Double station and spectroscopic observations of the Quadrantid meteor shower and the implications for its parent body

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ABSTRACT
Object 2003 EH1 was recently identified as the parent body of the Quadrantid meteor shower. The origin of this body is still uncertain. We use data on 51 Quadrantid meteors obtained from double-station video observations as an insight on the parent body properties. A data analysis shows that the Quadrantids are similar to other meteor showers of cometary origin in some aspects, but in others to Geminid meteors. Quadrantid meteoroids have partially lost volatile component, but are not depleted to the same extent as Geminid meteoroids. In consideration of the orbital history of 2003 EH1, these results lead us to the conclusion that the parent body is a dormant comet.

Key words: comets: individual: 2003 EH1 – meteors, meteoroids.

1 INTRODUCTION
The Quadrantid meteor shower is one of the most active annual meteor showers. Its zenithal hourly rate (ZHR) usually reaches values of about 100. Because of its very short and sharp activity profile and the typically bad weather – prevalent in January in the Northern hemisphere, where this shower is best observed – observations of the Quadrantids are not as frequent as for other active showers. The shower is named after the former constellation Quadrans Muralis, which is today a part of the modern constellation Boötes. The shower first became observable quite recently; no observations were made before AD 1800.

Until recently, the parent body was unknown. The Quadrantids were the last of the major meteor showers with an unidentified parent. Although there were several proposals – for example, comets 96P/Machholz and C/1490 Y1 – the connection was not proven for any of these objects. A summary of early searching for the parent body is provided, for example, by Williams et al. (2004).

Significant progress has been made only in recent years. On the bases of the photographic data, Jenniskens et al. (1997) show that the main component of the meteor stream is only about 500-yr old. The stream is much younger than was previously thought. They find that the comet 96P/Machholz is not the parent body and predicted an estimate of that orbit. When a new near-Earth object 2003 EH1 was discovered at Lowell Observatory on 2003 March 6, Jenniskens (2004) identified this object as the Quadrantid meteor shower parent body. Small discrepancies in the orbits of 2003 EH1 and the Quadrantids can be explained by different orbital evolution of the parent and its stream in the last 500 yr. He also calculated the total mass of the dust in the stream and found that a period of 1000 yr is necessary for the deposition of this amount of dust. Because this is inconsistent with the young age of the stream, he concludes that the breakup of a comet nucleus is responsible for the creation of the meteor stream. He also notes that the connection between 2003 EH1 and comet C/1490 Y1 is difficult to find because of close encounters with Jupiter and Earth. Williams et al. (2004) investigate the orbital evolution of 2003 EH1 and 500 of its clones. Their model shows that the perihelion distance of 2003 EH1 has been significantly smaller than it is today. The perihelion distance was smaller than 0.4 au for all clones and the parent body itself in AD 1000. They also note that the orbits of 2003 EH1 and the meteor stream were very close around AD 1500. The orbits of a few clones were similar to the orbit of C/1490 Y1 and their positions in the sky roughly match that of the comet. Porubčan & Kornoš (2005) distinguish five filaments in the Quadrantid meteor stream. Two of these follow the orbital evolution of 2003 EH1. Their simulations also show that the perihelion distance was much smaller in the past. Wiegert & Brown (2005) also simulate orbits of 2003 EH1 and of meteoroids released from it. Their model shows that the sharp activity profile and recent appearance of the meteor shower can be easily explained by meteoroid ejection near AD 1800.

In this paper, we use double-station video and spectroscopic observations as an insight to the Quadrantid meteor shower parent body properties.

2 DOUBLE-STATION OBSERVATIONS AND DATA PROCESSING
Our double-station observations of the Quadrantid meteor shower have been carried out within observational programmes of monitoring major meteor showers. The Czech team observed the
meteor shower in 2002 and the UK team 1 yr later, in both instances on January 3/4. Details of the configuration of both experiments are given in Tables 1 and 2. The term distance is the distance between the two stations, azimuth is the azimuth of the southern station (the azimuth of south is 0°).

The Ondřejov and Kunžak station were equipped with identical instruments, comprising Dedal-41 second-generation image intensifiers, Arsat 1.4/50 mm lenses and Panasonic S-VHS camcorders. This configuration gives a field of view (FOV) of about 25°. The same instrument equipped with a spectral grating – dispersion 600 grooves mm⁻¹ – for detection of meteor spectra was operated at Ondřejov Observatory. Similar instruments were used during the UK campaign. Both cameras employed second-generation image intensifiers (screen diameters 18 mm at Moreton and 25 mm at Pilling) coupled with Canon 1.4/50 mm lenses and Sony Hi8 and DV camcorders, which provide FOV of 20.5 and 28.5 at Moreton and Pilling, respectively.

The recorded video tapes were initially searched using METREC (Molau 1999) meteor recognition software. The data base of all recognized meteors was compiled and all double-station events were transformed into audio/video data format (AVI) files. These non-compressed files were measured using self-automatic software METPHO (Koten 2002). Finally, the atmospheric trajectory and heliocentric orbit were computed using our standard procedures.

In total, 125 double-station meteors were detected. Both Southworth–Hawking’s $D_{50}$ (Southworth & Hawkins 1963) and Drummond’s $D$ (Drummond 1981) criteria were calculated for the shower membership determination. Orbital parameters of the Quadrantid meteor stream provided by Cook (1973) were used for this calculation. Only meteors which satisfied both conditions $D_{50} < 0.20$ and $D < 0.105$ were used. 51 Quadrantid meteors were selected in this way. Light curves of 44 of these were complete or sufficiently complete to be used for the analysis. They cover the range of photometric masses between $4.8 \times 10^{-4}$ and $3.9 \times 10^{-2}$ g. Corresponding absolute maximum brightness lies between +1.2 and +5.6 mag.

3 RESULTS

Properties of the Quadrantid meteors are analysed in several ways. The beginning and terminal heights, the parameter $K_B$, the shape of the light curves and meteor spectra are compared to other meteor showers as well as to sporadic meteors with similar velocity.

3.1 Beginning heights

Fig. 1 shows that the beginning height of Quadrantid meteors slowly increases with increasing photometric mass. In comparison with the showers of cometary origin, this increase is less steep, but it is significantly different to the constant beginning height of the Geminid meteors. Nevertheless, the correlation coefficient is very low and the relationship between the photometric mass and the beginning height is weak (Table 3).

According to our earlier interpretation (Koten et al. 2004), the increasing beginning height of cometary shower meteors is caused by gradual ablation of the volatile part of the meteoroid material, which is released at higher altitudes. The Geminids do not contain this volatile component, and their ablation commences suddenly at an altitude of about 100 km. The Quadrantid meteoroids appear to have retained some volatile component. In comparison with Leonids or Perseids, this component is less abundant but not absent as in the case of the Geminids.

![Figure 1](image.png)

**Figure 1.** The plot shows beginning heights of shower meteors as a function of their photometric mass. Data on meteor showers other than the Quadrantids were taken from Koten et al. (2004). The lines represent linear fits through the grouped values for each shower. For an explanation see Koten et al. (2004).

<table>
<thead>
<tr>
<th>Shower</th>
<th>$k \pm \Delta k$</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leonids</td>
<td>$9.9 \pm 1.5$</td>
<td>0.88</td>
</tr>
<tr>
<td>Perseids</td>
<td>$7.9 \pm 1.3$</td>
<td>0.92</td>
</tr>
<tr>
<td>Taurids</td>
<td>$6.2 \pm 2.2$</td>
<td>0.66</td>
</tr>
<tr>
<td>Orionids</td>
<td>$5.0 \pm 0.7$</td>
<td>0.86</td>
</tr>
<tr>
<td>Quadrantids</td>
<td>$3.4 \pm 0.8$</td>
<td>0.30</td>
</tr>
<tr>
<td>Geminids</td>
<td>$0.5 \pm 0.3$</td>
<td>0.35</td>
</tr>
</tbody>
</table>

**Table 3.** Beginning heights of different meteor showers.

Note: $k$ is the slope of the relationship between the beginning height and the photometric mass.

Quadrantid meteor shower and its parent body

3.2 Parameter $K_B$

Ceplecha (1988) defined another parameter, which is used for the separation of different populations of sporadic meteors. He transformed the problem of classification to a one-dimensional parameter

$$K_B = \log \rho_B + 2.5 v_\infty - 0.5 \log \cos z_R + 0.15,$$

where $\rho_B$ is the atmospheric density at the beginning height, $v_\infty$ is the initial velocity and $z_R$ is the zenith distance of the radiant. We use this parameter to eliminate the potential effect of different zenith distance of the radiant on the beginning height of the meteor.

The $K_B$ criterion is calculated for Quadrantids as well as sporadic meteors with similar velocity. The results are presented in Fig. 3. The Quadrantid meteors lie exactly in the gap between the two groups of sporadic meteors. According to this criterion, the majority of Quadrantids belongs to Ceplecha’s class B, which is characterized as the ‘dense cometary material’ (Ceplecha 1988). Bellot-Rubio et al. (2002) also classify the Quadrantid meteors as class B. All asteroidal sporadic meteors belong to class A and almost all cometary meteors to class C.

The parameter $K_B$ also eliminates the influence of different initial velocity, so we can use it for comparison with other meteor showers. The result is somewhat surprising in that the values for the Quadrantids and Geminids are the same. The average value is $7.23 \pm 0.02$ for Quadrantid meteors and $7.22 \pm 0.02$ for Geminid meteors. Fig. 4 shows that the distribution of this parameter is also very similar for both showers. On the other hand, the histogram of $K_B$ for the Perseid meteors looks completely different. The width of the Quadrantid and Geminid showers’ distributions is very narrow, whereas that of the Perseid meteor shower is broad. This is caused by the broad range of Perseid beginning heights as a consequence of the increase of beginning height with increasing meteoroid mass.

3.3 Terminal heights

Jenniskens (2004) shows that the terminal heights of photographic Quadrantid meteors are similar to those of the Perseid and Lyrid meteor showers and concludes that the Quadrantid meteors are ‘cometary in nature’. Our results are different as is shown in Fig. 5. The Quadrantids penetrate deeper in the atmosphere than the Perseids, because their initial velocity is smaller. For a given photometric mass, the difference is about of 10 km. On the other hand, the terminal heights of the Quadrantids are similar to those of the Geminids with the same photometric mass. Their somewhat higher beginning height could be explained by a higher entry velocity in comparison with Geminid meteors. Comparable values of the parameter $K_B$ for both Quadrantid and Geminid meteors confirm this explanation. From this point of view, the zone of ablation for the Quadrantid and Geminid meteors is similar.
3.4 Light-curve shape

The meteor light-curve shape is another criterion, which can be used for distinguishing different meteor showers. The light curve is traditionally described using the $F$-parameter (e.g. Fleming, Hawkes & Jones 1993).

$$F_{\Delta M} = \frac{H_{B,\Delta M} - H_{\text{max}}}{H_{B,\Delta M} - H_{E,\Delta M}},$$

where $H_{B,\Delta M}$ and $H_{E,\Delta M}$ are heights, and the meteor brightness is $M_{\text{max}} - \Delta M$, where $M_{\text{max}}$ is the maximum brightness, $\Delta M = 0.25$.

0.5, 0.75, 1.0, ..., 2.5, 2.75 and 3.0. For each meteor, we compute $F$ as the average value of all $F_{\Delta M}$.

In simple terms, this parameter indicates the location of maximum brightness on the meteor light curve. Fig. 6 shows the parameter $F$ in relation to the meteor photometric mass, in which Quadrantid, Leonid and Geminid meteors are plotted. The light curves of 28 Quadrantid meteors were appropriate for the determination of this parameter. We can see that the distribution of the Leonid and Quadrantid meteors is quite similar. The parameter $F$ for the Geminid meteors with similar mass reaches somewhat higher values, which is usually interpreted as the proof for a more compact composition of the meteoroids. This difference is obvious also from the Table 4, which shows average values for other meteor showers (Koten et al. 2004).

According to this criterion, the Quadrantid shower seems to be more cometary than asteroidal. The average value of $F$ is more similar to that of the Leonid meteors than to the Geminids. We are conscious, however, of the wide spread of $F$ values for each shower, so we use this parameter only as the auxiliary criterion.

3.5 Quadrantid spectra

We obtained 10 video spectra of Quadrantids; two of these show only the beginning of the meteor. We have studied the monochromatic

<table>
<thead>
<tr>
<th>Shower</th>
<th>Number of meteors</th>
<th>$F \pm \Delta F$</th>
</tr>
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<tbody>
<tr>
<td>Leonids</td>
<td>83</td>
<td>0.49 ± 0.02</td>
</tr>
<tr>
<td>Quadrants</td>
<td>28</td>
<td>0.50 ± 0.02</td>
</tr>
<tr>
<td>Taurids</td>
<td>45</td>
<td>0.54 ± 0.03</td>
</tr>
<tr>
<td>Perseids</td>
<td>188</td>
<td>0.54 ± 0.01</td>
</tr>
<tr>
<td>Orionids</td>
<td>112</td>
<td>0.55 ± 0.01</td>
</tr>
<tr>
<td>Geminids</td>
<td>68</td>
<td>0.58 ± 0.02</td>
</tr>
</tbody>
</table>
light curves in sodium and magnesium lines and the total radiated energy in Na, Mg and Fe lines. Sodium was previously found to be ablated preferentially in the majority of Leonid meteors. The Na line started and ended earlier than the Mg line (Borovička, Štork & Boček 1999). This effect can be ascribed to meteoroid fragility and early fragmentation. Geminid meteors were found to be depleted in Na, which can be ascribed to their small perihelia and a loss of volatile Na due to solar heating (Borovička et al. 2005).

Fig. 7 shows the Mg and Na light curves of three Quadrantids and one sporadic meteor with velocity 40 km s$^{-1}$ (this a cometary meteor with $K_B = 7.1, a = 12$ au, $e = 0.93, i = 60^\circ$). The light curves in white light from non-spectral cameras are plotted for comparison (in a different scale). All Quadrantids show preferential ablation of Na to various extents, from quite pronounced to moderate. The sporadic meteor, on the other hand, does not show this effect. The total intensities of the Na, Mg and Fe lines in Quadrantids, Leonids and Geminids are compared in the ternary diagram in Fig. 8. It can be seen that Quadrantids fall between Leonids and Geminids. They have suffered a loss of sodium but not to the same extent as the majority of Geminids.

4 DISCUSSION

Our investigation of Quadrantid meteor properties shows that in some aspects they are similar to the Geminids but in others to cometary meteor showers. The intermediate beginning heights, the near independence of beginning heights on mass and the total intensity of Na in spectra show that Quadrantid meteoroids have suffered a partial loss of volatiles, though not as severe as in the case of the Geminids. The symmetrical light curves and the early ablation of Na indicate that the Quadrantids are subject to early fragmentation on atmospheric entry, similar to cometary shower meteoroids.

In the case of the Geminids, their small perihelion distance (0.14 au) is responsible for the volatile loss and general compaction...
of the meteoroids (Borovička et al. 2005). Recently, several papers have dealt with the orbital evolution of the object 2003 EH$_1$ (Jenniskens 2004; Williams et al. 2004; Porubčan & Kornoš 2005). All simulations show that the perihelion distance was much smaller (~0.1 au) in the period 1000–2000 yr ago. However, according to Jenniskens et al. (1997) the Quadrantid shower must be younger. He deduced the age of the main component of the stream to be about 500 yr. Very recently, Wiegert & Brown (2005) concluded that the age of the core of the stream is only 200 yr.

In that case, the meteoroids ejected from the parent body could not get closer to the Sun than about 0.6 au, which is insufficient for a loss of a significant part of the volatile component. We propose that the volatile loss occurred on the surface of the parent body when the perihelion distance was very small. The meteoroids were ejected from the surface layer later, probably during a period of cometary activity. They were not released from the interior of the body (e.g. during a catastrophic disruption) because in that case they would not show a sign of solar alteration. This leads us to the conclusion that the object 2003 EH$_1$ is a dormant comet.

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