}\right)^4 \] (A3)

where \( K, B_v, \) and \( D_v \) are rotational quantum number without spin and two rotational constants for the vibrational level of \( v \), respectively. The factor \( Z_2 \) is given by

\[ Z_2 = \frac{\Lambda^2 Y(Y-1) - \frac{4}{3} - 2K(K+1)}{3\left[ \Lambda^2 Y(Y-4) + \frac{4}{3} + 4K(K+1) \right]} \] (A4)

and

\[ Y = A/B_v \] (A5)
where $A$ is a spin-orbit interaction parameter [e.g., Huber and Herzberg, 1979]. The rotational constants $B_v$ and $D_v$ are given by

$$B_v = B_r - \alpha_r \left( v + \frac{1}{2} \right) + \gamma_r \left( v + \frac{1}{2} \right)^2$$  \hspace{1cm} (A6)

$$D_v = D_r + \beta_r \left( v + \frac{1}{2} \right)$$  \hspace{1cm} (A7)

where $B_r$, $D_r$, $\alpha_r$, $\beta_r$, and $\gamma_r$ are rotational constants at the equilibrium position and are obtained from spectroscopic measurements. The constants used in equations (A1) through (A7) are taken from Huber and Herzberg [1979] and Martin [1992].

[43] The spectral radiance $E_v$ of spontaneous emission from a rotational line is given by

$$E_v(\lambda) = \sum_{J'J''\lambda'} 4\pi^2 c N' 3(2J' + 1) \left| \overline{E}(\nu', \nu) \right|^2$$

$$\cdot q_{\nu', \nu} S_{J'J''\lambda', \lambda} \delta(\lambda - \lambda_v) \text{ (W/m}^3\text{/nm/sr)}$$  \hspace{1cm} (A8)

where the variables in equation (A8) are the speed of sound $c$, resultant orbital angular momentum of electrons along the internuclear axis $\lambda$, central wavelength of a rotational line $\lambda_v$, the dielectric constant of vacuum $\varepsilon_\infty$, characteristic internuclear separation $R_{\nu', \nu''}$ for the $(\nu', \nu'')$ transition (i.e., r-centroid), Franck-Condon factor $q_{\nu', \nu''}$, line strength factor $S_{J'J''\lambda', \lambda}$, the square of the electronic transition moment $\overline{E}(\nu', \nu)$, line broadening factor $\delta$, and number density of $C_2$ molecules in the upper energy level of the transition $N'$ [e.g., Arnold et al., 1969]. The Franck-Condon factor $q_{\nu', \nu''}$ and electronic transition moment $\overline{E}(\nu', \nu)$ are taken from the data by Danylewych and Nicholls [1974]. The line strength factor $S_{J'J''\lambda', \lambda}$ depends on rotational-line branch. If $J' = J'' - 1$, a rotational line belongs to the P branch; if $J' = J'' + 1$, it belongs to the R branch. Although there are other branches, those are negligibly small for Swan-band emission [e.g., Arnold et al., 1969]. The strength factor for P and R branches for Swan-band emission are given by

$$P\text{ branch : } S_{J'J''\lambda', \lambda} = S_{K'K''\lambda', \lambda} = K' + 1$$  \hspace{1cm} (A9)

$$R\text{ branch : } S_{J'J''\lambda', \lambda} = S_{K'K''\lambda', \lambda} = K'$$  \hspace{1cm} (A10)

where spin splitting is ignored [e.g., Herzberg et al., 1950]. The symbol $K$ denotes rotational quantum number without spin.

[45] The number density $N'$ of particles in their upper state is given by a Boltzmann distribution if they are in a thermal equilibrium:

$$N' = \frac{N_0 d'(2K' + 1)}{Q(T)} \exp \left\{ -\frac{hc}{kT} \left( E_r' + G'(\nu') + F'(K') \right) \right\} \text{ (m}^{-3}\text{)}$$  \hspace{1cm} (A11)

for are the total number density $N_0$ of $C_2$ molecules in the all energy levels, electronic multiplicity $d$, partition function $Q$, Planck constant $h$, Boltzmann constant $k$, and temperature $T$ [e.g., Herzberg et al., 1950]. Electronic multiplicity $d$ is given by

$$d = b(2S + 1)$$  \hspace{1cm} (A12)

where $b$ and $S$ are lambda doubling factor and quantum number of resultant spin of $C_2$ molecules, respectively. For the upper electronic state of Swan-band emission, $b$ and $S$ are 2 and 1, respectively [e.g., Herzberg et al., 1950].

[46] The partition function $Q$ of $C_2$ molecules is calculated with

$$Q(T) = \sum_{v=0}^{\nu_{\text{max}}} \sum_{j=0}^{\nu_{\text{max}}} kT \exp \left\{ -\frac{hcG(v_j)}{kT} \right\}$$

$$\exp \left\{ -\frac{hcG(\nu_{\text{max}})}{kT} \right\} \leq 0.001$$  \hspace{1cm} (A13)

where $\nu_{\text{max}}$ is the cut-off vibrational quantum number [Arnold et al., 1969]. The cut-off number satisfies either

$$G(\nu_{\text{max}} + 1) \geq G(\nu_{\text{max}}).$$  \hspace{1cm} (A15)

The right most summation of equation (A13) is carried out over twelve electronic states complied by Martin [1992].

[47] The rotational line profile $\phi(\lambda - \lambda_v)$ considers both Doppler and Lorentz broadening. The full width of half maximum (FWHM) $\sigma_D$ of Doppler broadening is given by

$$\sigma_D = \frac{2\lambda_v}{c} \sqrt{\frac{2RT\ln 2}{\mu}}$$  \hspace{1cm} (A16)

where $R$ and $\mu$ are gas constant and molecular weight, respectively [e.g., Mitchell and Zemansky, 1961]. Lorentz broadening in a high-pressure environment, as in the present experimental condition results from pressure broadening [e.g., Mitchell and Zemansky, 1961]. It is difficult, however, to estimate Lorentz breadth of the $C_2$ Swan-band emission on the basis of the observation in this study, because it is much smaller than the spectral resolution of the spectrometer system and the pressure in the vapor clouds is unknown. Consequently, the FWHM $\sigma_L$ of Lorentz broadening is given by a free parameter $\alpha$,

$$\sigma_L = \alpha \sigma_D.$$  \hspace{1cm} (A17)

The range of the broadening ratio $\alpha$ used in this study is from 0.1 to 10.
function. But this integral function is expensive to compute, particularly when a large number of rotational lines need to be calculated for each iteration step in the inversion calculation. We used an approximate formula for Voigt function derived by Whiting [1968],

\[
\phi(\lambda - \lambda_C) = \phi_C \left\{ (1 - a) e^{-2.772\Delta \lambda^2} + \frac{a}{1 + 4\Delta \lambda^2} \right\} \quad (\text{A18})
\]

\[
+ 0.016a(1 - a) \left[ e^{-0.44\Delta \lambda^{2.25}} - \frac{10}{10 + \Delta \lambda^{2.25}} \right] \left( \text{nm}^{-1} \right)
\]

where

\[
\phi_C = \frac{1}{\sigma_{V}\left[1.065 + 0.447a + 0.058\sqrt{a} \right]} \left( \text{nm}^{-1} \right) \quad (\text{A19})
\]

\[
\Delta \lambda = \frac{\lambda - \lambda_C}{\sigma_{V}} \quad (\text{A20})
\]

\[
a = \frac{\sigma_{L}}{\sigma_{V}} \quad (\text{A21})
\]

A line width \( \sigma_{V} \) is Voigt line width and defined as

\[
\sigma_{V} = \frac{\sigma_{L}}{2} + \sqrt{\frac{\sigma_{L}^2}{2} + \sigma_{D}^2} \left( \text{nm}^{-1} \right) \quad (\text{A22})
\]

The contribution of a rotational line is calculated up to 10 Voigt widths away from the center of the line. In the optimum case, error due to this truncation is \( 10^{-6} \) for the Voigt breadth equal to Lorentz breadth. In a worst case, the error is 6.3% for the Voigt breadth equal to the Doppler breadth. For our study, we used a wavelength increment of a tenth of the Voigt breadth in order to capture precise line profile of each rotational line. In other words, the contribution of each rotational line is calculated at 201 wavelengths. Although this spectral resolution is much higher than the instrumental resolution of our spectrometers, it is required for calculating the effect of self-absorption (see equation (1)).

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