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Photometric Calibration of the Barium Cloud Image in a Space Active Experiment: Determining the Release Efficiency

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The barium release experiment is an effective method to explore the near-earth environment and to study all kinds of space physics processes. The first space barium release experiment in China was successfully carried out by a sounding rocket on April 5, 2013. This work is devoted to calculating the release efficiency of the barium release by analyzing the optical image observed during the experiment. First, we present a method to calibrate the images grey value of barium cloud with the reference stars to obtain the radiant fluxes at different moments. Then the release efficiency is obtained by a curve fitting with the theoretical evolution model of barium cloud. The calculated result is basically consistent with the test value on ground.

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The space plasma active experiment usually creates some artificial plasma and releases them into any place of interest, to act either as tracer within or as a perturbation of the background. By observing the phenomena in experiment, corresponding physical problems can be studied. One of the most typical active experiments is the barium release experiment.[1–4] In the experiment, solid barium is first taken into space by a rocket. It is then vaporized by chemical reaction heat and then released somewhere near the terminator. It finally forms a cloud. Atomic Ba is rapidly ionized by solar ultraviolet light. Both the barium neutrals and ions emit resonance lines in visible wavelengths, thus an optical method can be chosen to observe the cloud. However, the observing site should be located in the shadow region to avoid the influence of sunlight.

The first Chinese barium release experiment was successfully carried out in Danzhou, Hainan Province on April 5, 2013. A total of 1.5 kg barium was carried into the ionosphere and released at an altitude of 189.068 kilometers (19.299°N, 108.190°E) by a sounding rocket. A spherical barium cloud formed immediately after the release. The cloud slowly moved and expanded and its evolution was recorded by ground instruments. Four ground-based observational stations were located at Leizhou (20.792°N, 109.979°E), Fuke (19.529°N, 109.119°E), Dongfang (19.108°N, 108.673°E) and Jianfeng (18.748°N, 108.863°E), respectively. Dongfang's result was the best and it will be presented in this study. The main instrument used for the observation was a Canon EOS 5D Mark Ⅱ digital SLR camera with Canon EF 85 mm f/1.2 L Ⅱ USM lens. We chose a TV shooting mode with a shutter speed of 1/8 and auto ISO. The camera image files were saved as RAW format. Both the barium cloud and the background stars can clearly be seen in the image (Fig. 1).

The monochromatic irradiance of a star on the lens can be given by

$$E_{\rm star}(\lambda, Z) = E_m(\lambda) \times T(\lambda, Z), \tag{1}$$

where T is the transmission function of the atmosphere, Z is the angular zenith distance, and E_m is the adjusted irradiance of the star at the top of the atmosphere, which is unrelated to Z while determined by the apparent magnitude of the star m. The apparent magnitude of a celestial body is a measure of its brightness as seen by an observer on Earth. For a modern standard star photometry system, the magnitude is usually measured in some specific wavelength bands and adjusted to the value it would have been in the absence of the atmosphere. The most common magnitude system at the moment is the UBVRIJHK photometric system,[5] in which the V band gives magnitudes close to those seen by human eyes or commercial cameras, with an average wavelength of 550 nm and a relative band width of 0.16.[6] The V band apparent magnitude can be given by

$$m_V = -2.5 \log_{10} \left(\frac{E_V}{E_{0,V}} \right), \tag{2}$$

where E_V is the irradiance (unit: W/m^2) of a given star at the top of the Earth's atmosphere in V band. $E_{0,V}$ is the irradiance for $m_V = 0$, which is about 8.79×10^9photons/(s·m^2). With $E_{0,V}$ and Eq. (2), we can estimate the E_V for any star with a given m_V.

As is known from Ref. [7], there is a linear relation between the gray value of the image and the irradiance of a given target.

$$G(\lambda) = k_{\rm c-g} t_0 A(\lambda) S E(\lambda) \eta(\lambda), \tag{3}$$

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where $E(\lambda)$ is the monochromatic irradiance of the target on the lens, $G(\lambda)$ is the corresponding gray value on the image, $A(\lambda)$ is the spectral transmission of the camera, $\eta(\lambda)$ is the quantum efficiency, t_0 is the exposure time, S is the effective area of the lens, and $k_{\mathrm{c-g}}$ is the converting factor from photo-generated charge to the gray value of the camera.

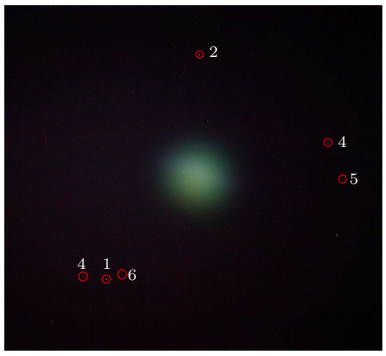

Fig. 1. The observed image at $t = 56$ s. The yellow-green cloud indicates the barium cloud. The circles and numbers indicate the positions and serial numbers of the reference stars.

The relative spectral responses for the G (green) channel of Canon EOS 5D Mark Ⅱ[8] and the V band of Johnson–Cousins UBVRI standard system[9] are shown in Fig. 2. They look very similar in both the profile and the central wavelength, and we can expect a connection between the V magnitude of a star and its gray value in G channel of the camera.

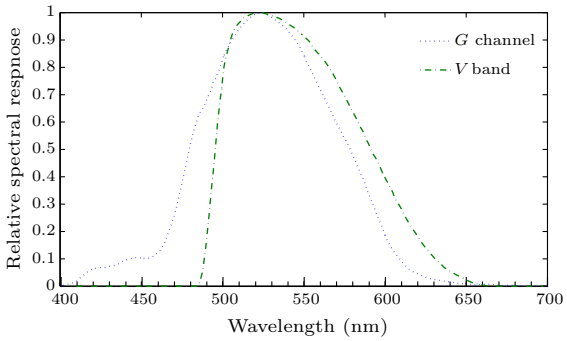

Fig. 2. The relative spectral responses for the G (green) channel of Canon EOS 5D Mark Ⅱ and the V band of Johnson–Cousins UBVRI standard system.

In Fig. 1, the background constellation is Hercules. We chose six stars that are different in brightness but which have approximately equal distances in the image from the barium cloud to serve as the reference stars. Their names, the V magnitudes and the corresponding irradiances at the top of atmosphere are listed in Table 1 (SIMBAD Astronomical Database).

Table 1. The names, V magnitudes and the corresponding irradiances of the reference stars.

Star number	1	2	3	4	5	6
Name	HIP 80816	HIP 84379	HIP 83207	HIP 80843	HIP 82587	HIP 80898
m_V	2.786	3.126	3.906	5.250	5.344	5.781
$E_V(10^8$ photons/(s·m^2))	6.7577	4.9408	2.4088	0.6986	0.6406	0.4283

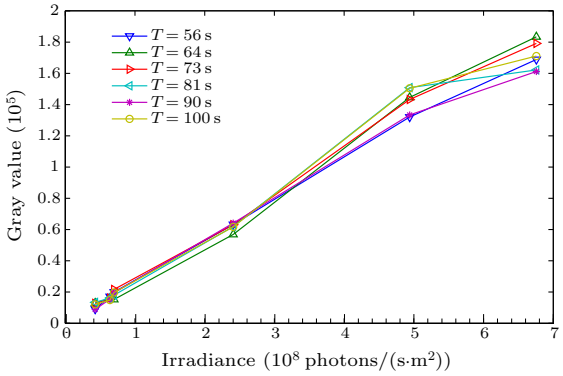

Fig. 3. The relation between the gray values and irradiances of the six stars. The six points from left to right represent the value of the six stars. The six curves represent the values at 6 different moments.

Table 2. The slop and R-square for each fitting.

Fitting	56 s	64 s	73 s	81 s	90 s	100 s
Slop (10^{-4})	2.544	2.812	2.711	2.578	2.475	2.688
R-square	0.9976	0.9940	0.9956	0.9719	0.9921	0.9830

After eliminating the background noise,[10] the gray values of the six stars in G channel of the images observed at different moments are shown in Fig. 3. The spacings of the points in the lower left corner are not obvious since the irradiances of star 4, 5 and 6 are very close (as shown in Table 1), while they can still reflect the relation between the gray value and the irradiance to some extent; thus, there is no need to remove any two of the three stars. By a linear fitting of the values in Fig. 3, the average ratio between the gray value and the irradiance of a star at each moment can be obtained as the slope of each fitting curve. In theory, the slopes of the six curves should be equal since the images at these six moments have the same exposure time and f-number. However, in fact, there are some differences between them because of the instrument error of the camera and also because of the error in the image processing (as shown in Table 2). However, for any linear fitting, the R-square value can be larger than 0.97. This means that the linearity of the camera is very good, which can guarantee the reliability of our calculation. On the other hand, since the irradiances in Fig. 3 come from a standard star photometry system, such a good linear relation between the gray value and the irradiance indicates that the camera we use really has a similar spectral response to the standard magnitude system, as discussed previously. Thus, it is reasonable to use the photometry data from the standard magnitude system to carry out the photometric calibration of barium images in our

experiment.

The barium cloud is an area light source, which can be seen as a sum of many equal-sized luminous units, any of which is approximate to a point light source. Then, the irradiance of barium cloud on the lens can be defined as

$$E_{\mathrm{Ba}}(\lambda, Z) = \sum\nolimits_{\theta} E_{\mathrm{Ba}}(\lambda, Z, \theta) = \sum\nolimits_{\theta} \frac{I(\lambda)\cos\theta}{H^2} \times T(\lambda, Z), \quad (4)$$

where θ is the angle of a luminous unit from the optical axis of camera lens, $E_{\mathrm{Ba}}(\lambda, Z, \theta)$ is the monochromatic irradiance of the luminous unit on the lens, $I(\lambda)$ is the monochromatic radiant intensity of the luminous unit in the direction of the lens, and H indicates the distance from the center of barium cloud to the lens which is about 193.292 km for Dongfang station. The radius of the barium cloud is about 6 km, which corresponds to a maximum θ of 1.78°. Therefore, $\cos\theta$ should satisfy the condition of $0.9995 \leq \cos\theta \leq 1$ for all the luminous units, which means $\cos\theta \approx 1$.

Table 3. The total gray value, radiant flux and V magnitude of the barium cloud at different moments.

Time (s)	56	64	73	81	90	100
Gray value	183944129	145025481	117062103	97745035	84678863	92442492
Radiant flux (10^{23}photons/s)	3.5740	2.5493	2.1344	1.8741	1.6912	1.6999
m_V	−4.8433	−4.4765	−4.2836	−4.1424	−4.0309	−4.0365

Since the angular zenith distance Z between reference stars and the barium cloud are small (about 5° as shown in Fig. 1), the emissions from the cloud and the stars have similar wavelengths and transmission paths through the atmosphere. We may assume that the transmission function of the atmosphere for the cloud is equal to that for the reference stars. According to Eqs. (3), (4) and Fig. 2, we have

$$\varphi = 4.2112\pi H^2 E_V \frac{\sum G_{\mathrm{cloud}}}{G_{\mathrm{star}}}, \quad (5)$$

where φ indicates the total radiant flux of barium cloud in unit of photons/s, $\sum G_{\mathrm{cloud}}$ is the sum of the gray value of the barium cloud, and G_{star} is the gray value of the reference star. After eliminating the background noise, the total gray value of barium cloud, the corresponding radiant flux and V magnitude of barium cloud at each moment are obtained according to Eqs. (2), (4) and (5) (as shown in Table 3).

The total emission from the barium cloud recorded by G channel of the camera includes two resonance lines 455.4 nm, 493.4 nm of Ba^+ and the 553.5 nm line of Ba.[11] For an optical thin cloud, each of them has

$$\sigma(\lambda)N = \sum 4\pi I(\lambda), \quad (6)$$

where σ is the emission rate for a given line, which is defined as the number of photons emitted per second from one atom or ion, and N is the number barium atoms or ions. For a barium cloud, the 553.5 nm emission is 20 times stronger than 455.4 nm and 493.4 nm emission lines.[12] Furthermore, the spectral response of the camera at 553.5 nm is also higher than the other two (as shown in Fig. 2). Consequently, the 553.5 nm line should dominate the gray value of barium cloud image most of the time. The correlation between the total radiant flux and the number of barium atoms and ions can be written as

$$\varphi = \sigma_{\mathrm{Ba}} N_{\mathrm{Ba}} + \sigma' N_{\mathrm{Ba^+}}, \quad (7)$$

where N_{Ba} and $N_{\mathrm{Ba^+}}$ are the number of barium atoms and ions, respectively; σ_{Ba} is the emission rate of Ba, which is about 8.4 photons/(s·atom);[13] $\sigma' N_{\mathrm{Ba^+}}$ indicates the contribution of emissions from ions; and, σ' is a parameter associated with the emission rates of ions and spectral response of G channel at 455.4 nm and 493.4 nm.

The barium cloud is optically thick in the first ten seconds due to the initial high density. In addition, the initial temperature of the cloud is higher than 2000 K.[14] In addition, long wavelength thermal radiation can contaminate the image.[11] As a result, we have decided to use the images observed from 56 to 100 seconds, when the barium cloud has cooled down, the effect of thermal radiation can be ignored, and the cloud is still bright compared with the background noise (Fig. 1).

Previous research has found that the evolution of barium neutrals can be seen as a self-diffusion process with mass loss by photoionization and oxidation, and the number of barium atoms can be described by[13]

$$N_{\mathrm{Ba}}(t) = N_0 e^{-(\tau + k_{\mathrm{c}} n_{\mathrm{O_2}})t}, \quad (8)$$

where $N_{\mathrm{Ba}}(t)$ indicates the number of barium atoms at time t, N_0 indicates the initial number of barium atoms, τ is the photoionization rate (a constant), k_{c} is the reaction constant of oxidation, and $n_{\mathrm{O_2}}$ is the number density of O_2. If $n_{\mathrm{O_2}}$ does not change much, $k_{\mathrm{c}} n_{\mathrm{O_2}}$ can be seen as a constant, then the number of barium ions can be given by

$$N_{\mathrm{Ba^+}}(t) = \frac{N_0(1 - e^{-(\tau + k_{\mathrm{c}} n_{\mathrm{O_2}})t})}{1 + k}, \quad (9)$$

where $k = k_{\mathrm{c}} n_{\mathrm{O_2}}/\tau$.

As the chosen images start from 56 s, we define $t' = t - 56$. Then Eq. (7) can be written in an exponential form:

$$\varphi(t') = a e^{-bt'} + c, \quad (10)$$

where

$$a = N_0 e^{-56(\tau + k_c n_{O_2})}(\sigma_{Ba} - \frac{\sigma'}{1+k}), \quad (11)$$

$$b = \tau + k_c n_{O_2}, \quad (12)$$

$$c = \sigma' N_0/(1+k). \quad (13)$$

With the radiant fluxes at different moments in Table 3 and curve fitting (as shown in Fig. 4, the root mean squared error of the fitting is 0.0536), we obtain

$$\varphi(t') = (1.918e^{-0.0876t'} + 1.644) \times 10^{23}. \quad (14)$$

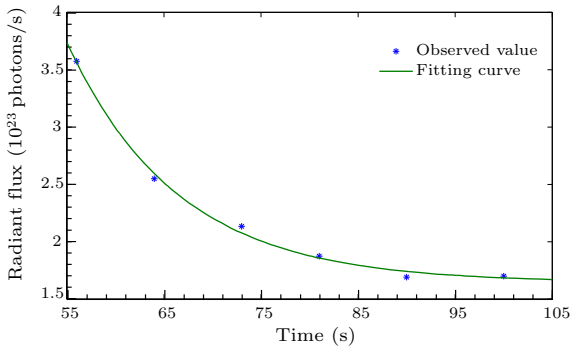

Fig. 4. The radiant flux of barium cloud changes over the time and the fitting curve.

According to Eqs. (10)–(14), N_0 can be calculated to be 3.1031×10^{24}, which corresponds to a mass of 0.7116 kg. Since the total mass of barium on the rocket is 1.5 kg, the release efficiency of barium can be estimated as 47%. During testing on the ground, the average release efficiency is about 52%. The relative error between the calculated result and the ground test value is about 9.6%. Considering the different conditions between the ground test and space experiment, generally speaking, the calculated result is basically acceptable, although various aspects, including the different spectral response between barium cloud and the stars in both the atmosphere and the optical system, the effects of thermal radiation on the images, the difference between the camera and the standard star photometry system, may introduce errors during the image calibration.

In conclusion, a method to calibrate the absolute brightness of a barium cloud with the gray value of images and the reference stars has been found. It is shown that there is a good linear relation between the gray values and the irradiances of the stars. With this relation, the radiant fluxes of barium cloud at different moments can be obtained, which decreases exponentially over time and which agrees with the theoretical evolution model of a barium cloud. With an exponential curve fitting, we obtain the release efficiency of barium to be about 47%, which is basically consistent with the test value on the ground.

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