Lightcurves of the Chelyabinsk bolide derived from a dashboard camera movie

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The bolide explosion on Feb. 15, 2013 over Chelyabinsk, Russia was the next most violent after the probable bolide explosion in Tunguska, Siberia in 1908. It has been estimated that a meteoroid about 20 m in diameter entered the atmosphere at about 19 km/s [1] with an impact angle measured from the horizon of about 19 degrees. It was recorded by many dashboard movie cameras, and the movies are released on the Internet. To obtain the lightcurves of the bolide, we analyzed a movie uploaded by Aleksandr Ivanov [2]. The event was recorded when his car stopped at an intersection in the city of Kamensk-Uralsky, Russia, located about 140 km north of Chelyabinsk.

The geographic coordinates of the intersection and the field of view of the camera were obtained with the help of the Google Maps. We corrected each frame of the movie for the non-linearity between the input light and output of the camera, and for the temporal variations of the camera gains. Because the bolide images were severely saturated, we measured the light isotropically scattered by a snow-covered region. Brightness of the blue sky at 650, 550, and 450-nm wavelengths, calculated by using a model, was used as brightness standards for the R (red), G (green), and B (blue) bands of the camera. The distance and the air mass between the bolide and the intersection were calculated for the bolide trajectory [3], and the source luminosities of the bolide were calculated for the three bands. The temporal variations of the luminosities thus obtained are shown in the figure with the bolide altitudes calculated on its trajectory [3]. It should be noted that the times in the figure are adjusted so that the maximum luminosity would occur at 3h20m32.2s (UT) [4].

A procedure has been used to estimate the impact energies from the US satellite observations in which the bolides are assumed to be 6000 K blackbodies [5]. We supposed that the spectral response of the satellite sensor would be close to the R band, and obtained the impact energy of 400 kton (1 kton = 4.2 x 10^{12} J) according to the procedure. It agrees with the results reported thus far [1, 4].

The bolide was not so bright in the R band relative to the G and B bands until 29.3 s (47 km in altitude). The R band brightness became comparable to or larger than the G and B brightnesses after that. Assuming the bolide to be a blackbody, and approximating the luminosity ratios in the three colors, G/B, R/G, and R/B, to be $B_T(550\,\mathrm{nm})/B_T(450\,\mathrm{nm})$, $B_T(650\,\mathrm{nm})/B_T(550\,\mathrm{nm})$, and $B_T(650\,\mathrm{nm})/B_T(450\,\mathrm{nm})$, respectively, where $B_T(\lambda)$ is the Planck function for the temperature T, we calculated temperatures for each ratio as shown in the figure. The temperatures for the G/B, R/G, and R/B ratios are not in agreement with each other before 29.3 s (above 47 km in bolide altitude). The disagreement suggests that the radiation would have been dominated by line spectra. On the other hand, the three temperatures agree with each other at about 3500 K, when the bolide was below 38 km and very bright. If the bolide was a 3500 K blackbody, the area which was necessary for the maximum luminosity at 32.2 s was about 120 km^2. The radiating region could be, for example, a sphere of 3 km in radius, or a cylinder of 1 km in radius and 20 km in length. However, the possibility that the agreement of the three temperatures could be a coincidence cannot be discarded.

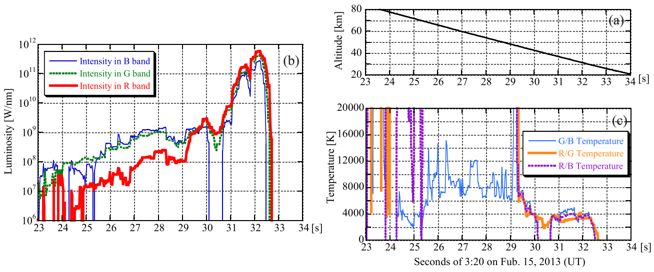

Figure: Temporal variations of the altitude (a), the luminosities (b), and the color temperatures (c) of the Chelyabinsk bolide (a).

References: [1] Yeomans, D., 2013, http://neo.jpl.nasa.gov/fireballs/ (on Mar. 2014). [2] Aleksandr Ivanov, 2013. https://www.youtube.com/watch?v=iCawTYPtehk (on Mar. 2014). [3] Borovicka, J. et al., 2013, Nature, 503, 235–237. [4] Brown, P. et al., 2013, Nature, 503, 238-241. [5] Brown, P. G. et al., 2002, Nature, 420, 294–296.