Properties of Alpha Monocerotid meteors from the observation of the 2019 outburst in the Czech Republic

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ABSTRACT

We observed the predicted outburst of the Alpha Monocerotid (AMO) meteor shower on 2019 November 22 with our modernized video and photographic cameras. Due to the short duration and moderate intensity of the outburst, atmospheric trajectories and radiants were obtained for only ten meteors, seven of which included velocities, magnitudes, and orbits. In addition, one incomplete video spectrum was captured. The radiants and orbits were found to be compatible with that of the 1995 outburst. The spectrum confirmed that AMO meteoroids are deficient in sodium. Unlike any other meteor shower, meteor end heights were found to be distributed along a constant level of 90 km for all meteors with magnitudes between +4 and −2 and with atmospheric trajectory lengths up to 40 km. We propose that Alpha Monocerotids were formed from a devolatilized and fragile cometary crust composed of relatively large fundamental grains.

Key words. meteorites, meteors, meteoroids

1. Introduction

The Alpha Monocerotids (AMO, IAU #246) is a meteor shower with a peak occurring around November 22 every year. The annual activity is low, but intense outbursts are occasionally produced. Five individual outbursts were observed in 1925, 1935, 1985, 1995, and 2017 (Jenniskens et al. 1997; Jenniskens & Odeh 2017; Roggemans et al. 2018). The observations in 1995 provided the first ten multi-station meteors with known radiants and heliocentric orbits giving the first evidence of the presence of a trail of a long-period comet. The peak zenith hourly rate (ZHR) of the 1995 AMO outburst was 500 (Jenniskens et al. 1997). Observations of the Cameras for Allsky Meteor Surveillance (CAMS) networks in 2017 provided 17 individual orbits of AMO meteors, even if no outburst was predicted (Roggemans et al. 2018). Median orbital elements of the majority of them (10 multi-station meteors were observed in the United Arab Emirates) are in good agreement with the observations obtained in 1995 (Jenniskens & Odeh 2017). Four television spectra of AMO meteors were obtained in 1995 by Štork et al. (1998). They observed a very faint Na I line (5892 Å) and concluded that the material of AMO meteoroids contains a lower amount of volatile elements, at least sodium. Borovička et al. (2005) classified AMO meteors near the boundary between Na-poor and Na-free meteoroids according to their spectral properties. Jenniskens et al. (1997) noted that Alpha Monocerotids have relatively low ends of their atmospheric trajectories compared to other cometary meteoroids with similar velocities (e.g., Perseids), and they are therefore stronger and might lack volatiles.

Lyytinen & Jenniskens (2003) found that only encounters with one-revolution trails can explain the observed outburst duration of 40 min. The best solution for the unknown orbital period of the parent comet was 650 yr. The original calculation showed the trail will pass far from the Earth’s orbit in 2019. Recently, Jenniskens & Lyytinen (2019) re-evaluated this result assuming a shorter orbital period of 500 yr, which moved the trail closer to the Earth. They predicted similar or even higher peak rate in comparison with the 1995 encounter. The 2019 encounter was expected at solar longitude 239.308°; that is, on November 22, 4h 50m UT with a full width at half maximum (FWHM) of only 0.29 h.

Following that prediction, we decided to organize a video and digital photography campaign to observe the outburst. The campaign was successful, though the number of observed AMO meteors was not high, and we report the results here. Section 2 is devoted to the description of the observations. The obtained data are described in Sect. 3 and analyzed from various points of view in Sect. 4. The implications are discussed in Sect. 5.

2. Observations

The peak timing was more favorable for Western Europe than for Central Europe; nevertheless, most of the outburst should still be visible before the beginning of dawn from Central Europe. The Moon was only 20% illuminated, so not creating much of a disturbance. Therefore, we planned to carry out the double station video observation within the Czech Republic. Due to the weather forecast, we finally selected two mountain stations in Southern Bohemia, which proved to be a lucky choice as almost the whole country was overcast that morning.

The first station was Churáňov, which is a regular station of the Czech part of the European Fireball Network (EN), equipped with Digital Autonomous Fireball Observatory (DAFO) and its spectral equivalent (SDAFO; see Spurný et al. 2017 and Borovička et al. 2019 for DAFO and SDAFO descriptions, respectively). Both observatories use two Canon 6D Digital Single-Lens Reflex (DSLR) cameras to take 35 respective 30 s long exposures of the sky. DAFO uses F3.5, 8 mm fish-eye lens,
while SDAFO uses F2.8, 15 mm lens. DAFO is equipped with a liquid crystal shutter (LCD) for the measurement of meteor velocities. SDAFO is equipped with a holographic grating to take spectra of bright fireballs. Nevertheless, direct images (zero orders) of meteors can be used to measure meteor trajectories, though without velocity information. Thanks to its lens properties, SDAFO is more sensitive than DAFO but it does not cover the whole sky (it is a diagonal fish-eye).

For the AMO campaign, two image-intensified video cameras were additionally run at the Churáňov station, one for direct imaging and one for spectroscopy. Both instruments contain a digital DMK23G445 GigE monochromatic camera, a CCTV imaging and one for spectroscopy. Both instruments contain a

| Camera            | Resolution (pixels) | MLM (mag) | fps or sector | FOV (deg) | Site      | Code |
|-------------------|---------------------|-----------|---------------|-----------|-----------|------|
| Video             | 1280 × 960          |           | 6             | 30        | Churáňov  | Cv   |
| DMK23G445 direct  | 1280 × 960          |           | 4             | 30        | Churáňov  | Csp  |
| DMK23G445 spectral| 1280 × 960          |           | 6             | 20        | Myslivna  | Mv   |
| ZWO ASI174MM      | 1936 × 1216         | +1.5      | 30            | 85        | Myslivna  | Msv  |

Photographic cameras:

| Camera            | Resolution (pixels) | MLM (mag) | fps or sector | FOV (deg) | Site      | Code |
|-------------------|---------------------|-----------|---------------|-----------|-----------|------|
| DAFO              | 5472 × 3648         |           | 16            |           | Fish-eye  | Churáňov | CD   |
| SDAFO             | 5472 × 3648         |           | –             | Diagonal fish-eye | Churáňov | CS   |
| Canon 6D          | 5472 × 3648         | +0.5      | –             |           | Fish-eye  | Myslivna | M10  |
| Canon 450D        | 4272 × 2848         | +1.5      | –             |           |           | Myslivna | M25  |
| Canon 6D II       | 6240 × 4160         | +2.5      | –             |           |           | Křišt’anov | K16 |
| Canon 550D        | 5184 × 3456         | +2.5      | –             |           |           | Křišt’anov | K21 |

Notes. MLM is meteor limiting magnitude, fps is frames per second. Camera codes: C is Churáňov, M Myslivna, K Křišt’anov, v is regular video camera, sp is spectral video camera, D is photographic DAFO, S is photographic SDAFO, sv is supplementary video camera, and number is focal length of supplementary photographic camera (35 mm equivalent).

For common detections with Churáňov’s DAFO, another video camera of type ZWO ASI174MM with a wide FOV (about 85 degrees horizontally) was operated to record brighter meteors. For common detections with Churáňov’s DAFO, another

Canon 4D DSLR camera equipped with a 25 mm lens (35 mm equivalent focal length) providing a FOV of 70 degrees. In addition, visual observations were performed by one of us (KH) at Myslivna. Finally, a third backup observing site was set up at Křišt’anov, between Churáňov and Myslivna. Two DSLR cameras with 16 and 21 mm lenses (35 mm equivalent focal length) were operated here. The parameters of all used video and photographic cameras, such as sensor pixel resolution, approximate limiting magnitude for meteors, field of view, and the frame rate (video) or shutter frequency (DAFO) are given in Table 1. The coordinates of the observing sites are given in Table 2.

The observation period was from 2:50 to 5:40 UT under clear sky throughout almost the whole period. Only high cirrus clouds shortly passed through the FOV of our video cameras. The end of the period was affected by dawn. The data records were inspected manually in order not to miss even very faint meteors. Meteor images and videos were measured and reduced by our standard methods (Spurný et al. 2017; Koten et al. 2020).

3. Data description

Three of us (JB, PS, KH) witnessed the 1995 outburst (Borovička & Spurný 1995; Znojil & Hornoch 1995), and our impression of the 2019 activity was definitely weaker. Nevertheless, KH, who is an experienced visual observer, counted 44 AMO meteors between 4h 26m and 5h 23m UT, 16 of them during the ten-minute interval centered at 4h 50m UT. The star-limiting magnitude was near 6.5 at that time. Altogether, up to 50 different meteors were detected by at least one of the narrow field video cameras, and 18 of them were double-station cases. However, only three of them belong to the AMO shower, as measurements and calculations finally showed. Interestingly, only one of the three AMO meteors was fainter than magnitude +2. Among the other 15 meteors, 12 were fainter than +2 mag. We are aware that the number of meteors is not sufficient for good statistics, but it looks like there was a lack of AMO meteors fainter than +2 mag. Our visual data contain faint AMO meteors down to magnitude +6, but in smaller proportions than for sporadic meteors.

Seven multi-station AMO meteors were recorded by photographic cameras; only one of them by DAFO, but three of them...
4. Results

4.1. Atmospheric trajectories and heights

Meteor beginning and end heights, trajectory lengths, and zenith distances of radiants are given in Table 3. Since all meteors occurred during a short time interval, their trajectory slopes are similar. Two values of beginning and end heights are listed for photographic meteors: the values from all detections, and the values based on SDAFO only. The first set depends on the type of instrument, while the second set is more homogeneous. The beginning and end heights of all AMO 2019 meteors are shown in Fig. 1 as function of the length of the atmospheric trajectory. The dependencies based on SDAFO are shifted to shorter trajectories, as expected. It is reasonable to assume that higher initial mass of the meteoroids implies longer atmospheric trajectory (in

The dependencies based on SDAFO are shifted to shorter trajectories, as expected. It is reasonable to assume that higher initial mass of the meteoroids implies longer atmospheric trajectory (in comparison to final solution. The meteor was recorded on the very edge of the FOV and the trajectory shows systematic shift of 70 m in comparison to final solution.

The wide-field video photometry should be, nevertheless, taken as approximative.

### Table 2. Geographical coordinates of observation sites.

| Video | Longitude E | Latitude N | Altitude (km) | Comment |
|-------|-------------|------------|---------------|---------|
| Churáňov | 13.61483 | 49.06836 | 1.118 | Direct ( Cv), spectral ( Csp) |
| Myslivna | 14.68723 | 48.63044 | 1.012 | Direct (Mv), wide fov (Msv) |
| Photographic | Churáňov | 13.61495 | 49.06843 | 1.119 | DAFO (CD), SDAFO (CS) |
| | Myslivna | 14.68714 | 48.63041 | 1.012 | All-sky (M10), wide fov (M25) |
| | Křišt’anov | 13.99785 | 48.90794 | 0.885 | Two wide fov (K16, K21) |

### Notes.
The comment column states the camera used.

### Table 3. Atmospheric trajectories of multi-station AMO meteors observed on 2019 November 22.

| Time (UT) | ∆t (s) | Hbeg (km) | HbegS (km) | Hend (km) | HendS (km) | L (km) | ZDh (deg) | Mabs (mag) | vinf (km s⁻¹) | N | Cam |
|-----------|--------|-----------|------------|-----------|------------|--------|-----------|------------|--------------|----|------|
| Video meteors | 4:40:53 | ±6 | 97.898 | 97.898 | 88.985 | 90.654 | 14.68 | 52.66 | – – | 2 | CS, M10, M25 |
| | 4:44:22 | ±5 | 100.594 | 100.594 | 90.713 | 90.713 | 16.26 | 52.62 | – – | 3 | CS, M25, K16 |
| | 4:47:20 | <1 | 95.176 | 95.126 | 90.038 | 90.741 | 8.63 | 53.83 | –0.9 | 62.7 ± 0.3 | 3 (2) | CS, Msv, K16 |
| | 4:50:30 | <1 | 100.080 | 90.660 | 16.16 | 54.42 | +4.1 | 64.4 ± 1.3 | 2 | CS, Mv |
| | 4:51:24 | <1 | 97.750 (a) | 88.269 | 16.43 | 54.8 | +1.2 | 62.8 ± 0.3 | 2 | CS, Mv, Msv |
| Photographic meteors | 4:51:24 | ±6 | 97.134 | 95.747 | 89.732 | 89.732 | 13.25 | 56.08 | – – | 2 | CS, M10 |

Notes. ∆t is an uncertainty in the beginning time, Hbeg and Hend are observed beginning and terminal heights, HbegS and HendS are beginning and terminal heights observed by a photographic spectral camera at station Churáňov (CS). L is the observed length of the atmospheric trajectory, ZDh is the zenith distance of the radiant at Hend, Mabs is the absolute (100 km distance) magnitude, vinf is the initial velocity, N is the number of stations where the meteor was observed (number in parentheses is number of stations used for the trajectory solution), and Cam refers to cameras by which the meteor was recorded (abbreviations follow the designation as in Table 1). (a)Beginning of video meteor at 4:51:24 UT was not in the FOV of our regular cameras, the beginning is from the supplementary ZWO camera with lower sensitivity; (b)record from Křišt’anov was not used since the meteor was recorded on the very edge of the FOV and the trajectory shows systematic shift of 70 m in comparison to final solution.

by the wide-field video (which recorded four AMO meteors in total). The velocity could therefore be computed for four photographic meteors. Photometry could be done for meteors with velocity measurements, either from DAFO or from wide-field video. The wide-field video photometry should be, nevertheless, taken as approximative.

The list of all ten multi-station AMO meteors is given in Table 3. The quality of the three video meteors is rather low. The meteor was recorded by SDAFO. Unfortunately, though the camera sensitivity range is from 3700 to 9000 Å, the record contains only the wavelengths from 5360 to 9000 Å, since the spectrum was out of the camera field of view for wavelengths shorter than 5360 Å. The spectrum belongs to the meteor at 5:01:51 UT, which was observed photographically. In the following section, we present the results of the data analysis. In particular, we concentrate on atmospheric heights, radiants, orbits, and the spectrum.
We removed one meteor with a value of the orbital similarity according to the procedure of Southworth et al. (2017) meteors designated as AMO. We then used the mean AMO record for the length of the atmospheric trajectory. We only found a few AMO meteors only. So, we searched for any AMO meteor with available data, and the terminal heights are distributed along a constant height of 90 ± 3 km, which also corresponds to our observation. We can conclude that terminal heights of AMO meteors with atmospheric trajectories shorter than 40 km are distributed along a constant height of 90 km. It is important to note that there are four AMO meteors in the CAMS catalog with atmospheric trajectories longer than 40 km. Their terminal heights decrease with increasing length of the atmospheric trajectory, as is observed for other meteor showers with cometary origin (Koten et al. 2004).

The terminal heights of AMO meteors shorter than 40 km were also directly compared to the terminal heights of Perseids in Fig. 1. Perseids have similar atmospheric velocities (60 km s$^{-1}$). We selected 31 video Perseids from the data published by Koten et al. (2004). Perseids with atmospheric trajectories shorter than 40 km and zenith distances of the radiant in the 50–60 degree range (corresponding to our AMO meteors) were used. Their terminal heights decrease with increasing length of the atmospheric trajectory. Moreover, most Perseid meteors terminate at higher altitudes in comparison with AMO meteors of the same length.

### 4.2. Radiants and orbits

The radiants of our AMO meteors are plotted in Fig. 2 and listed in Table 4. The area of the radiant is compact, and the mean radiant (weighted average) of the photographic meteors corresponds well to the radiant observed during the 1995 AMO outburst (Jenniskens et al. 1997). The comparison of AMO radiant data published so far is presented in Table 5.

Heliocentric orbits could be computed for seven meteors with measured velocities. The measurement of atmospheric velocity is always challenging in the case of fast and short meteors, especially for double-station meteors. Due to a narrow field of view, we were able to determine the initial velocities of video meteors with a standard deviation bellow or slightly above 1 km s$^{-1}$ (Table 3). The mean (weighted average) initial velocity of our three video meteors is 63.3 ± 0.4 km s$^{-1}$.

Atmospheric velocities of photographic meteors are based on two different instruments. The meteor at 4:58:28 UT was recorded by DAFO, and the other three meteors were recorded by the wide-field video camera. Short atmospheric trajectories lead to the initial velocities with a standard deviation of few tenths of km s$^{-1}$ (Table 3). The mean (weighted average) initial velocity of our four photographic meteors is 62.99 ± 0.06 km s$^{-1}$. The weighted average initial velocity of all seven AMO meteors is 63.00 ± 0.15 km s$^{-1}$.

Orbital elements of all AMO 2019 meteors and their weighted averages are presented in Table 4. It was not possible to determine a reliable semi-major axis on the basis of such small number of short and fast meteors. Even if the radiant is well determined, the uncertainty in initial velocity (velocities 62.7–64.4 km s$^{-1}$) results in orbits of either short-period or long-period comets or even hyperbolic orbits. From the nature of AMO outbursts, it is known that only encounters with a one-period comet or even hyperbolic orbits. From the nature of AMO outbursts, it is known that only encounters with a one-period comet can explain the shower (Lyytinen & Jenniskens 2003), so only elliptical orbits are possible. The weighted average value of the semi-major axis is 21 ± 6 AU, which gives an orbital period of around 100 yr. However, longer periods would be consistent with our data as
well, so this can be taken as a lower limit. Jenniskens (2006) also used the available AMO observations to determine the lower limit of the semi-major axis. He concluded that $a > 28$ AU (period $> 150$ yr).

4.3. The spectrum

The single recorded spectrum is shown in Fig. 3, where it is also compared with the spectrum of one Perseid recorded with the same equipment. In the covered spectral range, the line of sodium Na I at $5892 \text{ Å}$ is usually dominant along with the atmospheric lines of O I and N I and N$_2$ in the region between 7000 and 8500 Å, especially for fast meteors (Vojáček et al. 2015). Due to similar velocities, the relative intensities of atmospheric lines are similar for both spectra. The sodium, as the only significant meteoritic line visible in this spectral range, is present in the Perseid spectrum, but it is missing from the AMO spectrum. This is in agreement with the work of Štork et al. (1998), as they observed a low amount of Na in the spectra of members of the AMO outburst on 1995 November 22. Borovička et al. (2005) concluded that AMO meteors fall near the boundary between Na-poor and Na-free meteoroids according to their spectral properties (Mg-Na-Fe ratios).

5. Discussion

We can confirm that the predicted outburst of the Alpha Monocerotid meteor shower occurred on 2019 November 22. The number of recorded meteors is not sufficient to compute an activity profile or meteoroid flux. The data of sensitive video cameras suggest a deficit of meteors fainter than magnitude +2, but this result has low statistical significance. It would suggest a small population index, but $r = 3.00 \pm 0.18$ was reported by Miskotte (2020) from visual data. On the other hand, the radio data from Belarus reported by Roggemans et al. (2020) showed only a small enhancement of echoes during the outburst, indicating that the outburst was indeed inconspicuous at small masses.

The computed radiants and heliocentric orbits match those reported for the 1995 and 2017 outbursts. The radiant of the annual component reported by Roggemans et al. (2018) lies at a somewhat larger right ascension and declination. The radiant in 2019 was quite compact, with a diameter of less than one degree. The semi-major axis and period of the shower and the parent comet remains unknown. Our nominal mean solution of the period is only 100 yr, but the uncertainty is large, and much longer periods are possible as well.

The most important results come from spectroscopy and peculiar tendency of terminal heights. Our earlier observation that AMO meteoroids are deficient in sodium (Štork et al. 1998; Borovička et al. 2005) was confirmed. Borovička et al. (2005) identified three populations of Na-free meteoroids. The first population is of iron meteoroids, and the second one contains Sun-approaching meteoroids with small perihelia. Alpha Monocerotids do not belong to either of these. They belong to the third population, which feature meteoroids in Halley-type orbits. Na-free meteoroids in Halley-type orbits are mostly sporadic. Alpha Monocerotids is the only known meteor shower of this type. Borovička et al. (2005) proposed that these meteoroids originate from primordial cometary crusts, which were exposed to cosmic rays for a long period of time, and volatile elements including sodium were lost.

A new finding is that small and medium-sized AMO meteoroids finish their ablation at the same height in the atmosphere (near 90 km). This is unusual because in other meteor showers terminal height decreases with increasing meteoroid mass and trajectory length. The beginning height usually increases with mass, except for Geminids, where it is nearly constant (Koten et al. 2004). Geminids are also partly deficient in sodium because of their proximity to the Sun. But Alpha Monocerotids behave differently, with the beginning height increasing and terminal height being constant, demonstrating that their physical structure is different from any major meteoroid stream.

The meteor at 4:58:28 UT is our brightest and best observed AMO 2019 meteor. It was recorded from three sites and also by DAFO at Churáňov station, so it was possible to process...
Radiants and orbital elements of multi-station AMO meteors observed on 2019 November 22.

| Time (UT) | RA  | Dec | RA_G | Dec_G | v_G | e  | q  | ω  | i  | T_j |
|----------|-----|-----|------|-------|-----|----|----|----|----|-----|
| 4:47:47  | 117.366 ±0.016 | 0.84 | 116.686 ±0.017 | 0.47 | 62.9 | 1.016 | 0.491 | 89.8 | 133.21 | –0.77 |
| 4:50:30  | 117.67 ±0.05 | 1.49 | 116.99 ±0.11 | 1.13 | 63.6 | 1.04 | 0.495 | 89.0 | 135.1 | –1.0 |
| 4:51:24  | 117.81 ±0.03 | 0.92 | 117.11 ±0.11 | 0.54 | 62.0 | 0.969 | 0.481 | 92.4 | 133.17 | –0.25 |
| WA       | 117.48 ±0.16 | 0.94 | 116.81 ±0.16 | 0.57 | 62.5 | 0.989 | 0.485 | 91.1 | 133.3 | –0.5 |

Photographic meteors

| Time (UT) | RA  | Dec | RA_G | Dec_G | v_G | e  | q  | ω  | i  | T_j |
|----------|-----|-----|------|-------|-----|----|----|----|----|-----|
| 4:40:53  | 117.84 ±0.04 | 1.17 | 0.04 | 1.34 | ±0.05 | 0.07 | 0.06 | ±0.1 | ±0.011 | ±0.005 | ±0.9 | ±0.3 |
| 4:47:20  | 117.75 ±0.06 | 1.03 | 117.07 ±0.06 | 0.65 | 61.9 | 0.967 | 0.477 | 92.9 | 133.3 | –0.22 |
| 4:58:28  | 117.715 ±0.02 | 1.21 | 117.021 ±0.02 | 0.84 | 62.11 | 0.975 | 0.4767 | 92.7 | 133.65 | –0.32 |
| 5:01:51  | 117.94 ±0.06 | 1.25 | 117.24 ±0.06 | 0.86 | 62.4 | 0.983 | 0.484 | 91.6 | 134.1 | –0.4 |
| 5:07:31  | 117.790 ±0.017 | 1.25 | 117.087 ±0.018 | 0.88 | 62.2 | 0.977 | 0.478 | 92.5 | 133.84 | –0.35 |
| 5:10:09  | 117.99 ±0.07 | 0.97 | ±0.08 | 0.04 | 0.04 | ±0.04 | ±0.04 | ±0.002 | ±0.003 | ±0.20 | ±0.10 | ±0.11 |

WA stands for weighted average. The uncertainties of one standard deviation are given in rows below the values.

| Source | RA_G | Dec_G | v_G | a  | e  | q  | ω  | Ω  | i  | T_j |
|--------|------|-------|-----|----|----|----|----|-----|----|-----|
| 1      | 117.10 | 0.83 | 63.0 | 500 | 0.999 | 0.488 | 90.7 | 59.3 | 134.1 | –0.60 |
| 2      | 117.0 | 1.0 | 62.6 | 43 | 0.989 | 0.474 | 92 | 59.527 | 134.0 | –0.49 |
| 3      | 117.53 | 1.18 | 62.6 | 43 | 0.989 | 0.474 | 92 | 59.527 | 134.0 | –0.49 |
| 4      | 117.07 | 0.85 | 62.11 | 18.7 | 0.9745 | 0.4773 | 92.64 | 59.3 | 133.67 | –0.31 |
| 5      | 116.81 | 0.57 | 62.5 | 44 | 0.989 | 0.485 | 91.1 | 59.307 | 133.3 | –0.47 |
| 6      | 116.95 | 0.77 | 62.18 | 21 | 0.977 | 0.4788 | 92.4 | 59.307 | 133.59 | –0.34 |

References. (1) Jenniskens et al. (1997); (2) Jenniskens & Odeh (2017); (3) the annual component from Roggemans et al. (2018); (4) from photographic data of this work; (5) from video data of this work; (6) from both video and photographic data of this work.

this meteor using our standard procedures (Borovička 1990; Borovička et al. 1995; Cephelea 1987). We determined the value of a PE coefficient that describes the fireball ablation ability (Cephelea & McCrosky 1976). The value of PE = −5.31 lies on the border between types II and IIIA, which corresponds to meteoroids composed of carbonaceous chondrites or regular cometary material (Cephelea 1988). Moreover, it is similar to the mean PE value of Perseids and September epsilon Perseids (Shrbený & Spurný 2019). This meteor behaves like ordinary cometary meteoroids according to the PE criterion. However, this may just be a coincidence since its end height is not too different from Perseids of the same length (Fig. 1). Moreover, the PE criterion was originally developed for bright fireballs and may not be a fully appropriate measure for smaller meteoroids. The photometric mass of the 4:58:28 UT meteor was only 10^{-3} kg.

The light curve of meteor at 4:58:28 UT is shown in Fig. 4. Black crosses correspond to absolute (100 km distance) brightness from DAFO at Churáňov, and the gray curve corresponds to an intensity scan of the meteor on a spectral image from SDAFO
Fig. 3. Comparison between normalized calibrated spectra of Perseid and Alpha Monocerotid (5:01:51 UT) meteors. The spectrum of Perseid is shifted by 0.1 in intensity for clarity. No sodium Na I-1 and only weak molecular radiation of nitrogen N2 can be seen in the region between 5600 and 6100 Å for the Alpha Monocerotid spectrum. The sodium is visible in the Perseid spectrum.

Fig. 4. Light curve of the brightest AMO meteor (4:58:28 UT) computed from DAFO photometry. The intensity scan on the SDAFO image was scaled to match the light curve. Small-scale variations are due to noise.

at Churáňov. The meteor was not bright enough to be recorded by the DAFO radiometer. The light curve is without any significant flare, which corresponds to a material that did not break down suddenly into a large number of small grains in the later part of the trajectory (as bright Perseids often do). Nevertheless, the onset of the brightness is quite steep. The middle of the light curve is rather flat, with only a small increase in brightness. The fading at the end is steep again. Such a light curve does not correspond to a single ablating body, which would exhibit a steady brightness increase in the first three quarters of the trajectory and then somewhat steeper fading. The observed light curve could be explained by a disruption of the meteoroid into a large number of grains of similar sizes at the beginning, which then ablate independently and are all exhausted at similar heights, causing the sudden end of the meteor.

We therefore propose that AMO meteoroids are devolatilized but also very crumbly. Meteoroids of all sizes disrupt into grains at the beginning of the atmospheric entry. The grain size is a typical material property, so different meteoroids disrupt into similar grains. The end height depends on grain properties and does therefore not depend on the initial meteoroid size, at least up to a critical size. Larger meteoroids just produce more grains, which leads to greater brightness and earlier detection of the meteor. Meteoroids larger than the critical size may contain some larger grains or take longer to disrupt completely, so their end heights are progressively lower.

The comparison with small Perseids shows that Alpha Monocerotid grains must be more refractory than the Perseid material. The lack of volatiles causes the ablation temperature to be higher, and the beginning heights of Alpha Monocerotids are therefore lower. Perseids surely also fragment into grains, though possibly in a different way. Yet, the AMO grains must be either larger, denser, or more resistant, and they penetrate deeper. In this sense, the hypothesis of Jenniskens et al. (1997) that Alpha Monocerotids are stronger compared to other cometary meteoroids can be confirmed.

To get better insight into possible properties of AMO grains, we tried to model the light curve of the 4:58:28 UT meteor with the erosion model of Borovička et al. (2007), originally used for faint Draconid meteors. A model assuming disruption into grains of masses of about $10^{-8}$ kg near the beginning of the meteor was able to reproduce the light curve, but it produced a high deceleration of the meteor. The dynamics could be brought into rough agreement with the data if the grain release (erosion) started well

Fig. 5. Comparison of observed and modeled light curves (upper panel) and deceleration (lower panel) of the 4:58:28 UT meteor. Observed data are given as crosses, and the model is shown with smooth solid lines. Deceleration is expressed as the difference of the length along the trajectory (of the brightest part of meteor streak) at the given time from the length expected for constant meteor velocity of 63.35 km s$^{-1}$. CIRA72 model atmosphere was used to compute the drag.
before the observed beginning of the meteor (at heights around 115 km or more) and was finished near the meteor’s beginning (Fig. 5). In that model, the grains were already partly decelerated at the observed meteor’s beginning, so the actual entry speed was not the measured 62.93 ± 0.12 km s⁻¹ given in Table 3, but 63.35 ± 0.30 km s⁻¹. The corresponding eccentricity would be 0.992 ± 0.013, corresponding to a semi-major axis of 65 AU and an orbital period of 500 yr, with large uncertainties.

The grain masses were about 2 × 10⁻⁷ kg (uncertainty of about 50%), corresponding to a diameter of about 0.5 mm for an assumed density of 3000 kg m⁻³. Such grain sizes are larger than for the vast majority of cometary meteoroids modeled with the erosion model (Borovička et al. 2007, 2014; Campbell-Brown et al. 2013; Vojáček et al. 2019). We note that the lack of small grains was found as a common property for Na-poor and Na-free meteoroids (Vojáček et al. 2019). The ablation coefficient was found to be ≈0.025 s⁻² km⁻² (uncertainty of about 25%), which is comparable with Draconids. The 4:58:28 UT meteor disrupted into ≈500 grains (assuming the luminous efficiency of Pecina & Ceplecha 1983). A single grain would produce meteor with maximum absolute magnitude of about +4.

The fact that the parent comet of Alpha Monocerotids has not been yet discovered may be simply be because of its long period. Nevertheless, it is also possible that the comet is only weakly active and is still largely covered by its primordial crust.

6. Conclusions

We presented atmospheric trajectories and radiants of ten Alpha Monocerotid meteoroids observed by photographic and video techniques during the outburst on 2019 November 22. Velocities, magnitudes, and orbits were obtained for seven meteoroids, and one incomplete video spectrum was captured. The AMO activity was observed between 4h 26m and 5h 23m UT, with maximum rates from visual counts in the ten-minute interval centered at 4h 50m UT. The geocentric radiant was compact, with a diameter of less than one degree, and was centered at RA = 116.95 ± 0.08°, Dec = 0.77 ± 0.07° (one sigma errors). The geocentric velocity was found to be 62.18 ± 0.15 km s⁻¹. The orbital period is 100 yr, or possibly longer if the measured velocities were affected by deceleration, as it was found from detailed modeling of the brightest recorded AMO.

The most interesting aspects are the physical properties of Alpha Monocerotid meteoroids, which were found to be distinct from any other meteoroid stream analyzed so far. The observed meteor end heights were found to be distributed along a constant level of 90 km for all meteoroids with magnitudes between +4 and −2 and with atmospheric trajectory lengths up to 40 km. We also confirmed that AMO meteoroids are deficient in sodium. We propose that Alpha Monocerotids were formed from a devolatilized cometary crust that is structurally fragile and disintegrates into fundamental grains of a characteristic size of about 0.5 mm at the beginning of atmospheric entry. These grains are larger than grains of typical cometary meteoroids derived from active comets such as Perseids or Draconids.

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References

Borovička, J., 1990, Bull. Astron. Inst. Czech., 41, 391
Borovička, J., & Spurný, P. 1995, WGN, J. Int. Meteor Org., 23, 203
Borovička, J., Spurný, P., & Kecilová, J. 1995, A&AS, 112, 173
Borovička, J., Koten, P., Spurný, P., Boček, J., & Štork, R. 2005, Icarus, 174, 15
Borovička, J., Spurný, P., & Koten, P. 2007, A&A, 473, 661
Borovička, J., Koten, P., Shrubeny, L., Stork, R., & Hornoch, K. 2014, Earth Moon Planets, 113, 15
Borovička, J., Spurný, P., & Shrubeny, L. 2019, in International Meteor Conference 2018, eds. R. Rudawska, J. Rendtel, C. Powell, R. Lunsford, C. Verbeeck, & A. Knöfel, 28
Campbell-Brown, M. D., Borovička, J., Brown, P. G., & Stokan, E. 2013, A&A, 557, A41
Ceplecha, Z. 1987, Bull. Astron. Inst. Czech., 38, 222
Ceplecha, Z. 1988, Bull. Astron. Inst. Czech., 39, 221
Ceplecha, Z., & McCrosky, R. E. 1976, J. Geophys. Res., 81, 6257
Jenniskens, P. 2006, Meteor Showers and their Parent Comets (Cambridge: Cambridge University Press)
Jenniskens, P., & Lytinen, E. 2019, Central Bureau Electronic Telegrams, 4692,
Jenniskens, P., & Odeh, M. 2017, Central Bureau Electronic Telegrams, 4457, 1
Jenniskens, P., Betlem, H., de Lignie, M., & Langbroek, M. 1997, Apl, 479, 441
Jenniskens, P., Baggaley, J., Crumpton, I., et al. 2018, Planet. Space Sci., 154, 21
Koten, P., Borovička, J., Spurný, P., Betlem, H., & Evans, S. 2004, A&A, 428, 683
Koten, P., Borovička, J., Vojáček, V., et al. 2020, Planet. Space Sci., 184, 104871
Lytinen, E., & Jenniskens, P. 2003, Icarus, 162, 443
Miskotte, K. 2020, eMeteorNews, 5, 186
Pecina, P., & Ceplecha, Z. 1983, Bull. Astron. Inst. Czech., 34, 102
Roggemans, P., Johannink, C., & Bets, J.-M. 2018, eMeteorNews, 3, 12
Roggemans, P., Howell, J. A. A., & Guilon, T. 2020, eMeteorNews, 5, 13
Shrubeny, L., & Spurny, P. 2019, A&A, 629, A137
Southworth, R. B., & Hawkins, G. S. 1963, Smith. Contrib. Astrophys., 7, 261
Spurný, P., Borovička, J., Mucke, H., & Svreč, J. 2017, A&A, 605, A68
Štork, R., Borovička, J., Boček, J., & Šolc, M. 1998, Meteor. Planet. Sci. Suppl., 33, A151
Vojáček, V., Borovička, J., Koten, P., Spurný, P., & Štork, R. 2015, A&A, 580, A67
Vojáček, V., Borovička, J., Koten, P., Spurný, P., & Štork, R. 2019, A&A, 621, A68
Znojil, V., & Hornoch, K. 1995, WGN, J. Int. Meteor Org., 23, 205