Intensities of atomic lines and molecular bands observed in impact-induced luminescence

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[1] A series of hypervelocity impact experiments were conducted at NASA Ames Vertical Range, using spherical copper projectiles and polycrystalline dolomite targets. The intensities of atomic lines and molecular bands in the first 2 microseconds after each impact were measured using a high-speed spectrometer system and assessed as functions of impact velocity (2–5.5 km/s) at a fixed impact angle (45° from the horizontal). Although the measured emission intensities follow power law relations well, the power law exponents of individual emission lines and bands are very different, ranging from 2.1 to 9.1. In contrast, the exponent for wavelength-integrated visible light intensity (435–650 nm) is about 5. Such a large variation in exponents suggests a complex nature for the power law relations. In order to understand the physical processes controlling the power law relations, a theoretical model is developed considering chemical equilibrium of both molecular and atomic species, the electronic excitation of atoms, and ionization. This model accounts for the observed variety of the power law exponents well. Such a model will provide a physical framework for predicting the emission intensities from both artificial and natural impacts on planetary surfaces and for estimating size of an impactor from the emission intensity. INDEX TERMS: 5420 Planetology: Solid Surface Planets: Impact phenomena (includes cratering); 5494 Planetology: Solid Surface Planets: Instruments and techniques; 6022 Planetology: Comets and Small Bodies: Impact phenomena; 6205 Planetology: Solar System Objects: Asteroids and meteoroids; 6210 Planetology: Solar System Objects: Comets; KEYWORDS: impact cratering, hypervelocity impact, impact-induced luminescence, impact-flash spectroscopy, emission spectroscopy, impact vaporization


1. Introduction

[2] Laboratory experiments reveal that the intensity of light emission from a hypervelocity impact increases very rapidly with impact velocity [Gehring and Warnica, 1963; MacCormack, 1963; Rosen and Scully, 1965; Jean and Rollins, 1970; Eichhorn, 1975, 1976; Burchell et al., 1996; Ernst and Schultz, 2002]. The light intensity follows power law functions of impact velocity well, but the exponent varies greatly depending on projectile and target materials. [3] Using aluminum, steel, nylon, and glass projectiles with diameters ranging from 0.79 to 1.9 mm and both silica sand and granite targets, Gehring and Warnica [1963] showed that the exponents for peak visible luminosity of hypervelocity impacts at velocities between 2 and 7 km/s range from 3.5 to 8.3. Rosen and Scully [1965] measured the intensity of light emission from borosilicate glass (Pyrex) spheres of ~50 μm diameter impacting aluminum targets as a function of impact velocity ranging from 4.4 to 14.8 km/s. The emission intensity was measured with interference filters and photomultiplier tubes (PMTs), and the observed exponent for the peak emission intensity was about 4.5. Jean and Rollins [1970] measured Cd line emission at 361.0 nm generated from copper spherical projectiles (1.6 to 6.4 mm in diameter) impacting cadmium targets as a function of velocity (2–8 km/s) and obtained a power law exponent about 8 for peak intensity. Van de Graaf experiments by Eichhorn [1976] for micro-impacts showed that the exponents for peak luminous intensity from various kinds (C, Al, W, and Fe) of microscopic projectiles...
impacting Au targets are between 3.8 and 4.6 for velocities up to 30 km/s and that for total (i.e., time-integrated) radiation intensity is between 3.0 and 3.6. Burchell et al. [1996] obtained a power law exponent $3.65 \pm 0.35$ for the total radiation intensity from microscopic Fe projectiles impacting ice targets over a wide velocity range, 2 to 65 km/s.

[4] It is becoming more important recently to understand the mechanism controlling the intensity of optical emission from hypervelocity impacts because there are a number of opportunities to observe both artificial and natural hypervelocity impacts on solid planetary surfaces. For example, a strong flash was observed when a Japanese engineering satellite, Hiten (MUSES-A), impacted the lunar surface [Uesugi, 1993; Uesugi et al., 1994]. During the recent Leonid meteor showers, unambiguous observations of optical emission induced by meteoroid collisions on the lunar surface were made [Dunham et al., 1999, 2000; Ortiz et al., 2000, 2002; Bellot Rubio et al., 2000a, 2000b; Yanagisawa and Kisaichi, 2002]. In July 2005, NASA’s discovery-class mission, Deep Impact, is planned to have a metallic projectile collide with a comet and should be observable from the Earth. When Cassini spacecraft arrives at Saturn in 2004, it may be able to observe light emission due to the extremely high velocity (up to about 50 km/s [Cuzzi and Durisen, 1990]) impacts of small comets on the Saturn’s ring particles [Cuk et al., 2000]. It is difficult, however, to optimize the telescopic and spectroscopic conditions within the given dynamic ranges of instruments because there is a great uncertainty in luminous intensities of these impacts.

[5] The uncertainty in luminous intensities arises from the lack of understanding of the physical processes controlling the light emission in a hypervelocity impacts between solid bodies. In particular, the nature of the apparent power law relation between radiation intensity and impact velocity observed in laboratories has not been well understood. A simple analytical approach by Baird et al. [1997] shows that the radiation intensity may be proportional to the 2nd to 8th power of impact velocity, depending on the observed wavelength. This approach, however, assumes a blackbody radiation. Although some conditions of impacts exhibit strong blackbody radiation [Yang et al., 1992; Sugita et al., 1998], radiation from many different conditions of impacts is not dominated by blackbody radiation but by strong atomic lines and molecular bands, particularly during early stages [MacCormack, 1963; Jean and Rollins, 1970; Sugita et al., 1998; Sugita and Schultz, 1999]. Thus a simple blackbody model does not fully account for the apparent variation in power law exponents observed in the laboratories.

[6] Time-dependent, multidimensional numerical calculations considering both hydrodynamics and gas-phase radiation processes have been conducted to understand the light emission processes in hypervelocity impacts on an airless body [Nemtchinov et al., 1998, 1999; Artem’eva et al., 2001]. The results of the calculations show that the luminous efficiency, the ratio of the total yield of radiative energy output to the total impact energy, has been estimated to be on the order of $10^{-5}$ to $3 \times 10^{-4}$ for asteroids at 15–30 km/s [Nemtchinov et al., 1998, 1999] and $10^{-3}$ to $2 \times 10^{-2}$ for comets at 72 km/s [Artem’eva et al., 2001]. Although there are a number of assumptions and uncertainties, the luminous efficiencies calculated with the hydrocode are on the same order of magnitude as that estimated from the observations of meteoroid impacts on the Moon during a Leonid meteor shower [Artem’eva et al., 2001].

[7] It is uncertain, however, if theoretical luminous efficiencies fully agree with the observed power law dependence on impact velocity because neither the peak intensity nor the time-integrated intensity of luminosities is given as a function of impact velocity. Furthermore, the calculations indicate that the luminous efficiency for volatile-rich targets does not strongly depend on impact angle even though hydrodynamic flow field does [Nemtchinov et al., 1998]. Hypervelocity impact experiments with different angles, however, show that both the yield of vapor and luminous efficiency depend strongly on impact angle [Schultz, 1996]. Laboratory experiments also indicate that projectile failure processes may play a very important role in both vapor and radiation generation during hypervelocity impacts [Schultz and Gauld, 1990; Schultz, 1992, 1996]. Such processes are still difficult to incorporate in a hydrocode calculation. Thus there still is significant discrepancy between theories and experiments.

[8] A detailed direct comparison between theoretical calculations and laboratory experiments regarding the radiation process during hypervelocity impacts has not yet been made. One reason is the absence of time-resolved spectroscopic observation of hypervelocity impacts. Because impact flash has many components with different time constants [Schultz, 1996], it is difficult to characterize individual components from a time-integrated and/or spectrally unresolved observation. In order to understand this process, we have to dissect the complex impact flash process and examine each component separately. Only then can a more rigorous comparison between theory and experiments be possible.

[9] This study focuses on obtaining time-resolved high-resolution impact flash spectra during the early stage of impact among several stages of impact vaporization processes because this early stage exhibits the strongest atomic lines and molecular bands [Sugita et al., 1998; Sugita and Schultz, 1999]. Then we develop a physical model that considers chemical equilibrium, electronic excitation of atoms, and ionization to understand what controls the observed velocity dependence of radiation intensities of individual atomic lines and molecular bands.

2. Experiments

[10] A series of impact experiments were performed at NASA Ames Vertical Gun Range (AVGR) and used spherical copper projectiles (3.2 mm in diameter) and polycrystalline dolomite targets. The impact angle was fixed at $45^\circ$ from the horizontal, the most probable angle for natural impacts. The impact velocity ranged from slightly below 2 to about 5.5 km/s, with the pressure of the impact chamber kept lower than 0.7 mb. We used two spectrometers with intensified charge-coupled device (ICCD) camera units. Detailed description of the systems is given by Sugita et al. [1998] and Sugita and Schultz [1999]. The spectrometers are placed on the top of the
impact chamber viewing the target surface through a port. The field of view (FOV) is approximately 4 cm in diameter and located downrange from the point of impact. This is where most of the early stage impact flash is generated in oblique impacts [Schultz, 1996; Sugita et al., 1998; Sugita and Schultz, 1999].

[11] The significant improvement in the spectrometer systems in this study is the intensity calibration capability. Because the bundled optical fibers previously used had substantial spatial nonuniformity, it was difficult to obtain an accurate absolute scale for intensity calibration [Sugita et al., 1998; Sugita and Schultz, 1999, 2003a]. Although relative intensity calibration was sufficient for temperature measurements based on relative intensity ratios [Sugita et al., 1998; Sugita and Schultz, 1999] and on spectral pattern inversion [Sugita and Schultz, 2003a], an accurate absolute intensity calibration is essential in the present study.

[12] Consequently, optical fibers with liquid light guides (Oriel Corporation, Model 77568) were used here. The liquid light guides exhibit much better spatial uniformity throughout their core areas, thereby permitting accurate intensity calibrations. Cross examination of the intensity calibration using both a filament light source (Tungsten halogen lamp, (Oriel Corporation, Model 63355)) and an extended light source (Labsphere, Model USS-600) provides an accuracy of about 20%. This should be regarded as a lower estimate for the actual error. Because a thorough intensity calibration procedure takes more than an hour and machine time at AVGR is limited, we could not conduct frequent intensity calibration to examine temporal drift in the spectrometer systems. Furthermore, the two-stage light-gas at the AVGR shows a very good repeatability in impact point, but there is still some scatter (<5 mm). Slight error in impact point on the target may also introduce effective error in radiation intensity observed by the spectrometer systems because some light may not be fully captured in the FOV of the spectrometers. Nevertheless, as shown in section 3, the scatter of wavelength-integrated intensity around the best-fit line is approximately a factor of 1.5. Thus such potential errors should be about a factor of 1.5. Here, it is nevertheless important to note that the calibration for relative intensity within the same spectrum is much more accurate than that for absolute intensity. Cross examination using the two different types of light sources shows that the error is only about 3%.

[13] Exposure time is another important factor. The spectrometer systems are triggered by a photodiode placed near the impact point in the chamber. When the projectile makes a first contact with the target, impact flash starts to occur. In order to avoid having a false trigger due to sporadic electric/optical noise, we set the trigger threshold relatively high (1 V). Thus it takes a certain time before trigger signal is sent to the spectrometer systems. Combining this time lag and system response time, the total response time to a impact flash is approximately 0.5 μs. Consequently, the effective exposure time is 0.5 to 2.5 μs after the first contact of impact. Here, it is noted that the timescale for jet generation (~rρ/Vsinθ) is 0.4–1 μs for 2–5.5 km/s of impact velocity, where rρ, V, and θ are projectile radius, impact velocity, and impact angle (45°) measured from the horizontal, respectively [e.g., Vickery, 1993; Sugita and Schultz, 1999]. This is comparable to the trigger delay timescale. Thus exposure time starts immediately after or during jetting generation process.

3. Experimental Results

3.1. Spectral Contents

[14] Both the intensity of optical emission from an impact and the spectral content change drastically as functions of impact velocity. Figure 1 shows the progression of emission spectra. At impact velocities lower than 2 km/s, little optical emission is observed (Figure 1a). Above 2 km/s, atomic emission lines of both Cu and Na are observed along with CaO molecular emission bands (Figure 1b). Here, Na is present because the dolomite target is a natural sample containing a small amount of impurities.

[15] Within the first 2 μs, the impact flash spectra at lower velocities exhibit no strong blackbody radiation and are dominated by gas-phase radiation (i.e., atomic lines and molecular bands). This absence of blackbody radiation contrasts with results of other impact experiments in this velocity range by Yang et al. [1992], who observed only blackbody radiation from collisions between tungsten and carbon plates. A strong blackbody radiation is also observed at low impact angles (measured from the horizontal) when a quartz projectile and a dolomite target are used [Sugita et al., 1998]. The absence of blackbody radiation is probably due to the combination of both the ductile, high-impedance nature of copper and the high volatility of dolomite. The brittle, low impendence nature of quartz results in catastrophic fragmentation prior to significant penetration [e.g., Schultz and Gault, 1990; Schultz and Sugita, 1997]. The high boiling temperature of carbon may impede vaporization of carbon upon impact, thereby leading to ejection of melt/solid-dominated jet.

[16] The occurrence of a pure gas phase of both copper and dolomite around 2 km/s of impact velocities is rather remarkable. A one-dimensional plane-normal shock theory predicts that even carbonate does not fully vaporize at velocity as high as 6 km/s [e.g., Sugita and Schultz, 1999]. Although partial vaporization of CO2 degassing occurs much at lower velocities, the presence of CaO bands indicates that both CO2 and CaO components of the target carbonate vaporized. Thus vaporization of copper and dolomite must result from three-dimensional shock interference (i.e., jetting) and/or shear heating.

[17] As impact velocity increases, Ca atomic lines start to appear and grow strong. Such emergence and growth of Ca atomic lines can be seen very well around 559 nm. At 2.11 km/s, only CaO bands are seen (Figure 1b). At 3.03 km/s, it is difficult to discern a Ca line (Figure 1c). However, above 4 km/s, a clear Ca line is observed where (Figure 1d). This line (actually a cluster of lines) keeps growing as impact velocity increases. Its peak spectral radiation power becomes higher than that of the nearby CaO band around 555 nm at 5.54 km/s (Figure 1f).

[18] Among atomic lines, the dependence of emission intensity on impact velocity is very different depending on the species. For example, the sodium D doublet lines near 590 nm (appears as a single line in the spectrograms shown in Figure 1) are relatively strong at low velocities (Figures 1b and 1c), but they become weak relative to...
other lines at higher velocities (Figures 1d, 1e, and 1f). It is noted, however, that the intensities of Na D lines actually do increase with impact velocity but intensities of the other lines and bands increase at much higher rates. Thus the Na D lines become relatively less prominent at higher velocities.

[19] The relative intensities for emission lines from the same source element, also change substantially with impact velocity. The copper line at 510.6 nm has a lower upper-state energy \( E_n = 30,784 \text{ cm}^{-1} \), than that at 521.8 nm \( E_n = 49,942 \text{ cm}^{-1} \). At lower velocities only 510.6 nm can be observed (Figures 1b and 1c). However, Cu line at 521.8 nm

Figure 1. Optical spectra of impact-induced radiation as a function of impact velocity. The projectile and target are copper and dolomite, respectively. The impact angle is fixed at 45° from the horizontal. The exposure is 0.5–2.5 µs from the first contact of an impact. The impact velocity is indicated in the figures.
becomes more prominent at higher velocities (Figures 1d, 1e, and 1f).

3.2. Wavelength-Integrated Radiation Intensity

Figure 2 shows the wavelength-integrated intensities of impact flash observed by the two spectrometer systems covering two different wavelength ranges. The wavelength-integrated intensities can be approximated by power law functions of impact velocities, but their exponents are slightly different. The best-fit power law exponent for the shorter wavelength range (435–532 nm) is 5.37, and that for the longer (520–650 nm) is 4.97. The integrated intensity from 435 to 650 nm also follows a power law with an exponent of 5.05. Although the sum of two power law functions with different exponents is not a power law function in a strict mathematical sense, scatter in the data

Figure 1. (continued)
Figure 2. Wavelength-integrated emission intensity of hypervelocity impacts between spherical copper projectiles and polycrystalline dolomite targets as a function of impact velocity. The projectile diameter, impact angle, and exposure time are 3.2 mm, 45°, and 0.5–2.5 μs from the first contact of impact, respectively. The total emission intensities observed with the two spectrometers over different wavelength ranges (435–532 nm and 520–650 nm) are shown. The average radiant power (W) is given by the total emission intensity (J) observed by spectrometers divided by the exposure time (i.e., 2 μs).

The observed intensity of the CaO band around 555 nm is given in Figure 4 as well. All the line/band intensities can be fit well with power laws, but there is a wide range in the various power law exponents. As described qualitatively in section 3.1, the intensities of lines with higher upper-state energies grow more rapidly with impact velocity (i.e., higher exponents). A summary of the best-fit slopes is given in Table 1. There is a general trend that the power law exponents of Ca lines are higher than those of Cu and Na. The CaO band around 555 nm shows an exponent (4.4) lower than Ca (5.8–9.3) and Cu (5.2–5.8) atomic lines but higher than Na D doublet (2.1). The large power law exponents for Ca atomic line emission are similar to the exponent (~8) for the peak intensity of the Cd line at 361.0 nm in impact flash due to copper projectiles impacting cadmium targets [Jean and Rollins, 1970].

3.3. Intensities of Individual Atomic Lines and Molecular Bands

[22] The observed intensities of copper, calcium, and sodium emission lines are shown in Figures 3, 4, and 5, respectively. The observed intensity of the CaO band around 555 nm is shown in Figure 4 as well. All the line/band intensities can be fit well with power laws, but there is a wide range in the various power law exponents. As described qualitatively in section 3.1, the intensities of lines with higher upper-state energies grow more rapidly with impact velocity (i.e., higher exponents). A summary of the best-fit slopes is given in Table 1. There is a general trend that the power law exponents of Ca lines are higher than those of Cu and Na. The CaO band around 555 nm shows an exponent (4.4) lower than Ca (5.8–9.3) and Cu (5.2–5.8) atomic lines but higher than Na D doublet (2.1). The large power law exponents for Ca atomic line emission are similar to the exponent (~8) for the peak intensity of the Cd line at 361.0 nm in impact flash due to copper projectiles impacting cadmium targets [Jean and Rollins, 1970].

3.4. Correlation With Excitation Energy

[23] Radiant power \( P_{\text{nm}} \) (W) of a line emission due to electron transition of neutral atoms from an upper state \( n \) to a lower state \( m \) in an optically thin gas body in thermal equilibrium is given by

\[
P_{\text{nm}} = h v_{\text{nm}} A_{\text{nm}} g_m g_n \exp \left( -\frac{E_n}{kT} \right) N_0^{(n)}
\]

where \( h \), \( v \), \( A \), \( g \), \( E \), \( k \), \( T \), and \( N_0^{(n)} \) are Planck constant, photonic frequency, Einstein A coefficient, statistical weight, energy level, Boltzmann constant, temperature, and the number of ground-state neutral atoms [e.g., Griem, 1964; Cannon, 1985]. Thus logarithmic radiant power is

\[
\ln P_{\text{nm}} = -\frac{E_n}{kT} + C
\]
where $C$ is a constant. Since the range in the observed temperature $T$ in the impact flash due to a copper sphere impacting a dolomite target is not very large \cite{Sugita and Schultz, 1999}, $E_n/kT$ can be approximated by the following expression using Taylor’s expansion

\[ \frac{E_n}{kT} \approx \frac{E_n}{kT_0} \left\{ \ln \left( \frac{T(V_{in})}{T_0} \right) - 1 \right\}, \]  

(4)

where $T_0$ is the reference temperature within the observed range in which temperature $T(V_{in})$ is expanded to the first order. Usually, the mean temperature can be taken as the reference temperature $T_0$. Using equations (3) and (4), we have

\[ P_{nm} \propto T(V_{in})^{\beta_{calc}}. \]  

(5)

Observed temperatures for both Ca and Cu as functions of impact velocity (45° impact angle) approximately follow power laws \cite{Sugita and Schultz, 1999}. The best-fit exponents (i.e., $\frac{d \ln T}{d \ln V_{in}}$) for Cu and Ca temperatures are 0.55 and 0.99, respectively. Then, we can rewrite equation (5) as a power law function of impact velocity $V_{in}$:

\[ P_{nm} \propto V^{\beta_{calc}}. \]  

(6)

where

\[ \beta_{calc} \equiv \frac{E_n}{kT_0} \gamma_{obs}. \]  

(7)

\[ \gamma_{obs} \equiv \frac{d \ln T}{d \ln V_{in}}. \]  

(8)

Figure 6 shows the observed power law exponents $\beta_{obs}$ as a function of exponent $\beta_{calc}$ given by equation (7). Since most Na atoms are expected to come from the dolomite target, we use the Ca temperature exponent for the Na line intensity. Since the excitation energy of the CaO molecular band in the observed wavelength range is not determined \cite{Pearse and Gaydon, 1976; Huber and Herzberg, 1979}, it is not shown in Figure 6. There is a clear correlation between observed exponent $\beta_{obs}$ and $\beta_{calc}$, but the observed exponents $\beta_{obs}$ for Ca and Na are significantly lower than $\beta_{calc}$.

The above discussion, however, does not include the increase in vapor mass with impact velocity, which is predicted to increase significantly. Generally, the amount of impact-induced vapor increases in proportion to the square of impact velocity [e.g., O’Keefe and Ahrens, 1977; Vickery, 1993]. But then the discrepancy between observed exponents and predicted exponents $\beta$ would become even greater than that shown in Figure 6. In the following section, we investigate why the observed exponents are so much lower than equation (7) and why the discrepancy is greater for Na and Ca than Cu.

4. Model Calculations

Equation (2) gives radiant power $P_{nm}$ as a function of the number $N_{0i}^{(0)}$ of ground-state neutral atoms and temperature $T$ in the source vapor cloud, but the number of ground-state neutral atoms is controlled by many different factors such as chemical reaction among different molecules and atoms, electronic excitation, and ionization. These processes are further controlled by both temperature and pressure (or density). Although we know the temperatures of observed radiation source in copper impacts with polycrystalline dolomite targets in the first 2 μs \cite{Sugita and Schultz, 1999},...
[26] In the following sections, we estimate the pressure and density of the impact jetting. Using the approximate estimates of pressure (or density) and temperature measured by Sugita and Schultz [1999], we calculate equilibrium chemical composition of impact jetting, partition functions, and the degree of ionization. Then we discuss how the intensity of atomic emission from a gas body in a local thermodynamic equilibrium (LTE) reproduces the observed emission intensity in the impact experiments.

4.1. Pressure Assessments

[27] The total number $N_0^{(0)}$ of ground-state neutral atoms can be estimated from the luminosity of an atomic line emission using equation (2). The best-fit emission intensities of Cu emission at 510.5 nm and Ca emission around 445 nm at 5 km/s of impact velocity are 6.4 W and 3.3 W, respectively. Using the spectroscopic constants compiled by Sugita et al. [1998] and Sugita and Schultz [1999], we obtain $6.7 \times 10^{15}$ Cu atoms and $2.9 \times 10^{14}$ Ca atoms. Here 6000 K and 5000 K are assumed for temperatures of Cu and Ca, respectively, on the basis of the temperature measurements by Sugita and Schultz [1999]. These numbers of atoms correspond to $6.9 \times 10^{15}$ kg or $4.6 \times 10^{-6}$ projectile mass of copper and $8.8 \times 10^{-11}$ kg or $5.9 \times 10^{-7}$ projectile mass of dolomite. Such values are consistent with the extremely small mass ($10^{-8} - 10^{-5}$ projectile mass) of jetting due to quartz impacting dolomite target based on a measurement of self-absorption of a Ca emission line [Sugita et al., 1998]. They are several orders of magnitude smaller than the theoretical prediction of jetting mass by Vickery [1993]. Although this is a substantial difference, we cannot conclude if the observation is actually inconsistent with the jetting theory by Vickery [1993]. It is likely that the
high-temperature jetting represents a very small fraction of the entire impact-jetting phase, and the rest of the jetting may be not hot enough to be observed by the spectrometers. Expansion velocity $u_{exp}$ of the front of a highly compressed gas body is given by

$$u_{exp} = \frac{2}{\gamma - 1} \sqrt{\gamma \frac{RT}{\mu}}$$

where $\gamma$, $R$, and $\mu$ are the ratio of specific heats, gas constant, and molecular (or atomic) weight, respectively [Zel’ dovich and Raizer, 1967]. The expansion velocity $u_{exp}$ is 3.4 km/s for copper vapor and 5.9 km/s for dolomite vapor. The variables $T$ and $\mu$ for copper vapor are assumed to be 6000 K and $63.5 \times 10^{-3}$ kg/mol, and those for dolomite vapor are 5000 K and $18.4 \times 10^{-3}$ kg/mol, respectively, on the basis of the temperature measurements by Sugita and Schultz [1999]. The ratio of specific heats $\gamma$ for both copper and dolomite vapors are assumed to be 1.67, the value for monoatomic gas. This choice of $\gamma$ is consistent with the results of chemical equilibrium calculations as shown in section 4.2.

Since the three-dimensional shape of high-temperature jetting phase is not known, we estimate the volume $V$ of expanding jetting phase with

$$V \approx (u_{exp} \Delta t)^3$$

where $\Delta t$ is the time after the initiation of gas expansion. It is noted that the volume given by equation (10) is approximately 1/4 of a sphere. Because both theory [e.g., Vickery, 1993] and high-speed imaging show that the high-temperature jetting vapor is confined to the downrange quadrant above the target plane for an oblique impact, equation (10) provides a better approximation than a sphere. Nevertheless, it should be kept in mind that this is a first-order estimate. There is also uncertainty in the time between

Figure 4. (continued)
the beginning of exposure time and the generation of the high-temperature jetting phase; consequently, it is difficult to determine precisely the effective time $t_C$ for expansion. Since exposure time starts near completion of jet generation and lasts for 2 ms, a simple arithmetic average would be 1 ms.

Because jetting vapor reduces its radiation intensity rapidly as it expands and adiabatically cools, the emission spectrum is dominated by the earlier phase of expansion. Consequently, we consider 0.5 ms (the delay timescale for trigger) as the effective expansion time for observed impact vapor. With this timescale $\Delta t$ and equation (10), the nominal densities of jetting phases of copper and dolomite become $2 \times 10^{12}$ and $4 \times 10^{12}$ kg/m$^3$, respectively. Pressures corresponding to these nominal densities are 0.1 and 0.01 bar for copper and dolomite vapor, respectively, with the atomic number densities of $1 \times 10^{24}$ and $1 \times 10^{23}$ m$^{-3}$, respectively. Here, these values assume that all the vapor constituents are atoms. There is a circumstantial evidence to support these nominal density values. If the effective expansion timescale was increased to 1 ms, the pressure and density estimates would be 1/4 the nominal pressure values. This density estimate, however, would be probably a significant underestimate since Ca ionization would be too high (as discussed in section 4.4).

4.2. Chemical Equilibrium

[30] Approximate estimates for pressure in both copper and dolomite jets allow assessing the chemical composition in these gas bodies. Because of the high temperature of the jetting gas, chemical reactions presumably occur fast enough to achieve chemical equilibrium. Equilibrium chemical compositions are calculated with the Lewis thermodynamic code that considers, gas, liquid, and solid phases [Gordon and McBride, 1971]. Pure copper is assumed for the copper jetting. The composition for vapor from dolomite jetting is assumed to be the sum of 100 of CaMgC$_2$O$_6$ and 0.1 of Na$_2$O. Since an accurate compositional measurement of the samples is not available, we use a typical Na concentration (~200 ppm) of carbonates [Wolf et al., 1967]. Calculations with different Na ratios, however, indicate that specific value of Na ratio does not alter the calculation results in this study significantly.

![Figure 5](image_url). Emission intensities of Na lines (i.e., D lines) observed in hypervelocity impacts. The experimental conditions are the same as Figure 3.

![Figure 6](image_url). Power law exponents of emission intensities of atomic lines. Observed power law indexes $b_{\text{obs}}$, upper energy level of the electronic transition, Boltzmann constant, mean vapor temperature, vapor temperature, impact velocity, and the ratio of the number of ground-state neutral atoms to the total number of atoms in any excitation and ionization states, respectively.

Table 1. Comparison Between Observed and Theoretical Power Law Indexes of Emission Line Intensities

<table>
<thead>
<tr>
<th>Line/Band</th>
<th>$\beta_{\text{obs}}$</th>
<th>$E_{\text{ex}}/kT_{\text{ex}}$</th>
<th>$\ln T_{\text{im}}$</th>
<th>$\ln T_{\text{im}}/\ln T_{\text{ex}}$</th>
<th>$N_0/N_{\text{tot}}$</th>
<th>$\beta_{\text{calc}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu 510.5 nm</td>
<td>5.2</td>
<td>7.4</td>
<td>0.55</td>
<td>0.7</td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td>Cu 521.8 nm</td>
<td>5.8</td>
<td>12.0</td>
<td>0.55</td>
<td>0.6</td>
<td>8.2</td>
<td></td>
</tr>
<tr>
<td>Ca 443.6 nm</td>
<td>7.7</td>
<td>10.9</td>
<td>0.99</td>
<td>0.4</td>
<td>8.4</td>
<td></td>
</tr>
<tr>
<td>Ca 458 nm</td>
<td>9.3</td>
<td>12.1</td>
<td>0.99</td>
<td>0.4</td>
<td>9.6</td>
<td></td>
</tr>
<tr>
<td>Ca 487.8 nm</td>
<td>8.5</td>
<td>12.2</td>
<td>0.99</td>
<td>0.4</td>
<td>9.7</td>
<td></td>
</tr>
<tr>
<td>Ca 526 nm</td>
<td>7.1</td>
<td>11.3</td>
<td>0.99</td>
<td>0.4</td>
<td>8.8</td>
<td></td>
</tr>
<tr>
<td>Ca 559 nm</td>
<td>8.9</td>
<td>11.0</td>
<td>0.99</td>
<td>0.4</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td>Ca 610-2 nm</td>
<td>5.8</td>
<td>9.1</td>
<td>0.99</td>
<td>0.4</td>
<td>6.6</td>
<td></td>
</tr>
<tr>
<td>Na 589.0-6 nm</td>
<td>2.1</td>
<td>4.9</td>
<td>0.99</td>
<td>0.4</td>
<td>2.3</td>
<td></td>
</tr>
<tr>
<td>CaO 555 nm</td>
<td>4.4</td>
<td>0.99</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
as atoms in the pressure range between 0.01 and 100 bar and temperature range between 3000 and 6000 K. Thus, in the following discussion we assume that the molecular fraction is negligible and that all elements occur as either atoms or ions.

4.3. Partition Function

Electronic excitation of atoms is given by partition functions. The number \( N^{(o)} \) of ground-state neutral atoms in equation (2) is related to the total number \( N^{(o)} \) of neutral atoms at all excitation stages through the following equation:

\[
N^{(o)} = \frac{g_o}{Z^{(o)}} N^{(o)}
\]  

where \( Z^{(o)} \) and \( g_o \) are the partition function and the statistical weight of the ground state of neutral atoms, respectively [e.g., Griem, 1964]. If the partition function increases rapidly with temperature, \( N^{(o)} \) will decrease for a given value of \( N^{(o)} \). This will decrease the rate of increase in radiation power \( P_{nm} \) as a function of temperature and may account for the gap between observed and calculated exponents shown in Figure 6. In general, a partition function is a complex function of both temperature and electron density, and it cannot be expressed with an analytical function. However, it can be approximated accurately with a polynomial function of logarithmic temperature [Gray, 1992]. The formulae by Gray [1992] are given as functions of only temperature and not electron density. Nevertheless, calculations by Sugita et al. [1998] using more rigorous models by Griem [1964] show that the partition function is not significantly influenced by electron density at the temperatures \(<8000\) K relevant to jetting for impact velocities up to around 6 km/s. Consequently, Gray’s simpler formulae are used in this study.

4.4. Ionization

The total number \( N^{(o)} \) of neutral atoms is related with the total number \( N^{(o)} \) atoms in all the ionization stages through the following equation:

\[
N^{(o)} = N_{tot} - N^{(1)} - N^{(2)} - \ldots
\]

The numbers of atoms at different ionization stages are given by Saha’s equations [e.g., Griem, 1964; Gray, 1992]. For example, the number \( N^{(1)} \) of singly ionized atoms is given as a function of temperature \( T \), the number \( N_{e} \) of electrons, and the number \( N^{(o)} \) of neutral atoms:

\[
N^{(1)} = \frac{2(2\pi m_e kT)^{3/2}}{\hbar^3} \frac{N_{e} Z^{(1)}}{N^{(o)} Z^{(o)}} \exp\left(-\frac{I^{(o)}}{kT}\right)
\]

where \( m_e \), \( \hbar \), \( Z^{(1)} \), and \( I^{(o)} \) are electron mass, Planck constant, the partition function of singly ionized atoms, and first ionization energy, respectively. Since the temperatures relevant in this study are relatively low \((kT < 1 eV)\) with respect to ionization energies (several to several tens of eV), we consider here only singly and doubly ionized atoms. The number \( N_{e} \) of electrons is given by the local electric neutrality.

\[
N_{e} = \sum_i N_{i}^{(1)} + 2 \sum_i N_{i}^{(2)}
\]
where suffix $i$ indicates the atomic species. Similarly to the section 4.1, we assume pure copper vapor for projectile-induced jetting and Ca: Mg: C: O: Na = 1: 1: 2: 6: 2 for target-induced jetting phase.

[15] As shown in Figure 9, the degree of ionization based on the calculations is very small for copper in the experimental conditions in this study. Under the average condition (temperature of 6000 K and atomic density of $10^{24}$ m$^{-3}$), the ionization ratio is about 1.5%. Even at 8000 K and $10^{25}$ m$^{-3}$, the ionization ratio is about 30%. However, both calcium and sodium exhibit large ionization ratios. Under the nominal temperature and density condition (5000 K and $10^{23}$ m$^{-3}$), the ionization ratio is about 95% of Ca and Na are ionized. More importantly, the ionization process reduces the number of ground-state neutral atoms rapidly as a function of temperature. This effect is very prominent for Ca and Na but very small for Cu.

[36] The contribution of the effect of ionization to the power law exponent is more clearly seen in Figure 10. The relation between the power law exponent $\beta$ and logarithmic gradient of $N_o^{(i)}$ for copper under the nominal condition (6000 K and $10^{24}$ m$^{-3}$), is $-0.7$, and those for Ca and Na (5000 K and $10^{23}$ m$^{-3}$) are $-4.4$ and $-4.6$, respectively. Increase in vapor mass is assumed to be proportional to the square of impact velocity on the basis of theoretical calculations [e.g., O’Keefe and Ahrens, 1977; Vickery, 1993]: $d\ln N_{tot}/d\ln V_{im} = 2$.

[37] The uncertainty in $d\ln (N_o^{(i)}/N_{tot})/d\ln T$ for copper around the nominal condition is much less than that for calcium and sodium. This large uncertainty is greatly reduced if the electron density or the degree of ionization in the vapor cloud is known. There are a few ways to measure these parameters. Using Langmuir probes, Crawford and Schultz [1991] measured ion/electron density within impact-induced plasma clouds. Although the experimental conditions are different (Al projectiles and targets), their impact experiments show that significant ionization (ion/electron density $\sim 10^{15}$–$10^{17}$ m$^{-3}$) occurs during hypervelocity impacts over a long period of time (several ms). This strongly suggests that ionization processes may play an important role in a very early stage (~2 µs) of impacts.

[38] The degree of ionization also can be estimated on the basis of the intensities of ion emission lines. Although there is no ion line in the wavelength range covered in this study, spectroscopic observation of a similar impact between a quartz projectile and a polycrystalline dolomite target with a wider spectral range (and a lower resolution) shows a strong...
Ca ion lines at 393.4 and 396.9 nm [Sugita et al., 1998]. Since these lines are resonance lines, emission due to the transition between the lowest excitation state and the ground state, substantial self-absorption may occur [e.g., Mitchell and Zemansky, 1961]. Consequently, the intensity of the ion lines may appear weaker than expected, but a preliminary analysis indicates that the degree of ionization is about 6% during the first 2 μs after impact, which is consistent with the ionization ratio expected for the nominal condition. This coincidence supports the validity of the plasma condition calculated with the nominal temperature and pressure condition and local thermal equilibrium. It is also noted that the fact that the $d \ln (N_0/\bar{N}_{tot})/d \ln T$ for Na and Ca are much larger than that for Cu is not affected by a specific choice of $T$ and $N_{tot}$.

[39] The correction factor $d \ln (N_0/\bar{N}_{tot})/d \ln T$ for the nominal conditions are given in Table 1 along with power law exponents $\beta_0$ after correction. The correlation between observed and predicted power law exponent $\beta_0$ is greatly improved after the correction for the effect of ionization and partition function (Figure 11). This improved correlation strongly suggests that the ionization of atoms plays an important role in atomic line emission process in hypervelocity impacts.

4.5. Applicability of Model

[40] Since the model developed in this study uses a number of assumptions, it is important to clarify the validity of these assumptions. Such assessment helps us understand the applicability of the model. In this section, we discuss the possible problems as well as the applicability of this model.

4.5.1. Effect of Ambient Atmosphere

[41] There is a relatively large uncertainty in estimated density and pressure due to the uncertainty in expansion timescale $\Delta t$. The pressure of copper jet ranges from a maximum estimate of 1.1 bar to a minimum of 18 mbar. The range for dolomite jet is 80 mbar to 1.3 mbar. Although the upper estimates are substantially higher than the ambient pressure (<0.7 mbar), the lower estimates are close to the ambient pressure. Consequently, the possible effect of atmospheric interactions should be addressed. For example, the jetting gas may be heated in the shock induced by collision with the ambient atmosphere. An analytical calculation by Sugita and Schultz [2003b], however, shows that such heating does not occur unless the jetting is ejected at extremely high velocity ($>100 \text{ km/s}$) under the experimental conditions in this study.

[42] Another possible problem is the generation of ablation vapor form high-speed impact fragments and ejecta. A model calculation by Sugita and Schultz [2003b] indicates that the efficiency of ablation heating is a strong function of ambient pressure. The ambient pressure in this study is less...
than 1/20 of that of Sugita and Schultz [2003a]. Since aerodynamic heating takes longer at a lower pressure, the short exposure time immediately after impact minimizes the possibility of contribution by "light contamination" from ablation vapor. Furthermore, when ablation heating occurs, strong blackbody radiation occurs, and such radiation is not observed in this study.

Thus the only atmospheric interaction mechanism that might influence the radiation process is the deceleration of expansion velocity. If expansion velocity is reduced, the expanding gas cloud stays in high-temperature and pressure conditions for a longer period of time. This allows more energy to radiate from the gas cloud in a form of visible photons, as opposed to infrared photons, thereby increasing the radiation efficiency. Thus it should be kept in mind that the emission observed in this study may be higher than that in a true vacuum such as in space. Nevertheless, this delayed expansion does not change the entropy of the expanding vapor. Jetting gas in this ambient atmosphere follows the same evolution track in the P-T space as that in a vacuum does. The only difference is the rate of change along the P-T evolution track. The temperature-pressure condition of impact vapor in a vacuum changes more rapidly than that in a thin atmosphere. Thus all the thermodynamic properties measured in a thin atmosphere can be applied to an impact in a true vacuum condition. It is noted, however, that the P-T track will be different if significant radiative cooling takes place. Since an ambient atmosphere slows the rate of adiabatic temperature decrease of impact vapor, the efficiency of radiative cooling becomes higher. Then the resulting vapor temperature will become lower at a given pressure. This effect is important at high temperatures and low densities. A simple analytical assessment similar to that by Sugita and Schultz [2002], nevertheless, shows that the radiative cooling under the experimental conditions in this study is much smaller than cooling due to adiabatic expansion.

4.5.2. Effect of Ionization in Chemical Equilibrium

There is a minor inconsistency between the chemical equilibrium calculation and ionization calculation. The former assumes no ionization even though there is a significant ionization in the temperature and pressure conditions relevant to this study. The inclusion of the ionization process in the equilibrium calculation, however, would only increase the degree of atomization (or lower the ratio of molecules). This is because molecules would dissociate into neutral atoms in order to compensate for the decrease in the population of neutral atoms due to ionization. Thus this simplification does not influence the conclusion that practically all the molecules are dissociated into single atoms in the observed jetting phase.

4.5.3. Mechanism Controlling Temperature

Chemical equilibrium, partition function, and ionization are calculated on the basis of first physical principles.

Figure 10. (opposite) Power law exponents of the ratio of the number of ground-state neutral atoms of the total number of the atoms as functions of temperature. Note that the number of ground-state neutral atoms are controlled by both partition function (shown in Figure 8) and ionization (shown in Figure 9). The calculation conditions are the same as Figure 8.
in equation (2) has a lower slope at higher temperatures. Ionization also will lower the velocity dependence of the intensity of neutral emission lines at higher temperatures. Hence the effective power law exponent decreases as temperature increases.

[47] Nevertheless, measurements of peak intensity of total light emission from hypervelocity impacts over velocity ranges significantly broader than this study does not show such a decrease in power law exponents [Gehring and Warnica, 1963; Rosen and Scully, 1965]. Although scatter in the data may give the appearance that the relation between emission intensity and impact velocity resembles a power law, there may also be a real physical mechanism to maintain and account for the apparent constant power law exponent.

[48] As temperature increases, the temperature dependence \( d\ln P_{\text{total}}/d\ln T \) of the intensities of emission lines with low \( E_n \) decrease. Emission lines with higher \( E_n \), however, emerge as temperatures increase and begin to contribute to the total luminosity. Because of the high \( E_n \), those lines have greater temperature dependence (cf. equations (7) and (17)). Consequently, the dependence on temperature with the wavelength-integrated luminosity does not decrease at high temperatures. This helps to sustain strong velocity dependence (3), thereby leading to an apparent power law relation that holds over a wide range of impact velocity.

[49] Such a mechanism may not be strong enough, however, to keep the power law exponent constant. The exponent may change drastically as a function of impact velocity, as well as materials involved in the impact. This is consistent with the large variation in the power law exponents observed in impacts with different materials [Gehring and Warnica, 1963; Eichhorn, 1975, 1976]. Furthermore, this also may account for the large departure of intensity-velocity relation for carbon impacts from a single power law relation observed by Eichhorn [1976].

6. Concluding Remarks

[50] Time-resolved spectroscopic observations of impact flash were conducted at NASA AVGGR using spherical copper projectiles and polycrystalline dolomite targets. The intensities of atomic lines and a molecular band during the penetration stage of impacts were measured as functions of impact velocity at 45° of impact angle. We also developed a local thermodynamic equilibrium model to understand the observed impact-induced optical radiation. On the basis of both laboratory experiments and model calculations, we obtained the following results.

[51] 1. The total intensity of optical emission from 435 to 650 nm of wavelength range is approximately proportional to approximately 5th power of impact velocity, ranging from 2 to 5.5 km/s.

[52] 2. The spectral content of impact flash changes drastically as a function of impact velocity. In other words, the relative intensities of different lines and bands change greatly as impact velocity increases. The empirical power law relation between the total luminosity due to atomic/molecular emissions and impact velocity is therefore controlled not by a single process but by multiple processes.

[53] 3. The intensities of individual lines and bands follow power law relations with a variety of exponents,

Temperature as a function of impact velocity used in the calculation in this study, however, is based on purely empirical data. Spectroscopic observation of jet temperature and model analysis by Sugita and Schultz [1999] indicates that the jet temperature is not readily explained by pure shock heating given by the Rankine-Hugoniot equations and may require additional heating, such as shear heating. Thus accurate theoretical prediction of jet temperature is not straightforward. The general approach discussed in this study, nevertheless, should be applicable to most impact between solid bodies. Accurate prediction of the intensity of light during the penetration stage is possible when jet temperature as a function of velocity is obtained in laboratory experiments.

5. Discussion

[46] The experimental data and calculation results obtained in this study provide new insights about the nature of light emission from hypervelocity impacts and the intensity scaling law, in particular. Comparison between time-resolved spectroscopic observations and theoretical calculations strongly suggests that both electronic excitation and ionization of atoms controls the intensity of atomic line emission. Analysis of these processes shows that the emission intensity can be approximated with a power law function of impact velocity as given by equations (6) and (17). This power law approximation, however, should not hold for a wide range of temperature or for a wide range of impact velocities. For example, the Boltzmann factor \( \exp(-E_n/kT) \)
ranging from 2.1 for the Na D doublet at 589 nm to 9.3 for the Ca line at 458 nm.

The observed power law exponents show a good correlation with the respective upper energy levels $E_u$ of electronic transitions associated with the emission lines, but there is significant discrepancy between theoretical prediction and the observation, particularly for Ca and Na.

Model calculations indicate that chemical equilibrium between atoms and molecules or atomic partition function does not play an important role in controlling the intensities of atomic emissions under the experimental conditions in this study. The ionization process, however, plays a very important role in light emission.

Although there is significant uncertainty due to density estimate, the model considering ionization process can reproduce the observed power law exponents well.

The model developed in this study is based on impact experiments with one particular combination of projectile and target materials. Nevertheless, the model can account for general characteristics of emission intensity variation observed in other types of impacts, such as large variation in power law exponent for radiation intensity as a function of projectile/target materials. Thus this model may provide a useful framework for both prediction and analysis for the emission intensity of early stage impact-induced luminescence.

Such plasma diagnosis of impact vapor during the early stage of impacts is also very important for planetary applications. Because such early stage vapor (i.e., jetting phase) goes through much higher heating than the rest of impact vapor, it can be used as an analogue for impact-induced vapor cloud at velocities much higher than laboratory-scale velocities. Thus the model developed here may also help us understand the thermodynamic and chemical state of impact-vapor clouds at planetary-scale velocities.

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References


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