Mon. Not. R. Astron. Soc. **394,** 569–576 (2009) doi:10.1111/j.1365-2966.2008.14363.x

Observations of a very bright fireball and its likely link with comet C/1919 Q2 Metcalf

Josep Mª Trigo-Rodríguez,[1,2]⋆ José M. Madiedo,[3,4] Iwan P. Williams,[5]
Alberto J. Castro-Tirado,[6] Jordi Llorca,[7] Stanislav Vítek[6] and Martin Jelínek[6]

[1]Institute of Space Sciences (CSIC), Campus UAB, Facultat de Ciències, Torre C-5, parells, 2ª planta, 08193 Bellaterra (Barcelona), Spain
[2]Institut d'Estudis Espacials de Catalunya, Ed. Nexus, Gran Capità 2-4, 08034 Barcelona, Spain
[3]Facultad de Ciencias Experimentales, Universidad de Huelva, Huelva, Spain
[4]CIECEM, Universidad de Huelva, Parque Dunar S/N, 21760 Almonte, Spain
[5]Astronomy Unit, Queen Mary, University of London, Mile End Rd, London E1 4NS
[6]Instituto de Astrofísica de Andalucía (IAA-CSIC), PO Box 3004, 18080 Granada, Spain
[7]Institut de Tècniques Energètiques, Universitat Politècnica de Catalunya, Diagonal 647, ed. ETSEIB, 08028 Barcelona, Spain

Accepted 2008 December 10. Received 2008 December 9; in original form 2008 November 7

ABSTRACT

A very bright fireball called Béjar (SPMN110708), with a maximum brightness of −18, was observed over much of Spain as well as parts of Portugal and France on 2008 July 11 at 21:17:39 UTC. Fortuitously, it flew over many of the instruments that are part of the Spanish Meteor and Fireball Network so that accurate measurements of its properties were recorded. We describe these observations and make deductions from them regarding the nature and origin of the body that gave rise to this fireball. The bolide first became visible at a height of 98.3 km, attained its maximum brightness at a height of 26 km and finished at a height of 21.5 km. These values are very much in line with other well-known fireballs producing meteorites. Standard calculations based on the meteoroids' ability to survive in the atmosphere suggest a strength for the remnant that survived to this height of about 14 MPa, similar to those for meteorite-dropping bolides. So far, this fireball looks typical and one might well expect to find meteorites on the ground in due course. The heliocentric orbit of the meteoroid determined from the observations had a perihelion essentially at the Earth's orbit and an eccentricity of 0.775, so that the orbit extends far beyond Jupiter, nearly reaching Saturn's heliocentric distance and is a typical orbit for a member of the Jupiter family of comets. This is unlike other bright fireballs, where aphelion is within the asteroidal belt and clearly points to an asteroidal origin. The orbit is also very similar to the mean orbit of the Omicron Draconid meteor shower, which is an additional pointer to this fireball being of cometary origin. If the parent was indeed a comet, this has implications for the internal structure of comets in that significant-sized non-icy inclusions must exist there. This is not surprising, but this is probably the first time that direct evidence has been found showing that this is the case. Further, such chunks can only be released through the catastrophic breakup of the nucleus. Remarkably, a candidate for the parent of the Omicron Draconid meteor shower is comet C/1919 Q2 (Metcalf) which suffered a catastrophic breakup in the early decades of the last century.

Key words: comets: individual: C/1919 Q2 Metcalf – meteors, meteoroids.

1 INTRODUCTION

A fireball is the term used to describe bright meteors. These days, it is customary to call anything with a zenithal magnitude greater than −3 a fireball. Daylight fireballs, with a magnitude brighter than about −5, are caused when an object of about a centimetre in size under a typical asteroidal encounter velocity of 15 km s^{-1} ablates. As with all populations in the Solar system, the number of meteoroids decreases with increasing size so that very bright fireballs are also infrequent. For example, for an effective monitored area of sky seen at a single location (roughly 1 million km^2), fireballs that are brighter than the Moon (magnitude −12 say) occur roughly annually (Halliday, Griffin & Blackwell 1996), while in 3 yr of running up to the end of 1967, one fireball of magnitude

⋆E-mail: trigo@ieec.uab.es

−18 was observed by the Prairie network (McCrosky & Ceplecha 1968). That magnitude is about 250 times brighter than the well-known meteorite-dropping fireballs of Pribram, Innisfree and Lost City, and represents impact events rarely recorded. In order that an orbit is obtained, it is necessary for the fireball to be observed from multiple stations and, until recently, such stations were few and far between. An example of a bright fireball not being measured is well illustrated by the recent event that took place over Sudan on 2008 October 7. A fireball was produced by the impact of an asteroid (2008 TC3, discovered by the University of Arizona Mt. Lemmon survey) with the Earth's atmosphere. This event was remarkable as it was the first time that an impacting body had been discovered before entry into the Earth's atmosphere. Despite accurate predictions for the location and timing of the fireball, no ground-based observations capable of allowing orbit determinations were obtained. Data on the first three fireballs with measured orbits that produced meteorite falls, Pribram, Innisfree and Lost City, were obtained by means of multistation photographic networks, but, until recently, orbit determination for the few bright fireballs measured was only achieved in casual videotapes (Brown et al. 1994, 2004; Borovička et al. 2003; Trigo-Rodríguez et al. 2006). Fireball networks are currently being set up that embrace new detection techniques such as video and CCD imaging that do allow an accurate heliocentric orbit to be determined and thus give an insight into the likely parentage of these fireballs. As the brighter fireballs give rise to meteorites reaching the Earth, this also gives a clue to the possible source region of meteorites (Nesvorný et al. 2002; Porubčan, Williams & Kornoš 2004; Trigo-Rodríguez et al. 2007). So far, accurate orbits for only nine meteorite-dropping fireballs have been obtained, including the three early ones, Pribram, Innisfree and Lost City (for a review, see Trigo-Rodríguez et al. 2006), though Wylie (1948) attempted to obtain orbits for three meteorite falls, Tilden, Paragould and Archie, based on eyewitness accounts. All of them had their aphelia in the main asteroid belt. While it is undoubtedly true that most meteorites originate from asteroids, there is currently a consensus that believes that all meteorites present in museum collections, except for those coming from the Moon or Mars, originate from asteroids despite the fact there is no information regarding the orbit of most of them. Here, we report on the observation of a very bright fireball that appeared on Friday 2008 July 11 at 21:17:38.9±0.1 s UTC over central Spain. Observations of this allowed the Spanish Meteor and Fireball Network to obtain reliable measurements of its properties. We also discuss the implications of these derived properties and discuss its origin. This paper consists of three sections. Section 2 explains the instruments and techniques used for obtaining the trajectories, and orbits of the imaged meteors and the fireball. Section 3 discusses the peculiar properties of the meteoroid progenitor of the SPMN110708 bolide, introducing the similitude of its orbit with the Omicron Draconid stream, and finally deriving the main implications that the cometary origin of this meteoroid would have in our understanding of meteorites currently derived from comets. Section 4 includes the main conclusions of the present work.

2 OBSERVATIONS AND DATA REDUCTION

The Spanish Meteor and Fireball Network continuously monitors the sky for fireballs (Trigo-Rodríguez et al. 2004a). As part of this routine monitoring, unexpected meteor activity radiating from the constellation of Draco was detected on the night of 2008 July 3–4 when three bright meteors were measured and their orbits obtained. More meteors were observed emanating from this radiant, but unfortunately they were not recorded from double stations and so no orbit could be derived. We will discuss the details later, but these three meteors belong to the Omicron Draconid meteor shower. The principal topic of this paper took place one week later. On 2008 July 11, at 21:17:38.9s±0.1 s UTC a very bright fireball (SPMN110708) appeared over central Spain, and was also widely observed from Portugal, and marginally from the South of France. By chance, a professional photographer obtained an amazing image of this fireball with a 15-s exposure. This casual picture was taken from Torrelodones (Madrid). Fortunately, the event was also recorded by three video cameras of our fireball network located in Andalusia (details of the observing locations are given in Table 1). The reconstructed trajectory (Table 2) shows that this fireball passed over the Béjar region in the south of Salamanca province, from which the event has been named. Its luminous trajectory started at an altitude of 98.3 km, about 1.6 km east of Monterrubio de la Sierra (Salamanca), and terminated at an altitude of about 22 km, about 2.5 km south-east of Sotoserrano (Salamanca, Spain). The angle of the atmospheric trajectory to the Earth's surface was 59°.2. There were four consecutive flares observed at heights of 40.5, 38.2, 33.2 and 26.8 km. These were probably caused by successive fragmentations of the incoming meteoroid. The last flare was the brightest, reaching an absolute magnitude of roughly −18. This produced an unforgettable spectacle for the eyewitnesses who saw the countryside illuminated as if it were broad daylight (Fig. 1). All witnesses reported a green colour for the flares, and most of them also mentioned audible thunder and successive explosions that were heard at a distance of more than 200 km away. The last flare was the brightest, reaching an absolute magnitude of −18 ± 1 (see the magnificence of that flare in Fig. 2).

Observations of the Béjar superbolide were made by using high-sensitivity 1/2 arcsec black and white CCD video cameras (Watec, Japan) and 1/3 arcmin progressive-scan CMOS sensors attached to modified wide-field lenses covering a 120° × 80° field of view. The three additional Omicron Draconids, mentioned earlier, were also recorded using the above-mentioned Watec cameras and the low-scan-rate all-sky CCD cameras. Coordinate measurements on the images were obtained for comparison stars and meteors by using our recently implemented AMALTHEA software package (Trigo-Rodríguez et al. 2007). The astrometry was performed using our NETWORK software (Trigo-Rodríguez et al. 2004b), which computes the equatorial coordinates and determines the apparent and geocentric radiant. From the sequential measurements of the video frames and the trajectory length, the velocity of the meteoroids along the

Table 1. Location of the stations of the Spanish Meteor and Fireball Network collecting 2007 and 2008 data presented in this paper. The location of the casual picture is also listed as #4.

#	Station (province, country)	Longitude (W)	Latitude (N)	Altitude (m)
1	Sevilla (Sevilla, Spain)	05°58′50″	37°20′46″	28
2	La Mayora (Málaga, Spain)	04°02′40″	36°45′35″	60
3	El Arenosillo (Huelva, Spain)	07°00′00″	36°55′00″ N	30
4	Torrelodones (Madrid, Spain)	03°53′04″	40°35′25″	874

Table 2. Basic trajectory and orbital data for the SPMN110708 'Béjar' fireball. Errors are standard deviations propagated from the astrometric uncertainty.

SPMN110708 'BÉJAR' 2008 July 11, T= 21:17:38.9 UTC (beginning time)			
Atmospheric trajectory data			
	Beginning	Max. light	Terminal
Velocity (km s^{-1})	29.6 ± 0.3	24.7 ± 0.5	(8 ± 2)
Height (km)	98.3 ± 0.7	26.9 ± 0.5	21.5 ± 0.5
Longitude (°W)	5.674 ± 0.002	5.974 ± 0.001	5.996 ± 0.005
Latitude (°N)	40.751 ± 0.002	40.446 ± 0.001	40.424 ± 0.005
Absolute magnitude	−5 ± 1	−18 ± 1	−10 ± 1
Total length (km)		83.1 ± 0.1	
Slope (°)		56.9 ± 0.1	
Duration (s)		2.8 s (video-imaged part)	
SPMN stations:		El Arenosillo, La Mayora, and Sevilla (+ casual from Torrelodones)	
Radiant data (J2000.0)			
	Observed	Geocentric	Heliocentric
Right ascension (°)	280.06 ± 0.3	277.5 ± 0.3	–
Declination (°)	60.8 ± 0.3	62.7 ± 0.3	–
Ecliptical longitude (°)	–	–	204.3 ± 0.4
Ecliptical latitude (°)	–	–	43.8 ± 0.4
Initial velocity (km s^{-1})	29.6 ± 0.3	27.3 ± 0.3	39.4 ± 0.3
Orbital data (J2000.0)			
a (au)	4.5 ± 0.4	ω(°)	187.4 ± 0.6
e	0.775 ± 0.021	Ω(°)	109.80489 ± 0.00001
q (au)	1.0128 ± 0.0006	i (°)	43.8 ± 0.4
Q (au)	8.0 ± 0.9		

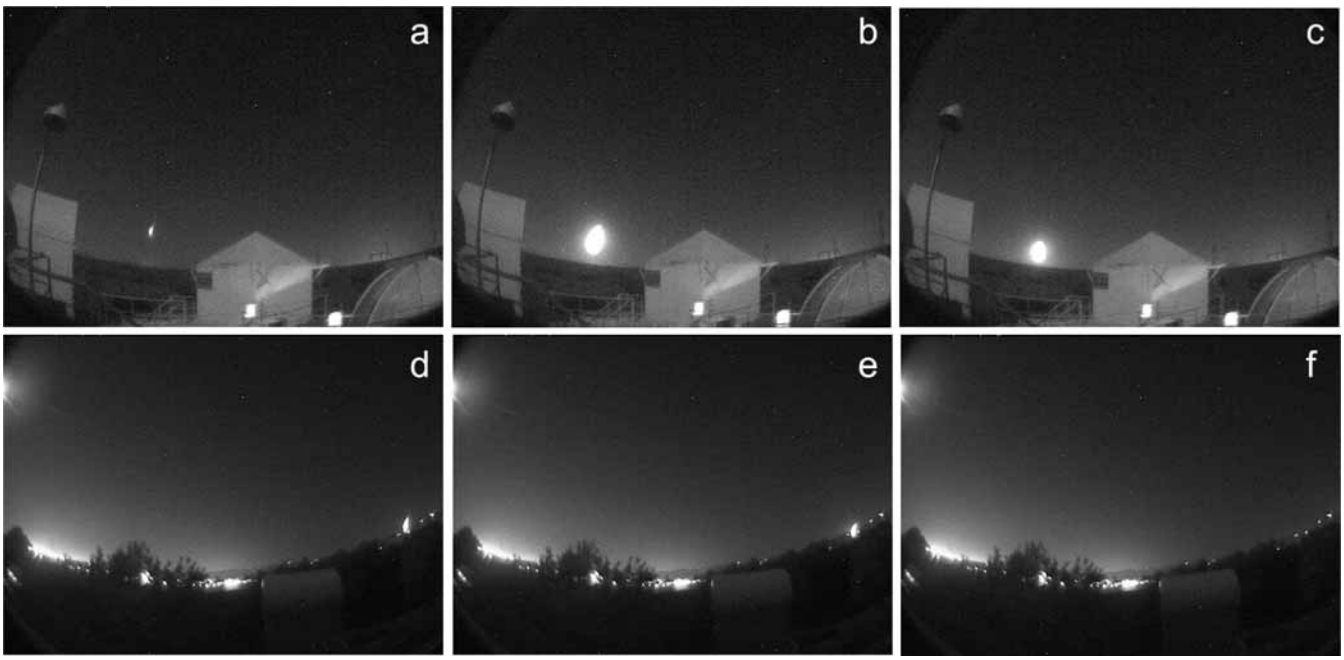

Figure 1. Composite sequences of 1-s images recorded from the more distant video stations. From the BOOTES-1/ESAt-INTA El Arenosillo astronomical station (images: a, b and c), the bolide was recorded at 300 km of distance, and from the BOOTES-2/EELM-CSIC La Mayora astronomical station (images d, e and f), it was observed at 450 km of distance. The presence of stars allowed the astrometric calibration of the images.

path was obtained. The pre-atmospheric velocity V_∞ was found from the velocity measured from those video frames containing the earliest parts of the meteor trajectories. In order to determine the orbital elements from the radiant, trajectory and velocity data, we used the MORB program of Ceplecha, Spurný & Borovička (2000).

Meteoroid masses were computed using a dynamic approach described elsewhere (Ceplecha 1988; Halliday et al. 1996; Ceplecha et al. 1998). The initial and final masses for the fireball were obtained from the derived value of the deceleration of the meteoroid in the atmosphere, considering a value of 1.1 for the drag-coefficient and

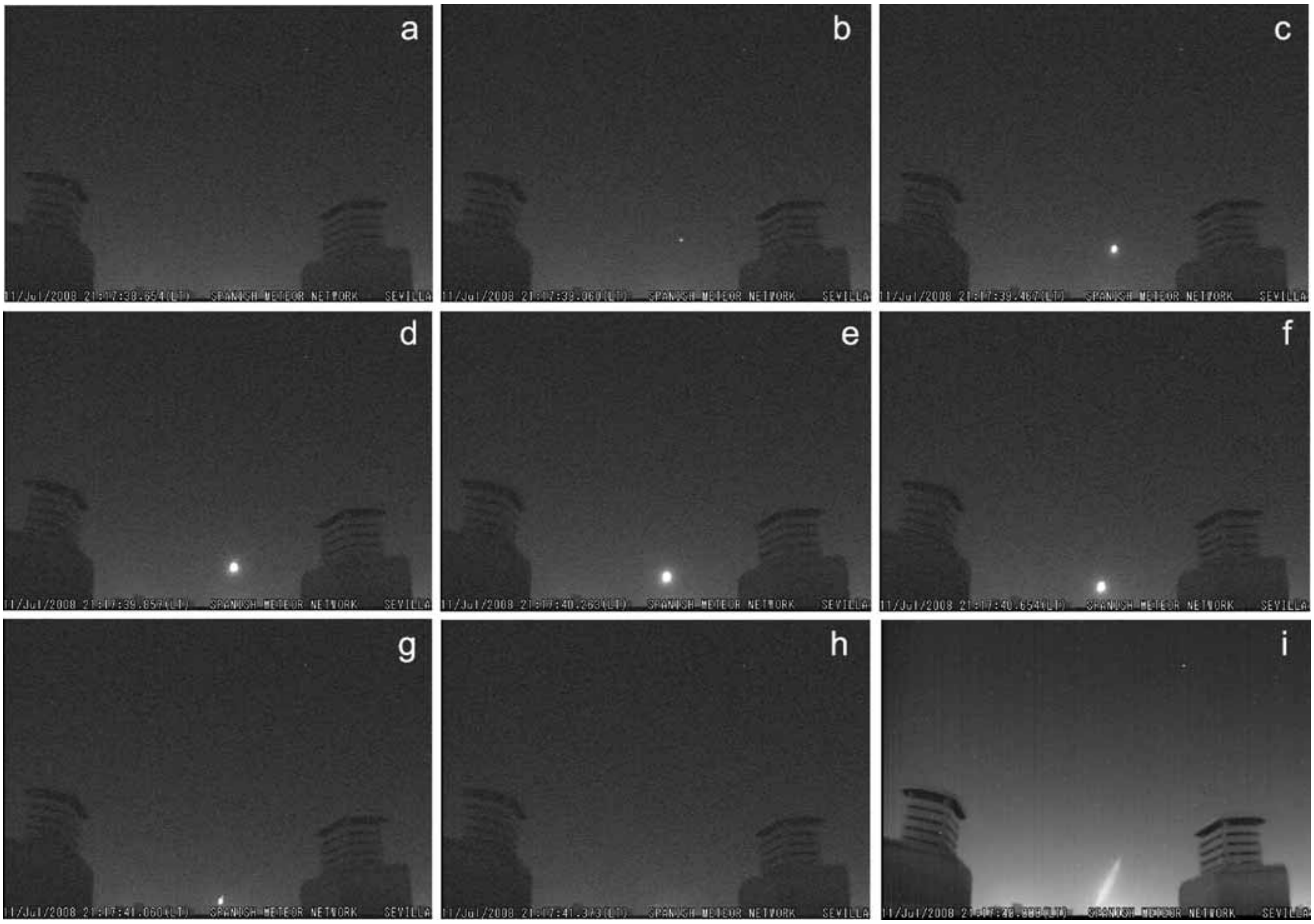

Figure 2. The evolution of the Béjar bolide as seen from the Sevilla video camera. For simplicity, we show the frames separated 0.4 s (images a to h). The image labelled i is the composite of all frames after background reduction.

assuming a meteoroid density of 2200 kg m^{-3}, a value that takes into account the probable chondritic nature of the meteoroid.

3 RESULTS AND DISCUSSION

From the determined value of the deceleration, the estimated mass of the Béjar meteoroid entering into the atmosphere was of about 1.8 $\pm$ 0.5 metric tons, with a diameter of about 1 m. Meteoroids typically explode when the strength of the meteoritic fragments is similar to the aerodynamic loading suffered during atmospheric passage (Ceplecha et al. 1993). Most meteoroids are of cometary origin, and catastrophic disruption is regularly observed in the last stages of ablation, when the aerodynamic loading strength reaches a value of 10 kPa (Trigo-Rodríguez & Llorca 2006, 2007). This is because cometary particles have fluffy structures composed of tiny mineral grains weakly bound together (Brownlee et al. 2006; Hörz et al. 2006). Most visible meteors do this at a typical height of about 100 km or more (e.g. Elford, Steel & Taylor 1997). This meteoroid displayed unexpected high strength as shown by the pattern of successive fragmentation, each producing a bright flare, but obviously leaving a surviving fragment until the next fragmentation. This is well exemplified in Fig. 3. The presence of stars in this casual image allowed its astrometric calibration, together with the determination of the exact height of the experienced flares. The recorded heights of each outburst were 40.5, 38.2, 33.2 and 26.8 km. We note that even the first is well below normal meteor ablation height. The aerodynamic pressures experienced by meteoroid-producing flares at these given heights imply material strengths of 2.3, 3.2, 6.6 and 14 MPa, respectively. Those are loading pressure values about three orders of magnitude higher than those expected for the survival of cometary materials.

3.1 The heliocentric orbit of the meteoroid that caused the Béjar bolide

The heliocentric orbit of the Béjar bolide was computed from the time of the fireball. Its initial velocity and the position of its radiant are given in Table 2 along with the derived orbital elements. Of particular interest are the date, July 11, the perihelion distance, 1.01 au, the inclination, 43$.^{\circ}$8, the eccentricity, 0.775, and the semi-major axis at 4.5 au. From these, the period at 9.5 yr and aphelion distance at 8 au can be deduced. This orbit is unlike near-Earth asteroid orbits, and indeed those of other fireballs, where aphelion is within the main asteroid belt that we have mentioned, but is typical of Jupiter family comet orbits (see Snodgrass, Lowry & Fitzsimmons 2008). Jupiter family comets probably originate in the trans-Neptunian region (Levison & Duncan 1997) and have been recently suggested as a source of meteorites reaching the Earth (Gounelle et al. 2008). This raises the possibility that the original bolide was associated with a comet. Additional support for

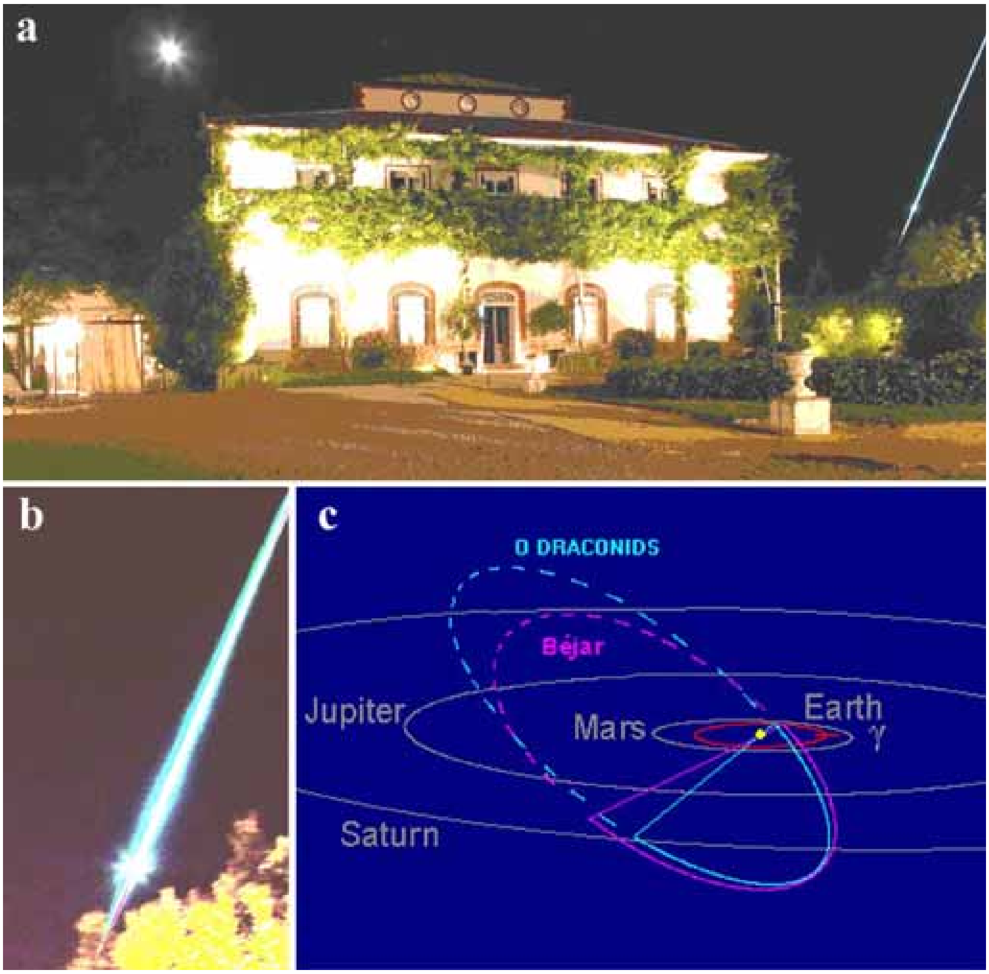

Figure 3. The Béjar bolide as photographed from Torrelodones (Madrid). (a) Full image where the Moon appears on the left, while the fireball appears in the right corner. (b) Magnified view of the fireball, intensifying the bolide contrast to better see the flares. (c) The orbit of the Béjar bolide (SPMN110708) compared with the mean orbit of the Omicron Draconids obtained in this work. The picture of the bolide is courtesy of Javier Pérez Vallejo.

this comes from the similarity of the orbit to that of the Omicron Draconid meteor shower. This meteor shower is not a particularly well-known shower and so it is useful to digress slightly to describe it, especially as the three other meteors measured during the same interval are probable members of this stream.

3.2 The Omicron Draconid meteor shower

Meteor activity with a radiant close to the star Omicron Draco was first identified in the nineteenth century by Denning (1879). The activity was, however, modest with a Zenithal Hourly Rate (ZHR) of only 10–12. Denning (1929) also reported observations in 1929 but in neither case was an orbit given, only a radiant position (RA $\sim 271^\circ$, Dec. $\sim 60^\circ$). However, for a considerable time after Denning's observations, no records of any activity exist. Whether this is due to a lack of observers at the pertinent time (early July and thus close to the longest day and also close to the activity period of the delta Aquarids and observers may have preferred to study those) or an intrinsic lack of activity from the Omicron Draconids is not clear. The next record appears to be by Cook et al. (1973), reporting on the work of the Harvard Meteor Project in the 1950s. In this paper, they also suggested that the formation of the stream was associated with the disintegration of the nucleus of comet C/1919 Q2 Metcalf. Unfortunately, they assumed the default parabolic orbit for both, but gave a perihelion distance of 1.01 au and an inclination of 43°. The stream is included in the working list of meteor showers published by Cook (1973) with the same orbital parameters as given above. The confirmation of the existence of the shower arrived with the 1968–69 Radio Meteor project. Based on the records obtained here, Sekanina (1976) determined a proper set of orbital elements, with a perihelion distance of 1.001 au, inclination of $46\overset{\circ}{.}2$ and eccentricity of 0.768. Since then, other observations have confirmed the existence of the stream, for example on 1987 July 4, during a visual observation performed by seven members of the Valencia Astronomical Association, an outburst of about 20 meteors h^{-1} was reported from three different locations (Trigo-Rodríguez 1989). On 1996 July 15–16, an outburst was also noted by Dutch meteor observers (Terentjeva 2003). However, good orbits were not obtained since Sekanina's work.

It is important to remark that the Béjar bolide was probably not alone: four other superbolides were detected during 2008 on July 8, 10, 11 and 12 at other locations around the globe by DoD/DoE US satellites (Revelle, personal communication). The meteor activity of the Omicron Draconid shower was mainly recorded on the night of 2008 July 3–4, with an hourly rate of about 10 meteors h^{-1}

Table 3. *o* Draconids meteors imaged during 2008 July. Magnitude, beginning and ending height, geocentric radiant and velocity (at infinity, geocentric and heliocentric). Equinox (2000.0).

SPMN Code	M_v	H_b	H_{max}	H_e	$\alpha_g(^\circ)$	$\delta_g(^\circ)$	V_∞	V_g	V_h
030708	0	95.1	–	81.4	278.9 ± 0.7	58.1 ± 0.7	31.0 ± 0.3	28.8	40.0
030708b	0	94.3	–	79.2	278.6 ± 0.5	58.9 ± 0.5	30.3 ± 0.4	28.1	39.6
040708	−1	90.7	–	82.1	274.0 ± 0.8	56.6 ± 0.8	29.1 ± 0.5	27.0	39.9

Table 4. Orbital elements for *o* Draconids meteors imaged during the 2008 campaign. Equinox (2000.00).

SPMN Code	q	$1/a$	e	i	ω	Ω
030708	1.0071 ± 0.0016	0.163 ± 0.029	0.835 ± 0.029	45.7 ± 0.5	191.7 ± 0.9	102.20600 ± 0.00002
030708b	1.0005 ± 0.0012	0.198 ± 0.032	0.801 ± 0.021	44.8 ± 0.4	192.9 ± 0.7	102.24819 ± 0.00001
040708	1.0007 ± 0.0024	0.177 ± 0.035	0.823 ± 0.034	45.3 ± 0.6	195.2 ± 1.2	102.39773 ± 0.00003
Average	*1.004*	*0.179*	*0.819*	*44.3*	*193.3*	*102.284*
Metcalf (1919V)	1.115	–	1.0	46.4	185.7	121.4

peaking on solar longitude 102°.299. Three double-station meteors were recorded on that night allowing the determination of their atmospheric trajectories and orbits (Tables 3 and 4). The mean orbit for these gives $q = 1.004$, $i = 45°.5$ and $e = 0.829$. These are actually very close, and this together with the date and radiant position means that we are confident that these three meteors belong to the Omicron Draconid stream. Taking a straight mean of Sekanina's orbit and this orbit produces the mean orbit for the Omicron Draconids of $q = 1.0025$, $i = 45°.6$ and $e = 0.789$.

The question is whether the bright fireball also belongs to this shower. The positions of the radiant are in agreement, and the superbolide is within the accepted date range for the Omicron Draconids. The impact speed is also virtually identical at 29.6 and 30 km s^{-1}. More importantly, the orbital elements are in excellent agreement as can be seen from the tables. With these values, the aphelion distance Q is about 8.0 au (close enough to Saturn to experience some perturbations). The distances of the two nodes are one near the Earth and one about 8 au from the Earth. As is obvious from ω, the nodes are close to perihelion and aphelion, hence one node is also moderately close to Saturn. With the same values of q and e, the semimajor axis a lies between 4.5 and 5 au giving the stream an orbital period of between about 9.5 and 11 yr, though this should not be treated as too exact a figure. It is interesting that recorded observations of the Omicron Draconids also show roughly this periodicity, with observations of activity in 1889, 1929, 1956, 1968, 1987, 1996 and 2007. An interesting topic for future work is if the occurrence of the meteors a week earlier than the Béjar bolide would be the consequence of mass segregation within the C/Metcalf meteoroid stream.

3.3 The parent of the stream: on the nature and diversity of cometary fireballs

Both the orbit and the similarity of this orbit to the Omicron Draconid meteor shower strongly suggest that the parent body is a comet. However, most work on the ejection of meteoroids from comets (e.g. Ma, Williams & Chen 2002; Williams 2004) shows that it is impossible for the normal outgassing process to eject meteoroids with dimension of the order of 1 m. Hence, if the Béjar fireball originated from a comet, some other release mechanism is called for. Recently, a number of authors (Jenniskens 2004; Williams et al. 2004; Jenniskens & Vaubaillon 2008) have suggested that the fragmentation of a comet nucleus is responsible for the formation of many streams. C/1919 Q2 Metcalf did indeed fragment and did have an orbit that matches that of the stream. However, it did fragment after the first recorded sighting of the Omicron Draconids, if Denning is to be believed. There are three possibilities: (i) Denning did not really observe the stream in 1879, but only a fortuitous grouping of sporadic meteors; (ii) Denning observed a stream formed by the normal outgassing process from comet Metcalf before it split; and (iii) comet Metcalf is not the parent of the stream. If we disregard the first Denning observation and assume a split of comet Metcalf in 1919, then the remaining observations do coincide with the rough period we suggest. There is no real way of distinguishing between these, and in some respects it is irrelevant, the case is made that the superbolide is related to a meteor stream and that a cometary origin through disintegration of the nucleus is the most likely explanation. Identifying the disintegrated comet would be useful, but not essential.

If the Béjar meteoroid, as we have demonstrated above, had a cometary origin, it has important implications for the inner structure of the interior of cometary nuclei. Among the models developed to explain some of the features revealed in 1P/Halley images taken during Giotto and Vega spacecraft flybys is this by Gombosi & Houpis (1986). This model is usually known as the icy-glue model and introduces the idea of refractory boulders with similar compositions to carbonaceous chondrites, cemented by highly porous ice-rich materials that would act as a 'glue'. The model has not received wide support due to the apparent 'lack' of evidence for a population of 'refractory boulders' from disrupted comets (Weissman & Lowry 2008). We think that the observations of bright bolides can provide useful evidence in this regard. Many meteoroid streams crossing the orbit of the Earth produce bright fireballs (typically up to the full-Moon brightness), but such meteoroids are much smaller than the tens of metres boulders observed during disruption of comet C/1999 S4 (LINEAR) (see e.g. Weaver et al. 2001). In that case, a few weeks after the splitting event these boulders could not be detected, so they disappeared, either by further fragmentation or by becoming undetectable due to exhaustion of cometary activity. This second option would produce metre-sized remnants like this one represented by Béjar. Consequently, we contend that most phenomena can be explained using two widely accepted arguments.

(1) Many meteoroid streams are produced by sublimation of cometary nuclei near perihelion that release particles by gas drag from active regions as predicted by Whipple (1951). Even when the process we describe under (2) below is the dominant source of meteoroids, some meteoroids released by the above process will be present.

(2) Some meteoroid streams are formed by a different process, namely the near total destruction of the nucleus. The best known example is comet 2D/ Biela and the Andromedid meteor shower (Babadzhanov et al. 1991). This was also shown to be the case for the Quadrantids (see Jenniskens 2004; Williams et al. 2004), but Jenniskens & Vaubaillon (2008) give a list of eight other streams, including the κ Cygnids with this origin. It is important to distinguish between the two processes. The first relies on gas drag to remove particles, and this, as we said earlier, imposes a limit on the size of meteoroids. Meteoroids are also ejected into the stream at every perihelion passage. In the second mechanism, much larger bodies, originally in the deep interior of the nucleus, are released and these can be of substantial size. For example, in the case of the Quadrantids, one of the fragments is recognized as NEO 2003 EH1 with a diameter of about 2 km, but many other smaller fragments, as yet undetected, must exist. Meteoroids reaching the Earth as part of cometary dust trails or evolved periodic streams are subjected to solar heating and collisions with interplanetary dust (Trigo-Rodríguez et al. 2005). Consequently, these processes are apparently able to disrupt efficiently large cometary meteoroids over the time-scales that we expect for intercepting young meteoroid streams (Jenniskens 1997). In fact, progressive decaying of cometary boulders is also supported by high-resolution *Hubble Space Telescope* images of D/1999 S4 LINEAR. Weaver et al. (2001) estimated that the fragments imaged after the catastrophic disruption of this comet had typical radii of 25 and 60 m. We think that perhaps some of the boulders that are observed in cometary disruptions are finally decaying into smaller, probably unobservable, metre-sized meteoroids like Béjar. If we are correct, at least some comets would produce high-strength materials, and meteorite survival from these (quite rare events) would be guaranteed if impact geometry is favourable. The presence of high-strength materials from collisionally evolved comets would also be consistent with a recent review of the collisional rates suffered by cometary families (Bottke et al. 2008). Collisional evolution can strongly modify the internal structure of comets (Orosei et al. 2001; Coradini et al. 2008). In fact, the presence of materials with heterogeneous strength properties would be tested by the CONSERT experiments on the Rosetta spacecraft during its visit to comet 67P/Churyumov-Gerasimenko (Kofman et al. 2007).

Consequently, in view of the above-mentioned evidence, we suggest that the fragmentation of the parent comet is the likely origin of this heterogeneous stream, a mechanism recently identified to deliver large cometary meteoroids to the Earth (Jenniskens & Vaubaillon 2007).

4 CONCLUSIONS

The main conclusions of the present work are as follows.

(i) The Omicron Draconid stream is a heterogeneous source of meteors probably produced by its peculiar origin. The mean derived orbit of this stream suggests that its origin was the fragmentation of comet C/1919 Q2 Metcalf, although the orbit of this comet was not determined with accuracy.

(ii) All the above-mentioned evidence indicates that the Béjar superbolide (SPMN110708) is linked with the Omicron Draconid stream, and was produced by a fragment of a cometary nucleus arising from the disruption of the nucleus at the time when the Omicron Draconid stream was also formed.

(iii) In view of the present results, the formation of a cometary meteoroid stream populated by dense meteoroids capable of producing meteorite-dropping bolides seems to be feasible. These high-strength boulders would be released during the fragmentation of a cometary nucleus as opposed to the grains ejected by normal outgassing. There is an important difference between the two mechanisms. In the former, material from deep inside the original cometary nucleus forms part of the stream as opposed to the fragile grains released during outgassing.

(iv) We conclude that the Béjar progenitor meteoroid was sufficiently large and of high enough tensile strength to produce meteorites. If so, for the first time meteorites can be tied to the fragmentation of a comet nucleus. If we are correct, despite being rare events, there is room to say that a few meteorites present in terrestrial collections would have an origin in comets.

To test our ideas, we suggest a global campaign to measure the strength and composition of the meteoroids reaching the Earth from comet 73P/Schwassmann-Wachmann 3. This comet disrupted progressively between 1995 and 2006, and future encounters with these catastrophe-generated dust trails are expected for the next few years (Jenniskens 2006). In particular, we predict that disrupted comets would be a source of meteorite-dropping events, and also a source of hazard for artificial satellites under high meteoric fluxes. Finally, given the forthcoming visit of the Rosetta spacecraft to comet 67P/Churyumov-Gerasimenko, we emphasize the importance of the CONSERT experiment using deep penetrating radar to search for heterogeneous materials in the deep interior of the nucleus.

ACKNOWLEDGMENTS

This work has been supported by the Spanish Ministry of Science and Innovation (projects: AYA2007-63677 and ESP2007-61593), the National Institute of Aerospatial Technique (INTA), CSIC-IEEC and the Junta de Andalucía. We thank Javier Pérez Vallejo for providing us with the picture of the bolide. We also acknowledge the detailed eyewitness reports received from Dr Matthew Genge (Imperial College London), Jaime Izquierdo (Univ. Complutense Madrid) and Diego Rodríguez (M1 group). The present work is the result of a continuous fireball monitoring over Spain. In particular, we thank the contribution of Ronan Cunniffe in setting up new video stations in Andalusia. JMTR thanks CSIC for a JAE-DOC research grant.

REFERENCES

Babadzhanov P. B., Wu Z., Williams I. P., Hughes D. W., 1991, MNRAS, 253, 69

Borovička J., Spurný P., Kalenda E., Tagliaferri E., 2003, Meteorit. Planet. Sci., 38, 975

Bottke W. F., Levison H. F., Nesvorný D., Morbidelli A., Gounelle M., 2008, Asteroids, Comets, Meteors 2008, LPI Contribution 1405, paper 8096

Brown P. G., Ceplecha Z., Hawkes R. L., Wetherill G., Beech M., Mossman K., 1994, Nat, 367, 624

Brown P. G., Pack D., Edwards W. N., Revelle D. O., Yoo B. B., Spalding R. E., Tagliaferri E., 2004, Meteorit. Planet. Sci., 39, 1781

Brownlee D. et al., 2006, Sci, 314, 1711

Ceplecha Z., 1988, Bull. Astron. Inst. Czech., 39, 221

Ceplecha Z., Spurný P., Borovička J., Keclikova J., 1993, A&A, 279, 615
Ceplecha Z., Borovička J., Elford W. G., Revelle D. O., Hawkes R. L., Porubčan V., Šimek M., 1998, Space Sci. Rev., 84, 327
Ceplecha Z., Spurný P., Borovička J., 2000, A&A, 357, 1115
Cook A. F., 1973, in Hemenway P. M., Cook A. F., eds, Evolutionary and Physical Properties of Meteoroids. NASA SP-319, p. 183
Cook A. F., Lindblad B. A., Marsden B. G., MrCrosky M. A., Posen A., 1973, Smithsonian Contrib. Astrophys., 15, 1
Coradini A., Capria M. T., De Sanctis M. C., McKinnon W. B., 2008, in Barucci M. A., Boehnhardt H., Cruikshank D. P., Morbidelli A., eds, The Solar System Beyond Neptune. Univ. Arizona Press, Tucson, p. 243
Denning W. F., 1879, Observatory, 3, 116
Denning W. F., 1929, Observatory, 52, 329
Elford W. G., Steel D., Taylor A. D., 1997, Adv. Space Res., 20, 1501
Gombosi T. I., Houpis H. L. F., 1986, Nat, 324, 43
Gounelle M., Morbidelli A., Bland P. A., Spurný P., Young E. D., Sephton M., 2008, in Barucci M. A., Boehnhardt H., Cruikshank D. P., Morbidelli A., eds, The Solar System Beyond Neptune. Univ. Arizona Press, Tucson, p. 525
Halliday I., Griffin A. A., Blackwell A. T., 1996, Meteorit. Planet. Sci., 31, 185
Hörz F. et al., 2006, Sci, 314, 1716
Jenniskens P., 1997, A&A, 317, 753
Jenniskens P., 2004, AJ, 127, 3018
Jenniskens P., 2006, Meteor Showers and Their Parent Comets. Cambridge Univ. Press, Cambridge
Jenniskens P., Vaubaillon J., 2007, AJ., 134, 1037
Jenniskens P., Vaubaillon J., 2008, AJ., 136, 725
Kofman W. et al., 2007, Space Sci. Rev., 128, 413
Levison H. F., Duncan M. J., 1997, Icarus, 127, 13
Ma Y., Williams I. P., Chen W., 2002, MNRAS, 337, 1081
McCrosky M. A., Ceplecha Z., 1968, Smithsonian Astrophys. Observ. Spec. Rep., 288, 1
Nesvorný D. et al., 2002, Nat, 417, 720
Orosei R., Coradini A., De Sanctis M. C., Federico C., 2001, Adv. Space Res., 28, 1563
Porubčan V., Williams I. P., Kornoš L., 2004, Earth Moon Planets, 95, 697
Sekanina Z., 1976, Icarus, 27, 265
Snodgrass C., Lowry S. C., Fitzsimmons A., 2008, MNRAS, 385, 737
Terentjeva A., 2003, WGN J. IMO, 31, 106
Trigo-Rodríguez J. M., 1989, Universo, J. Liga Iberoamericana de Astronomía, Mérida, Venezuela
Trigo-Rodríguez J. M., Llorca J., 2006, MNRAS, 372, 655
Trigo-Rodríguez J. M., Llorca J., 2007, MNRAS, 375, 415
Trigo-Rodríguez J. M., Llorca J., Lyytinen E., Ortiz J. L., Sánchez Caso A., Pineda C., Torrell S., 2004a, Icarus, 171, 219
Trigo-Rodríguez J. M. et al., 2004b, Earth Moon Planets, 95, 553
Trigo-Rodríguez J. M., Betlem H., Lyytinen E., 2005, ApJ, 621, 1146
Trigo-Rodríguez J. M., Borovička J., Spurný P., Ortiz J. L., Docobo J. A., Castro-Tirado A. J., Llorca J., 2006, Meteorit. Planet. Sci., 41, 505
Trigo-Rodríguez J. M. et al., 2007, MNRAS, 382, 1933
Weaver H. A. et al., 2001, Sci, 292, 1329
Weissman P. R., Lowry S. C., 2008, Meteorit. Planet. Sci., 41, 505
Whipple F. L., 1951, ApJ, 113, 464
Williams I. P., 2004, WGN J. IMO, 22, 11
Williams I. P., Ryabova G. O., Baturin A. P., Chernitsov A. M., 2004, MNRAS, 355, 1171
Wylie C. C., 1948, Pop. Astron., 56, 273

This paper has been typeset from a Microsoft Word file prepared by the author.