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The 2007 Aurigid meteor outburst

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ABSTRACT

A rare outburst of the Aurigid meteor shower was predicted to occur on 2007 September 1 at 11:36 ± 20 min UT due to Earth's encounter with the one-revolution dust trail of long-period comet C/1911 N1 (Kiess). The outburst was predicted to last $\sim$1.5 h with peak zenithal hourly rate of $\sim$200 h^{-1}, which is $\sim$20 times higher than the annual Aurigid shower. Three members of Armagh Observatory observed this outburst from the general area of San Francisco, CA, USA, where the shower was anticipated to be best seen. Observed radiant, velocity and activity peak time were consistent with the predictions, whereas the zenithal hourly rate was about half of the predicted value. Five Aurigids were observed by two stations simultaneously, enabling their spatial trajectory to be worked out. The orbits of these double station meteors are in good agreement with that of their parent comet Kiess. The outburst was abundant in bright (-2 to $+1$ mag) meteors. The first high-altitude Aurigid, with a beginning height of 137.1 km, was recorded.

Key words: meteors, meteoroids

1 INTRODUCTION

Meteor showers occur when Earth encounters streams of dust particles along its orbital path. These dust particles are generally ejected from comets as they approach the Sun, and become dispersed due to their different ejection speeds. The evolution of this dust stream is affected by radiation pressure and planetary perturbations, the combination of which acts differently on different particle sizes and positions along the stream (Kresak 1976; Jones 1995; Asher 2008). Sometimes Earth encounters a dense clump of debris causing meteor outbursts. Predicting those meteor outbursts with confidence is possible with accurate modelling of the dust ejection from the comet (Crifo & Rodionov 1997) and the evolution of its orbits (Kondrat'eva, Murav'eva & Reznikov 1997; Asher 1999).

The α-Aurigid annual shower is one of the less active showers, and occurs from about August 25 to September 8 every year. Though the zenithal hourly rate (ZHR) is only 7, the population index $r = 2.6$ and velocity at infinity (top of the atmosphere) $V_\infty = 66\,\mathrm{km\,s^{-1}}$ (Dubietis & Arlt 2002) produces bright and fast meteors.

Aurigid outbursts occurred in the years 1935, 1986 and 1994. The recent model by Jenniskens & Vaubaillon (2007a, hereafter referred to as JVa) reproduced all these outbursts with great accuracy and, in addition, predicted one on 2007 September 1. The model predicted a peak time of 11:36 ± 20 min UT, best seen from locations in Mexico, the western parts of Canada and the United States. The shower was expected to last about $\sim$1.5 h, reaching a peak ZHR of $\sim$200 over a short (10-min) interval. The meteors were predicted to emanate with a speed of 67 $\mathrm{km\,s^{-1}}$ from a radiant at right ascension (RA) = 92° and declination (Dec.) = +39° (J2000). Like past Aurigid outbursts, this one was expected to be rich in bright, -3 to $+3$ mag, meteors with few faint ones. This is the first prediction made for a meteor outburst due to dust ejected from a known long-period comet. This comet, C/1911 N1 (Kiess) which was discovered in 1911 July and observed only for 71 d, has a near parabolic orbit and takes more than 2000 yr to complete one revolution around the Sun. Integrating the orbit of the comet backwards in time, the nominal calculated perihelion passage was found by JVa to be 83 BC. Although there is some uncertainty in the orbit of the parent comet, the precise position of the dust trail is not sensitive to the adopted perihelion time since planetary perturbations occur only on the inward leg of the orbit (JVa).

Outbursts of the Aurigid shower were observed visually by chance in 1935 (Teichgraeber 1935; Guth 1936), 1986 (Tepliczky 1987) and 1994 (Zay & Lunsford 1994). All these outbursts had ZHR greater than 100, and were rich in bright meteors. The full width at half-maximum of the outburst was $\sim$30 min. Zay & Lunsford (1994) described the 1994 Aurigids as having greenish or bluish colour, perhaps due to strong iron and magnesium ablation, which in turn would suggest different particle morphology compared to the annual Aurigid shower. Very little scientific information was recorded during these past outbursts. The outburst in 2007 provided the opportunity to use modern instruments to gather a wide range of data pertaining to the physical and dynamical properties of a long-period comet and its constituent matter.

Only one outburst from a long-period comet's dust trail, that of the α-Monocerotids in 1995, has been observed by modern instruments (Jenniskens et al. 1997). These meteoroids, whose parent object

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is still unknown, were found to be low in volatile elements such as sodium (Borovička, Spurný & Koten 2002), compared to the meteoroids from short-period comets. One possible hypothesis is that because of the infrequent visits of long-period comets to the inner Solar system, the meteoroids ejected from these comets could be from their pristine crusts, possibly exposed to cosmic rays in the Oort cloud (Jenniskens et al. 1997). Thus, Aurigid meteoroids detected in 2007 could provide us with new information on the properties of long-period comets and their surroundings.

2 OBSERVATIONS

We observed the 2007 Aurigid outburst from San Francisco, USA, as part of the observation campaign organized by Dr Peter Jenniskens (NASA Ames Research Center, USA). Two observing stations were set up, one at Fremont Peak (latitude = 36°45′ N, longitude = 121°29′W) and the other at Lick Observatory (latitude = 37°21′ N, longitude = 121°38′W). WaTec 902DM2s CCD video cameras (f0.8, 8.0-mm lens, 39° × 27° field-of-view at Fremont Peak and f0.8, 3.8-mm lens, 82° × 55° field-of-view at Lick Observatory) were used, which are similar to the ones operating in Armagh Observatory (Atreya & Christou 2008). The cameras were connected to a laptop computer where meteors were recorded using the UFO CAPTURE V2.0 software.[1] In addition two camcorders, equipped with image intensifiers, with 30° fields of view were provided by the campaign organizer to operate from Lick Observatory. The group at Fremont Peak was joined by a team from Germany with two Mintron cameras (f0.8, 6-mm lens, 58° × 40° field-of-view) using METREC software (Molau 1999) to record meteors.

Our observations lasted for more than 3 h, starting from 9:00 UT until 12:30 UT (until 6:30 AM local time). The sky was clear, but the gibbous-phase moon was high (∼69° at 11:30 UT). However, the Aurigids were expected to be bright and the cameras were pointed away from the moon during the expected peak time of the outburst.

3 DATA ANALYSIS

The meteors were analysed by the SPARVM software (Software for Photometric and Astrometric Reduction of Video Meteors) currently being developed at Armagh Observatory (Atreya & Christou 2007). The core part of the software is written in IDL (Interactive Data Language), and performs meteor Astrometry, Photometry, Double station analysis, and computation of orbital elements. A double station triangulation method is implemented from Ceplecha (1987). SPICE (Acton 1996) is used to calculate the set of osculating conic orbital elements corresponding to the six-dimensional state vector (position and velocity) of a meteor at a given epoch.

Meteors from the Mintron cameras were analysed by the German group using METREC (Molau 1999). The time, radiant position (RA, Dec.) and apparent magnitudes were computed by METREC. METREC also distinguished whether single-station meteors belonged to the sporadic background or to the Aurigids. This information was incorporated in SPARVM for double station analysis and computation of orbital elements. The current version of SPARVM is not optimized for photometric reduction of meteors recorded by the image-intensified camcorders.

SPARVM uses an approach similar to that of Ceplecha's double station method to distinguish between single-station sporadics and Aurigids. In the terminology used by Ceplecha (1987), the 'plane of station$_A$-meteor trajectory' of a known Aurigid (one of the double station Aurigids) intersects the 'plane of station$_B$-meteor trajectory' of a single-station meteor to yield the radiant of that individual single-station meteor. The result from this method was compared with that of METREC (using the Mintron data), and two additional meteors were identified as Aurigids in addition to the 21 Aurigids already identified by METREC. These Aurigids were also checked manually to see if they seemed to originate from the theoretical radiant. Details of the SPARVM software, and exposition of the various methods used for meteor astrometry and photometry, will be presented in a forthcoming paper.

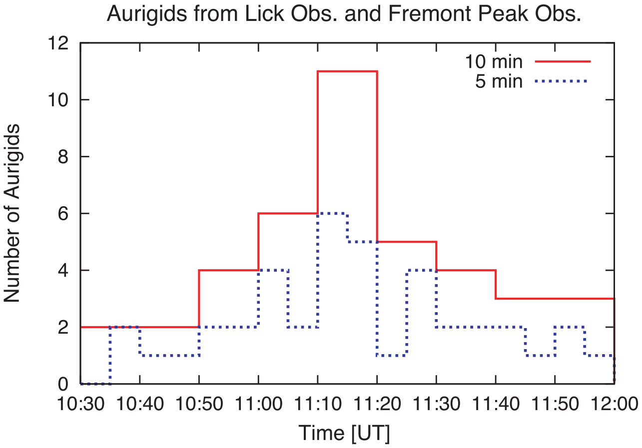

Figure 1. Observed Aurigid counts for 10 (red bold) and 5 min (blue dashed) interval from Lick and Fremont Observatory on 2007 September 1.

4 RESULTS

4.1 Outburst profile

Fig. 1 shows the Aurigid count combined from all six cameras from both stations. The 10-min interval counts show that the peak occurred between 11:10 and 11:20 UT. Jenniskens & Vaubaillon (2007b) came to a similar conclusion, giving a peak time of 11:15 ± 5 min UT. The predicted time for the outburst was 11:36 ± 20 min UT (JVa). Historically, the observed peaks were 1, 16 and 7 min earlier during the previous Aurigid outbursts (1994, 1986, 1935, respectively) than the calculated values from the model (JVa). So a peak time of 11:15 UT is consistent with this empirical correction to the model predictions.

A peak of ZHR = 136 ± 26 was computed based on counts by visual observers over 5-min intervals (Rendtel 2007). Similarly, ZHR ∼ 100 was calculated using Aurigids from the airborne observations (Jenniskens & Vaubaillon 2007b). Both these ZHR estimates are short of the predicted 200 ± 25. One of the reasons could be that the Earth did not pass through the exact centre of the dust trail, as the peak occurred ∼20 min prior to the modelled time. However, since the annual α-Aurigids have ZHR = 7 ± 1 (Dubietis & Arlt 2002), the enhancement was very significant.

4.2 Radiant and velocity

There has been some confusion regarding the radiant of the α- and the θ-Aurigids (Habuda 2007). The annual Aurigid shower (IAU shower code 206), or more precisely the α-Aurigids, has a radiant

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[1] http://sonotaco.com/e_index.html

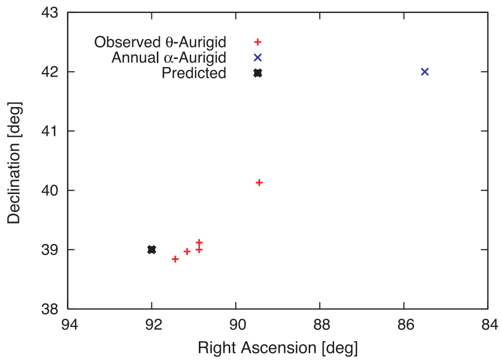

Figure 2. Radiant of observed θ-Aurigids, the predicted radiant for the outburst, and the annual α-Aurigid shower.

at[2] RA = 84° and Dec. = 42° or RA = 85°.5 and Dec. = 42° (Cook 1973). The three outbursts of the Aurigids in 1935, 1986 and 1994 appeared from a slightly different radiant at RA = 92° and Dec. = 39°, referred to as θ-Aurigids (Jenniskens 1995). The meteors from these outbursts, including the one in 2007 September, are known as the θ-Aurigids, while the annual shower meteors are called α-Aurigids.

Five double station Aurigids were successfully detected at Lick Observatory and Fremont Peak, from a combined four cameras used by the authors, and two from the German group. Two of the double station Aurigids were observed with a third camera, thus increasing the confidence in the radiant and orbit solutions.

The radiant of the observed θ-Aurigid outburst, annual α-Aurigid shower and the predicted radiant for the outburst are shown in Fig. 2. The measured values are also shown in Table 1 (columns 2–3). The median values for the radiant of the outburst are RA = 90°.87 and Dec. = +39°.00, with the observed RA of the radiant $\sim$1° lower than that of the prediction of JVa. Four of the Aurigids seem to form a compact radiant while one of the Aurigids is $\sim$1° further apart away, towards the direction of the annual Aurigid radiant. With only five points, it is difficult to speculate on the reason for the outlier. The observational accuracy of the radiant is 0°.03 and thus does not account for the outlier. One possibility could be a slightly diffuse radiant of $\sim$2° in diameter.

Double station analysis allows the precise computation of meteor position and velocity vectors from which their heliocentric orbital elements can be worked out. Table 1 compares the results for the five double station Aurigids with the annual α-Aurigid shower and with the parent comet Kiess. The first four columns show the time of occurrence (in UT), RA and Dec. of the radiant, and the velocity at infinity (V_∞). The median computed V_∞ of $67.3 \pm 0.8\,\mathrm{km\,s^{-1}}$ is in very good agreement with JVa's predicted value of $67\,\mathrm{km\,s^{-1}}$.

4.3 Heights

Columns 5–7 in Table 1 show the beginning height (H_b), terminal height (H_e) and height of maximum brightness (H_max). The Aurigid at 11:04:36 UT exits the field of view with its brightness still increasing, thus only upper limits for H_max and H_e can be estimated for this Aurigid. The H_b depends strongly on the limiting magnitude of the camera and the threshold detection limit of the software.

The median values for the beginning height ($H_\mathrm{b} = 120.8$ km), the height of maximum brightness ($H_\mathrm{max} = 104.4$ km) and the terminal height ($H_\mathrm{e} = 96.7$ km) are comparable to those of the Leonids ($H_\mathrm{b} = 120.0 \pm 3.5$ km, $H_\mathrm{max} = 106.9 \pm 3.8$ km and $H_\mathrm{e} = 96.5 \pm 3.7$ km) given in Koten et al. (2004). The outburst of α-Monocerotids had meteors which penetrated 5 km deeper into the atmosphere compared to meteors of same brightness, velocity and entry angle. It had been suggested that this was due to the lack of volatile elements such as sodium in the meteoroids (Jenniskens et al. 1997). However, the terminal heights of the observed Aurigids were comparable to those of other meteor showers. With the observed minimum value of $H_\mathrm{e} = 92.5$ km, there was no sign of Aurigids penetrating deep into the atmosphere.

The H_b of the Aurigid at 11:04:36 UT, 137.1 km, is significantly higher compared to 120–125 km for the remaining four double station Aurigids. This meteor is the first high-altitude Aurigid ($H_\mathrm{b} > 130$ km) recorded (discussed in detail in Section 5).

4.4 Orbital elements

The orbital elements of the Aurigids are given in columns 9–14 in Table 1. These are perihelion distance (q), semimajor axis (a), inclination (i), longitude of the ascending node (Ω), argument of perihelion (ω) and mean anomaly (M_o). These are compared with those of the annual shower and the theoretical radiant of parent comet Kiess.

These orbits are highly eccentric, and it is difficult to compute the semimajor axis accurately. Semimajor axis is very sensitive to the geocentric velocity, so even a small uncertainty in this quantity results in large uncertainty in semimajor axis. All other orbital elements of the Aurigid dust trail are in good agreement with that of their parent comet Kiess. The dispersion in the inclination of the meteoroids is low, only $\sim$2°. The median value of $i = 148°.988$ is in very good agreement with the parent comet's 148°.421 (compared to that of the annual shower 146°.4). The values of Ω for all five meteoroids are consistent, increasing with UT as expected. The meteoroids seem to be spread in ω, with a standard deviation of 4°.68. The median value of $\omega = 111°.484$ is in good agreement with that of parent comet's $\omega = 110°.378$, whereas ω of the annual shower is 121°.5, significantly higher than that of the observed outburst. The close resemblance between the orbital elements of the comet Kiess and the observed five double station Aurigids strongly suggests that these meteoroids were indeed ejected from Kiess $\sim$2000 yr ago. The difference of the orbital elements of the 2007 outburst from the annual shower also demonstrates the existence of this distinct component within the Kiess debris stream.

4.5 Photometry

The maximum visual magnitude M_max (Optical Johnson V band, 500–600 nm) of the double station meteors are shown in column 8 of Table 1. The absolute magnitude of a meteor indicates its brightness as it would appear at a distance of 100 km in the direction of the zenith. For single-station meteors, their exact height is not known, so their height at maximum brightness ($\sim$$103 \pm 3$ km, calculated from the double station Aurigids) is used instead. The error caused by this is $\sim$0.12 mag, less than our photometric uncertainties ($\sim$0.2 mag). The absolute magnitude distribution for the Aurigids and the sporadics are shown in Fig. 3. The meteors observed by the image-intensified camcorders were not included in this plot, as the spectral sensitivity of the image-intensified camera is different than that of the CCD video cameras (WaTec and Mintron). The sporadic background was abundant in meteors with magnitude +0.5 to +2.5. In contrast, the Aurigid outburst was abundant in bright,

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[2] http://www.imo.net

Table 1. Osculating orbital elements of Aurigids at the epoch of the meteor.

Time (UT)	RA[a] (°)	Dec.[a] (°)	V_∞ (km s^{-1})	H_b (km)	H_e (km)	H_{max} (km)	M_{max}	q (au)	$1/a$ (au^{-1})	i^a (°)	Ω^a (°)	Ω^a (°)	M_o (°)
10:53:31	89.44 ± 0.03	+40.13 ± 0.03	67.4 ± 0.6	120.8	96.7	100.5	−1.0	0.714	−0.119	147.698	158.526	116.805	1.422
10:55:50	90.87 ± 0.03	+39.00 ± 0.03	66.5 ± 1.3	119.9	97.2	106.7	−0.6	0.669	−0.045	148.988	158.528	110.232	1.018
11:04:36	91.44 ± 0.02	+38.84 ± 0.02	67.3 ± 0.8	137.1	<112.9[b]	<116.4[b]	<0.6[b]	0.670	−0.127	149.400	158.534	111.484	1.656
11:30:01	90.87 ± 0.27	+39.12 ± 0.10	64.5 ± 1.7	119.9	92.5	104.4	−0.6	0.638	0.128	147.884	158.551	103.876	2.869
12:02:40	91.16 ± 0.10	+38.97 ± 0.09	67.5 ± 1.5	125.2	94.0	100.8	−3.4	0.680	−0.137	149.216	158.572	112.601	2.456
							Annual shower[c]						
	85.5	+42.0	66.3					0.802		146.4	158.978	121.5	
							C/1911 N1 Kiess[d]						
	91.6 ± 1.11	+39.4 ± 1.11	66.1 ± 1.1					0.684	0.005	148.421	158.978	110.378	0.037

[a] Equinox J2000.
[b] Not real end, meteor leaves field of view.
[c] Cook (1973).
[d] Jenniskens (2006).

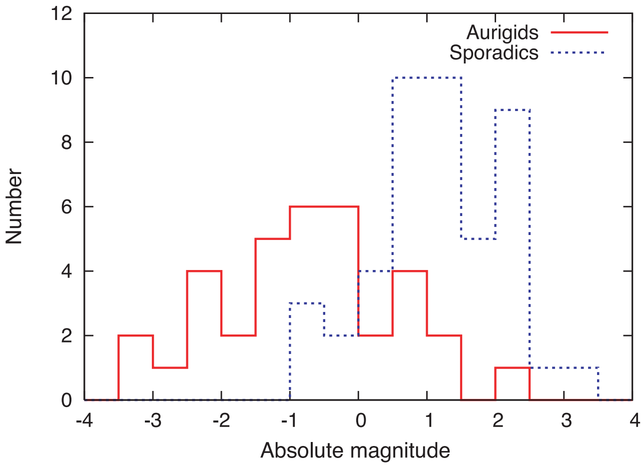

Figure 3. Absolute magnitude distribution of Aurigids (red bold) and sporadics (blue dashes).

−1.5 to 0 mag meteors. There were 14 Aurigids recorded brighter than a magnitude of −1.0, that of the brightest sporadic recorded. The brightest Aurigid, recorded at 12:02:40 UT, was of magnitude −3.4. Similar to past Aurigid outbursts, the 2007 outburst was rich in bright meteors. Jenniskens & Vaubaillon (2007b) also reported an observed abundance of bright, −2 to +3 mag meteors from airborne observations.

5 DISCUSSION

Our observations of the 2007 Aurigid meteor outburst are consistent with most of the predictions made by JVa. However, the terminal heights of the meteoroids H_e were not as low as expected. This suggests that the 2007 Aurigid outburst was different in some way to the 1995 α-Monocerotids, even though they are both caused by ejecta from long-period comets.

The H_b of the Aurigid recorded at 11:04:36 UT is significantly higher than those of the other four Aurigids. The H_b of the 11:04:36 UT Aurigid observed by the Mintron camera at Fremont Peak is 131.5 km, and by the image-intensified camcorder at Lick Observatory is 137.1 km. This is because the image-intensified camcorders are more sensitive light detectors, as they recorded on average ~3.7 times more meteors per unit time and sky surface area than the Mintron cameras. The absolute magnitude of the 11:04:36 and 10:55:50 UT Aurigids, observed with the same Mintron camera at Fremont Peak, plotted against height are shown in Fig. 4. The light curve of the 10:55:50 UT Aurigid is smooth, whereas that of the 11:04:36 UT Aurigid fluctuates. This fluctuation is similar to the high-altitude meteors studied by Koten et al. (2001). The light-curve shape and H_b of the high-altitude meteors could be explained by taking into account sputtering from the meteoroid surface along with the traditional ablation model (Vinkovic 2007). Spurný et al. (2000) distinguished three distinct phases of high-altitude meteor radiation: (i) a diffuse phase with the sputtering-dominated region (above ~130 km); (ii) the intermediate phase where both processes contribute comparably (120–130 km); (iii) the ‘sharp’ ablation phase where the radiation is given solely by meteoroid ablation (below ~120 km).

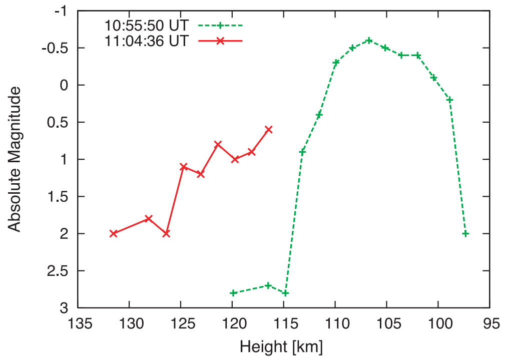

Figure 4. Absolute magnitude of 11:04:36 (red bold) and 10:55:50 UT (green dashed) Aurigids observed by the same Mintron camera at Fremont Peak.

Koten et al. (2006) studied the beginning heights and light curves of high-altitude (>130 km) meteors, using double station data obtained at Ondřejov/Kuunžak during 1998 April–2005 May and, in addition, Leonid outburst data from 1998–2001 obtained at various locations. Only 164 meteors, about ~5 per cent, had H_b greater than 130 km. This emphasizes the rare occurrence of high-altitude meteors. Also noteworthy is that 148 of those high-altitude meteors were Leonids, with only a tiny fraction (16) being Perseids, Lyrids, η-Aquariids or sporadics. Koten et al. (2006) give a relationship between maximum brightness M_{max} and beginning heights H_b shown in equation (1), according to which any meteor brighter than magnitude -1.6 would have a beginning height of 130 km or higher. There were in total nine Aurigids observed (out of 35 Aurigids) with maximum magnitude brighter than -1.5, and thus these Aurigids could also have $H_{\rm b}$ greater than 130 km, resembling the 11:04:36 Aurigid:

$$H_{\rm b} = -3.5(\pm 0.1)M_{\rm max} + 124.4(\pm 0.4). \qquad (1)$$

The 2007 Aurigid outburst is similar to the Leonid outbursts during 1998–2001 in that they both have similar $H_{\rm b}$, $H_{\rm e}$, $H_{\rm max}$ and contain high-altitude meteors. Leonids are among the fastest meteor showers, with $V_\infty = 71\,{\rm km\,s^{-1}}$. The parent comet of the Leonids, 55P/Tempel-Tuttle, has an orbital period of 33.24 yr (Jet Propulsion Laboratory Small-Body Database). It is important to note that the comparison is not being made with the annual Leonid shower, but rather with Leonid outbursts that happened during 1998–2001. This points to a similarity between meteor outbursts due to ejecta from short- and long-period comets.

The beginning height of cometary meteors increases with increasing mass (Koten et al. 2006). The high-altitude meteoroids are loosely cohesive and probably contain volatile elements such as Na which starts to ablate high in the atmosphere. This suggests that the 2007 Aurigids were perhaps rich in volatile elements, such as Na, which causes bright and high-altitude meteors. Such volatile elements could be still present in the one-revolution ejecta as the meteoroids ejected from the comet at the perihelion 2000 yr ago have spent very little time in the inner Solar system.

6 CONCLUSION

The 2007 Aurigid meteor outburst occurred as predicted. The observed ZHR was half of the predicted value. However, the predictions for peak activity time, radiant and velocity were consistent with the observed values. These Aurigids were bright as expected with 26 brighter than 0 mag. The close agreement between the predicted and the observed parameters of this outburst highlights the advancement in meteoroid ejection models from comets and their evolution through time for up to several millennia.

The compactness of the radiant, velocities and the good agreement of the orbital parameters of the outburst Aurigids with that of the parent object demonstrates the fidelity of SPARVM.

The Aurigid recorded at 11:04:36 UT is the first high-altitude Aurigid documented. However, inferred from the magnitude distribution, there should be more Aurigids with similar beginning heights.

The $H_{\rm b}$, $H_{\rm e}$ and $H_{\rm max}$ of the 2007 Aurigid outburst are similar to those of Leonid outbursts (1998–2001). The discovery of at least one high-altitude meteor among the 2007 Aurigids further highlights this similarity. The presence of bright, high-altitude meteors also suggests the possibility of volatile elements such as Na in the meteoroids.

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