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The January 7, 2015, superbolide over Romania and structural diversity of meter-sized asteroids

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ABSTRACT

Superbolides, i.e. extremely bright meteors produced by entries of meter-sized bodies into terrestrial atmosphere, are rare events. We present here detailed analysis of a superbolide, which occurred over Romania on January 7, 2015. The trajectory, velocity, and orbit were determined using two all-sky photographs from a station of the European Fireball Network (EN) in Slovakia and five casual video records from Romania, which were carefully calibrated. Bolide light curve was measured by EN radiometers. We found that the entry speed was 27.76 ± 0.19 km s^{-1}, significantly lower than reported by US Government sensors. The orbit was asteroidal with low inclination and aphelion inside Jupiter's orbit. The atmospheric behavior was, however, not typical for an asteroidal body. The peak brightness of absolute magnitude of -21 was reached at a quite large height of 42.8 km and the brightness then decreased quickly. The bolide almost disappeared at a height of 38.7 km, leaving just a stationary luminous trail visible for several seconds. Only one small fragment continued until the height of 36 km. Brief meteorite searches were unsuccessful. The modeling of the light curve revealed that the body of initial mass of about 4500 kg remained almost intact until the dynamic pressure reached 0.9 MPa but it was then quickly disintegrated into many tiny fragments and dust under 1–3 MPa. A comparison was made with three other superbolides for which we have radiometric light curves: ordinary chondrite fall Košice, carbonaceous chondrite fall Maribo, and cometary Taurid bolide of October 31, 2015. The Romanian superbolide was not similar to any of these and represents probably a new type of material with intrinsic strength of about 1 MPa.

1. Introduction

Superbolides are extremely bright meteors, brighter in maximum than absolute (i.e. as seen from the distance of 100 km) visual magnitude of -17 (Ceplecha et al., 1999). Although bolide brightness depends on many parameters, e.g. meteoroid size, structure, composition, and entry speed and entry angle, we can roughly say that superbolides are caused by meteoroids of the sizes of the order of one meter and larger. In fact, meter-sized bodies are now often called asteroids rather than meteoroids (Borovička, 2016a). Regardless the terminology, bodies of these sizes belong to the least known objects in the Solar System. Current astronomical telescopes are sensitive enough to detect them when passing within few hundreds of thousands kilometers from the Earth, nevertheless, rarely is more information obtained than the orbit. Even the size is only approximate if albedo is not known. Properties, and in particular internal structure, of small asteroids are, nevertheless, of great interest from several reasons. Rotational rates of asteroids larger than about 200 m (and smaller than about 10 km) suggest that large majority of them are weakly bound gravitational aggregates, the so-called rubble piles (e.g. Pravec and Harris, 2000). Smaller asteroids rotate generally much faster and can be monolithic, although it was suggested that many of them may be rubble piles as well, bound together by small van der Waals forces (Sánchez and Scheeres, 2014). Clarifying the question if small asteroids are monolithic or aggregates would shed light to the impact processes, in which these bodies are born. But even monolithic materials can have various structures and strengths, depending on the presence of cracks and other failures. Finally, even pristine Solar System materials have significant diversity as evidenced by meteorites, ranging from hard pure metals to relatively soft carbonaceous bodies.

Although meteorites are our best source of knowledge about microscopic and small-scale properties of asteroidal material, they are telling only part of the story. First, meteorites represent only the strongest parts of the original meteoroid or asteroid – the part, which

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was able to survive the atmospheric flight. Second, there are certainly meter-sized objects that are so weak that they do not drop any meteorites. An example was the body which produced the Šumava superbolide (Borovička and Spurný, 1996).

The structure of small asteroids is of interest not only from purely scientific reasons. There are ideas of future retrieval and exploitation of small asteroids (e.g. Hasnain et al., 2012). The knowledge of physical properties of the target asteroid would be certainly crucial for the success of such an attempt. Small asteroids also pose non-negligible hazard when they enter the Earth's atmosphere. The hazard was demonstrated by the crater producing Carancas impact (Borovička and Spurný, 2008; Tancredi et al., 2009) and by the damaging blast wave produced by the Chelyabinsk entry (Brown et al., 2013; Popova et al., 2013). The actual effects on the ground caused by each particular entry depend to large extent on the internal structure of the impactor.

Observations of superbolides can, in fact, most easily provide information about the structure of meter-sized asteroids. Superbolides, however, are extremely rare events when observed from one site or from a limited region. Ceplecha (1994) compiled 13 bolides from decades long observations by three fireball networks (plus one satellite tracked bolide), which he believed were all produced by bodies larger than 1 m. He classified them according to the PE criterion developed earlier for smaller bolides (Ceplecha and McCrosky, 1976) and based on bolide end height. Five of the 14 bodies were classified as soft cometary (the weakest known material). The remaining ones were mostly classified as carbonaceous.

These results were not confirmed by the recent study of Brown et al. (2016), which was based mostly on data from the US Government sensors obtained on global scale. The available data about 47 superbolides included only the location, height of maximum, velocity vector, and total radiated energy. Only one event had very high maximum (59 km), suggesting its cometary nature. The others had maxima at wide range of heights, 19–45 km, without obvious grouping. While those penetrating deeply were likely compact stones or metals, the nature of most bodies is not possible to judge from the data. They may have been fractured objects or bodies composed from weaker (e.g. carbonaceous) material. Popova et al. (2011) compiled data on 13 instrumentally observed meteorite falls. They were able to compare the atmospheric behavior with the properties of the recovered meteorites. More detailed observational data enabled the authors to find individual fragmentation points along the bolide trajectories. For all ordinary chondrites, the inferred strength of the incoming body was found to be one to two orders of magnitude lower than the meteorite tensile strength, presumably as a result of their collisional history. Low strength of some carbonaceous bodies may result, on the other hand, from their porous structures, more than fractures.

The study of Popova et al. (2011) was restricted to meteorite dropping events (of all sizes) and the study of Brown et al. (2016) was based on very limited amount of data for individual events. Here we take advantage of good observational data we collected on the superbolide which occurred over Romania on January 7, 2015. It was a very bright event caused by a meter-sized asteroid but did not drop meteorites (at least none was found and none larger than few grams could be expected). In addition to photographic and video records we have also obtained detailed radiometric light curves and we could model the atmospheric behavior of the body. The results could be compared with the modeling of three other superbolides of similar brightness, one ordinary chondrite, one carbonaceous chondrite, and one cometary body. The January 7, 2015, superbolide was also among those observed by the US Government sensors and we can compare our trajectory and orbital data with those reported by Brown et al. (2016).

2. Description of the event and available data

The superbolide studied here occurred over central Romania on January 7, 2015, 1:06 UT (3:06 local time). Despite the late night time, the bolide caused wide attention in the country, including news media. A number of videos, mostly from security cameras, showing intense illumination of the ground lasting for about two seconds were published on the Internet. Note that bright Moon (two days after the full Moon) was present high on the sky; the bolide was, nevertheless, much brighter. Several video cameras, including some cameras in neighboring countries Moldova and Serbia, captured the bolide itself. Sonic booms were reported in the region located about 100 km north of Bucharest.

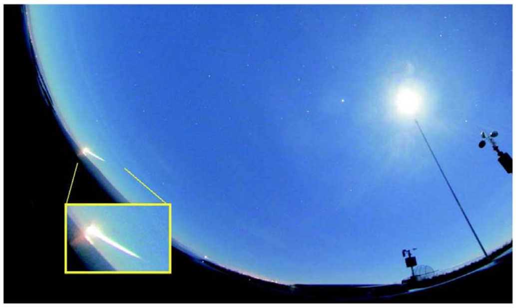

Fig. 1. Part of the all-sky image taken by the Digital Autonomous Fireball Observatory in Stará Lesná showing the January 7 bolide over the south-eastern horizon (enlarged in the inset). The brightest object on the sky is the Moon (exposed for 35 s).

The superbolide was also photographed by two all-sky cameras of the European Fireball Network (EN) located at Stará Lesná in Slovakia. Although the bolide was more than 600 km distant from there, it was well visible close to the horizon. Fig. 1 shows part of the image from the Digital Autonomous Fireball Observatory (DAFO). DAFO contains two Canon EOS 6D digital cameras equipped with Sigma 8mm F3.5 EX DG Circular Fisheye lens. The exposure was 35 s long and sensitivity ISO 3200 was used. The camera contains a LCD shutter alternating between the open and close states with the frequency of 16 Hz. Due to the high brightness and low angular speed of the bolide, the breaks caused by the shutter are difficult to see. Nevertheless, the breaks were measurable on the original image (taken in the raw CR2 format) along part of the trajectory.

The second image from Stará Lesná (Fig. 2) was taken by an older device, the Autonomous Fireball Observatory (AFO), which was run simultaneously with DAFO. AFO uses photographic film Ilford FP125 and the 30 mm fish-eye lens Zeiss Distagon F3.5 (Spurný et al., 2007). The sensitivity is lower and shorter part of the bolide was recorded by this camera. On the other hand, the brightest part was not so heavily saturated and shutter breaks could be measured, though with difficulties, along the whole recorded trajectory. Here the shutter was mechanical with the frequency of 15 Hz.

Both DAFO and AFO are also equipped with radiometers. Both radiometers are of the same type and are based on photomultiplier tube directed to zenith without any optics. The radiometers recorded total brightness of the sky during the bolide event with data frequency of 5000 Hz. The radiometers at even more distant stations of the EN

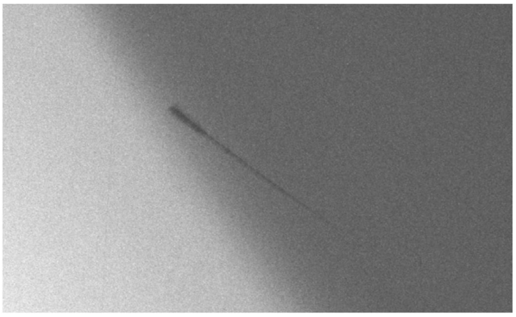

Fig. 2. The January 7 bolide on the all-sky image taken by the Autonomous Fireball Observatory in Stará Lesná on photographic film.