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The 2006 Orionid outburst imaged by all-sky CCD cameras from Spain: meteoroid spatial fluxes and orbital elements

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ABSTRACT

By using high-resolution low-scan-rate all-sky CCD cameras, the SPanish Meteor Network (SPMN) detected an outburst of Orionid meteors associated with comet 1P/Halley on 2006 October 20–21. This detection was made possible due to the operational concept of the SPMN that involves continuous monitoring of meteor activity throughout the year. Accurate heliocentric orbits have been obtained for three meteors imaged simultaneously from two stations during the outburst. Additional astrometry of 33 single-station meteors indicates that the activity was produced from a conspicuous geocentric radiant located at $\alpha = 92\overset{\circ}{.}2 \pm 0\overset{\circ}{.}5$ and $\delta = +15\overset{\circ}{.}4 \pm 0\overset{\circ}{.}6$ which is similar to the radiant observed during the 1993 Orionid outburst despite the fact that the last one peaked on a different date. The radiant position obtained by the SPMN is consistent with that derived from digital pictures taken a few hours before from Ankara (Turkey). The extent of the outburst (a background of bright meteors was observed over several days), its absence in other years, and the orbital period of the three Orionid orbits suggest that the outburst could be produced by meteoroids trapped in resonances with Jupiter but additional data are required. The SPMN's continuous coverage of meteor activity allowed the identification of the main sources of meteors during 2006 October: mostly due to the Orionid stream, the two branches of the Taurid stream associated with comet 2P/Encke, and the δ Aurigids. Surprisingly, once a detailed analysis of the double-station video meteors was completed, some additional minor stream activity was discovered, that is, the ν Aurigids. In consequence, we also present two accurate orbits of this unexpected, but previously identified, minor shower.

Key words: comets: individual 1P/Halley – meteors, meteoroids.

1 INTRODUCTION: 1P/HALLEY METEOROID STREAMS

Since McKinley (1961) suggested that comet 1P/Halley was the source of the Orionid and η Aquarid meteor showers, there has been increasing understanding of the dynamics and internal structure of these interesting meteoroid streams. McIntosh & Jones (1988) pointed out that, given the small inclination of the comet orbit with respect to the ecliptic plane (17°), the Earth has the opportunity to make two close approaches to the comet's orbit. The first Earth encounter with 1P/Halley debris takes place in May when the Earth approaches at a distance of about 0.07 au, producing the η Aquarids between solar longitudes (hereafter $\lambda_{\odot}$) 35° and 55°. The second approach takes place in October when the Earth is as close as 0.16 au from the comet orbit (McIntosh & Jones 1988). It is in this latter position when meteoroids of this famous comet are entering the Earth's atmosphere with a geometry that makes them appear to radiate from the constellation of Orion, being consequently called Orionids. A striking feature of both 1P/Halley meteoroid streams is the filamentary structure, which has been explained as due to the orbital evolution of the meteoroid stream being affected by major planets, particularly Jupiter (McIntosh & Hajduk 1983). These authors first suggested a shell model able to explain most of the observed peculiarities. Later, McIntosh & Jones (1988) developed a better numerical model that included the long-term evolution of

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1P/Halley. One interesting feature of the Orionid shower is that despite the Earth crossing the comet's orbit at a greater separation distance, it is not weaker than the η Aquarids (McIntosh & Jones 1988; Wu & Williams 1992). In fact, several authors have noted that the activity of the Orionid meteor shower varies significantly from year to year (Lovell 1954; Hajduk 1970).

Perhaps the most intriguing point on the behaviour of both meteoroid streams in the past is that they have been a source of important meteor outbursts, that is, increases in the meteor rate over the normal (annual) level (see e.g. table 1, Jenniskens 2006). The complete absence of periodicity in these outbursts makes it very difficult to correlate this behaviour with the crossing of recently ejected dust trails (that in fact lie far from Earth's path). The only notable increase observed in modern times was the detection of the 1993 Orionid outburst by members of the Dutch Meteor Society (Jenniskens 1995, 2006). Trigo-Rodríguez et al. (2006a) previously reported the outburst of 2006 Orionids by using all-sky CCD cameras operated as part of the SPanish Meteor Network (SPMN). In this paper, we include an accurate determination of Orionid fluxes from the recorded outburst, an astrometric determination of the radiant, and three accurate Orionid orbits that can give new clues on the origin of these meteoroid outbursts. During the data reduction of the October observations, we also found activity from some poorly studied minor showers. In consequence, we also include a short discussion of the overall meteor activity present during 2006 October. In particular, the orbits of two video meteors associated with the ν Aurigids minor shower are included.

2 INSTRUMENTATION, DATA REDUCTION AND OBSERVATION SITES

Trigo-Rodríguez et al. (2004a) previously reported the first steps in the development of the SPMN that deployed low-scan-rate all-sky CCD cameras with +2/+3 meteor limiting magnitude. During 2006 further expansion of the network was made by setting up two new all-sky CCD stations in Catalonia and three video stations in Andalusia. The main goal was to increase the atmospheric coverage of meteor and fireball activity (Trigo-Rodríguez et al. 2006b, 2007). As the two already active cores of the network (Andalusia and Catalonia) are separated by 1000 km, there is a higher probability of clear skies and of meteor activity being recorded every night. Unfortunately, all-sky and video observations from Andalusia were unavailable due to bad weather during the 2006 Orionid outburst. As a consequence, the focus here is on the results obtained from the three SPMN stations operating in Catalonia (Table 1), two of them being high-resolution all-sky CCD cameras equipped with rotating shutters for measuring meteor velocities. One of the two all-sky Catalonian stations had partially cloudy skies which impeded continuous double-station monitoring. Fortunately, a third station (#3) operating a CCD camera with a field of 45° × 35° was also participating in monitoring meteor activity. Additionally, for several nights (October 12–18) before the maximum video observations were performed from two stations in Andalusia.

The combined set of SPMN video stations use 11 high-sensitivity CCTV cameras to monitor the night sky. All of them are equipped with a 0.5-inch Sony interline transfer CCD image sensor with their minimum lux rating ranging from 0.01 to 0.0001 lx at f1.4. Aspherical fast lenses with focal length ranging from 2.6 mm (fisheye) to 12 mm and focal ratio between 1.2 and 0.8 are used for the imaging objective lens. In this way, different areas of the sky can be covered by every camera and point-like star images are obtained across the entire field of view. The cameras generate video imagery at 25 fps with a resolution of 720 × 576 pixels. The computers execute software that automatically detects meteors and stores the corresponding frames on hard disk. We use this program for capturing meteor sequences, but we use our own astrometric reduction procedure and software. A video time inserter that employs a GPS device allows measurement of time with an accuracy of 10^{-1} s along the entire meteor path. During 2006 October this video equipment was operated from two video stations in Sevilla province (#4 and 5 in Table 1). The video cameras were optimally pointed in order to maximize the common atmospheric volume by using the program PHOTOGRAPHIC CENTERS FOR MULTIPLE STATION METEOR OBSERVATIONS in the same way as was explained in Trigo-Rodríguez et al. (2004b).

Low-scan-rate CCD images were directly measured by using the MAXIM DL software package. Accurate astrometry was obtained for stars and meteors. The astrometric measurements from each station were then introduced into our NETWORK software (Trigo-Rodríguez et al. 2002, 2004b), which computes the equatorial coordinates of the meteors with an astrometric accuracy of about 0°.01 and also determines the apparent and geocentric radiant of common meteors. Another program called AMALTHEA was also developed by the SPMN for allowing quick astrometric reduction of video meteors. From the astrometric measurements of the shutter breaks and the trajectory length, the velocity of the meteoroid was derived. The average value of observed velocities for each shutter break was obtained as well as the pre-atmospheric velocity V_∞ from the velocity measured in the earliest of the meteor trajectories. Finally, in order to determine orbital elements from our trajectory data we used the METEOR ORBIT (MORB) program provided by Ceplecha, Spurny & Borovicka (2000). As a consequence of the observational data-reduction effort, reliable trajectory and orbital data were obtained and are presented in Section 3.

3 OBSERVATIONS: SPATIAL FLUXES, TRAJECTORY, RADIANT AND ORBITAL DATA

CCD cameras allow the estimation of stellar and meteor magnitudes very accurately because they provide photon counts for every pixel. In all-sky CCD imaging, we adopt a simplistic approach where meteor magnitudes were derived by comparing the intensity level of the

Table 1. Stations of the SPMN involved in this work. Acronyms for the different imaging systems are: AS (low-scan-rate CCD all-sky camera), WF (low-scan-rate CCD wide-field camera) and WFV (wide-field video cameras).

Station #	Station (province)	Longitude	Latitude (N)	Altitude (m)	Imaging system
1	Montsec (Lleida)	00°43′46″E	42°03′05″	1570	AS
2	Montseny (Girona)	02°31′14″E	41°43′17″	300	AS
3	Folgueroles (Barcelona)	02°19′33″E	41°56′31″	580	WF
4	Seville (Seville)	05°58′50″W	37°20′46″	28	WFV
5	Cerro Negro (Seville)	06°19′35″W	37°40′19″	470	WFV

Table 2. Magnitude distribution of Orionids imaged by CCD cameras on 2006 October 20–21.

Magnitude	−8	−7	−6	−5	−4	−3	−2	−1	0	+1	+2	+3	*r*
Number	1	0	0	1	1	0	3	4	5	5	9	4	1.4 ± 0.4

pixels near the maximum luminosity of the meteor trail and nearby stars. The different angular velocities of the meteors as a function of the distance to the radiant, and the typical duration of flares should be taken into account. Additional corrections are required for those meteors that appeared below 30° of altitude because they experience atmospheric extinction. By estimating the meteor magnitudes from the images we have obtained the magnitude distribution for the night of 2006 October 20–21 (Table 2). We derived a population index $r = 1.4 \pm 0.4$ ($N = 33$) that was used to estimate the spatial flux of meteoroids producing meteors brighter than +6.5 mag, as well as to convert to a visual Zenithal Hourly Rate (ZHR). The activity imaged during October 20–21 was three times higher than the typical measured during the maximum of this meteor shower of 20 meteors h^{-1} (Trigo-Rodríguez et al. 2006a). This high ZHR was confirmed by using the count rates obtained from the all-sky systems, and correcting them using a high-fidelity meteor simulation that accounts for sensor sensitivity characteristics, geometric loss terms, radiant position changes, and the meteor stream's particle distribution. The activity was stable during the October 20–21 night with an incident flux of 415 meteoroids brighter than +6.5 mag. From this flux value and a simulation model for human visual perception of meteors, we have estimated a visual (human) ZHR = 50 ± 15.

In total, during the night of October 20–21, 30 Orionid meteors were imaged by SPMN station #2 (together with four sporadics, and two Taurids) in 90-s CCD exposures (read-out time of 30 s). The Orionid outburst was very evident once the radiant rose above the horizon. The display was mainly composed of bright meteors that were easily recorded by our all-sky system. Two out of the three Orionid imaged double-station meteors (SPMN011006 and 021006) were very bright (−1 and −5 mag) and are shown in Figs 1 and S1 (see Supplementary Material section). A third meteor was fainter (+2 mag) but still measurable (SPMN051006). These Orionid

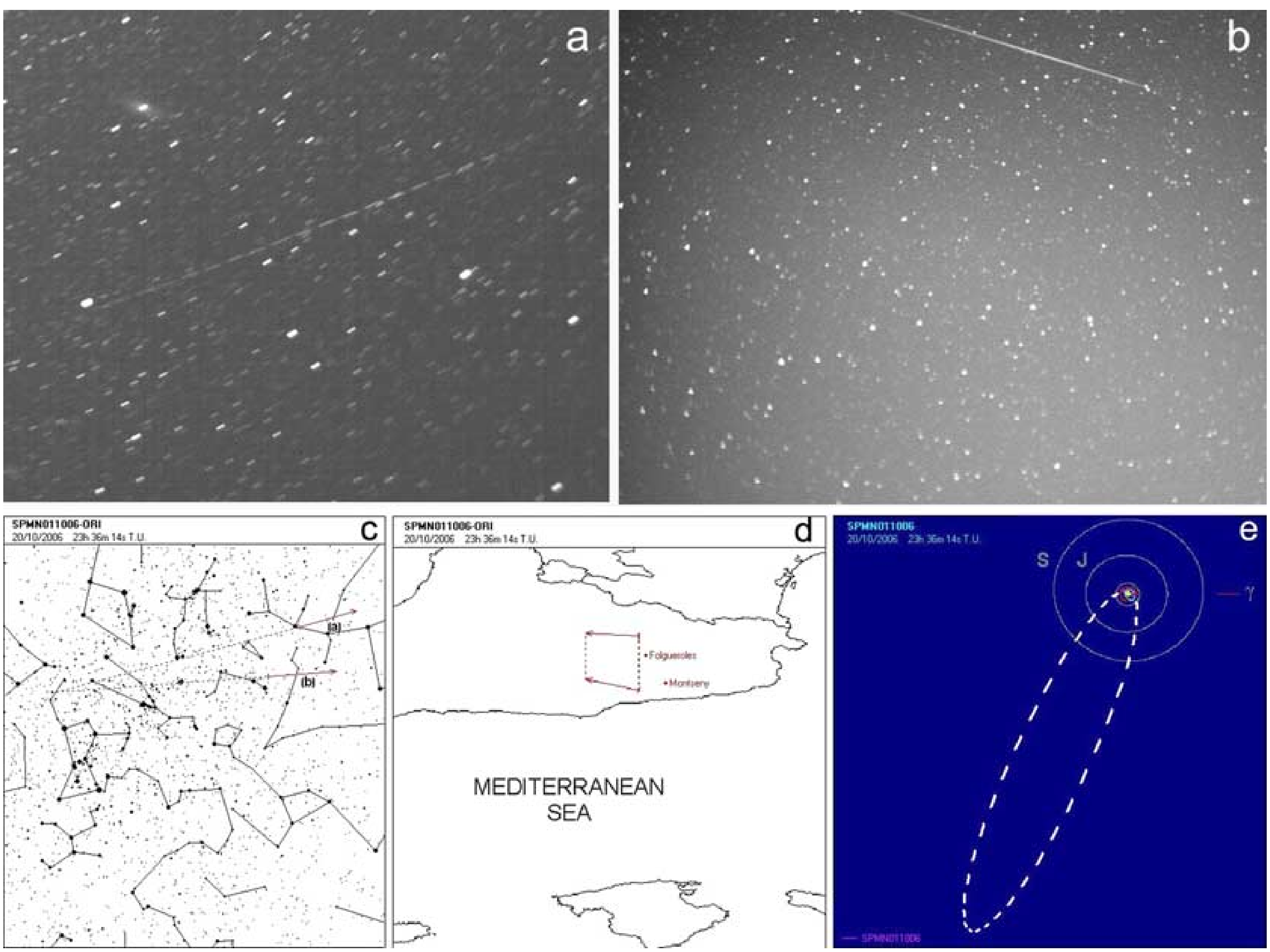

Figure 1. Part of the CCD image centred on the −2 mag Orionid (SPMN011006) recorded from (a) Montseny and (b) Folgueroles. (c) Apparent trajectory of the meteor from both stations. (d) Atmospheric trajectory and its projection on the ground. (e) The heliocentric orbit of the meteoroid projected on the ecliptic plane, where the orbits of Jupiter (J) and Saturn (S) are shown for comparison.

Table 3. Trajectory and radiant data, equinox (2000.0).

SPMN code	Stream	M_V	H_b	H_{max}	H_e	α_g (°)	δ_g (°)	V_∞	V_g	V_h
011006	Orionid	−1	117.2	107.4	100.9	90.92 ± 0.14	17.00 ± 0.06	67.0 ± 0.2	65.8	41.8
021006	Orionid	−5	119.5	94.8	89.2	92.75 ± 0.16	15.79 ± 0.05	67.2 ± 0.2	66.2	41.7
051006	Orionid	+2	107.8	97.2	93.9	93.81 ± 0.23	16.00 ± 0.21	67.8 ± 0.3	66.6	41.6
061006	ν Aur.	−2	94.0	86.3	82.0	67.8 ± 0.6	39.7 ± 0.6	54.4 ± 0.3	53.2	36.6
091006	ν Aur.	−1	98.7	79.7	78.0	70.6 ± 0.5	40.1 ± 0.4	54.4 ± 0.3	53.3	36.2

Table 4. Orbital elements of Orionid meteors, equinox (2000.00). For comparison we show the averaged orbital elements for outburst Orionids photographed by the DMS.

SPMN code	q	$1/a$	e	i	ω	Ω
011006	0.491 ± 0.004	0.040 ± 0.019	0.980 ± 0.009	165.55 ± 0.14	91.4 ± 0.8	27.34436 ± 0.00017
021006	0.540 ± 0.005	0.046 ± 0.019	0.975 ± 0.010	163.48 ± 0.13	85.8 ± 0.8	27.50407 ± 0.00017
051006	0.571 ± 0.007	0.054 ± 0.028	0.969 ± 0.015	164.2 ± 0.4	82.31 ± 1.15	27.36133 ± 0.00017
2006 Orionid average ($N = 3$)	0.534 ± 0.006	0.045 ± 0.022	0.975 ± 0.012	164.4 ± 0.4	86.5 ± 0.9	-
1993 DMS Orionids ($N = 5$)	0.602 ± 0.008	0.045 ± 0.022	0.973 ± 0.023	162.9 ± 0.4	78.6 ± 1.5	-

meteor magnitudes are produced by meteoroid masses, respectively, of 0.3, 16 and 0.13 g (by using equation C-12 of appendix, Jenniskens 2006). The trajectory data of these accurately reduced meteors are given in Table 3, which shows the SPMN code used for identification, the apparent visual magnitude (M_V), the meteor trail beginning and end height on the Earth's surface (H_b and H_e in km), the geocentric radiant coordinates (α_g and δ_g to equinox 2000.00) and the velocity in km s^{-1} (at the top of atmosphere, geocentric and heliocentric). From the radiant position, apparition time and velocities estimated for the Orionid meteors listed in Table 3, we derived the orbital elements shown in Table 4.

Although video observations from Andalusia during the nights around the Orionid outburst were impeded by bad weather, the campaign on October 12–16 was very rich in meteors. Among the several hundreds of imaged meteors, it is worth mentioning the unexpected presence of the ν Aurigids stream on October 14 and 15. This stream was first noted by Sekanina (1976) and also included in the list of minor showers (#229 in table 7 of Jenniskens 2006). We recorded two bright double-station meteors for this stream (SPMN061006 and 091006) where accurate trajectory, radiant and orbital data were obtained (Tables 3 and 5).

4 DISCUSSION

If we plot on a gnomonic star chart the accurately measured apparent trajectories of 33 Orionids (26 are included in Fig. 2), we can see that most of them are radiating from a conspicuous apparent radiant in $\alpha = 95\overset{\circ}{.}6 \pm 0\overset{\circ}{.}5$ and $\delta = +15\overset{\circ}{.}5 \pm 0\overset{\circ}{.}6$ ($\lambda_o = 207\overset{\circ}{.}4$). This value corresponds to a geocentric radiant of $\alpha = 92\overset{\circ}{.}2 \pm 0\overset{\circ}{.}5$ and $\delta = +15\overset{\circ}{.}4 \pm 0\overset{\circ}{.}6$ that is consistent (to within the error bounds) with the accurately determined geocentric radiant for two out of the three double-station meteors (SPMN021006 and 051006). On the other hand, SPMN011006 has a clear RA deviation from this position but it would be produced by the marginal detection of the trail from SPMN station #3. Fig. 1(b) clearly shows that the trail's beginning occurred out of the field of view covered by the wide-field CCD camera. This fact and an additional error introduced by optical distortion nearby the field border would introduce a significant astrometric error when propagated to the radiant distance. However, we cannot discard that this Orionid was coming from a separate component like, for example, the annual Orionid background. In any case, it deserves to be mentioned that the derived geocentric radiant for almost all imaged Orionids (except perhaps SPMN011006) is consistent with one measured from Orionid pictures collected in Turkey on the same night (Fig. S2, see Supplementary Material section), but inside a previous observing interval (20^{h}35–22^{h}35 UTC). We compared this geocentric radiant with the average of two Orionid fireballs photographed by the DMS during the 1993 Orionid outburst that occurred on October 17–18 ($\lambda_o \sim 204\overset{\circ}{.}5$). The 1993 geocentric radiant was located at $\alpha = 92\overset{\circ}{.}2$ and $\delta = 15\overset{\circ}{.}2$ (Betlem et al. 1998; Jenniskens 2006) and we find an excellent match to our derived radiant for 2006. This is indeed an important point because the two 1993 Orionids were observed on October 18 while the 2006 Orionids were observed on October 21. We should expect a daily drift of the radiant position of about $\Delta\alpha = +0\overset{\circ}{.}7$ and $\Delta\delta = +0\overset{\circ}{.}1$ that is usually observed in the annual shower. Particles trapped in resonances tend to be organized in narrow features. The radiant drift results from the change in configuration between the stream and the Earth. Regular showers like the Orionids are organized in filaments broader than resonant particles, but this has no influence on the overall geometry. Therefore, the observed absence of radiant drift is consistent with the presence of resonant particles

The radiant position of the outburst (bright) Orionids imaged on nights surrounding the maximum (see some examples in Fig. 3)

Table 5. Orbital elements of ν Aurigids for equinox (2000.00). The averaged orbital elements of ν Aurigids (stream #229 given in table 7, Jenniskens 2006) are shown for comparison.

SPMN code	q	$1/a$	e	i	ω	Ω
061006	0.218 ± 0.009	0.491 ± 0.025	0.893 ± 0.006	123.1 ± 1.3	311.1 ± 1.3	199.54955 ± 0.00001
091006	0.231 ± 0.007	0.529 ± 0.021	0.878 ± 0.006	124.6 ± 1.0	310.1 ± 1.0	200.59263 ± 0.00001
Average	0.225	0.510	0.886	123.9	310.6	–
#229	0.267	0.770	–	134.3	311.0	208.0

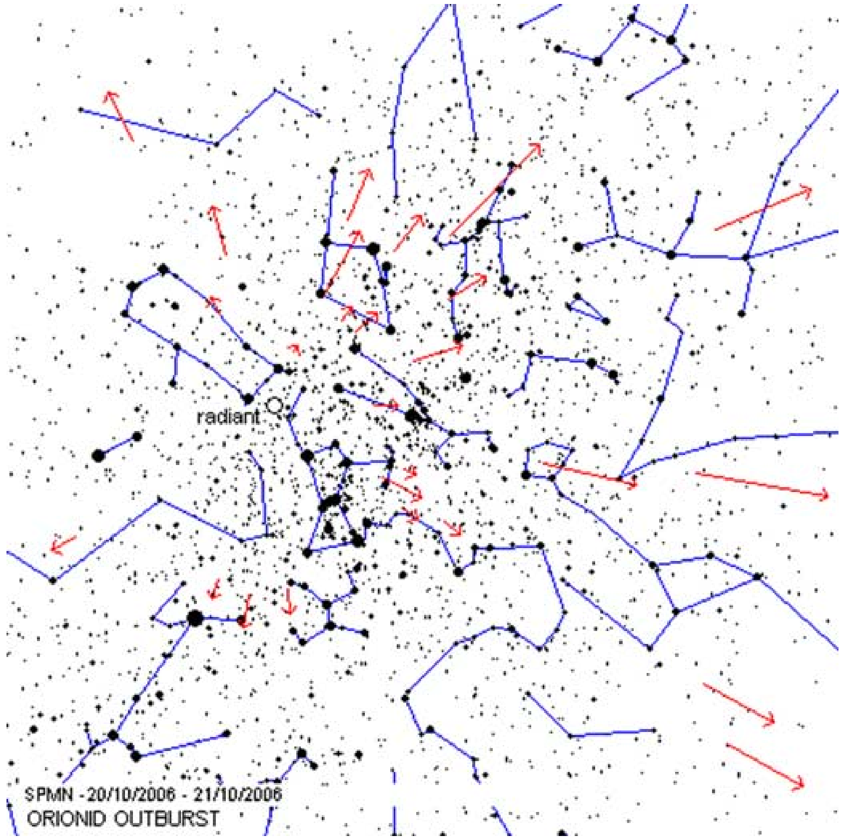

Figure 2. This stellar chart shows 26 out of the 33 astrometrically reduced Orionid meteors, showing an apparent radiant centred at RA = 96° and Dec. = +16°. This position is fully consistent with two of the double-station Orionid meteors imaged by the SPMN Catalan stations.

seems to be similar. In any case, the small number of events makes it difficult to be conclusive and, unfortunately, no additional double-station Orionids were obtained.

On the other hand, in order to check if the meteoroids producing the Orionid outbursts are trapped in an orbital resonance with Jupiter, we can study the 2006 Orionid orbits. Taking into account that the orbital period can be written as $P = a^{3/2}$, we can estimate the period of the 2006 Orionid meteors from the derived semimajor axis (a). This value is strongly dependent on the measured entry velocity where the estimation uncertainty is usually high, and in turn generates significant errors in the semimajor axis (Table 4). However, by directly comparing the orbital period of Jupiter (P_J = 11.85 yr) with those estimated for the three Orionids $P_1 = 121.78$ yr, $P_2 = 100.37$ yr and $P_3 = 79.03$ yr, we found that (within the observational uncertainty) some of these meteoroids would be in clear resonance with Jupiter, respectively, in a 41:4, 17:2 and 19:3 resonance. Unfortunately, the errors in semimajor axis for meteoroid orbits are strongly affected by the uncertainty in the entry velocity. Consequently, a much larger number of orbits are required to confirm that the 2006 Orionid outburst was produced by 1P/Halley meteoroids trapped in Jovian resonances. It is important to point out that Sato & Watanabe (2007) have recently found that the 2006 Orionid outburst would be caused by the dust trails ejected from 1P/Halley in the years −1265, −1197 and −910. The meteoroids belonging to these cometary trails were in a 6:1 resonance with Jupiter; the orbits of meteoroids extended into the Earth orbit faster than usual due to the mean motion resonance of Jupiter.

In reference to the ν Aurigids members imaged by our video systems, Table 5 is showing the orbital similarity with the orbital elements obtained by Sekanina (1976). It was completely unexpected to find members of this meteoroid stream so early in the month because the previously reported activity period is October 20–22 (Jenniskens 2006). However, other single-station meteors recorded by the SPMN video cameras were also well associated by alignment and angular velocity with this radiant. We also found in the imagery a weak level of δ Aurigid activity, but curiously no trace of the Ursa Majorids radiant claimed by Uehara et al. (2006)on exactly the same dates. In any case, our findings suggest that meteor activity during October deserves to be studied in further detail in the future.

5 CONCLUSIONS

We have presented the first detection of an unexpected outburst recorded by a recently developed all-sky high-resolution CCD camera described in Trigo-Rodríguez et al. (2004a). Despite the probability that recording a meteor outburst is very low, the excellent performance of these cameras and deployment in a wide-area network permit the collection of very valuable information. The main conclusions of this work are as follows.

(i) CCD results are almost obtained in real time, just allowing the provision of quick alerts of unusual meteor/fireball activity to the astronomical community (e.g. Trigo-Rodríguez et al. 2006a). Among the advantages of the CCD cameras first applied to this field by Trigo-Rodríguez et al. (2004a) is the recording of meteor activity not only covering bright fireballs as in the case of photographic all-sky cameras, but also including visual meteors as faint as +3 mag. Future development of this and other CCD monitoring systems around the world can promote significant progress in meteor science.

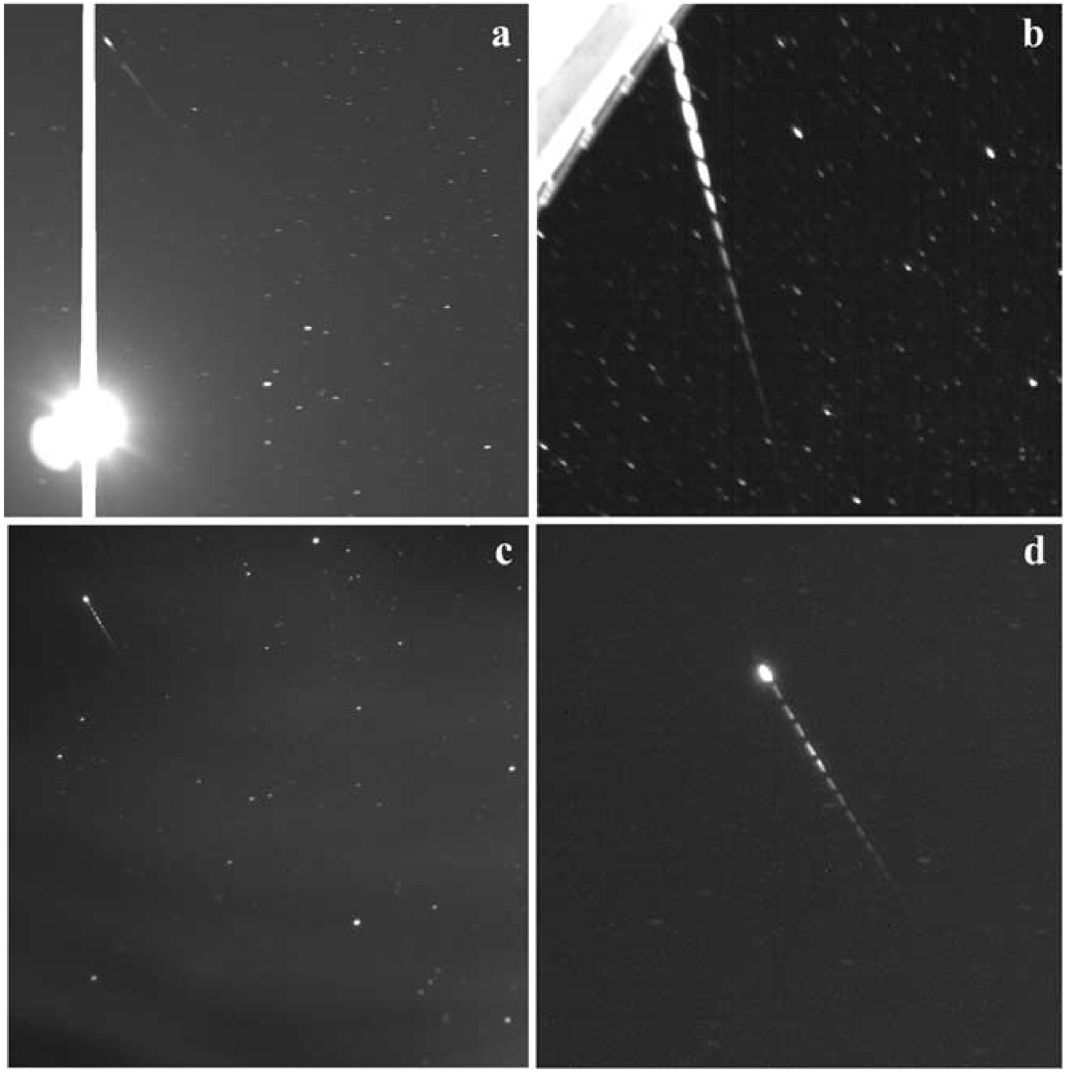

Figure 3. These images are a good example of the excellent performance of our all-sky CCD cameras, operated under very different sky conditions. All were obtained from Montseny (station #2) and are clear evidence of the background of bright bolides observed during the nights around the maximum. (a) −4 Orionid fireball projected on Leo Minoris appeared on 2006 October 15 at $3^{h}16^{m}28 \pm 45^{s}$ UT. This fireball was imaged near a Moon blooming artefact that appeared across the focal plane as well as under a bright sky. Note that the shutter velocity was lower than that in the rest of the images. (b) The brightest Orionid fireball reached −8 mag crossing Ursa Minoris and as a consequence of the perspective was apparently 'falling' on the roof of a nearby building. This event was recorded on October 21 at $3^{h}41^{m}41 \pm 45^{s}$ UT under a dark crystalline sky (Lm = 6.3). (c) Impressive Orionid fireball exhibiting a −7 mag flare imaged on October 22 at $3^{h}19^{m}34 \pm 34^{s}$ UT despite high clouds. The fireball path exhibits several flares as evidenced in the magnified image shown in (d).

(ii) In reference to the origin of the Orionid outburst, Jenniskens (2006) already pointed out that 1P/Halley outbursts appear to be limited in extent along the comet orbit, and then suggesting that they are produced by meteoroids that are resonantly trapped. The resonant origin of the 1P/Halley outbursts seems to be also supported by recent dust trail studies obtained by Sato & Watanabe (2007). In any case, additional orbital data from this and future outbursts are required in order to decipher the origin of the 2006 outburst, and answer some unresolved issues in the dynamics of 1P/Halley meteoroids.

(iii) SPMN video observations were also able to detect activity from a minor stream previously identified by Sekanina (1976), but no clear evidence of the October Ursa Majorids, a new shower identified by Uehara et al. (2006). In any case, additional observations in October during the next few years are required to get additional clues on several poorly known streams that are currently under study by our community.

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SUPPLEMENTARY MATERIAL

The following supplementary material is available for this article:

Figure S1. Part of the CCD image centred in the −5 mag Orionid (SPMN021006) recorded from (a) Montseny and (b) Folgueroles (under a partially cloudy sky). (c) Apparent trajectory of the meteor from both stations. (d) Atmospheric trajectory and its projection on the ground. (e) The heliocentric orbit of the meteoroid projected on the ecliptic plane, where the orbits of Jupiter (J) and Saturn (S) are shown for comparison.

Figure S2. Composition of the Orionid meteors imaged from Ankara (Turkey) with a Canon EOS 300D digital SLR at ISO 1600 and a 10-mm f/3.5 wide-angle lens. A total of 130 1-min shots of about the same part of sky were taken between 2035 and 2235 UTC. The radiant (marked as a white circle) is clearly consistent with that derived from astrometric measurements from Spanish CCD images (for more details see the text and Fig. 3).

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