The Analysis Technique for Ejecta Cloud Temperature Based on Atomic Spectrum

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Abstract

Six hypervelocity impact tests of aluminum projectiles impacting aluminum plates were carried out. The range of projectile diameters was 2.0mm-5.0mm and the impact velocities varied from 3.0 km/s to 6.0 km/s. All the tests were normal impact. The atomic emission spectra of hypervelocity ejecta cloud are obtained by the instantane ous spectrometer. Six aluminum peaks and two concomitant peaks are identified in the emission spectrum. The effects of the concomitant peaks are analyzed and decoupled. Based on the spectral data, the ejecta cloud temperatures are analyzed using the Boltzmann diagram method and the configuration fitting method independently and the results are basically the same. The implication of the fact that the particle temperature of the ejecta cloud is uneven is discussed. It is found that for the uneven particles, the measurement result tends to be shifted toward the highest temperature of measuring time.

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Keywords: Hypervelocity impact, Ejecta Temperature, Spectroscopy

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>emission intensity (W/Sr)</td>
</tr>
<tr>
<td>N</td>
<td>the number of particles</td>
</tr>
<tr>
<td>h</td>
<td>Planck constant (6.626×10^{-34} J•s)</td>
</tr>
<tr>
<td>c</td>
<td>velocity of light (2.998×10^8 m/s)</td>
</tr>
<tr>
<td>g</td>
<td>the statistical weight</td>
</tr>
<tr>
<td>A</td>
<td>the transition probability (s^-1)</td>
</tr>
<tr>
<td>Z</td>
<td>the partition function</td>
</tr>
<tr>
<td>E</td>
<td>the energy level of upper state (cm^-1)</td>
</tr>
<tr>
<td>k</td>
<td>Boltzmann constant (0.695 cm^-1K^-1)</td>
</tr>
<tr>
<td>T</td>
<td>temperature (K)</td>
</tr>
<tr>
<td>a₀</td>
<td>the integral of the profile function</td>
</tr>
<tr>
<td>a₁</td>
<td>Lorentz width (nm)</td>
</tr>
<tr>
<td>a₂</td>
<td>Gaussian width (nm)</td>
</tr>
<tr>
<td>V</td>
<td>the velocity of impact (km/s)</td>
</tr>
<tr>
<td>d</td>
<td>the diameter of projectile (mm)</td>
</tr>
<tr>
<td>n(T)</td>
<td>the number of particles with temperature of T</td>
</tr>
<tr>
<td>T'(Eᵢ)</td>
<td>the equivalent temperature with energy level of Eᵢ</td>
</tr>
<tr>
<td>Nₑ</td>
<td>the total number of particles in measurement region</td>
</tr>
<tr>
<td>Tₑ</td>
<td>the boiling point temperature (K)</td>
</tr>
</tbody>
</table>

Greek symbols

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1. Introduction

The flash emission of debris cloud produced by hypervelocity impact is an important physical phenomenon. Through analysis of the flash emission, many characteristics such as the lethality of impacted objects, impacted materials and impact parameters can be analyzed. Analysis of the spectral data of a hypervelocity impact, including temperature estimation, is one of the key technologies in hypervelocity impact mechanism research, which is very valuable in the field of astrophysics, space debris shielding technology, etc.

The temperature measurement of hypervelocity impact products by detecting and analyzing impact flash has already been studied for dozens of years. Eichorn[1] performed impact experiments with a Van De Graf dust accelerator and obtained the impact flash spectrum. From the spectral distribution of the emitted light, the temperature of the radiating material was estimated to be between 2,500 K and 5,000 K. Nebolsine and Gelb[2] studied the impact flash spectrum produced by hypervelocity impact of aluminum spheres on aluminum plates, and used spectroradiometry to diagnose the temperature of the radiating ejecta. Sugita etc.[3] performed HVI test for copper spheres impacting polycrystalline dolomite targets and used the intensities of atomic lines and molecular bands to determine the temperature of the radiating ejecta, which was found to be in the range of 4000 K to 6000K. Ramjaun[4] studied the UV spectrum of CN produced by high density polyethylene impacting a aluminum plate. Compared with calculation result of SPRADIAN, the temperature of the radiating material was determined to be about 7730K for an impact velocity of 5 km/s. Tsemblis[5] performed experiments with a 2 MV Van De Graf accelerator, studied the spectrum produced by iron dust particles impacting soda-lime glass. The light flash temperature was determined by comparing the emitted spectra with the blackbody radiation. It was found that the average temperature was 2600 K, independent of the projectile speed. Heunoske[6] performed impact experiments with a two stage light gas gun, and studied the spectrum produced by aluminum spheres impacting solar panel targets. The density and temperature of electrons was determined by analyzing the spectrum.

TANG En-ling and ZHANG Qing-ming[7] studied the temperature of impact plasma using Langmuir probes on two stage light gas gun driven projectile. SHI An-hua etc.[8] made an attempt to get the color temperature of the debris cloud with ultra-high speed camera.

In this paper, the UV spectra of the ejecta cloud produced by hypervelocity impacts of aluminum projectiles on aluminum plate targets are obtained using instantaneous spectrometer in the waveband of 250 nm~340 nm. The feasibility of temperature measured based on atomic spectrum data using the Boltzmann diagram method and the configuration fitting measure is validated. The effects of temperature unevenness in space and time are discussed.

2. Temperature Measurement Theory

In the process of an aluminum sphere impacting an aluminum plate target at hypervelocity, the impacted materials are melted and gasified under the condition of extremely high pressure and temperature. The gasified materials contain several kinds of particles, such as atoms and ions at the ground state or excited states, free electrons and so on, which emit light and is viewed.

It is assumed that the particle cloud is optically thin[9] and in local equilibrium, the particles obey the Boltzmann distribution. So the emission intensity of self-transition for upper(i) state to lower(k) state in solid angle is expressed as follows:

\[ I_{i,k} = N / 4\pi \cdot (hc / \lambda_{i,k}) \cdot (g_i \cdot A_{i,k} / Z) \cdot \exp(-E_i / kT) \]  \hspace{1cm} (1)

2.1. Boltzmann Diagram Method

Taking the logarithm of Eq.(1), we get:

\[ \log[I_{i,k} \lambda_{i,k} / (g_i \cdot A_{i,k})] = -E_i / (kT) + \log[Nhc / (4\pi Z)] \]  \hspace{1cm} (2)

\[ \lambda \text{ wavelength(nm)} \]
\[ Y(\lambda, \lambda_{i,k}) \text{ the profile function of emission line} \]
\[ \tau \text{ exposure time(\mu s)} \]

Subscripts
\[ i,k \text{ transition from } i \text{ energy level to } k \text{ energy level} \]
\[ i \text{ energy level} \]
\[ 0 \text{ ground state of aluminum atom} \]
\[ 1 \text{ ground state of Al}^+ \]
In the process of temperature measurement, it is assumed that \( N \) is constant and \( Z \) is not sensitive to temperature, so \( \log(Nhc/4\pi Z) \) is a constant. If the intensity of some spectrum lines are obtained in hypervelocity impact (HVI) tests, then the diagram with the x axis of \( E_i \) and y axis of \( \log(I_{i,k}/g_i A_{i,k}) \) can be made. The temperature can then be obtained by a linear fit to the data, whose slope is equal to \(-1/kT\). The spectrum constants (such as \( \lambda_{i,k}, g_i, A_{i,k}, E_i \)) of aluminum can be found in reference texts[10] or calculated with atomic structure theory[11].

2.2. Configuration Fitting Method

In fact, due to the uncertainty in the measured photon energy and many kinds of particle interactions, the radiation emitted by a certain upper state transiting to a low state is not monochromatic light, but is a broadened “line” with some profile shape, which can be defined by Eq.(3):

\[
I(\lambda) = \sum_i I_{i,k} Y(\lambda, \lambda_{i,k})
\]  

(3)

In general, the profile shape is related to many mechanisms, like the natural broadening, Doppler broadening, pressure broadening and instrument broadening. The profile function \( Y(\lambda, \lambda_{i,k}) \) can be expressed as Eq.(4) approximately:

\[
Y(\lambda, \lambda_{i,k}) = \frac{a_0 a_i}{2\pi^{3/2} a_i^{5/2}} \int_{-\infty}^{\infty} \exp(-t^2) \frac{\exp(-\frac{(\lambda - \lambda_{i,k} - t)^2}{2a_i^2})}{\sqrt{2\pi a_i^2}} dt
\]  

(4)

Associated with Eq.(1), Eq.(3) and Eq.(4), the specific expression of emission intensity of self-transition for upper (i) state to lower (k) state is obtained. With the expression and spectrum data measured in HVI test, the temperature could be obtained by data-fitting methods. When fitting the test data, the appropriate initial parameter values are conducive to make the fitting process convergence as soon as quickly.

3. Experimental Setup

3.1. Experimental System

HVI Tests were performed with Range A of HVIRC (Hypervelocity Impact Research Center) of CARDC (China Aerodynamics Research and Development Center).

As shown in Fig.1a, two stage light gas gun launches the projectile to the expected velocity, and then the projectile triggers the velocity measurement system. The A-B stations and B-C stations measure the velocity of the projectile respectively, and the reduction rate of the velocity is calculated, so the velocity of projectile arriving at the plate target position can be calculated, which is the impact velocity.

At the time B station is triggered, B station sends a signal to the delay timer of the spectrometer. When the clock of delay timer conforms to set-value, the spectrum collection is started. After 100μs the spectrum collection is finished.

The resolution of spectrometer used in HVI test is 0.1nm with the optical grating of 300 lines/mm. The window is quartz glass. The spectrometer and transmittance of quartz glass were calibrated using standard blackbody oven(Fig.1b).

3.2. Measurement Scheme

3.2.1 Measurement Region

In the case of hypervelocity impacts (for example spacecraft impacted by debris, or planets impacted by meteorites), the flash observed is emitted by material ejected from the impact point. So to study ejecta cloud flash is conducive to searching those hypervelocity impacts mechanism. In the current study measurements were focused on the ejecta cloud exiting from the impacted face of the aluminum plate. The measurement region was confined to 5 cm from the impacted face as shown in Fig.1c.
3.2.2 Test Parameters

Projectile and target plate were pure aluminum (99.9%). The thickness of plate target was 2.0 mm. The diameters of projectiles were 2–5 mm. The impact velocities were 3–6 km/s, and all tests were normal impacts. With the resolution of 0.1 nm, the bandwidth of the spectrometer is only 90 nm. For obtaining more data, the measured waveband is 250–340 nm, which covers 8 spectrum lines of aluminum atom and 1 spectrum line of aluminum ion[10]. If all the 9 lines are obtained in HVI tests, the ionization degree can be determined.

Considering the impact time is 0, the exposition time of the spectrometer is 100μs and measurement begins at -50μs to make sure that the spectra are obtained. The pressure of chamber is 200 Pa before impact.

4. Test Results

4.1 Identification of Peaks

With the resolution of 0.1 nm, nearly all spectra contained 6 peaks, which are at the wavelength of 256.80 nm, 257.51 nm, 265.25 nm, 266.04 nm, and 308.22 nm, and 309.27 nm (shown in Fig. 2a). The spectrum peaks of 256.80 nm, 257.51 nm, 265.25 nm, 266.04 nm are unapparent in a few spectra when impact velocity is slow (Fig. 2b). All peaks belong to the aluminum atom, but not aluminum ion or other elements.

It is reported in Ref[10] that there are two aluminum atom lines near 309.27 nm, which are 309.27 nm and 309.28 nm. For the reason of resolution of spectrometer, they are overlapped. Both lines are emitted from the excited state 3s23d to the ground state 3s23p, and the ratio of intensity is definite and is about 9.0:1.0. So the two lines’ intensities could be calculated from the measurement intensity of 309.27 nm respectively.

There are two aluminum atom lines near 257.51 nm similarly, which are 257.51 nm and 257.54 nm with the ratio of intensity about 4.2:1.0. The two lines’ intensities could be calculated from the measurement intensity of 257.51 nm respectively too. The spectrum lines data mentioned above are shown in Table 1.

![Fig. 2. Typical emission spectrum with different impact parameters: (a) test 3; (b) test 5](image)

Table 1. The spectrum lines data of aluminum atom

<table>
<thead>
<tr>
<th>Index</th>
<th>( \lambda_i / \text{nm} )</th>
<th>( E_i / \text{cm}^{-1} )</th>
<th>( g_i )</th>
<th>( A_i / \text{s}^{-1} )</th>
<th>Index</th>
<th>( \lambda_i / \text{nm} )</th>
<th>( E_i / \text{cm}^{-1} )</th>
<th>( g_i )</th>
<th>( A_i / \text{s}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>256.80</td>
<td>38929.41</td>
<td>4</td>
<td>2.30E7</td>
<td>5</td>
<td>266.04</td>
<td>37689.41</td>
<td>2</td>
<td>2.64E7</td>
</tr>
</tbody>
</table>

![Fig. 1. Experimental setup for (a) Experimental setup diagram (b) quartz window’s transmittance and spectrometer’s response coefficient (c) measurement region](image)
4.2. Temperature Measurement

4.2.1 Temperature Measurement with Boltzmann Diagram Method

It is found that the spectrum noise turns out to be a horizontal background (Fig.2); there is no apparent background blackbody continuum emission which increases with increasing wavelength over the measurement waveband. So the background removal is not needed.

The temperatures are measured with Boltzmann diagram method and shown in Fig.3. The results are shown in Table 2. For the test 5, the peaks in the range of 256.80nm~266.04nm are not apparent and there are only two peaks of 308.22nm and 309.27nm. Because the upper states of energy levels are almost the same, the x-coordinate of data are the same and the effective slope cannot be obtained, so the temperature cannot be obtained either. For other tests, data points are scattered near the fitting-line (Fig.3a). While data points are apart from fitting-line a bit further for test2 and test9 (Fig.3b) and the reasons are discussed in section 5 of the paper.

![Fig. 3. Typical diagram of temperature measurement with Boltzmann diagram method](image)

4.2.2 Temperature Measurement with Configuration Fitting Method

The temperatures are measured with configuration fitting method and diagrams are shown in Fig.4. The results are shown in Table 2. As shown in Fig.4, the fitting-lines and test data agree well, the maximum of residual value is lesser than 15%.

The results with two methods are compared in Table 2. It is found that the results with different methods are similar and the relative differences are smaller than 20%, with an error less than 5% for test1, test2 and test3, and errors of 14.6%, 15.6% for test7 and test9 respectively.

![Fig. 4. Typical diagram of temperature measurement with configuration fitting method](image)

**Table 2. Measurement results comparison of two methods**

<table>
<thead>
<tr>
<th>Test No.</th>
<th>d /mm</th>
<th>V /km/s</th>
<th>Boltzmann diagram method</th>
<th>configuration fitting method</th>
<th>relative differences</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>257.51</td>
<td>38933.97</td>
<td>2.80E7</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>257.54</td>
<td>38929.41</td>
<td>4.40E6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>265.25</td>
<td>37689.41</td>
<td>1.33E7</td>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test No.</th>
<th>d /mm</th>
<th>V /km/s</th>
<th>Boltzmann diagram method</th>
<th>configuration fitting method</th>
<th>relative differences</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6</td>
<td>308.22</td>
<td>32435.45</td>
<td>6.30E7</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>309.27</td>
<td>32436.80</td>
<td>7.38E7</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>309.28</td>
<td>32435.45</td>
<td>1.23E7</td>
<td>4</td>
</tr>
</tbody>
</table>
For the test 7, the intensities of peaks and the noise are in the same order of magnitude for 256.80nm, 257.51nm and 266.04nm, and the peak of 265.25nm is submerged in the noise. In the data fitting process, the peaks values are used only for Boltzmann diagram method and almost all the data are used for configuration fitting method. So the effect of noise is more notable for configuration fitting method than Boltzmann diagram method. On the other hand, as shown in Fig3.a, the linearity of the test data is consistent, which indicates the Boltzmann diagram method is adaptive too.

For the test 9, the intensities of six peaks are much greater than noise. In the data fitting process, all data are used for configuration fitting method and the shape consistence of fitting line and raw data is well. So configuration fitting method is good for this condition. On the other hand, the data are apart from fitting line a little further in Boltzmann diagram (shown in Fig3.b), which indicates the Boltzmann diagram method is inapplicability. Compared with result of Ref[12], the result of Boltzmann diagram method is higher while the result of configuration fitting method is appropriate.

5. Discussion of Results

5.1. The Effect of Temperature Distribution in Space

The temperature distribution of ejecta cloud is uneven and varies spatially and temporally. The spectrum obtained in HVI testing is spatially and temporally integrated. In the temperature measurement processing, it is assumed that the temperature is invariable with space and time, so the temperatures measured are the “average” temperature.

Making the $n(T)$ to be the number of particles with temperature of $T$, then emission intensity is expressed as follow:

$$I = \int_{T_{min}}^{T_{max}} n(T) / 4\pi \cdot h \cdot c \cdot \lambda_{i,k} \cdot g_{i,k} \cdot A_{i,k} / Z \cdot \exp(-E_{i} / kT) dT$$

(5)

On the other hand, the temperature is assumed to be invariable, there is:

$$I = N_{\Omega} / 4\pi \cdot h \cdot c \cdot \lambda_{i,k} \cdot g_{i,k} \cdot A_{i,k} / Z \cdot \exp[-E_{i} / kT(E_{i})]$$

(6)

Where,

$$N_{\Omega} = \int_{T_{min}}^{T_{max}} n(T)dT$$

(7)

Comparing the Eq.(5) and Eq.(6), there is:

$$T'(E_{i}) = \frac{-E_{i}}{k \cdot \log[\int_{T_{min}}^{T_{max}} n(T) / N_{\Omega} \cdot \exp(-E_{i} / kT) dT]}$$

(8)

It’s obvious from Eq.(8) that if the $n(T)$ is not invariable, $T'(E_{i})$ is variable with $E_{i}$ varies, which is one of reason that the data points are apart from fitting line in Boltzmann Diagram.

Making cumulative temperature distribution function $CFD(T)$ defined as follows:

$$CFD(T) = \int_{T_{min}}^{T} n(T) / N_{\Omega}dT$$

(9)

Particles emitting atomic spectrum are in gaseous state generally. It is assumed that the particles whose temperature is higher than boiling point temperature are all in gaseous state. Hence, only the particles whose temperature is higher than boiling point temperature $T_{b}$ ($T_{b} = 2333K$) are considered for the sake of simplicity. According to the results of simulation by AUTODYN[12], $CFD(T)$ could be expressed as that:

$$CFD(T) = 1 - \exp[A \cdot (T / T_{b} - 1)^{B}]$$

(10)

Where A and B are experiential parameters related with impact parameters and they are could be gotten by data fitting. For the impact state of 3mm@4.9km/s, A and B is -3.56 and 0.76 respectively. For the impact state of 3mm@5.8km/s, A and B is -2.90 and 0.65. For the impact state of 5mm@5.85km/s, A and B is -2.49 and 0.62 respectively. With Eq.(8)~Eq.(10), the differential of $T'(E_{i})$ with variable $E_{i}$ could be gotten (Fig.5a).
From Fig.5a it is found that $T^*(E_i)$ is increased with $E_i$ increasing and the maximum of differential of $T^*(E_i)$ is 250K for the 3mm projectile while about 600K for 5mm projectile in the range of 32000-39000cm$^{-1}$. It is notable that the result above reflects the effect of temperature distribution in space but not in time.

5.2. The Effect of Temperature Distribution in Time

The temperature distribution of ejecta cloud is uneven, which varies with time [6, 7]. That’s to say, the number of particles is the function of temperature of $T$ and time of $W$, which is expressed as $n(T,W)$, then Eq.(8) is changed to be that as follows:

$$T^*(E_i) = \frac{-E_i}{k \cdot \log \left[ \int_0^t \int_{t_0}^{t_0} n(T,\tau) \cdot \exp \left(-E_i/kTd\tau \right) \right] \int_0^t \int_{t_0}^{t_0} n(T,\tau)dTd\tau}$$

Defining $N_{\Omega}(\tau)$ and $T'(\tau)$ is the total number and equivalent temperature of particles in measurement region and in time of $\tau$. There is :

$$T^*(E_i) = \frac{-E_i}{k \cdot \log \left[ \int_0^t N_{\Omega}(\tau) \cdot \exp \left[-E_i/kT'(\tau)\right]d\tau \right]}$$

Where $T^*(E_i)$ is the equivalent temperature with energy level of $E_i$ for whole measurement region and all exposure time. According to the results of simulation (Fig.5b), $N_{\Omega}(\tau)$ rises in the 2~3$\mu$s after impact and then keeps invariable. So in the measurement processing, it could be assumed that $N_{\Omega}(\tau)$ is constant and Eq.(11) is simplified as follow:

$$T^*(E_i) = \frac{-E_i}{k \cdot \log \left[ \int_0^t \exp \left[-E_i/kT'(\tau)\right]d\tau \right]}$$

For the ejecta cloud produced by aluminum sphere hypervelocity impacting aluminum plate target, the temperature raises to the maximum in 2$\mu$s and decreases quickly [2]. It is assumed that the temperature rises to the maximum $T_{max}$ in the initial 2$\mu$s from room temperature linearly then the temperature decreases exponentially. Fitting the test data of test89 mentioned in Ref[2] (aluminum projectile diameter =0.88cm, thickness of aluminum plate target=0.41cm, impact velocity=7.3km/s, normal impact), the specific expression of relationship of temperature and time is obtained as follow:

$$T'(\tau) = \begin{cases} 
300 + \frac{\tau}{2}(7234 - 300) & 0 \leq \tau \leq 2 \\
300 + 6934 \cdot \exp[-(\tau-2)^{0.6}/10.05] & 2 \leq \tau 
\end{cases}$$

If $\tau$ is viewed as the exposure time, with Eq.(13) and Eq.(14), the relationship of $T^*(E_i)$ and $\tau$ would be gotten (Fig.5c). In generally, the average temperature $T_{mean}$ is defined as follows:

$$T_{mean} = \frac{\int_0^\infty T'(\tau)d\tau}{\tau}$$

From Fig.5c it is found that the equivalent temperatures $T^*(E_i)$ with varied $E_i$ are the same for short exposure time. With longer exposure time, $T^*(E_i)$ with different $E_i$ varies notably. When the exposure time reaches 50$\mu$s the difference between $T^*(E_i)$ with $E_i$ being 32435cm$^{-1}$ and 38929cm$^{-1}$ is about 180K.

With the time increasing, the equivalent temperature $T^*(E_i)$ of particles in measurement region increases to peak value rapidly and then decreases exponentially form, and the transient equivalent temperature $T'(\tau)$ increases first and then decreases too. The time of $T^*(E_i)$ reaches peak value is behind the time $T'(\tau)$ reaches peak value. The peak value of $T^*(E_i)$ is lower than that of $T'(\tau)$, the decrease rate of $T^*(E_i)$ is slower than that of $T'(\tau)$.

The time of $T_{mean}(\tau)$ reaching the peak value is after the time $T^*(E_i)$ reaching the peak value and the peak value of $T_{mean}(\tau)$ is lower than that of $T^*(E_i)$, the decrease rate of $T_{mean}(\tau)$ is faster than that of $T^*(E_i)$. 
6. Conclusion

The technique of temperature measurement based on atomic spectrum is investigated for aluminum spheres impacting aluminum plate targets at hypervelocity in this paper. It is found that:

(1) Both the Boltzmann diagram method and configuration fitting method could diagnose the temperature of ejecta cloud and the results are the same approximately. When the intensity ratio of signal peaks to the noise is small, Boltzmann diagram method is better. When the ratio of the intensity of peaks to that of the noise is large, the configuration fitting method is better.

(2) The temperature measured is an overall effect integration over space and time, which is lower than the peak value of transient equivalent temperature $T'(\tau)$. With a longer exposure time, the measured temperature is much nearer to the peak value of the transient equivalent temperature $T'(\tau)$ than to average temperature $T_{\text{mean}}$.

(3) The technique is applicable to the situation where the radiation of atom spectrum is notably. In general hypervelocity impact events are in this category. For lower velocity impact events, since the atomic spectrum flash is too slight to be obtained, the technique cannot be applied.

If the spectrometer used in HVI test has space and time discernibility, the temperature field varying with time could be obtained by this technique.

Acknowledgments

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Reference

[8] SHI An-hua, LIU Sen, HANG Dong. etc. 2011. The preliminary application of high-speed photography in the temperature measurement for debris cloud. 6th national space debris symposium, P517.