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Asteroid 2002NY40 as a source of meteorite-dropping bolides

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ABSTRACT

The existence of asteroidal meteoroid streams capable of producing meteorite-dropping bolides has long being invoked, but evidence is scarce. Recent modelling of previously reported associations suggests that the time-scales to keep the orbital coherence of these streams producing meteorites are too short. We present an unequivocal association between near earth object (NEO) 2002NY40 and at least one bright fireball detected over Finland in 2006 August. Another two additional fireballs recorded from Spain and Finland seem to be related, together producing a fireball-producing stream (β Aquarids). On the basis of historical data, the 2006 finding suggests the existence of a meteoroid complex capable of producing meteorites. Taking into account present time-scales for orbital decoherence, if 2002NY40 has large meteoroids associated with it, such behaviour would be the consequence of a relatively recent asteroidal fragmentation. Supporting our claim, the heliocentric orbits of two recently discovered NEOs, 2004NL8 and 2002NY40, were found to exhibit a good similarity to each other and also to the orbits of the three bolides. The fireball spectra of the two Finish bolides showed that the chemical abundances of these objects are consistent with the main elements found in chondrites. This result is consistent with the probable Low iron, Low metal (LL) chondritic mineralogy of asteroid 2002NY40. Consequently, this asteroid may be delivering LL chondrites to the Earth. Additional fireball reports found in the literature suggest that the associated β Aquarid complex may have been delivering meteorites to the Earth during, at least, the last millennium.

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

1 INTRODUCTION

The existence of meteoroid streams capable of producing meteorite-dropping bolides is a hot topic in planetary science. The existence of such streams was first proposed by Halliday (1987). Their existence has important implications because they can be naturally delivering to the Earth different types of rock-forming materials from Potentially Hazardous Asteroids (PHA). It is believed that near earth objects (NEOs) in the Earth's vicinity are undergoing dynamical and collisional evolution on very short time-scales (Bottke et al. 2002). Many of these objects are crumbly bodies, as a consequence of the collisions responsible for forming them. Catastrophic disruptions in the main asteroid belt have been extensively studied, but little is known about the importance of the process in the NEO population. Due to the relatively low population of the NEO region, fracturing caused by the irregular shape and fragile structure of a fast rotator should be considered in addition to that caused by collisions. The escape velocity is considerably smaller than the orbital velocity, and catastrophic disruptions are characterized by a large amount of the initial mass being ejected away at escape velocity (Bottke et al. 2005). Consequently, after the fracturing, metre-sized pebbles and even larger boulders are released forming a stream of asteroidal fragments moving on nearly identical orbits (Williams 2002, 2004; Jenniskens 2006). When these fragments encounter the atmosphere of the terrestrial planets, bright fireballs will be produced, but these fireballs have rarely been associated with asteroids.

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We present trajectory and orbital data for three meteorite-dropping bolides that exhibit similar orbits, and probably form a meteoroid stream that we call β Aquarids. These orbits are remarkably similar to the orbits of two recently discovered NEOs, particularly asteroid 2002NY40. Moreover, the fact that the luminous trajectories measured for the bolides show deep penetration in the atmosphere is highly suggestive of asteroids being a likely source of meteorites. The description of the observational methods, reduction procedures and results is given in next section. Finally, in Section 3, the main implications of this work in the context of meteoroid, meteorites and NEO research are discussed.

2 OBSERVATIONS AND DATA REDUCTION

Continuous monitoring of fireball activity was performed during 2006 by the Finish Fireball Network (hereafter FN) and the Spanish Meteor Network (SPMN). In order to check unidentified fireball activity, we interchanged information on the fireballs detected during 2006. The locations of FN and SPMN stations are given in Table 1. The SPMN stations and the fireball activity detected in 2006 (including the SPMN310806 event) are described in Trigo-Rodríguez et al. (2007). Both Finish fireballs were captured by the same four stations (Table 1), although in Pieksämäki with different cameras located a few hundred metres from each other. The data were measured and further reduced using the UFOANALYZER program, but the astrometric measurements were checked manually and reduced by using our own Excel-spreadsheet program. The entry trajectory was calculated with another Excel-spreadsheet solver for iterative least-squares solutions.

Fireballs' codes were named after the date of appearance. In particular, FN300806 appeared on 2006 August 30, at 1 h 11 m 50 ± 1 s UTC, SPMN310806 appeared on 2006 August 31, at 1 h 44 m 42.4 ± 0.1 s UTC and FN100906 appeared on 2006 September 10, at 21 h 31 m 45 ± 1 s UTC. The Spanish event was named after the population that was located below it: 'Cortes de la Frontera' located in Malaga province. In the same way were named Finish events: 'Lahti' (FN300806) and 'Varkaus' (FN100906). Fireball recordings were achieved by using high-sensitivity Watec video cameras (Watec Co. Ltd, Yamagata, Japan) and low-scan-rate all-sky CCD camera images (Fig. 1). Coordinate measurements on the images were obtained for stars and meteors by using the MAXIM DL software package for the Spanish part and the UFOA program for fully automatic and party manual (by clicking) image positions and IRFANVIEW program for fully manual reading of the pixel-coordinates for the Finish one. The astrometry was later performed when the data were introduced into our NETWORK software (Trigo-Rodríguez et al. 2003), which computes the equatorial coordinates and determines the apparent and geocentric radiant. Another program called AMALTHEA was used by the SPMN for allowing quick astrometric reduction of the SPMN310806 video. From the sequential measurements of the video frames and the trajectory length, the velocity of the meteoroids along the path was obtained. The pre-atmospheric velocity V_∞ was found from the velocity measured in the earliest parts of the meteor trajectories. In order to determine orbital elements from the radiant, trajectory and velocity data, we used the MORB program provided by Ceplecha, Spurný and Borovička (2000). As a consequence of the observational data reduction effort, reliable trajectory and orbital data were obtained, which are given in Tables 2 and 3.

Figure 1. Part of an all-sky CCD image taken from La Mayora SPMN station showing the magnificence of the 'Cortes de la Frontera' (SPMN310806) bolide. The first flare likely associated with fragmentation occurred at a height of 43.6 km when the meteoroid had been decelerated to 18 kms^{-1}. Successive secondary flares occurred at heights of 39.2, 33.7 and 30.9 km.

Meteoroid masses were computed using a dynamic approach described elsewhere (Ceplecha 1988; Halliday, Griffin & Blackwell 1996; Ceplecha et al. 1998). We obtained the initial masses and ending masses for these fireballs by taking into account the deceleration of the meteoroids in the atmosphere, considering a value of 1.1 for the drag-coefficient and assuming a meteoroid density of 3.5 g cm^{-3}. These values are given in Table 2. The ending masses after deceleration suggest possible meteorite survival, although only the Spanish event was deepening enough (because of their largest initial mass) for being convinced about its landing. In any case, no meteorites have yet been found.

Table 1. Location of the FN and SPMN stations which collected the data presented here.

Station no.	Station (province, country)	Longitude	Latitude (N)	Altitude (m)
1	Sevilla (Sevilla, Spain)	05°58′50″W	37°20′46″	28
2	La Mayora (Málaga, Spain)	04°02′40″W	36°45′35″	60
3	Vaala (Vaala, Finland),	26°44′04″	64°23′32″	100
4	Pieksämäki (Pieksämäki, Finland)	27°06′25″	62°15′26″	140
5	Järvenpää (Järvenpää, Finland)	25°07′39″	60°29′39″	62
6	Pukinmäki (Helsinki, Finland)	24°59′18″	60°15′00″	20

Table 2. Mass, trajectory and radiant data. m_{abs} is the absolute magnitude, M_{b} and M_{e} are the initial and terminal masses, H_{b}, H_{max} and H_{e} are the height for the beginning, maximum and ending parts of the computed trajectory. Radiant is given for equinox (2000.0). Last three columns are the velocity at infinity, geocentric and heliocentric.

Code	m_{abs}	M_{b} (kg)	M_{e} (kg)	H_{b}	H_{max}	H_{e}	α_g (°)	δ_g (°)	V_∞	V_g	V_h
FN300806	-8.8 ± 0.5	0.6	0.03	85.5	56	41.4	328.50 ± 0.20	-1.80 ± 0.22	21.3 ± 0.1	18.3	36.6
SPMN310806	-11 ± 1	10	0.5	120.8	39.2	19.8	329.9 ± 0.7	2.15 ± 0.5	21.8 ± 0.5	19.1	36.6
FN100906	-9.7 ± 0.5	0.3	0.01	93.7	51	41,5	338.72 ± 0.21	0.7 ± 0.3	22.1 ± 0.5	19.1	37.4

Table 3. Orbital elements of imaged fireballs, and of the two NEOs (in italics) given for comparison. Equinox (2000.00).

Code	q	1/a	e	i	ω	Ω
FN300806	0.689 ± 0.003	0.470 ± 0.007	0.676 ± 0.005	5.94 ± 0.14	257.78 ± 0.38	156.46377 ± 0.00006
SPMN310806	0.669 ± 0.008	0.47 ± 0.03	0.687 ± 0.022	8.22 ± 0.23	260.1 ± 1.5	157.45183 ± 0.00005
FN100906	0.685 ± 0.007	0.410 ± 0.029	0.719 ± 0.022	5.3 ± 0.3	256.3 ± 0.38	167.94226 ± 0.00006
2002NY40	*0.594875*	*0.48776*	*0.709841*	*5.884*	*268.5633*	*146.4379*
2004NL8	*0.720697*	*0.38807*	*0.720315*	*4.93*	*268.8902*	*159.3874*

3 DISCUSSION

When Drummond (1982) first calculated meteor radiants for bodies approaching within 0.2 au of the Earth's orbit, the number of asteroids known was relatively low, and relatively few reliable orbits of meteorite-dropping bolides were known. Both problems have been a significant handicap for the identification of meteoroid streams producing meteorites in the last decades. Despite this, present achievements in completing the NEO inventory and size distribution (Bottke et al. 2002) together with a significant increase in fireball monitoring efforts can provide new orbital clues on this exciting topic. At the same time, increasing reflectance spectroscopy data of asteroids are being obtained, and can be compared with chemical composition of meteoroids deduced from meteor spectroscopy (Borovicka 1993, 1994; Trigo-Rodríguez et al. 2003). Both topics will be discussed separately in the context of our recorded fireball events.

3.1 Orbital clues on the origin of β Aquarids

Halliday et al. (1996) suggested the existence of groups of meteorite-producing bolides. Of course, there is an additional difficulty because metre-sized bodies suffer significant gravitational and non-gravitational perturbations (e.g. the Yarkovsky effect) that produce an extremely fast evolution of the meteoroid orbits. Spurny, Oberst & Heinlein (2003) also claimed the possible common origin of Pribram and Neuschwanstein meteorites, but the fact that they are different meteorite types keeps this result controversial. On the basis of dynamic grounds, the association between these two meteorites was treated recently by Pauls & Gladman (2005) who concluded that the time-scales for orbital decoherence are too short (10^4 to 10^5 yr). Pauls and Gladman (2005) also concluded that the statistical evidence for meteorite-producing streams is insufficient. We carried out a search among the orbits of all NEOs currently catalogued (NeoDys 2007) for orbits which are similar to those deduced for the bolides. We found several NEOs having orbital elements approximately matching the orbits of the bolides, but two of them have extraordinary similarity: 2004NL8 and 2002NY40 (Table 3). If we accept the above arguments, the β Aquarid members detected here should point to a relatively recent collision or fragmentation of the progenitor asteroids.

In order to test the link between the three bolides and these two objects, we performed numerical integrations of the orbits backwards in time. The integrations were performed using the MERCURY6 program (Chambers 1999), a hybrid symplectic integrator widely used in Solar system dynamics studies. The orbits of each of the three fireballs and two NEOs were integrated back for at least 100 000 yr. Perturbations from the planets Venus, Earth, Mars, Jupiter and Saturn were included. The result of these integrations is shown in Figs 2 and 3. Surprisingly, we found a good match in the orbital evolution of 2002NY40 and the more accurately determined orbit in our sample: FN300806 (Fig. 2) and also a good match between the same NEO and fireball SPMN310806 (Fig. 3). This result is evident not only over a 5000-yr time-scale, but also even over at least 30 000 yr. The third fireball, FN100906, also evolves similarly to 2002NY40 over a time-scale of about 5000 yr. The D-criterion used in each plot is that of Southworth and Hawkins (1963). This is a quantitative measure of the similitude among the orbits, by drawing an analogy with a five-dimensional orthogonal coordinate system and considering each orbital element as a coordinate (see e.g. Jopek et al. 2002). As a consequence, this unprecedented association gives additional credit to the hypothesis of a close link among the orbits. We can affirm that the FN300806 and SPMN310806 bolides were produced by fragments of NEO 2002NY40.

By looking at the orbital data presented in Table 3, we observe a clear similarity in the orbits of the three bolides. The D-criterion applied to the three orbits is showing values clearly below $D < 1.0$ (0.2 for FN300806-SPMN310806 and FN300806-FN100906, and 0.7 for SPMN310806-FN100906) that are suggestive of a dynamical association of the orbits. A common source for the three meteoroids producing these bolides is very likely.

The next step was to carry out a literature search for other possible evidence of activity coming from this source. Among the previously identified sources of fireball activity (Terentjeva 1989, 1990; Gavajdová 1995; Babadzhanov 1996; Halliday et al. 1996), we did not identify common cases, but probable associated meteor activity (Lindblad 1971a,b; Sekanina 1976). Except for data obtained from continuous monitoring FN, the rest can be very biased towards periods of high meteor activity. This is not the case for the last week of August, being an epoch of the year that deserves additional study. By looking at a detailed study of the appearance time of bright fireballs from the *Millman Fireball Archive* made recently by Beech (2006), we found a remarkable aspect. This author pointed out the relevance of fireball activity peaking at solar longitude $\lambda_o = 165 \pm 4°$. This value is close to the longitude of the node of

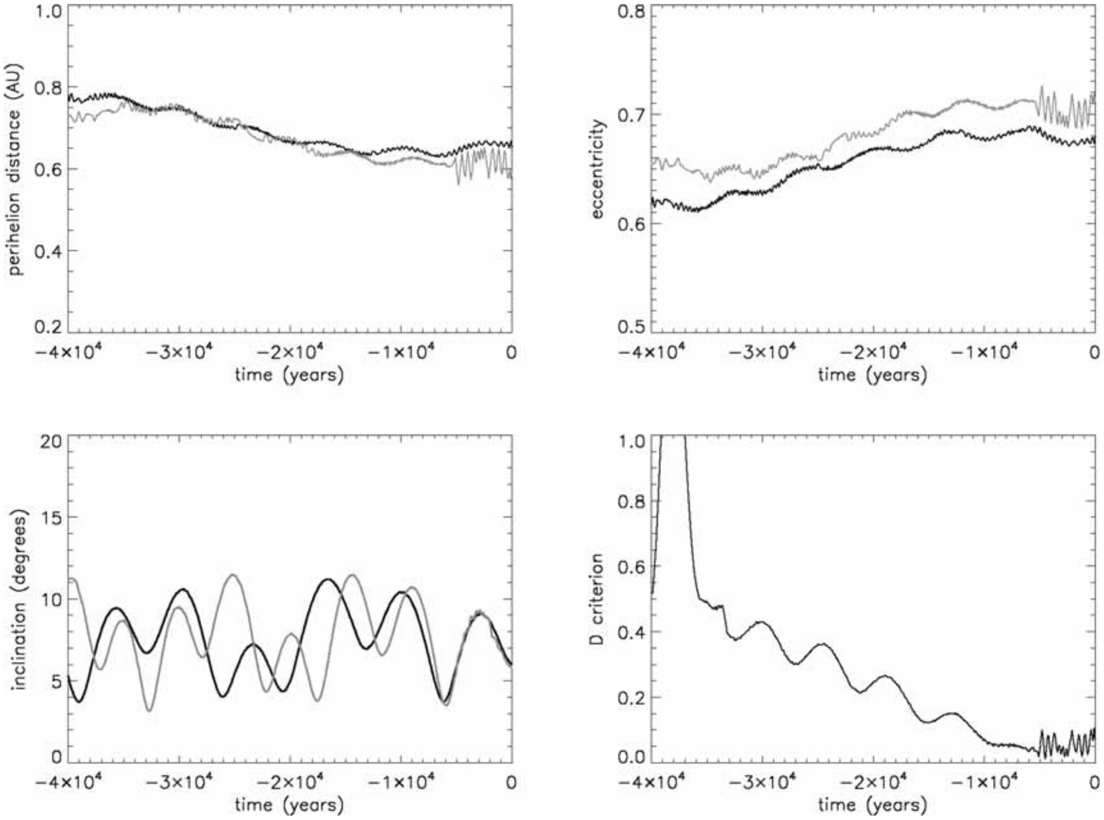

Figure 2. Numerical integration of the orbital elements of FN300806 (black line) and asteroid 2002NY40 (grey line) over 40000 yr. The perihelia and eccentricities evolve similarly for this whole time period and the D-criterion stays below 0.4 for about 30000 yr.

our three fireballs, but additional data are required. We think that the 2006 fireball activity reported here would be contributing to this peak in the distribution of bright fireballs compiled in the Millman archive. However, Beech (2006) suggested that the origin of such fireball activity would be the stream group number 3 previously identified by the Meteorite Observation and Recovery Project (MORP) in Canada (Halliday et al. 1996). Clear differences in the radiant position and orbital elements for both sources (see Table 4) suggest that a multiple origin is better at explaining the large number of bolides historically observed in the above-mentioned solar longitude interval.

By looking at previous identification of this fireball source or any linked meteor stream, we found in the literature mention to the κ Aquarids (Table 4) with activity period, radiant position and orbital elements near to those we found for the 2006 β Aquarid fireballs.

The detection of this stream of large meteoroids is intriguing and opens new questions. Should disruptive events be frequent among bodies crossing the orbit of the Earth? Certainly, asteroidal fragments following NEO orbits would be dynamically unstable, evolving in very short time-scales under the influence of the planets. Consequently, these fragments would lose orbital coherence relatively quickly, just after a few hundred revolutions of the Sun. This is an important point because such orbital decoherence would make these fragments not identifiable from the sporadic background in short time-scales. The fast dynamical evolution of the NEO population makes the identification of large bolides as being produced by asteroids difficult, although some remarkable cases have been pointed out before (Halliday et al. 1996; Jopek et al. 2002; Williams 2004). Due to the relatively low flux density expected for these asteroidal streams, larger atmospheric volumes than usual are required to have a significant chance of recording linked bolide events. Consequently, we think that possible future identifications should involve a closer collaboration among present-day fireball monitoring projects. Released lists of fireball events would also be very useful in order to look for this kind of associated fireball event. To identify the sources of large meteoroids will be important not only for defining the main sources of meteorites to the Earth, but also to get better data on the present impact hazard for artificial satellites and spacecraft.

3.2 Chemical abundances of the 2002NY40 meteoroids

Fortunately, by including the fireball monitoring we obtained additional low-resolution spectra of two of the three bolides. These meteor spectra are clearly suggestive of a chondritic nature for the progenitor body of FN300806. Fig. 4 shows a composite image of the spectrum of the August 30 bolide as seen from Station 6 (Table 1). The resolution of these spectra is poor ($\sim$2 nmpixel^{-1}), but provides insights on the nature of its parent asteroid (2002NY40). The Na I-1 (centred at 518.4 nm), Mg I-2 (518.4 nm) and the Ca I-1 (422.7 nm) lines of the main component are the most prominent features in the spectra of both Finish fireballs. As we expect for spectra produced by low-geocentric velocity meteoroids, the second component is very weak except for the presence of the blended Ca II-1 doublet in 393.4 and 396.8 nm, and the Mg II-4 (448.1 nm) line. We used the same procedure to analyse the spectrum as in Trigo-Rodríguez et al. (2003). The raw spectrum was subtracted of background and later corrected for the sensitivity of the cameras in each wavelength. Fig. 5(a) shows the raw spectrum of the FN300806 fireball, and the calibrated one (Fig. 5b), once corrected for the sensitivity of the video cameras depending on the wavelength. Sensitivity was normalized

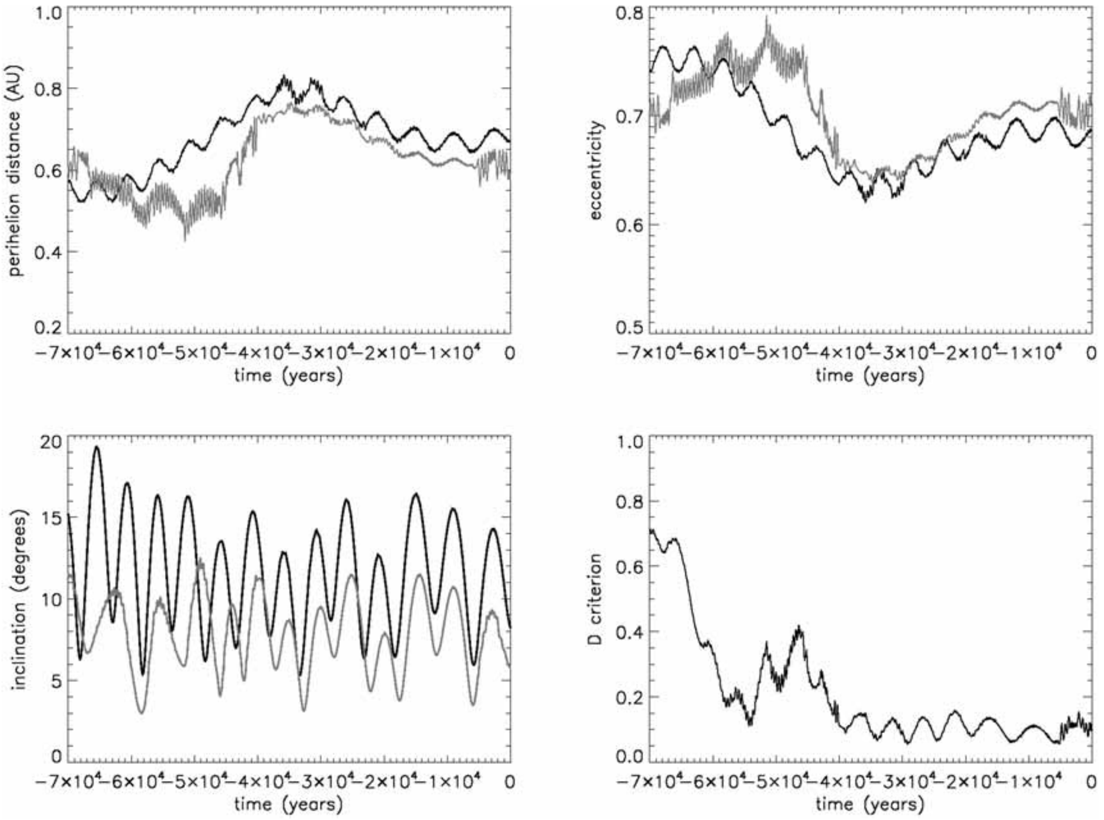

Figure 3. Numerical integration of the orbital elements of SPMN310806 (black) and asteroid 2002NY40 (grey). In this case, the D-criterion for the NEO and fireball orbits remains below 0.2 for 40 000 yr and only moves permanently above 0.4 at about 65 000 yr.

Table 4. Other meteoroid streams identified with similar orbital elements. *N* gives the number of orbits identified and averaged in each work. Other possible cases, but with significant differences in geocentric velocity, are given in table 7 (no 76) of Jenniskens (2006).

		Main orbital elements					Radiant position		
Name (*N* = number)	V_g (kms^{-1})	*q*	1/a	*I*	*ω*	Ω	RA (°)	Dec. (°)	Source
Average (*N* = 3)	18.8	0.687	0.450	6.48	258.06	160.62	334.04	+03.79	This work
κ Aquarids (*N* = 35)	18.0	0.741	0.384	7.6	247.8	179.5	343.0	+08.3	Sekanina (1976)
κ Aquarids (*N* = 6)	18.1	0.725	0.388	4.4	250.6	168.5	336.2	−01.2	Sekanina (1973)
κ Aquarids (*N* = 9)	18.2	0.705	0.423	3.9	253.7	181.3	350.2	+03.2	Sekanina (1973)
Group 3 MORP	14.6	0.94	–	2	205	170	292	−13	Halliday et al. (1996)

to 600 nm where the chip efficiency is the highest (70 per cent). In order to get the physical parameters in the meteor column, we fitted the intensity of the Fe I lines, mainly the multiplets Fe I-687 and Fe I-15 centred, respectively, at 495.0 and 537.2 nm. The resulting values for the averaged temperature and Fe I column density were 4400 K and 1×10^{15} cm^{-2}. Once we fixed these values, 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 = 1.2 ± 0.1, Na/Fe = 0.05 ± 0.01 and Ca/Fe = (3.0 ± 0.5) × 10^{-2}. Such abundance ratios are close to chondritic, e.g. CI chondrites have, respectively, 0.9, 0.05 and 61 × 10^{-3} (Rietmeijer 2000), but not identical. In fact, the elemental ratios for LL chondrites (Mg/Fe ∼ 1.5, Ca/Fe ∼ 0.11, Na/Fe ∼ 0.1) obtained by Jarosewich (1990) fit better the measured chemical composition of both fireballs. Of course, the lower Ca/Fe value than chondritic in FN300806 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). On the other hand, the spectrum of FN100906 has lower resolution, but we got approximate ratios of Mg/Fe = 1.2 ± 0.1, Na/Fe = 0.03 ± 0.01 and Ca/Fe = (2 ± 1)×10^{-2} for similar physical parameters. These results can be compared with our present knowledge on the nature of asteroid 2002NY40. Rivkin et al. (2003) performed spectrophotometry of 2002NY40 that revealed its possible mineralogical association with LL ordinary chondrites. Our relatively high Mg/Fe ratios (compared to CIs) would be consistent with this nature because particles leaving 2002NY40 in the size range estimated for these meteoroids would be rich in Mg-rich olivine (forsterite). Of course, the composition of 2002NY40 fragments would be highly variable, but Mg-rich silicates would be relatively abundant for the above-mentioned mineralogical nature. In light of this evidence, we conclude that asteroid 2002NY40 is likely a present source of LL chondrites to the Earth. On the other hand, to our knowledge there is not enough mineralogical information available for NEO asteroid 2004NL8, but from its possible common origin we would predict a similar mineralogy. Additional physico-chemical data of this asteroid are needed.

Figure 4. Fireball spectrum of the 2006 August 30 bolide. A diffraction grating of 1000 grooves mm^{-1} was used.

4 CONCLUSIONS

The orbital and spectroscopic analyses performed on the three bolides detected from Finland and Spain in 2006 give us the following clues on their origin.

(1) Three meteorite-dropping bolides observed in Finland and Spain during August and September probably form a stream capable of producing meteorites. Orbital elements show a clear association among these three cases.

(2) Backwards integration of the orbital elements of these meteoroids shows that two fireballs (FN300806 and SPMN310806) clearly come from asteroid 2002NY40. Since the FN300806 event is the more accurately determined of the three, the third event may well be associated with this asteroid. A relatively recent disruption or collisional event would explain the present encounter of these fragments with the Earth.

(3) We suggest that the three meteoroids detected in 2006 form a meteoroid complex that was born in an asteroidal fragmentation. Of course, this hypothesis should be demonstrated with additional observational work.

(4) NEO asteroid 2002NY40 is able to produce meteoroid fragments that are approximately chondritic in composition. The Mg/Fe enrichment observed in both fireball spectra would be related with

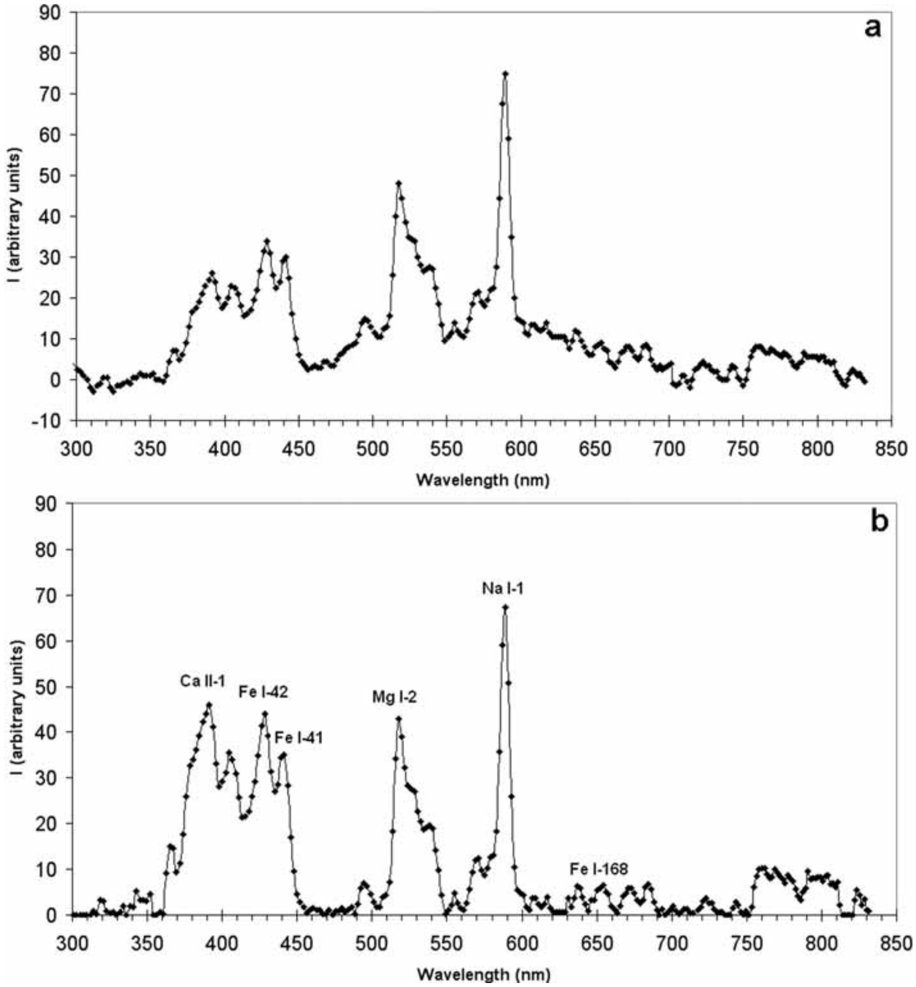

Figure 5. (a) Raw spectrum of the FN300806 fireball as directly scanned from Fig. 4. (b) The FN300806 spectrum, once calibrated for the cameras' sensitivity. The overall background was subtracted for determining the relative abundances of the main-forming chemical elements. The main lines discussed in the text, and their multiplet number, are indicated.

the possible abundance of Mg-rich olivine (forsterite). This is consistent with the deduced LL chondrite mineralogical nature of the progenitor asteroid.

(5) If the other NEO asteroid sharing orbital similitude (2004NL8) was originated by a disruption event, we predict that this body should exhibit a similar LL chondritic reflectance spectrum.

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