Geophysica (2017), 52(1), 21–29

Orbit Determination of the Kylmälä Fireball

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(Submitted: Apr 29, 2016; Accepted: Jun 2, 2017)

Abstract

We study observations of a fireball that occurred in Kylmälä, Finland with the aim of determining its Keplerian orbital elements. The fb_entry program is used to determine the fireball's trajectory based on the observations. The orbit is then determined using this trajectory as the input parameters with the Meteor Toolkit software. We successfully determine the fireball's orbit, which appears to be an ordinary near-Earth asteroid orbit. We find that the fireball's semi-major axis is 1.94 AU, which corresponds to the inner edge of the main asteroid belt and gives cause to suspect that the object originated in the main belt and evolved into a NEA due to the effect of the secular ν_6 *resonance. Several related bodies were also identified.*

Keywords: meteoroids, meteors, atmospheric trajectory analysis, orbital analysis

1 Introduction

The Earth's atmosphere is impacted daily by hundreds of tons of small objects from space, nearly all of which are destroyed as they pass through the atmosphere. During their fall, the objects heat up and begin to glow, and thus larger impacting objects may be seen as meteors. According to the definition of the International Astronomical Union (IAU) bright meteors (apparent magnitude of $V = -4$ mag or brighter) are called fireballs. The International Meteor Organization (IMO), in turn defines a fireball as a meteor that would have a magnitude of $V = -3$ mag or brighter when seen at the zenith. This definition corrects for the dimming of the brightness of a fireball due to the greater distance and atmospheric absorption when the fireball is seen near the horizon. While larger ones with sufficiently low entry velocity can reach the ground and cause an impact, smaller meteoroids usually burn out in the atmosphere and there are several reports of such in Finland throughout the year. For a more comprehensive review of meteors, there are numerous papers and books on the subject, for instance *Mason* (1984).

In this study, we use the fb_entry (*Lyytinen and Gritsevich*, 2013) software developed for trajectory analysis of meteors to determine the recent Kylmälä fireball's trajectory and then utilize the Meteor Toolkit (*Dmitriev et al.*, 2015) software which numerically integrates a meteor's equations of motion to determine the fireball's orbit based on the trajectory and any potential parent bodies.

Table 1. Coordinates and operators of the used FFN stations.

FFN station	Altitude (km)	Longitude	Latitude	Camera operator
Oulu	0.02	25.43689900	65.04730200	Jarmo Moilanen
Kempele	0.01	25.53616667	64.86202778	Jarmo Leskinen
Muhos	0.065	26.01337166	64.95492848	Pekka Kokko
Vesanto	0.11	26.36860000	62.89180000	Timo Kuhmonen
Lappeenranta	0.078	28.56595609	61.15328448	Toni Hallikas
Tampere	0.12	23.61851833	61.49577352	Jari Juutilainen

2 *Observations*

The fireball appeared at 19:45:13 UT on the 25th of March, 2015. The observations we used for this work were taken by the Finnish Fireball Network (FFN), which is a network established in 2002 consisting of 24 active stations with permanent instrumental setups that continuously monitor the skies above Finland and its neighboring areas for meteors and fireballs. Recently, FFN observations also enabled recovery of the Annama meteorite (*Gritsevich et al.*, 2014; *Trigo-Rodríguez et al.*, 2015; *Kohout et al.*, 2015; *Kohout et al.*, 2017).

The Kylmälä fireball was observed by a total of 6 different FFN sites shown in (Fig. 1). The Lappeenranta and Tampere stations were equipped with digital cameras while the other four sites are equipped with video cameras. We used data from each of these (Detailed in Table 1) for estimating the trajectory of the fireball with lower weight given to the Muhos and Oulu sites due to observational constraints. Interestingly, analysis of only two images of the fireball taken at the Muhos and Vesanto sites yields a similar trajectory solution compared to the analysis with all six stations. Images of the fireball taken at the Muhos and Vesanto sites are shown in Figure 2.

3 *Results*

We calculated the fireball's atmospheric trajectory values with the flexible fireball entry track calculation program fb_entry[1] (*Lyytinen and Gritsevich*, 2013), which is commonly used with raw FFN data. The resulting trajectory is shown in Table 2. As fb_entry does not directly give any error estimates, the errors were estimated with the program by obtaining a set of different solutions with the program with different combinations of the stations' data and different weight values assigned to individual observations. The error analysis of the orbit is described in detail by *Dmitriev et al.* (2015).

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[1] http://lyytinen.name/esko/fb_entry_vers_1.zip

Fig. 1 Map of Finland with the used Finnish Fireball Network sites marked. The red arrow represents the trajectory of the fireball.

Fig. 2. Images of the Kylmälä fireball. The left and right images respectively were taken at the FFN's Muhos and Vesanto sites by Pekka Kokko and Timo Kuhmonen.

Table 2. Trajectory of the Kylmälä fireball (FN20150325) as determined by fb_entry.

Pre-atmospheric velocity	13.05 ± 0.25 km/s
Azimuth direction	264.22 ± 0.1 °
Radiant elevation angle	66.08 ± 0.1 °
Height above sea level	82.9 ± 0.2 km
Longitude (WGS84)	25.65 ± 0.01 °
Latitude (WGS84)	64.554 ± 0.005 °

The fireball had an angle of impact of 66 degrees and a terminal height of 21 km, penetrating in the atmosphere much lower than the average value (*Moreno-Ibáñez et al*., 2015; *Moreno-Ibáñez et al*., 2017). We used the computed trajectory with the open source Meteor Toolkit[2], which is software for processing meteor data in order to determine e.g. the meteor's orbital elements and potential parent bodies of the meteoroid. As parameters for the program we enabled all eight perturbers and all output settings. The atmospheric parameters were all set as zero, since the initial conditions were those determined by the fb entry program (which accounts for atmospheric conditions) at the earlier stage and shown in Table 2. Finally, a starting time of 2015-03-25T19:45:13 was chosen. The resulting pre-impact solar system osculating Keplerian orbital elements are shown in Table 3 and a 2D projection of the orbit is provided in Figure 3.

Table 3. Keplerian orbital elements of the Kylmälä fireball during the 16th of March 10 days before the impact (J2000).

a (AU)	1.9403 ± 0.069
e	0.4864 ± 0.0183
i (°)	4.5451 ± 0.1761
Ω (°)	4.7301 ± 0.0045
ω (°)	175.9306 ± 0.1987
M (°)	357.5478 ± 0.0735

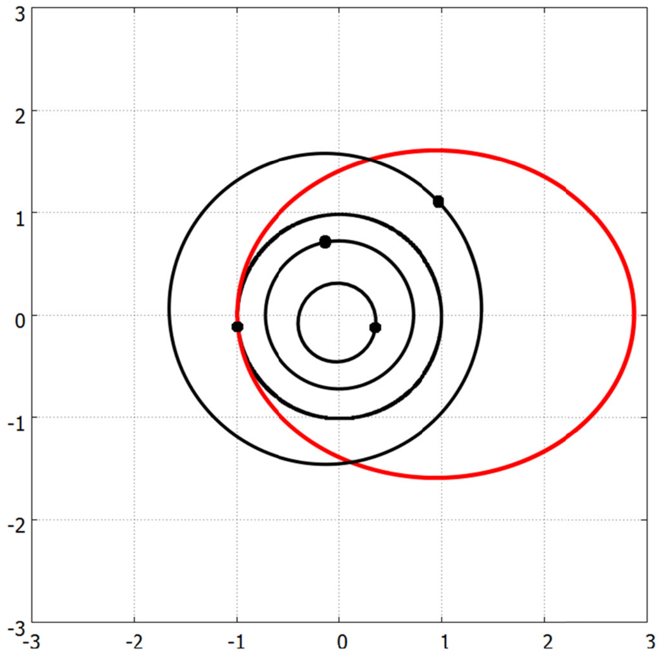

Fig. 3. Orbits and locations of the Kylmälä fireball (in red) and the inner solar system planets (in black) 10 days before the impact, i.e. at the epoch of Table 3. The units are in AU.

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[2] http://sourceforge.net/projects/meteortoolkit/

We attempted to use the Meteor Toolkit's related bodies search function for detecting any objects with related orbits and successfully found several possible parent bodies. For this purpose we chose to use the D SH criterion which is used to compare the similarity between the orbits of two bodies (for a detailed explanation of the criterion, see e.g. *Southworth and Hawkins* (1963)). The best 5 candidates based on the criterion are shown in Table 4.

Table 4. The Kylmälä fireball and the 5 best related objects as found with the D SH criterion.

Family	Name	a (AU)	e	i (°)	Ω (°)	ω (°)	$(\mathrm{D\ SH})^2$
	Kylmälä-FB	1.9403	0.4864	4.5451	4.7301	175.9306	
Apollo	(2012 FM)	1.9413	0.4849	3.2158	11.3427	151.3998	0.0006101
Apollo	(2009 ER)	1.8946	0.4683	4.4459	350.0966	154.2259	0.0008482
Apollo	(2012 DW32)	1.9431	0.4805	3.1833	354.6458	179.0886	0.0009005
Amor	(2009 SN1)	1.9580	0.4778	4.1496	357.5652	33.6979	0.0009455
Apollo	(1999 FR5)	1.8515	0.4780	3.8559	355.8531	148.9534	0.001251

4 Discussion

The derived trajectory corresponds to the value of ballistic coefficient $\alpha = 24.00$ and a relatively low mass loss rate described by the parameter $\beta = 0.64$; see *Gritsevich* (2009); *Lyytinen and Gritsevich* (2016) for a general description and other examples of the parameters. The ballistic coefficient is somewhat higher than for the Pribram, Lost City, Innisfree Neuschwanstein, Park Forest and Košice meteorite falls (*Gritsevich*, 2008b; *Meier et al.*, 2017; *Gritsevich et al.*, 2017), but is comparable to e.g. the Bunburra Rockhole case (*Sansom et al.*, 2014, 2015; *Sansom*, 2017). These values according to *Gritsevich* (2008a); *Gritsevich et al.* (2012) allow us to suspect possible meteorite fall and estimate a terminal survived mass of about 0.82 kg despite the entry mass of meteoroid being relatively low (approximately 5 kg assuming a bulk density of 3.3 g/cm^3). Some preliminary meteorite searches were conducted by the FFN (see the map at Fig. 4), but no fragments have been recovered so far.

To elucidate the reader on how the Kylmälä fireball's determined orbit compares to other minor planets in the inner solar system, we have chosen to include plots of known minor planet semi-major axes versus their eccentricities and inclinations. These plots are shown in Figure 5. From the semi-major axis, it is clear that the fireball's orbit appears to be situated on the edge of the main asteroid belt. The semi-major axis matches that of the Hungaria asteroid family, which is seen as a concentration of asteroids with a similar semi-major axis. The inclination however is quite low. The Hungarias have a much higher inclination in comparison; from this one may infer that the object most likely did not originate from the Hungaria family. In comparison to main belt asteroids, the eccentricity is quite high, which is what one would expect from a near-earth asteroid. Considering this and the semi-major axis being situated on the inner edge of the asteroid belt, it is likely that the object evolved into a near-earth asteroid due to the effect of the secular ν_6 resonance (*Froeschle and Scholl*, 1986).

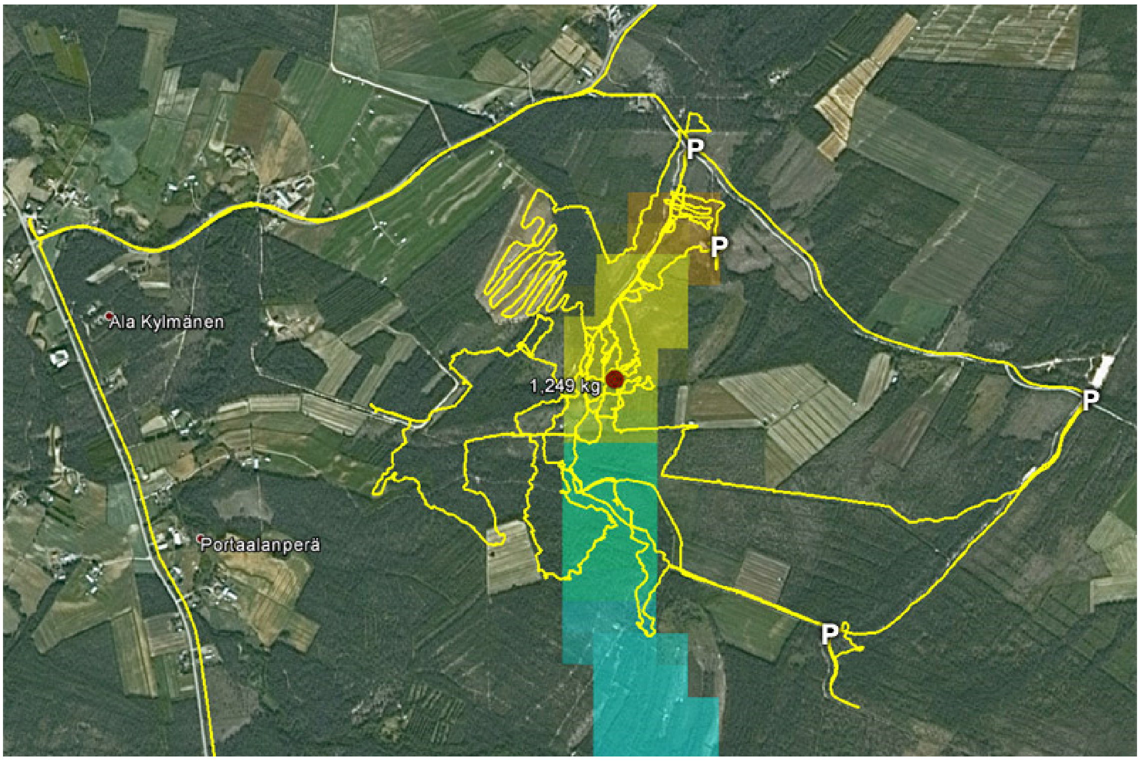

Fig. 4. The search area for fragments of the Kylmälä fireball (Jarmo Moilanen). The yellow lines represent the actual search area while the teal, yellow and orange colored regions represent the predicted impact location depending on estimated masses of the surviving fragments.

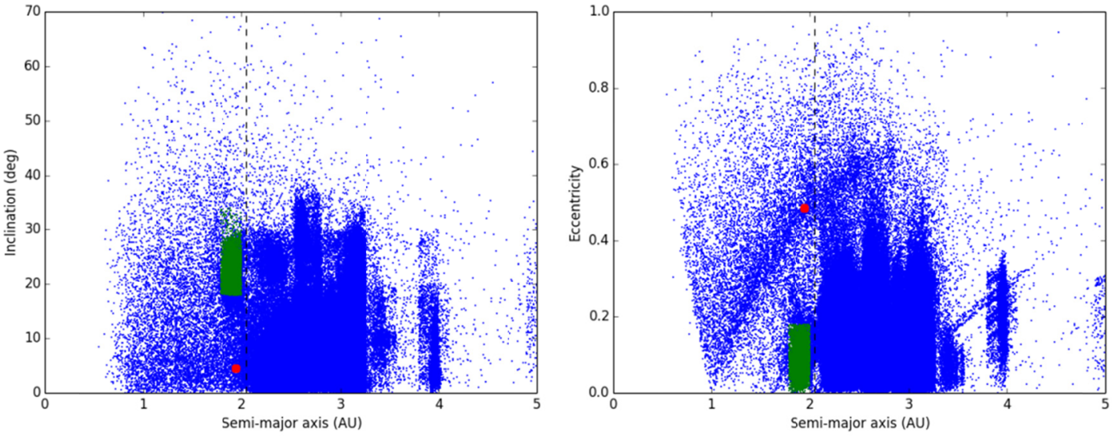

Fig. 5. Semi-major axes versus inclinations and eccentricities for minor planets up to 5 AU. The red dot represents the Kylmälä fireball's orbit. The Hungaria region is colored green. The dashed line represents the location of the ν_6 resonance. Data for other objects taken from the Minor Planet Center.

5 *Conclusions*

We have studied in detail the Kylmälä fireball (FN20150325) - one of the recent potentially meteorite-producing cases registered by the Finnish Fireball Network. We have successfully determined the Kylmälä fireball's orbit based on reconstructed atmospheric trajectory and ascertained that it most likely originated from the inner asteroid belt and has a fairly ordinary NEA orbit. A possible meteorite fall was predicted, though conducted brief meteorite searches have been unsuccessful.

Acknowledgements

This research at the Department of Physics of the University of Helsinki was performed in collaboration with the participants of the course "Space geodesy" lectured in autumn 2015 by Markku Poutanen and Maria Gritsevich. This research has also made use of NASA's Astrophysics Data System. We would like to thank Panu Lahtinen from the Finnish Meteorological Institute and Peter Völger from the Swedish Institute of Space Physics for their help with obtaining the actual atmospheric data and valuable discussions. We would like to thank Tomas Kohout and the other anonymous referee for their useful comments and suggestions regarding our paper. We thank all members of the Finnish Fireball Network and acknowledge the Ursa Astronomical Association for the support with the Finnish Fireball Network coordination. This study is supported, in part, by the ERC Advanced Grant No. 320773, the Academy of Finland projects No. 260027, 299543 and 307157, by the Russian Foundation for Basic Research (project Nos. 16-05-00004 and 16-07-01072), and by the Act 211 of the Government of the Russian Federation (agreement No. 02.A03.21.0006). The calculations were partly done by MG, VD and VL at MIIGAiK under the support of the Russian Science Foundation, project No. 14-22-00197 "Studies of Fundamental Geodetic Parameters and Topography of Planets and Satellites". Finally, we would like to thank Mikael Granvik from the University of Helsinki for his insightful comments on the fireball's orbit.

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