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The outburst of the κ Cygnids in 2007: clues about the catastrophic break up of a comet to produce an Earth-crossing meteoroid stream

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ABSTRACT

Using high-resolution, low-scan-rate, all-sky CCD cameras and high-level CCD video cameras, the SPanish Meteor and fireball Network (SPMN) recorded the 2007 κ Cygnid fireball outburst from several observing stations. Here, accurate trajectory, radiant and orbital data obtained for the κ Cygnid meteor are presented. The typical astrometric uncertainty is 1–2 arcmin, while velocity determination errors are of the order of 0.3–0.6 km s^{-1}, though this depends on the distance of each event to the station and its particular viewing geometry. The observed orbital differences among 1993 and 2007 outbursts support the hypothesis that the formation of this meteoroid stream is a consequence of the fragmentation of a comet nucleus. Such disruptive process proceed as a cascade, where the break up of the progenitor body leads to produce small remnants, some fully disintegrate into different clumps of particles and other remaining as dormant objects such as 2008ED69, 2001MG1 and 2004LA12 which are now observed as near-Earth asteroids. In addition to the orbital data, we present a unique spectrum of a bright κ Cygnid fireball revealing that the main rocky components have chondritic abundances, and estimations of the tensile strength of those fireballs that exhibited a catastrophic disruption behaviour. All this evidence of the structure and composition of the κ Cygnid meteoroids is consistent with being composed by fine-grained materials typically released from comets.

Key words: comets: general – meteors, meteoroids – minor planets, asteroids.

1 INTRODUCTION

The activity of the κ Cygnid meteoroid stream (currently catalogued in the IAU list as No 12) was first reported about 150 years ago (Denning 1877). Nowadays, this meteor shower is active in the interval August 3–31 with a peak on August 18 (Jenniskens 2006). Jenniskens (1994) found that its maximum Zenithal Hourly Rate (ZHR) is 2.3± 0.4. According to Kronk (1988), the first κ Cygnid displays were noted by Konkoly in 1874 while observing the Perseid shower. Denning (1893) observed a high activity in the shower, with several fireballs in 1877, during a campaign to observe the Perseids, though he called them the Theta Cygnids. A high level of activity was also recorded in 1901 (Besley 1903). Denning (1922), summarizing the observations of a number of observers, noted that the Theta Cygnids radiant was active between August 15 and 26. King (1929), also summarizing the observations of others, commented on the large number of exploding fireballs that were observed. Despite the recognition of this activity of meteors radiating from Cygnus with moderate angular velocity during the activity span of the Perseids, the unequivocal identification of a separate meteoroid stream and its radiant was not achieved for several more decades. The multistation photographic work by Jacchia (1952) and Whipple (1954) eventually allowed velocities to be determined, and the existence of the κ Cygnids was established. The duration of activity and the associated spread in the longitude of the nodes suggest that the stream may be old (Jenniskens 2006). Jones, Williams & Porubcan (2006) investigated the orbital evolution of the Cygnid complex and concluded that the vast majority of meteoroids displayed a sinusoidal evolutionary behaviour with a period of approximately 2100 years, a value that is consistent with the value obtained by Obrubov (1995) for the secular variation cycle. Jones et al. (2006) also found that a minority of meteoroids evolved differently and also found two asteroids, 2001MG1 and 2004LA12, associated with this

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minor component, but could find no asteroid related to the majority. The behaviour of the κ Cygnids is reminiscent of the behaviour of the Quadrantids as described by Wu & Williams (1992). Also like the Quadrantids, the stream has no comet recognized as being the obvious parent. When Jenniskens (2004) demonstrated that asteroid 2003EH1 was clearly associated with the Quadrantids, he also suggested that the original parent comet that was responsible for the broad background activity in the Quadrantids had suffered a major disruption in the near past, releasing large quantities of meteoroids that are today recognized as the narrow central peak in the Quadrantid activity and leaving a dormant or dead comet fragment as the asteroid 2003EH1. Recently, outbursts observed in 1993 and 2007 (Trigo-Rodríguez et al. 2008) suggest that the κ Cygnid shower is also relatively young. Jenniskens & Vaubaillon (2008) have shown that asteroid 2008ED69 evolves with a similar sinusoidal variation to that of the majority of the κ Cygnids and has a similar orbit now, but was even more similar around 1000 years ago. It is thus very likely that the κ Cygnids are indeed moderately young and were formed following a catastrophic disruption of the parent body, leaving 2008ED69 as a dormant remnant. This makes the study of the two recent outbursts very important and this paper deals with these aspects.

A significant advancement in the study of the κ Cygnid stream occurred during a multistation photographic campaign organized by the Dutch Meteor Society, initially focusing on the 1993 Perseid outburst. They detected the first outburst of the κ Cygnids since the early reports around 1900. During four consecutive nights, orbits of 10 bright bolides were obtained (Betlem et al. 1998). From that time, the activity of the κ Cygnid shower remained weak until 2007 August when a further outburst was observed. Many of the fireballs observed exhibited extremely bright flares, a clear indication of a catastrophic disruption at the end of their path through the atmosphere (see e.g. Fig. 1). The flares are produced when a large amount of typically sub-micron-sized mineral grains are released following the break up, and almost instantaneously ablated due to the temperatures reached in the thermal front (Borovička & Jenniskens 2000; Trigo-Rodríguez & Llorca 2006). Such break ups are characteristic of relatively weak aggregates of cometary origin, but before the fragmentation a substantial ablation of the meteoroid is required. A plausible explanation is that some mineral phases are ablated when the meteoroid is progressively heated, contributing to decrease its strength. Fireball spectra of cometary meteoroids reveal differential ablation: those moderately volatile phases are ablated preferentially on top of the meteor trajectories (see e.g. Trigo-Rodríguez et al. 2003). Due to this, volatile elements like Na contribute preferentially to the light emitted during the first stages of ablation (Trigo-Rodríguez & Llorca 2007). It is important to remark that the study of their catastrophic ending points allows an estimate of the tensile strength of the meteoroids to be made.

This paper gives additional data on the nature of these particles. Tensile strength measurements are complemented by the spectrum of a fireball also obtained during the 2007 display. Additionally, we also discuss the dynamics and evolution of the κ Cygnid meteoroid stream orbit by using the measured orbital elements of the 1993 and 2007 members. We have also determined the relative chemical abundances from the spectrum of bright flare produced by a κ Cygnid bolide imaged by two SPanish Meteor and fireball Network (SPMN) stations.

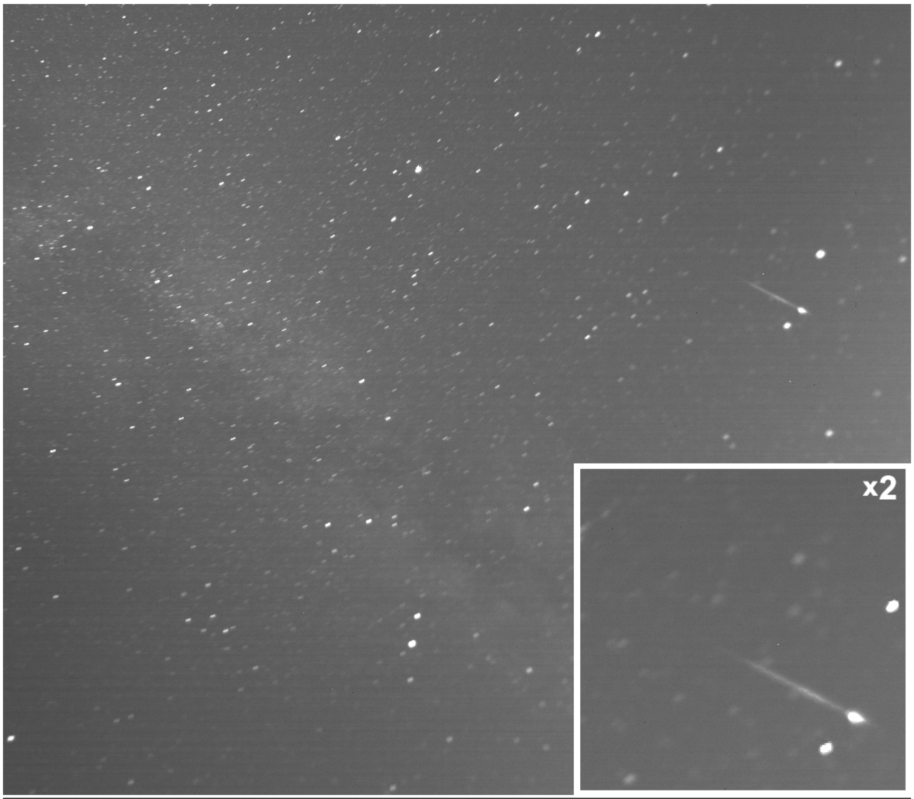

Figure 1. Section of all-sky CCD 45 s exposure image taken from station Montseny (Girona) of the −5 mag κ Cygnid fireball SPMN100807 that appeared on 2007 August 10 at $22^{\mathrm{h}}26^{\mathrm{m}}$UTC. The Milky Way denoting extremely clear sky conditions crosses the image. A window on the right lower corner shows a magnification of the fireball where the characteristic catastrophic flare at the end of the luminous path is clearly visible.

2 INSTRUMENTATION, DATA REDUCTION AND OBSERVATION SITES

During the 2007 κ Cygnid period, the *Spanish Meteor and Fireball Network (SPMN)* monitored the sky using two video stations and three CCD all-sky stations described in Madiedo & Trigo-Rodríguez (2008); observing conditions were excellent, and the activity from the κ Cygnid shower was recorded between 2007 August 9 and 21, including several fireballs as previously reported (Trigo-Rodríguez et al. 2007a,b, 2008). All-sky CCD cameras were operated in a sequential imaging mode, each making 30 or 90 s exposures followed by a typical readout time of 15 or 30 s, depending on whether the readout is controlled by a parallel or USB port, respectively. Currently, the CCD all-sky imagery is analysed using a set of image-processing modules that have recently been developed (Trigo-Rodríguez et al. 2008). Additionally, automatic video detection of meteors were achieved by using the software UFO CAPTURE (SonotaCo, Japan).

Accurate astrometry of medium-sized field-of-view images was obtained for both stars and meteors by using the polynomic astrometric method published by Steyaert (1990). However, all-sky images have a more complex astrometric reduction to account for the image distortion of wide-eye lenses (Ceplecha 1987; Borovička, Spurný & Keclikova 1995). Both methods are currently implemented in our AMALTHEA software (Madiedo & Trigo-Rodríguez 2008). The new AMALTHEA software has wider applicability than our previous NETWORK software (Trigo-Rodríguez et al. 2004a). With the present angular resolution (~1 arcmin) of the camera systems, the equatorial coordinates of the meteors are computed with an astrometric accuracy of approximately $0\overset{\circ}{.}01$, which also determines the apparent and geocentric radiant of any meteor. Reconstruction of the atmospheric trajectory and calculation of the radiant were performed by using the method of intersecting planes developed by Ceplecha (1987). From the astrometric measurements of the shutter breaks along the trajectory and chopping rate, the velocity of the meteoroid was derived. The velocity measured for each shutter break was obtained along with the pre-atmospheric velocity V_∞ from the velocity measured in the earliest portion of each meteor trajectory (usually in the three or five breaks, when deceleration is small). Deceleration corrections have not been applied to the measured velocity. Finally, in order to determine orbital elements from our trajectory data we used the MORB program (Ceplecha, Spurny & Borovička 2000).

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

Continuous monitoring of meteor activity allows the determination of meteoroid spatial fluxes for minor showers (Trigo-Rodríguez et al. 2006a, 2008). By estimating the meteor magnitudes from the images, we obtained a magnitude distribution for the night of 2007 August 12–13. From the derived population index ($r = 1.9 \pm 0.4$, $N = 30$), we determined an incident flux Q ($m < 3.5$) $= 5 \times 10^{-4}$ that is equivalent to have six meteoroids of masses producing meteors brighter than magnitude +3.5 per km^2 using the procedure described by Bellot (1994). We computed the area subtended at the meteoric level by the video cameras operated from Cerro Negro (Seville) taking into account that they covered a field of 74° × 58°. Using these detectors, we estimated a visual (human) maximum ZHR $= 8 \pm 3$ for the 2007 August 12–13 night that is quite modest in comparison to other meteor showers. The meteor activity was over ZHR = 3 at least during three days, August 11–13, but the background of bright κ Cygnid meteors persisted for several nights around those dates. During such period, the population index was also below the characteristic value of the annual component of 2.2 (Jenniskens 1994). We noted that there is an almost total absence of faint meteors of this shower below the limiting video magnitude of +4. In fact, the visual observations performed by our team under ideal circumstances were unable to see κ Cygnid meteors in the range [+4, +6], which is consistent with the low population index that was determined. It appears that the activity of the shower is highly variable from year to year which is also indicated by the absence of κ Cygnid recorded activity during 2006 despite the fact that the SPMN coverage was similar in both 2006 and 2007 (Trigo-Rodríguez et al. 2008). The appearance of an outburst depends critically on the distance between the Earth and the nodal position of the densest part of the meteoroid stream. This distance is affected by the displacement of the Sun from the barycentre of the system, which is dominated by Jupiter and Saturn. This is known as the reflex motion of the Sun, and has been discussed in detail by Jenniskens (1997). This produces a roughly 12 yr periodic behaviour, but is significantly modified by the effects of Saturn.

Multiple-station detections of meteors allow the determination of accurate- trajectory and orbital data to be obtained. In 2007, κ Cygnid meteors were imaged from several SPMN stations and these are listed in Table 1. The radiant position, apparition time and velocities measured for the meteors are given in Table 2, along with the absolute magnitude (M_v) in the visual range, the height for beginning, maximum and terminal light (H_b, H_max, H_end), the geocentric radiant (α_g, δ_g) and the infinity, geocentric and heliocentric velocities (V_∞, V_g, V_h). The SPMN code reflects the day, month and year of observation. From these, the orbital elements for each meteoroid are given in Table 3. Note that only those events whose convergence angle between the stations and the meteor is larger than 20° have been considered. The observational uncertainties in trajectory data and orbital elements reported in Tables 2 and 3 are similar to those reported by small photographic camera networks (Betlem et al. 1998).

Fig. 2(a) is a plot of the sky in the neighbourhood of Cygnus that contains 90 per cent of all the measured meteors. Figs 2(b) and

Table 1. Stations of the SPMN involved in the 2007 observations described here. Acronyms for the different imaging systems are: AS (low-scan-rate CCD all-sky camera), and WFV (Wide field video cameras).

Station no.	Station (province)	Longitude	Latitude (N)	Alt. (m)	Imaging system
1	Seville (Seville)	05° 58′50″W	37°20′46″	28	WFV
2	Cerro Negro (Seville)	06°19′35″W	37°40′19″	470	WFV
3	El Arenosillo (Huelva)	07°00′00″W	36°55′00″	30	AS
4	Montsec, OAdM (Lleida)	00°43′46″E	42°03′05″	1570	AS
5	Montseny (Girona)	02°31′14″E	41°43′17″	300	AS

Table 2. Trajectory and radiant data for meteors observed in the 2007 outburst. Equinox (2000.0).

SPMN code	Stream	M_{v}	H_{b}	H_{max}	H_{e}	$\alpha_{\mathrm{g}}(^\circ)$	$\delta_{\mathrm{g}}(^\circ)$	V_∞	V_{g}	V_{h}
120807	κ Cygnid	0	96.0	–	82.3	289.5± 0.4	55.8± 0.3	26.8± 0.8	24.4	38.3
130807	κ Cygnid	−1	98.2	–	79.9	277.1± 0.3	43.0± 0.3	23.0± 0.6	20.3	39.6
130807b	κ Cygnid	0	104.5	–	88.9	281.8± 0.3	48.2± 0.3	25.3± 0.3	22.9	39.9
130807c	κ Cygnid	−1	98.0	–	76.1	284.4± 0.3	48.6± 0.4	26.0± 0.4	23.7	39.9
130807d	κ Cygnid	−3	97.1	74.0	70.5	287.1± 0.4	42.5± 0.5	24.2± 0.5	21.8	39.2
140807	κ Cygnid	−2	117.3	–	(101)	282.6± 0.4	49.8± 0.4	24.0± 0.4	21.2	38.5
160807	κ Cygnid	−9	110.8	84.6	72.2	283.1± 0.3	48.8± 0.3	24.3± 0.2	21.8	39.0
170807	κ Cygnid	−4	103.8	82.9	81.1	281.8± 0.2	50.2± 0.2	24.6± 0.4	22.0	39.3
230807	κ Cygnid	−8	111.3	76.0	75.8	285.2± 0.3	56.0± 0.3	26.4± 0.5	24.0	39.3
Average		–		–		283.6± 0.3	49.2± 0.3	25.0± 0.5	22.5	39.2

Table 3. Orbital elements for meteors imaged during the 2007κ Cygnid outburst. Equinox (2000.00).

SPMN code	q	$1/a$	e	i	ω	Ω
120807	0.9798± 0.0012	0.33± 0.05	0.68± 0.05	38.9± 1.0	203.3± 0.8	139.78271± 0.00003
130807	0.979± 0.003	0.20± 0.05	0.80± 0.05	28.4± 0.8	202.5± 1.0	139.80375± 0.00005
130807b	0.977± 0.001	0.184± 0.021	0.821± 0.020	33.5± 0.4	203.0± 0.3	139.87009± 0.00001
130807c	0.9712± 0.0013	0.181± 0.026	0.825± 0.026	34.8± 0.5	204.6± 0.4	139.88456± 0.00001
130807d	0.9492± 0.0021	0.24± 0.03	0.767± 0.029	30.9± 0.7	211.3± 0.5	139.95221± 0.00003
140807	0.980± 0.003	0.31± 0.03	0.697± 0.029	32.2± 0.5	202.9± 1.1	141.62435± 0.00002
160807	0.9777± 0.0010	0.256± 0.014	0.749± 0.014	32.4± 0.3	203.2± 0.3	142.77265± 0.00001
170807	0.9840± 0.0012	0.24± 0.03	0.766± 0.028	32.8± 0.5	200.7± 0.5	144.58016± 0.00001
230807	0.9892± 0.0012	0.24± 0.03	0.77± 0.03	36.9± 0.6	198.2± 0.6	150.30102± 0.00001
Average	0.9740± 0.0016	0.24± 0.03	0.76± 0.03	33.4± 0.6	203.3± 0.3	(142.06)

(c) show the same fireball (SPMN160807 'Isla Cristina') imaged from two SPMN stations dotted, respectively, of all-sky CCD and video imaging detectors. It is remarkable that the average computed radiant for all astrometrically reduced meteors was $\alpha = 291^\circ$ and $\delta = +52^\circ$. This value is consistent with the radiant derived for meteors recorded at double station (Table 2).

4 RESULTS: ORBITAL DATA, STRENGTH AND CHEMICAL COMPOSITION

4.1 Orbital data and tensile strength

There have been a number of attempts at deriving the mean orbital elements of the κ Cygnids, starting with Whipple (1954), who based his mean orbit on the orbits of only five meteors. He gave the elements (equinox B1950) as

$$q = 0.975,\ e = 0.757,\ i = 37.0,\ \Omega = 144.8,$$
$$\omega = 203.5 \text{ and } a = 4.01.$$

Lindblad (1995) concluded that there were several sub-streams within the complex. He gave the orbital elements (equinox B1950) of what he defined as the κ Cygnid sub-stream, based on the orbits of nine meteors, as

$$q = 0.980,\ e = 0.731,\ i = 36.8,\ \Omega = 144.9,$$
$$\omega = 200.5 \text{ and } a = 3.65.$$

As the number of observed meteor orbits increased, so the value of the mean orbit also changed. Jones et al. (2006), using a critical value of 0.2 in the Southworth and Hawkins criteria (a fairly large value), thus capturing all potential sub-streams or filaments, gave the mean orbital elements of 51 meteors as (equinox J2000)

$$q = 0.988,\ e = 0.702,\ i = 33.1,\ \Omega = 142.1,$$
$$\omega = 197.3 \text{ and } a = 3.32.$$

If, however, only the κ Cygnid sub-stream as identified by Lindblad is included, the mean orbit, now based on only 10 meteors, becomes

$$q = 0.981,\ e = 0.743,\ i = 36.8,\ \Omega = 145.8,$$
$$\omega = 201.3 \text{ and } a = 3.82.$$

Jones et al. (2006) also categorized the membership in terms of orbital behaviour. The vast majority (35 meteors) showed a sinusoidal evolutionary behaviour. The mean orbit of this set is

$$q = 0.996,\ e = 0.651,\ i = 33.0,\ \Omega = 141.6,$$
$$\omega = 193.6 \text{ and } a = 2.86.$$

It should be remarked that the selection of meteors for inclusion in the computation for the above orbit is the sinusoidal evolution. No account on the similarity of orbits is taken, other than their inclusion in the very wide net used by Jones et al. (2006). The sinusoidal behaviour is also a characteristic of orbital evolution that is strongly influenced by Jupiter but where close encounters do not take place. This would include many orbits in the general region of interest. The likelihood is thus that many of the meteors included in this orbit are not true κ Cygnid members, though most are.

Ignoring this orbit, there is some general consistency between all the remaining orbits, which is not surprising as many of the meteors are common to all the set, in particular the five meteors identified by Whipple (1954) are included in all the other data sets and can be ignored. The elements of the remaining orbits all lie in the following

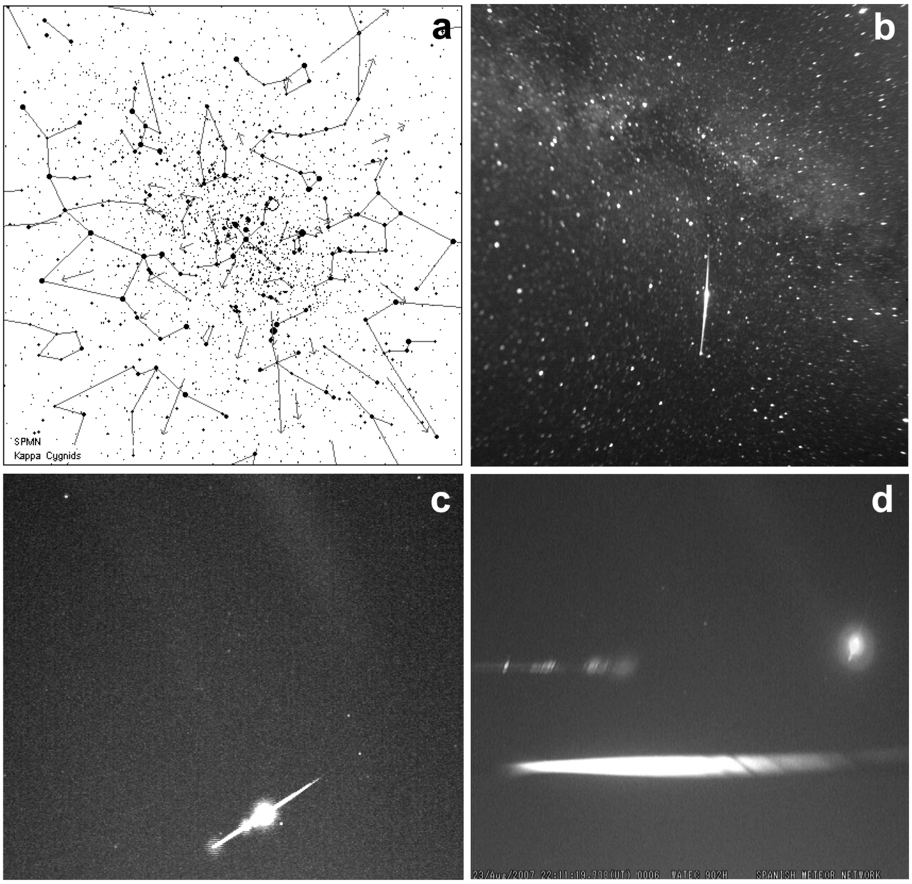

Figure 2. (a) Astrometric trajectories of the κ Cygnid meteors imaged by the SPMN during 2007 August. The averaged radiant is marked by a circle. (b) Section of all-sky CCD 30 seconds exposure image taken from station El Arenosillo (Huelva) of the -9 mag fireball SPMN160807 'Isla Cristina' that appeared on 2007 August 16 at $2^{\mathrm{h}}25^{\mathrm{m}}26.1 \pm 0.1$ s UTC. (c) Composite sequence of the same fireball as imaged by high-sensitivity video cameras from Sevilla. (d) Impressive ending flare produced by the -8 mag fireball SPMN230807. The spectrum of the flare appears on the left-hand side. Note that the bright Moon spectrum appears below it.

ranges:

$q = 0.980\text{–}0.988$, $e = 0.702\text{–}0.743$, $i = 33.1\text{–}36.8$,

$\Omega = 142.1\text{–}145.8$,

$\omega = 197.3\text{–}201.3$ and $a = 3.32\text{–}3.82$.

There was an outburst in 1993 and the mean elements for the meteors measured in this outburst (Betlem et al. 1998) are given in Table 4, also compared with the orbital elements derived here for the 2007 outburst and with the presumable linked Near Earth Objects (NEOs). The orbital data from these two outbursts are quite similar, and certainly close enough to suggest that these two outbursts are caused when the Earth passes through the same meteoroid stream or filament. The only question of interest is whether this filament is different from the stream that gives rise to the much weaker showers observed in years when an outburst is not observed. Of the orbital elements, q and e are very marginally different for the outburst, but are almost certainly not significant and the general conclusion must be that the meteors observed in the two outburst must belong to the κ Cygnid complex and that by including them in the data base, the mean orbit of this stream can be improved further. A further topic of interest is identifying the parent of the κ Cygnid stream.

Jones et al. (2006) found two asteroids 2001MG1 and 2004LA12 that matched the current orbital elements and evolutionary pattern of the minority, but none that matched the majority behaviour. This situation changed when Jenniskens & Vaubaillon (2008) identified 2008ED69 (not of course discovered in 2006) as matching this sinusoidal behaviour. The present-day orbit as given in MPEC-F11 is shown in Table 4 compared with the orbits of the two κ Cygnid outbursts. Though the match is reasonable, the orbit is far from identical to any of the κ Cygnids orbits. However, Jenniskens & Vaubaillon (2008) show that by AD 2340, the orbit of 2008ED69

Table 4. Averaged orbital elements for κ Cygnid meteors imaged during the two outbursts compared with the orbits of the presumable parent body remnants. Orbital elements of 2001MG1 and 2004LA12 were taken from NEODyS online data base, while 2008ED69 is taken from MPEC-F11. The orbital elements of 2008ED69 given in AD 2340 were taken from Jenniskens & Vaubaillon (2008).

Object	q	a	e	i	ω	Ω
1993 outburst	0.97	4.0	0.76	35.6	204.8	140.1
2007 outburst	0.97	4.0	0.76	33.4	203.3	142.06
2008ED69	0.722	2.90	0.751	36.3	172.5	145.0
2008ED69 by AD2340	0.97	2.9	0.67	39.4	186.8	145.9
2001MG1	0.893	2.5	0.64	28.4	218.3	142.48
2004LA12	0.633	2.51	0.748	39.4	199.4	159.25

would evolve to a quite different orbit (shown again in Table 4) that they claim would be very similar to the orbit of the κ Cygnids at that time, extrapolated from the integrations of Jones et al. (2006). Since there is a basic periodicity in all orbits in this region of about 2100 yr (see Section 5), this implies similarities also around AD 200, 1900 BC and 4100 BC. Table 4 also includes for comparison the orbits of 2001MG1 and 2004LA12.

In reference to the tensile strength, it is remarkable that about 60 per cent of the imaged κ Cygnid meteors exhibited a bright flare at its end. This is produced by the catastrophic fragmentation of the meteoroids when penetrating towards denser atmospheric regions. Trigo-Rodríguez & Llorca (2006) adopt a simple approach where the tensile (aerodynamic) strength of a given particle is estimated from the equation:

$$S = \rho_{\mathrm{atm}}\, v^2 \qquad (1)$$

given by Bronshten (1981), where ρ_{atm} is the atmospheric density at the height where the meteoroid breaks up and v is the velocity of the particle at this point. We computed S for those meteors in Table 2 that exhibited a catastrophic ending flare. Two fireballs (SPMN160807 and 170807) exhibited fracture at a very similar altitude, and for them we estimated $S = 4.2 \pm 0.6$ kPa. We note from Figs 2(b) and (c) that the first fragmentation was not catastrophic, so remaining material allowed the continuity of the fireball's luminous path. That fireball also ended exhibiting a bright flare. Another fireball event (SPMN130807d) probably involved a tougher particle because it penetrated deeper into the atmosphere than the other ones, but also end with a bright flare when a loading value of 18±2 kPa was achieved. In a similar way, the SPMN230807 'Trigueros' fireball exhibited a bright ending flare under a dynamic pressure of 15 ± 2 kPa.

4.2 Analysis of a $-8\,\kappa$ Cygnid spectrum

The spectrum of an extremely bright flare produced by the SPMN230807 bolide was obtained by our cameras operating with a diffraction grating. The composite image of the spectrum (adding all frames) is shown in Fig. 2(d).

The resolution is poor ($\sim$1.2 nm pixel^{-1}), but provides an insight into the nature of the particle. The lines of Na I-1 (centred at 518.4 nm), Mg I-2 (518.4 nm) and the Ca I-1 (422.7 nm) are the most prominent features in the spectrum. The line of Ca I appears to be blended with the Fe I-152 multiplet line, but the Ca contribution can be separated by taking into account the overall contribution of Fe. Spectra produced by very low geocentric velocity meteoroids have usually a weak second (high-temperature) component, but in the present spectrum is almost non-existent (Trigo-Rodríguez et al. 2003). In consequence, all lines identified in Fig. 3b belong to the main component, and this assumption allows us to obtain the relative abundances of the main rocky elements. We used the same procedure to analyse the spectrum as in Trigo-Rodríguez et al. (2003). The raw spectrum was background-subtracted and corrected for the sensitivity of the cameras in each wavelength. Fig. 3(a) shows the raw spectrum of the FN300806 fireball, while the calibrated one is shown as Fig. 3(b). Sensitivity was normalized to 400 nm where the chip efficiency was 35 per cent. In order to get the physical parameters in the meteor column we fitted the intensity of the Fe I lines, mainly using the different Fe multiplets distinguishable in Fig. 3(b). The resulting values for the averaged temperature and Fe I column density were 4200±100 K and 5×10^{15} cm^{-2}. Once these values are fixed, we modified the abundances of Ca, Mg and Na until the best fit was achieved. The measured abundance ratios referred to Fe were: Mg/Fe = 0.9± 0.1, Na/Fe = 0.06 ± 0.01

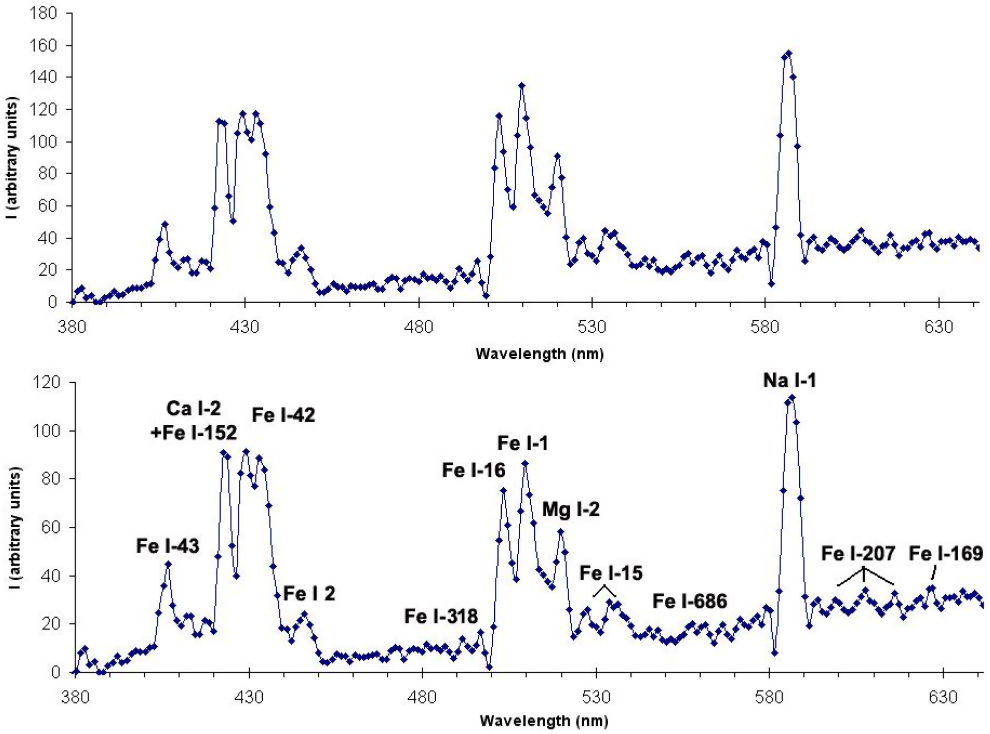

Figure 3. (a) Raw spectrum of the SPMN230807 bolide as directly scanned from Fig. 1(d). (b) Same spectrum, once calibrated for the camera's sensitivity. The overall background was subtracted for determining the relative abundances of the main-forming chemical elements. The main lines discussed in the text, and their multiplet number, are indicated.

and Ca/Fe = $(4 \pm 2) \times 10^{-2}$. Such abundance ratios are close to the chondritic abundance, e.g. CI chondrites have, respectively, 0.9, 0.05 and 6×10^{-2} (Rietmeijer 2000). The lower Ca/Fe value than chondritic in SPMN230807 is explicable because Ca is a refractory element that is not completely vaporized in the ablation of low-velocity meteoroids (Trigo-Rodríguez et al. 2003).

5 DISCUSSION: ON THE NATURE OF THE κ CYGNID STREAM'S PROGENITOR

As we have shown in the previous section, the fragile properties of the κ Cygnid meteoroids, their chemical composition and their dynamic link with 2008ED69 indicate that this complex of bodies provide a valuable opportunity of studying the catastrophic disruption of a cometary body while was populating the NEO region. The chemical composition of the meteoroid here studied supports a chondritic nature for the progenitor body, and consequently also for 2008ED69. Future reflectance spectroscopy studies of this body will reveal its nature, but we think its surface would be similar to a dark C- or D-type asteroid. Supporting this point is the evidence on the extraordinarily fragile structure for the κ Cygnid meteoroids. The unique nature of the κ Cygnid ending flares suggests that these particles are formed by weak aggregates that are easily disrupted as tiny dust. The particle, once disrupted, exposes fine-grained materials to the thermal front, and it produces the bright flares observed in many of these fireballs. Most of these large meteoroids producing fireballs disrupt at aerodynamic pressures over 4 kPa. It is remarkable that these results are consistent with those of Verniani (1969) who pointed out that meteoroids following typical cometary orbits fragment when the pressure exceeds 2×10^3 Pa. In any case, some particles of similar size are significantly tougher, and are able to reach deeper atmospheric layers. The asteroidal-like remnants would be tougher parts of the progenitor body, dotted of higher strength than the progenitor and consequently preventing their disruption. The nature and physical properties of those NEOs would provide new clues on the possibility that comets were composed of tougher parts, capable of producing meteorites.

The idea that dormant comets exist within in the NEO population is not new. Several decades ago, Öpik (1963) and Wetherill (1988) suggested that dormant cometary nuclei should be present in the NEO region. What is new is the idea that the original comet experiences significant disruption or fragmentation, releasing large quantities of meteoroids in the process and leaving one or more NEOs as a lasting evidence of the existence of the progenitor (Jenniskens & Vaubaillon 2007; Babadzhanov, Williams & Kokhirova 2008a,b; Jenniskens & Vaubaillon 2008).

It is interesting to speculate as to whether the outbursts of meteor activity, in particular the last two, namely those observed in 1993 and 2007, can shed further light on the process of stream formation through the fragmentation or partial disintegration of the parent nucleus. The values a for all the orbits lie in the range 3.32 to 3.82, and the orbital period must lie in the range of 6 to 7.5 yr. The outbursts seen in 1993 and 2007 are 14 years apart and so cannot be caused by the Earth passing through the same set of very young meteoroids which have not yet had time to spread away from the initial formation point on two successive passages through the node. Of course, it would be possible for the outburst in 2007 to be caused by meteors that have completed two more orbits than those observed in 1993, thus requiring an orbital period of 7 years. One object to this solution is that no outburst was observed in 2000. A more serious objection to a very young age is that a comet that fragmented within the last few decades would surely have been observed. The only alternative, since the outburst were similar, is that the meteoroids have spread all around the orbit and an outburst is seen whenever the Earth-stream geometry is such that the Earth passes through the central part of the stream. Based on this assumption, we can derive a minimum age for the meteoroids in the outburst.

Now, the rate of spreading of meteoroids about the orbit has been discussed in many papers (e.g. Williams 1992, 2002) and gives the number of completed orbits required to do this as

$$N = \frac{V(1-e)}{3v(1+e)}, \tag{2}$$

where V is the perihelion speed of the comet, v the component of the ejection velocity of the meteoroids along the direction of motion and e the eccentricity. For the κ Cygnids, e is about 0.72, while the perihelion speed is about 37 km s^{-1}. Hence, $N = 2000/v$, with v measured in m s^{-1}.

This quantifies the obvious, namely that the time taken by meteoroids to spread about the orbit is inversely proportional the component of the ejection velocity along the orbit of the parent body. Determining the value of v is more problematic. There are three general ways in which this has been attempted and are summarized in Williams (2001). The first method deduce this speed from the observed characteristics of the stream at the present time. In this way, Arlt et al. (1999) found a value of 50 m s^{-1} for the Leonids while Rendtel & Brown (1997) found a value of 60 m s^{-1} for the Perseids. Ma & Williams (2001) found slightly larger values, 70 m s^{-1}, for the Leonids and 80 m s^{-1}, for the Perseids. Arter & Williams (2002) concluded that the ejection velocity for the April Lyrids had to be in the range 25–150 m s^{-1}. The second method involves modelling the ejection process and numerically integrating the motion of the ejected meteoroids and comparing the theoretical outcome with the observed outcome. Göckel & Jehn (2000) concluded that a speed of about 40 m s^{-1} gave the best fit, while Asher (1999) found that 25 m s^{-1} gave the best results for the Leonids. For the κ Cygnids, Jenniskens & Vaubaillon (2008) concluded that a value of about 20 m s^{-1} was appropriate. The final method involves deducing the velocity from observations of dust trails (Sykes & Walker 1992), where values of less than 10 m s^{-1} were found. Thus, a significant range of values for the ejection speed have been proposed, roughly from 10 to 70 m s^{-1}. It should be noted that the first method tends to give an upper limit to the values while the third a lower limit. Bearing this in mind, a value of the order of 20 m s^{-1} would appear reasonable. With such a value, the number of orbits required for meteoroids to spread all around the parent orbit is 100. With a period of 6–8 years, the κ Cygnids must be at least 600 years old.

Given this minimum age, we can enquire whether we can deduce anything more. Williams & Jones 2007, (2007) investigated whether or not the mean stream was a meaningful tool in investigating the behaviour of a meteoroid stream, bearing in mind the dispersion that takes place between the evolution of individual meteoroids. They concluded that for most streams, it was a good approximation. By chance, one of the streams they used to test this hypothesis was the κ Cygnids. Their integrations of this stream show the periodic cycle much clearer than Jones et al. (2006). The period of the cyclic variation, at slightly over 2000 years, is quite clear. Based on the assumption that any fragmentation of the parent is likely to have taken place when the perihelion distance is smallest, these plots suggest that the stream formed at about AD 300, 1800 BC or 3700 BC and by extrapolation 3900 BC. These dates are derived from different considerations to those derived by Jenniskens &

Vaubaillon (2008), but agree exceedingly well, and support their contention that the stream formed at one of these dates.

A further possibility is that the filament could be trapped in a resonance with Jupiter, in which case arguments based on orbital evolution are not valid, the evolution is highly constrained. The initial argument for a minimum age of at least 600 yr is still valid as spreading about the orbit is still required. It would be highly unusual, however, for the Earth to pass through the same resonant-capture trail in an interval of 14 years.

6 CONCLUSIONS

Joint operation of the low-scan-rate, all-sky CCD cameras applied to meteor monitoring (Trigo-Rodríguez et al. 2004b) together with video stations allows a wide coverage of meteor activity (Trigo-Rodríguez et al. 2008), even for meteoroid streams producing relatively weak meteoric flux. Detection of the κ Cygnid outburst in 2007 August allowed the determination of nine accurate orbits, and one fireball spectrum during a wide monitoring of August activity. The main conclusions of this paper are as follows.

(a) Due to the low spatial density of the κ Cygnid meteoroid stream (at least of the cross-section intercepting the Earth), a continuous monitoring program is required for detecting any weak meteor outbursts. Only such a program is able to provide a reasonable number of orbits to allow dynamic studies of these rare-occurring outbursts.

(b) From the orbital elements of the nine members of the 2007 κ Cygnid outburst, we conclude that all of them, and the meteors seen in the 1993 outburst, are essentially part of the same κ Cygnid stream complex.

(c) The analysis of the orbital evolution confirms the hypothesis of Jenniskens & Vaubaillon (2008) that the stream is old. We conclude that the stream formed around AD 300, 1800 BC or 3900 BC. By our considerations, we cannot narrow it down further, though Jenniskens & Vaubaillon (2008) ruled out the later date.

(d) The κ Cygnid spectrum obtained in the present work has allowed obtaining the relative abundances of the main rocky elements. The results indicate that the main flare of that bolide reached 4200 ± 100 K, and was produced by quick ablation of the tiny particles released during catastrophic fragmentation. The relative abundances suggest a chondritic nature of the meteoroid-forming materials. All these clues also support a cometary nature of the progenitor body.

Finally, we wish to encourage the minor bodies community to obtain more reflectance spectra of NEO 2008ED69 as a surviving fragment of the parent of this fascinating meteoroid stream. It would also be very beneficial if studies of the physical properties of other two probably linked bodies, 2001MG1 and 2004LA12, were also carried out.

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