

Physical properties of the superbolide of Tajikistan based on combined satellite and ground-based observations

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In this paper we present the study of the photometric mass and density for the Tajikistan superbolide of 23 July 2008. Using the combined data from satellite and ground-based observations the mass was calculated by three approaches: photometric (based on the light intensity at the height of maximum brightness), graphics (using published data of cars) and using the kinetic energy of the superbolide. As a result, the calculated values of the mass are 25.3, 19.9 and 18.9 tons, respectively (with average value of 21.3 ± 2.1 tons).

The superbolide density was evaluated using the drag equation, the equation density of atmosphere at the heights of the maximum luminosity and beginning of the train and criterion-PE. The densities calculated by these three methods are equal to 1.1, 0.53 and 0.95 g/cm³ (with the average superbolide density as 0.86 ± 0.15 g/cm³).

Key words: meteorites, meteors, meteoroids

INTRODUCTION

Population of small bodies of the solar system like meteoroids, asteroids and comets that cross the Earth's orbit can not only bring great danger and colossal damage to the national economy, but also pose a threat to the vital activity of all living beings. Decameter and kilometer-sized celestial objects are particularly dangerous, because their collisions with hydroelectric and nuclear power plants can cause catastrophic damage to the economy of an individual state or continent, as well as endanger the existence of humanity and the planet. The destructive consequences of a collision with a celestial object will primarily depend on the kinetic energy and their physical and chemical properties (e.g. chemical composition, strength, porosity, etc). Therefore, the study of the physical parameters of small bodies is not only of great scientific importance, but also essential for the expansion of human ideas about celestial bodies. Of special interest are the objects that generate the phenomena of superbolides, as they often do not burn up completely in the Earth's atmosphere and fall to its surface in the form of meteorites.

THE SUPERBOLIDE OF 23 JULY 2008

On 23 July 2008 many residents of the central and south-western regions of the Republic of Tajikistan witnessed the flight of a very bright fireball, which was accompanied by a massive sound blast. In Figure 1 we present the photos of the initial stage of fireball trail (left panel) and the dust trail of the superbolide curved by the turbulent movements of the atmosphere over 30 minutes of flight (right panel).

At the time of the superbolide appearance the weather in Dushanbe was cloudy, however a number of citizens (including some members of the Institute of Astrophysics: O. Alimov, M. Gulyamov, U. Khamroev, etc) managed to record the dynamics of the development of the superbolide trail using a video camera and telephones, some of the results were released on the web-page of the meteor physics group of the University of Western Ontario¹ (hereinafter the bolide release). According to our observations the dust trail continued to exist until the full sunset (more than 1 hour 25 minutes). The flight of the superbolide was accompanied by a powerful explosion, the sound of which was heard by residents of a huge territory, starting from the east of

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¹United States Department of Defence Public Releases of Bolide Data: Bolide Detection Notification 2008-205 <https://aquarid.physics.uwo.ca/research/fireball/usaf/sandia28001.pdf>

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Dushanbe, including the residents of Romit valley, village of Ziddy in Varzob district, town of Vahdat, Rudaki, Hissar, and Shahrinav districts, city of Tur-sunzade, and some border districts of Surkhandarya region of the Republic of Uzbekistan, as well as the southwestern regions of the Khatlon region, that is, from the city of Kulyab and Mir Said Ali Hamadoni district to Shaartuz and Beshkent districts.

At the beginning of this event, the first author was at the park of the Tajikistan coat of arms, where he heard and accurately recorded the course of propagation of a sequential directional blast wave. The sound of the superbolide was perceived as three consecutive explosions. Moreover, we clearly recorded the direction of the propagation of the sound wave relative to the terrain. The azimuth of the blast directions was located on the line from the point in the north to the southwest (Mount Bobomalik in Hissar district), and its azimuth from the point in the south to the west was $67^\circ \pm 5^\circ$. The sound of the explosion resembled a loud thunderclap, which coinciding with three flashes in the light curve obtained by the satellite, meaning that every flash was accompanied by an explosive sound. The intensity of the sound of the explosion was in the range of 120-130 decibels.

The Tajikistan superbolide was detected by the optical sensors of NASA military Satellite Network (SN) at 14:45 UT. The first scientific report on this superbolide together with some of its physical characteristics are presented in [9]. According to the bolide release, the superbolide showed a stellar magnitude of -20.7^m and a speed of 16 km/s, while the altitude of the main maximum of the explosion was equal to 35 km. The calculated radiation energy of the superbolide was $2.1 \cdot 10^{11}$ J, and the weight of the bolide was estimated as 15-20 tons (see Table 1).

On contrary, in [9] was showed that the initial kinetic energy of the bolide was 2.1×10^{12} J, which is equivalent to 0.53 kilotons in TNT explosion equivalent based on the superbolide mass of 20-25 tons estimated in the bolide release. Such large variations of the superbolide mass are caused by the different techniques used for this estimation and therefore require additional methods for its specification. At the same time, the density of the superbolide has not been investigated before. The values of the radiant, speed, height of the beginning, maximum luminosity, and end of the trail, as well as the value of deceleration given by [6] were obtained from the interpretation of satellite and terrestrial photographs obtained simultaneously at Hissar Astronomical Observatory (HisAO) and Dushanbe.

To determine the atmospheric trajectory and predict the region of the fallout of the superbolide fragments, authors in [5] used the photographs of the trail obtained at HisAO and Hulbuk that are located at a distance of 100 km from each other. As expected, the accuracy of measured parameters of the bolide trajectory improves significantly because of the usage

of a long base. However, the photographs of the trail were obtained with a time difference of 15 minutes, which include some distortion to the obtained results. Therefore, to determine physical characteristics of the superbolide more accurately we used the average values of the atmospheric parameters (including the height of the beginning, the maximum luminosity, and the end of the trail that are shown in the last row of Table 1), obtained from the satellite and ground observations. The atmospheric parameters of the superbolide from [5, 7, 9] and the bolide release are presented in Table 1, where α_r , δ_r are the radiant coordinates, v_0 is the velocity, z_r is the zenith distance of the radiant, h_b , h_m , h_e are the heights of the beginning, maximum luminosity and end of the trail of bolide, M_m is the apparent stellar magnitude determined from the light curves obtained by the satellite, E is the kinetic energy and m is the mass of the bolide.

EVALUATION OF THE SUPERBOLIDE MASS

The estimates of the superbolide mass were produced using three methods: a) the photometric, based on the luminosity at the height of maximum luminosity, b) the graphical, using the dependence of the stellar magnitude as a function of the mass (i.e. based on the published bolide data) and c) using the kinetic energy of the superbolide.

The meteoroid's mass according to the photographic method is determined by integrating the luminosity along the trail and the luminosity at the height of maximum luminosity. Since the results of ground-based observations did not contain the trail at the stage of formation, we used the maximum value of luminosity obtained by satellite observations. The preliminary photometric mass of a meteoroid can be determined by the following well-known equation from [8]:

$$m_p = \frac{9H^* I_p}{2\tau_p v_0^3 \cdot \cos z_r}, \quad (1)$$

where H^* is the height of the homogeneous atmosphere, τ_p is the luminosity coefficient, I_p is the maximum luminosity, v_0 is the velocity of the bolide, and z_r is the zenith distance of the radiant. Eq. (1) is based on the theory of evaporation, and hence it does not take into account the fragmentation of the meteor. To consider the fragmentation effect and its influence on the mass determination, we used the correction coefficients from [1]. The semi-empirical formula then can be rewritten as:

$$m_p = \frac{3H^* I_p}{4\tau_p v_0^3 \cdot \cos z_r} \quad (2)$$

To calculate the photometric mass of the superbolide, we used the average stellar magnitude calculated from luminosity maximum, which is -20.4^m . However, to determine the photometric mass, it is necessary to convert the apparent stellar magnitude (i.e. luminosity) into the absolute one. For this, we used the following equation to transform the luminosity I_p into the absolute stellar magnitude M [2, 8]:

$$M = 24.3 - 2.5 \lg I_p,$$

The resulting absolute magnitude is -20.3^m , assuming the distance as 100 km. The luminosity coefficient then is:

$$\tau_p = 1.05 \cdot 10^{-18} \times (\vartheta_0 - 7 \cdot 10^5) \times 5.25 \cdot 10^9,$$

Assuming the average values of the velocity $\vartheta_0 = 15 \cdot 10^5$ cm/s, the height of the homogeneous atmosphere $H^* = 7 \cdot 10^5$ cm, the zenith distance of the radiant $z_r = 7.6$ and $I_p = 1.9 \cdot 10^{17}$ erg/s in Eq. (2) we obtained the photometric mass as 25.3 tons.

In order to estimate the mass by the second method, we selected the meteors with velocities of 13–16 km/s from the publicly available catalogue of fireballs of the Prairie Network and plotted the mass as a function of the stellar magnitude. Based on the absolute stellar magnitude of the studied bolide (-20.3^m) the corresponding bolide mass was found as 19.9 tons. At the same time, the mass calculated by the kinetic energy equation as $m_p = 2W_k/\vartheta_0^2$ was 18.9 tons.

Thus, the average value of the mass obtained by three methods is 21.3 ± 2.1 tons, which is close to the boundary mass value estimated in [9] and the bolide release.

DETERMINATION OF SUPERBOLIDE DENSITY

Using the parameters of the atmospheric trajectory of the bolide obtained from the combined satellite and ground observations and the average values of mass obtained in the previous section we estimate the superbolide density using a) the value of atmospheric density corresponding to the maximum luminosity, b) the measured values of deceleration, and c) the PE criterion. The most important parameters required for density calculation are the altitude of appearance, maximum luminosity and disappearance of the meteoroid.

The coordinates of the radiant and the altitude of the superbolide were taken from [7] obtained from images taken at HisAO and in the city of Dushanbe. The difference between the times of photographing the trail at these two sites is less than 1 minute and therefore its effect on the final result is negligible.

However, we should note that the values of the altitude and radiant obtained in [5] is slightly different with respect to the results from the bolide release and [7]. Such difference caused by the fact that [5] used images obtained at HisAO and Hulbuk were taken 15 minutes apart. On the other hand, in [6] the wind speed was calculated to be 18 km/s. This wind speed for 15 minutes shifts the trail of the bolide by more than 13 km, not accounting for which distorts the final results.

The analysis of the infrasonic signals received by two stations [9], the heights of the beginning and the end of the track were estimated at 55 and 15 km with an accuracy of ± 5 km. According to the images obtained in HisAO and Dushanbe, as well as in the bolide release, the maximum height is very close to the height of the beginning of the trail. Therefore, the values on the height of trail's beginning estimated in [9] are clearly overestimated. On contrary, the altitude of the disappearance of the bolide is close to the value obtained in [5]. Therefore, to calculate the bulk density we used the averaged values obtained from combined satellite and ground-based observations [5, 9], that are also presented in Table 1.

The first method of the superbolide density determination is based on the relation between the density and the initial parameters of the bolide and the atmosphere [8] considering the fragmentation according to [1]. The initial equation has the following form:

$$\delta = \gamma_1 \gamma_2 \left[\frac{3A\lambda H^* \vartheta^2 (\rho_m - \rho_b)}{6Qm^{1/3} \cdot \cos z_r} \right]^{3/2},$$

where ρ_m is the density of the atmosphere at the height of the maximum luminosity, ρ_b is the density of the atmosphere at the height of the event beginning, A is the form coefficient, λ is the heat transfer coefficient, and γ_1, γ_2 are the correction coefficients including the effect of fragmentation on the density determination. We assumed $A = 1.21$, $\tau_p = 0.08$, $Q = 8 \cdot 10^{10}$ erg/g, and m as the average mass of the superbolide. As a result, we obtained the values of density $\delta = 0.53$ g/cm³.

To determine the meteoroid density from the measured values of deceleration we used the equation from [2]:

$$\delta = \left[\frac{A\Gamma\rho\vartheta^2}{m^{1/3}(-d\vartheta/dt)} \right]^{3/2},$$

where Γ is the coefficient of resistance, $(-d\vartheta/dt)$ is the deceleration of the studied superbolide. Assuming the end-of-bolide height as $h = 16.3$ km and the deceleration value from [7] as $(-d\vartheta/dt) = -8$ km/s², the resulting density of the bolide is 1.1 g/cm³, which

is slightly different from the density value calculated above.

To determine the density according to the Criterion-PE, which characterises the strength or destructibility of meteoroids, we used the well-known relation between superbolide parameters (see [2]) as:

$$\text{PE} = \log \rho_E + 0.42 \log m - 1.49 \log \vartheta_0 + 1.29 \log \cos z_r, \quad (3)$$

where ρ_E is the density of the atmosphere at the height h_E of the trajectory of the bolide. According to the classification in [3, 4], fireballs are divided into four groups: Group I includes bodies similar in composition to ordinary chondrites with a density of 3.7 g/cm^3 ; meteoroids of Group II are carbonaceous chondrites with a density of 2.1 g/cm^3 ; group IIIA consists of meteoroids with an average density of 0.6 g/cm^3 from cometary-like materials; and finally, meteoroids of group IIIB have a density of 0.2 g/cm^3 and represent the loose cometary substance of the Draconid type. Depending on the types of fireballs, the values of the PE criterion vary within the following limits: $\text{PE} > -4.6$ (for the group I), $-5.25 < \text{PE} \leq -4.6$ (for group II), $-5.7 < \text{PE} \leq -5.25$ (for group IIIA) and $\text{PE} \leq -5.7$ (for group IIIB).

According to the equation (3) the averaged initial parameters of the bolide is resulting in the value of the parameter $\text{PE} = -5.08$, which corresponding to group II with the density 0.95 g/cm^3 . In this way, the average superbolide density calculated by the three methods is $0.86 \pm 0.15 \text{ g/cm}^3$, which characterising the group II of the asteroid type. The orbital characteristics of the superbolide obtained in [7] also indicate the asteroid origin of the studied superbolide.

CONCLUSIONS

The analysis of the atmospheric trajectory of the superbolide obtained both from ground-based observations and from the light curves from a satellite showed that the height of the maximum luminosity is close to the height of the beginning of the trajectory. Among the meteorites that have light curves similar to the light curves of the studied superbolide,

there is only one case, the Bunburra Rockhole meteorite of type LL. The height of the main flare of this meteorite was located close to the height of appearance similarly to the case of Tajikistan bolide studied in this work. The close location of the height of the maximum to the beginning of the trail usually inherent to meteorites with porous structure indicating that the studied superbolide possibly had a granular structure.

Thus, in accordance with the obtained results on the bulk density of the superbolide, it should be concluded that the studied superbolide has an asteroid origin. At the same time, the loose structure of the superbolide was caused by the explosion at an altitude of 35 km, which is close to the height of the beginning of the trajectory with the aerodynamic pressure of 1.6 MPa.

ACKNOWLEDGMENTS

NK work in this study was supported by the International Science and Technology Center project T-2113.

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Table 1: The parameters of the atmospheric trajectory of the studied superbolide from literature calculated from the combined satellite and ground-base observations. The last column presents the averaged values of each corresponding parameter among values available in the literature.

	[7]	the bolide release ¹	[9]	[5]	Average
α_r , deg	221.3 ± 2.1	—	—	234.8	228.1
δ_r , deg	32.4 ± 2.1	—	—	34.0	33.2
ϑ_0 , km/s	14.3 ± 0.5	16	14.5	—	14.9
z_r , deg	10	—	—	5.1	7.6
h_b , km	38.2 ± 0.5	—	—	43.4	41.05
h_m , km	35.0 ± 0.5	35.0	31.5	37.5	34.9
h_e , km	19.6 ± 0.5	—	15.0	14.3	16.3
M_m	—	−20.0	−20.3	−21.0	−20.4
E , J	—	$2.1 \cdot 10^{11}$	$2.1 \cdot 10^{12}$	—	$2.1 \cdot 10^{12}$
m , ton	—	15–20	20–25	—	20



Fig. 1: *Left:* The initial trail of the bolide, recorded at 19:46:20 UT. *Right:* The dust trail of the bolide after 30 minutes of flight from the beginning.