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# Atmospheric trajectory and heliocentric orbit of the Ejby meteorite fall in Denmark on February 6, 2016

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ABSTRACT

A very bright bolide illuminated the sky over Denmark and neighboring countries on February 6th, 2016 at 21:07:18-23UT. It terminated by a multiple meteorite fall in the heavily populated area of the western outskirts of Copenhagen. Several meteorites classified as the H5/6 ordinary chondrites have been found shortly after the fall and total recovered mass reached almost 9 kg (Haack, 2016). Although this spectacular bolide has been reported by many casual witnesses, the instrumental records are very scarce, mainly due to bad weather over Denmark and neighboring countries. Despite it we were able to collect five instrumental records taken from different locations which were useful for the analysis of this event. We used three high resolution digital photographic images taken in Germany, one high resolution radiometric light curve taken by the northernmost Czech automated fireball observatory and one video record taken by a surveillance camera on the Danish west coast where a part of the fireball trajectory was recorded. It allowed us to reliably determine basic parameters defining the luminous trajectory of the bolide in the atmosphere and also heliocentric orbit of the initial meteoroid causing this spectacular meteorite fall. We found that this event was caused by a relatively fragile 50 cm meteoroid with initial mass about 250 kg. It entered the atmosphere with velocity of 14.5 km $s^{-1}$ and quite steep entry angle of 62°. Its luminous flight started at 85.5 km and after 76 km long trajectory it terminated at 18.3 km. The heliocentric orbit of this meteoroid was of Apollo type with low inclination of 1° and perihelion distance just inside the Earth's orbit. It had a relatively large semimajor axis of 2.8 AU and aphelion distance 4.64 AU. It is the second largest aphelion distance among all meteorites with known orbits and the orbit had the same character as that of the Košice meteorite (H5 ordinary chondrite), which fell on February 28, 2010 (Borovička et al., 2013).

## 1. Introduction

Every instrumentally documented fireball terminating by a meteorite fall with reliable data describing its atmospheric trajectory and heliocentric orbit, especially when it is associated with recovered meteorites, is very important. It provides valuable information about the processes accompanying the atmospheric flight of the initial meteoroid and also about populations and physical characteristics of small interplanetary bodies in near Earth space and their relations to the larger parent bodies – asteroids and comets. To our knowledge 26 instrumentally documented bolides connected with recovered meteorites is published until now (22 cases until end of 2013 are collected in Borovička et al. (2015b), for four new cases see Trigo-Rodriguez et al. (2015), Spurný (2015), Bland et al. (2016), Spurný et al. (2016)).

Here we report a new instrumentally documented bolide and meteorite fall in Denmark named Ejby after the suburb in the western part of Copenhagen where first meteorites were recovered already next day after the fall. This very bright bolide illuminated the sky over Denmark and neighboring countries on Saturday's late evening on February 6th, 2016 at 21:07:18–23 UT. It terminated by a multiple meteorite fall in the heavily populated area of the western outskirts of Copenhagen and several meteorites classified as H5/6 ordinary chondrites have been found in districts Ejby, Herlev, Glostrup and Vanløse shortly after the fall (Haack, 2016). Total recovered mass is almost 9 kg and the largest recovered piece found in Herlev district weighed about 6.5 kg and it was found shattered on many pieces as it fell on the paved

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**Table 1**
Basic data on the instrumental records used for the Ejby bolide analysis.

| Site | Type of record | Coordinates Lon. °E Lat. °N | | Range of distances (km) | Range of recorded heights (km) | Recorded length (km) | Astrometric precision (°) | Type of camera | Exposure details |
|---|---|---|---|---|---|---|---|---|---|
| KBORN | Photo | 11.7721 | 54.1169 | 170.6–177.9 | 73.2–18.3 | 62.1 | 0.003 | Canon EOS 550D, 18MPx,28 mm/2.0 | ISO 1600, 10 s |
| BDBR | Photo | 11.9209 | 54.0963 | 173.9–178.8 | 85.5–18.4 | 76.0 | 0.010 | GoPro Hero4 12Mpx, 3 mm/2.8 | ISO 800, 30 s |
| Binnewies | Photo | 9.1756 | 50.6167 | 580.8–599.8 | 77.9–23.8 | 61.3 | 0.006 | Canon EOS 6D 20MPx,14 mm | ISO 3200, 45 s |
| Růžová | Radiometric | 14.2865 | 50.8341 | 544.8–551.9 | 65–20[a] | 51[a] | – | DAFO/radiometer | 5000 Hz |
| Ho | Video | 8.2315 | 55.5496 | 250.8–253.4[b] (250.0–257.8) | 51.9–36.4[b] (59.7–18.7 | 17.5[b] | 0.11 | Y-cam Evo Outdoor HD Pro,1280 × 720 | 27.33 fps |

[a] Estimated values from correlation of the photographic (function of heights) and radiometric (function of time) light curves.
[b] Corresponds to the part of the trajectory where positions on individual frames were reliably measurable (altogether 12 frames) and which could be used for velocity calculation. Other measured points are only of limited precision because most of the bolide luminous path was obscured by trees close to the camera (Fig. 3).

surface (Haack, 2016). Although conspicuous luminous and acoustic effects of this spectacular bolide have been observed and reported by hundreds of casual witnesses, the instrumental records, which could serve for complex description of this extraordinary event, are very scarce mainly due to bad weather over Denmark and neighboring countries. In this study we present results of the analysis of the available instrumental records, which we were able to collect and which were useful for the analysis. It allowed us to reliably determine basic parameters describing the luminous trajectory of the bolide in the atmosphere and also heliocentric orbit of the initial meteoroid causing this spectacular meteorite fall.

## 2. Instrumental observations

After quite extensive effort to find any useful instrumental record, we were able to collect five records which proved to be useful for complete description of the Ejby meteorite fall. This spectacular bolide was instrumentally recorded by three kinds of instruments as it is listed in Table 1. For the bolide description we used three high resolution digital photographic images taken in Germany, one high resolution radiometric light curve taken by the northernmost Czech digital automated fireball observatory (Spurný et al. 2007; Spurný 2015) and one video record taken by a surveillance camera on the Danish west coast where a part of the fireball trajectory was recorded and which was useful especially for independent determination of the initial velocity. As it will be shown later, these records proved to be suitable and sufficiently precise for reliable determination of the atmospheric trajectory, luminosity and heliocentric orbit of the Ejby meteoroid.

Two most important photographic records were taken by digital cameras from northern Germany. These images as shown in Fig. 1 were taken from Kühlungsborn (further abbreviated as KBORN) and a nearby town Bad Doberan (BDBR), two places located only 10 km apart close to the shore of Baltic Sea. In spite of this relatively bad geometry which is caused by proximity of the sites (Fig. 6 - right) resulting in the intersection angle of only 3.5°, high quality of these images along with sufficient number of positional stars measurable around all field of view of both cameras enabled us to determine the atmospheric trajectory of the bolide with reasonable precision. Fortunately, complete luminous part has been recorded on both images (except the very beginning on the Kühlungsborn image). These stations were also suitably placed to the fireball trajectory because distance to the bolide remained almost constant around 175 km for both sites as can be seen in Table 1 and Fig. 6. Additionally several months after the bolide we obtained still third high resolution digital image of the Ejby bolide taken by Dr. Stefan Binnewies from Central Germany (Fig. 2, Table 1). Unfortunately, the clock in the camera had not been adjusted for a long time and it was not possible to reconstruct the correct time of the exposure so long time after the event. From the Exif information we know that length of the exposure was 45.1 s, and from radiometric record we know the absolute timing of the fireball, which was 21:07:18–23 UT. From it we know that the real uncertainty in exact time of the exposure can be 40 s in the maximum which means that the beginning of the exposure must be in the time interval from 21:06:38 to 21:07:18 UT. This uncertainty did not allow us to use this image for independent determination of the trajectory because for such a big distance it results in positional uncertainty of several hundred meters in trajectory determination. However we could check if some solution including this image with beginning of the exposure from the above mentioned interval will comply with the solution from all other records. From this check we found that the beginning of the exposure at 21:07:07 UT perfectly satisfy this condition. This value is well inside possible interval and it means that also this image supports and increases the reliability of the solution which we found from all other records.

Apart from the available photographic records, high time resolution (5000 Hz) radiometric light curve was taken by the Digital Autonomous Fireball Observatory at the northernmost station Růžová of the Czech Fireball Network. Position of the station is shown in Fig. 6 (right), the light curve is in Fig. 4 and corresponding details are listed in Table 1. In fact also other radiometers on the stations of the Czech Fireball Network recorded the light curve of the Ejby bolide, but with much worse signal-to-noise ratio. Although the fireball was below the local horizon, the light scattered in the atmosphere was sufficient for the radiometric detection at Růžová. It was taken from a distance of 550 km to the fireball and practically the entire luminous trajectory of the Ejby bolide below the height 65 km is covered by this record. This light curve was very important because it could be used not only for precise timing of the event (signal of the radiometer is continuously corrected by PPS pulse of the GPS) but also for the determination of the initial velocity, brightness and initial mass of the meteoroid as it will be shown later.

The latest instrumental record which we obtained after all preliminary analyses and which we incorporated into the final solution was a video record from the Ho village on the west coast of Denmark. It was taken by a fixed HD surveillance camera (details are again in Table 1) and most of the bolide trajectory was obscured by trees close to the camera. Fortunately, the position of the bolide could be determined on 12 frames in the first half of the fireball trajectory. After correct reduction of this video record (described below) it enabled direct and independent determination of the fireball velocity. It perfectly fitted the existing solution and significantly increased its reliability.

## 3. Results

Using our standard procedures (Borovička, 2014) we reduced all three digital images and the video record. Astronomical refraction was