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PF120916 Piecki fireball and Reszel meteorite fall

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Abstract. On September 12, 2016, at 21:44:07 UT, a -9.2 ± 0.5 mag fireball appeared over northeastern Poland. The precise orbit and atmospheric trajectory of the event are presented, based on the data collected by six video stations of the *Polish Fireball Network (PFN)*. The PF120916 Piecki fireball entered the Earth's atmosphere with the velocity of 16.7 ± 0.3 km/s and started to shine at a height of 81.9 ± 0.3 km. Clear deceleration started after first three seconds of the flight, and the terminal velocity of the meteor was only 5.0 ± 0.3 km/s at a height of 26.0 ± 0.2 km. Such a low value of the terminal velocity indicates that fragments with the total mass of around $10 - 15$ kg could survive the atmospheric passage and cause fall of the meteorites. The predicted area of possible meteorite impact is computed and it is located south of Reszel city at the Warmian-Masurian region. The impact area was extensively searched by experienced groups of meteorite hunters, but without any success.

Key words: meteors – meteorities – asteroids

1. Introduction

Multi-station meteor observations have been conducted for several dozen years. It is a well-tried and proven method for detecting this kind of phenomena, determining their absolute brightness, meteoroid mass, trajectory in the atmosphere, orbital parameters and also calculating the places of meteorite falls. During the last 50 years of 20th century the European Fireball Network leading in this area, with their fully automated photographic stations (Spurný 1997, Spurný et al. 2007).

The *Polish Fireball Network (PFN)* is a project established in 2004, whose main goal is to constantly monitor the sky over Poland in order to detect bright fireballs occurring over the whole territory of the country (Olech et al. 2006, Wiśniewski et al. 2016). It is run by amateur astronomers associated in the *Comets and Meteors Workshop (CMW)* and coordinated by astronomers from the Copernicus Astronomical Center in Warsaw, Poland. Today there are over 35 fireball stations belonging to *PFN* that operate during each clear night. In total over 70 sensitive CCTV cameras with fast and wide angle lenses are used.

In this paper we report an analysis of the multi-station observation of the PF120916 Piecki fireball made by cameras of the *Polish Fireball Network*. The trajectory, orbit and possible area of meteorite fall are calculated.

2. Observations and data reduction

The PF120916 Piecki fireball was observed by six *PFN* video stations. They are listed in Table 1 together with their respective coordinates and equipment used for recording the fireball. The most detailed recording comes from the PFN52 Stary Sielc station which works using a digital Full HD (1920×1200 pix) camera with a recording speed of 25 frames per second. It captured the meteor almost in the center of the field of view (see Fig. 1). Valuable recordings were also obtained by PFN47 Jeziórko, PFN72 Koźmin Wielkopolski and PFN74 Brwinów stations which work in PAL resolution 786×584 with 25 frames per second, offering 0.04 second temporal resolution. Data from the PFN48 Rzeszów were not included into the calculations due to the location of the station along the trajectory of the fireball, a large distance (almost 500 km) from the fireball and capturing it through the clouds. Location of the PFN63 Łódź creates a substantially different convergence angle with respect to three stations: PFN52, PFN74, PFN47. In spite of this we did not decide to use its data for computation, mainly because of a low image scale. The PFN63 is an all-sky station equipped with a circular fish-eye lens. Combination of the vertical field of view of 180 deg with 1200 pixels of the vertical resolution gives the image scale of around 9 arc minutes per pixel. Additional reason was a large distance (around 300 km) from the fireball and capturing only part of its trajectory (the terminal point is missing due to the obstruction near the horizon).

Table 1. Basic data on the PFN stations which observed the PF120916 Piecki fireball.

Code	Site	Long. [°]	Latit. [°]	Elev. [m]	Camera	Lens
PFN47	Jeziórko	21.0572	51.9927	125	Siemens CCBB1320-MC	Ernitec 4mm f/1.2
PFN48	Rzeszów	21.9220	50.0451	230	Tayama C3102-01A1	Computar 4mm f/1.2
PFN52	Stary Sielc	21.2923	52.7914	90	DMK23GX236	Tamron 2.4-6mm f/1.2
PFN63	Łódź	19.4795	51.6865	189	DMK23GX236	Lensagon 1.4mm f/1.4
PFN72	Koźmin W.	17.4548	51.8283	139	Tayama C3102-01A4	Lenex 4mm f/1.2
PFN74	Brwinów	20.7068	52.1368	110	Mintron 12V6H-EX	Computar 2.6mm f/1.0

The data from four stations used for calculations, after a preliminary conversion, were additionally reduced astrometricaly by the UFO Analyzer application (SonotaCo 2009). Initially, only automatic data were taken into account but during later processing it became obvious that significant overexposures, presence of the wake and a possible fragmentation after the flare caused substantial errors in position of the points of the phenomenon calculation. To improve the measurement precision, the bolide's position was determined with the help of an UFOAnalyzer astrometric solution using a manual centroid measurement.

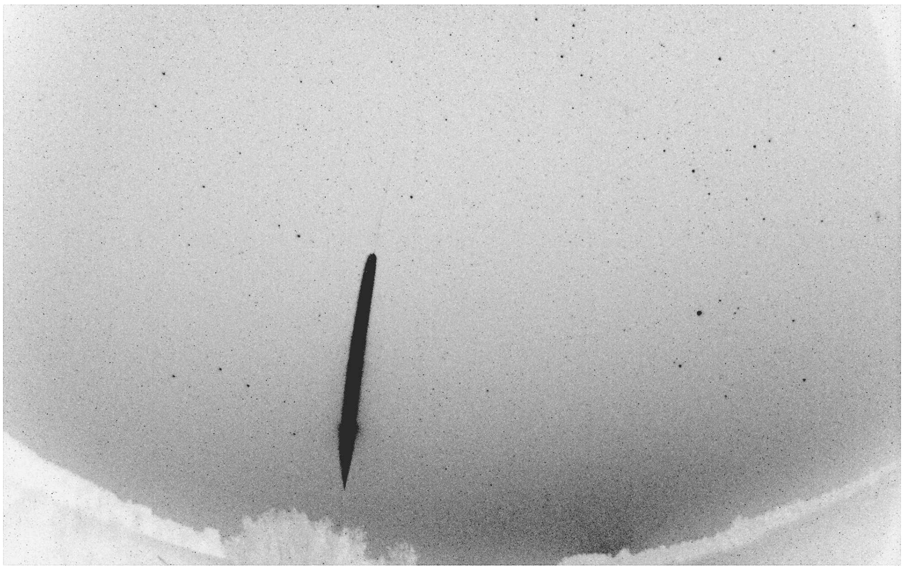

Figure 1. The video image of the PF120916 Piecki fireball captured in Stary Sielc station (PFN52).

The trajectory and orbit of the fireball were computed using the PyFN software (Żołądek 2012). PyFN is written in Python with usage of the SciPy module and the CSPICE library. For the purpose of trajectory and orbit computation, it uses the plane intersection method described by Ceplecha (1987). Moreover, PyFN accepts data in both MetRec (Molau 1999) and UFOAnalyzer (SonotaCo 2009) formats and allows a semi-automatic search for double-station meteors.

3. Results

3.1. Trajectory of the fireball

The Piecki fireball moved almost directly from south to north following a moderately steep trajectory having a total length of 91.1 ± 1.1 km. The beginning of the bolide was located at the following coordinates: $\phi = 53.2446(20)^\circ$ N, $\lambda = 21.2091(2)^\circ$ E at the height of 81.9 ± 0.3 km. During next seconds the bolide traveled north and flew 39.5 ± 0.2 kilometers over Piecki village, reaching its maximum brightness there. The terminal point of the trajectory was situated at the height of 26.0 ± 0.2 km over the following coordinates: $\phi = 53.884(3)^\circ$ N, $\lambda = 21.1504(4)^\circ$ E (10 km west of Biskupiec). The trajectory of the PF120916 fireball is shown in Fig. 2 and all important parameters are summarized in Table 2.

Table 2. Characteristics of the PF120916 Piecki fireball.

2016 September 12, T = $21^h44^m07^s \pm 1.0^s$ UT			
Atmospheric trajectory data			
	Beginning	**Max. light**	**Terminal**
Vel. [km/s]	16.7 ± 0.3	14.0 ± 1.0	5.0 ± 0.3
Height [km]	81.9 ± 0.3	39.5 ± 0.2	26.0 ± 0.2
Long. [°E]	21.2091 ± 0.0002	21.1638 ± 0.0004	21.1504 ± 0.0004
Lat. [°N]	53.2446 ± 0.002	53.726 ± 0.05	53.884 ± 0.003
Abs. magn.	-1.6 ± 1.0	-9.2 ± 0.5	-4.6 ± 1.0
Slope [°]	38.4 ± 0.4	37.9 ± 0.4	37.1 ± 0.4
Duration		6.45 sec	
Length		91.0 ± 1.1 km	
Stations	Stary Sielc, Brwinów, Jeziórko, Koźmin Wlk., Rzeszów, Łódź		
Radiant data (J2000.0)			
	Observed	**Geocentric**	**Heliocentric**
RA [°]	341.09 ± 0.02	339.83 ± 0.06	-
Decl. [°]	1.66 ± 0.36	-6.52 ± 0.50	-
Vel. [km/s]	16.7 ± 0.3	12.5 ± 0.3	34.3 ± 0.3

3.2. Velocity

Based on our observations the velocity of the phenomena was estimated for different points of its trajectory. In the initial part of the flight the velocity did not change in a noticeable way and was almost constant at a value of around 17 km/s. After the third second of the flight the velocity decrease became clearly visible, with final deceleration as high as 2457 m/s^2. At the end of the luminous trajectory the velocity of the fireball was only 5.0 ± 0.3 km/s (see Fig. 3).

3.3. Brightness

The photometry of the fireball was not trivial because of the partial saturation observed. Two independent methods have been applied to estimate the real brightness of the fireball. The first one is based on the measurements of the sky brightness during the fireball flight. These measurements have been compared with the sky brigtness caused by the full Moon in the same camera. The second method uses for comparison several objects recorded by cameras of different types with the same optics working in similar sky conditions. A detailed description of both methods was given in Olech et al. (2016).

The light curve of the PF120916 Piecki fireball is shown in Fig. 4. At the first point of the observed trajectory the brightness of the meteor was estimated to -1.3 ± 1.0 mag. On the next frame it raised to -3.1 ± 0.6 mag. During the first two seconds of flight the absolute brightness of the meteor increases systematically from -3.1 to -6 mag. There is a rapid brightening from -6 to

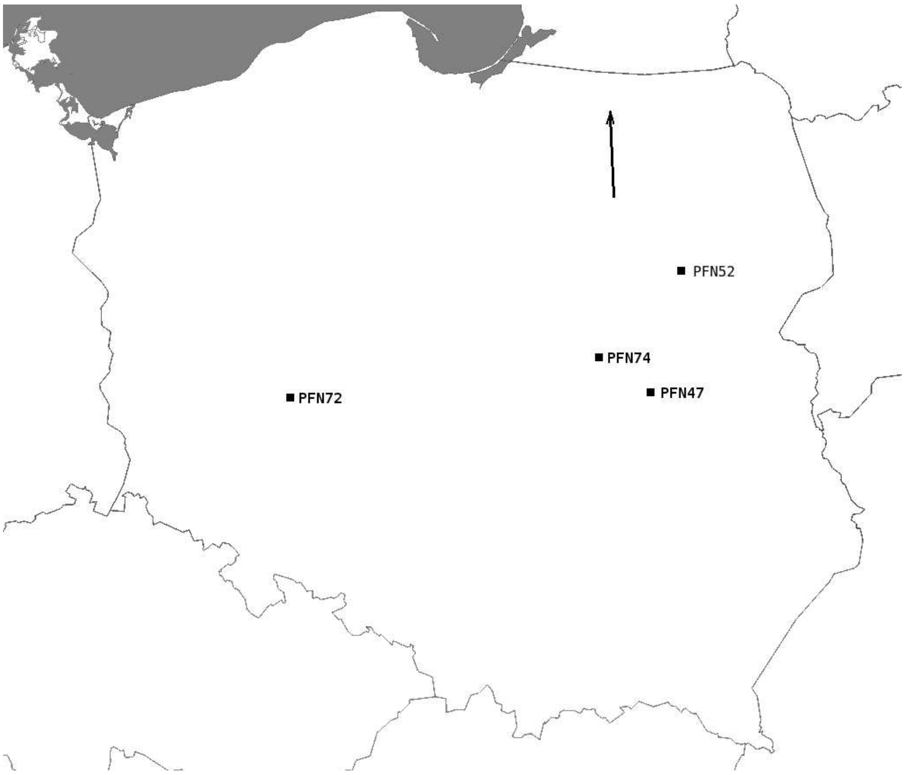

Figure 2. The luminous trajectory of the PF120916 Piecki fireball over Poland and the location of the PFN stations which recorded the phenomenon.

-8 mag around $t = 1.9$ sec. After that moment a plateau, lasting about three seconds, is observed with brightness reaching almost -9 mag. The maximal absolute magnitude was detected during a small flare at $t = 4.62$ seconds with $m = -9.2 \pm 0.5$.

After appearance of the flare brightness starts to decrease - slowly at first, but then very quickly. At the terminal point of the luminous trajectory the meteor had brightness of -4.5 mag.

Both, evolution of the velocity and the light curve of the meteor indicate that we are dealing with a type I fireball, which is usually identified with stony material, mostly ordinary chondrities. Taking into account the occurrence of the fragmentation, the calculated entry mass is at a level of 50 kg. For this mass, terminal height and entry velocity, the PE parameter (Ceplecha and McCrosky 1976) is around -4.3, indicating a type I fireball. To include the Piecki fireball to type II meteoroids (carbonaceous material with $-5.25 < PE < -4.6$) one should increase the initial mass to over 200 kg, which is unlikely in this case.

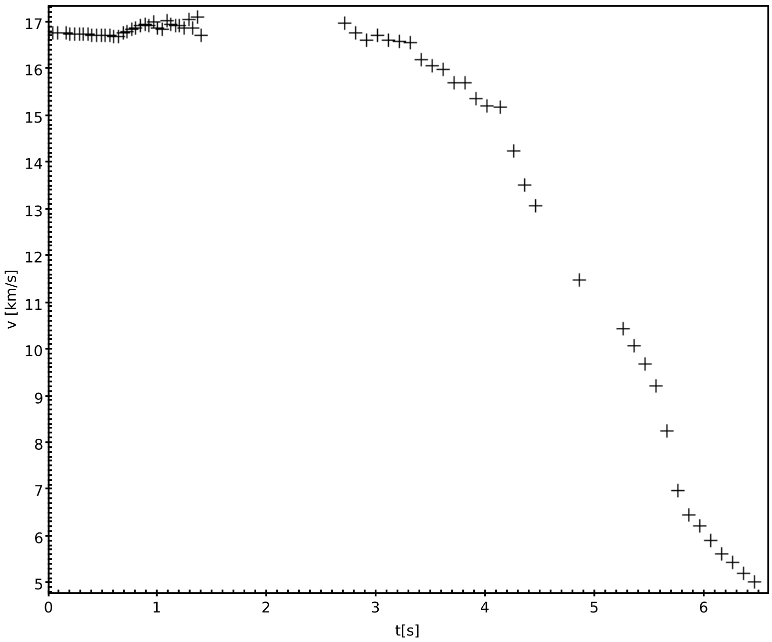

Figure 3. The evolution of the velocity of the PF120916 Piecki fireball.

3.4. Dark flight and a possible fall of the meteorite

The observed final velocity of 5.0 km/s at the height of 26 km indicates a possible meteorite fall south of Reszel city. The total mass which survived the atmosphere passage is estimated to be around $10 - 15$ kg. This is dynamical mass estimated from the parameters of the terminal points of the trajectory of the main fragment. We deal here with the most probable case of a meteorite fall in the history of our project.

Calculations for the dark flight in the atmosphere were performed using the standard method for the European Fireball Network (Ceplecha 1987). As the initial parameters we used observational data from the final part of the trajectory, such as the terminal velocity, final height, deceleration, azimuth and inclination. For dark flight calculations profiles of the atmosphere achieved by a balloon from Kaliningrad and Łeba were used. Fortunately, during that night the winds at different altitudes blew mostly from the north and from the south, thus there were no large lateral deviations from the original trajectory.

Fig. 5 shows the computed trajectories for the dark flight for meteorites with the mass in a range $2 - 15$ kg. Different colors of the tracks are used to distinguish the atmosphere profiles from Kaliningrad and Łeba. Despite of significant differences in tracks at a height of around 10 km, the fall points are located in the well defined region.

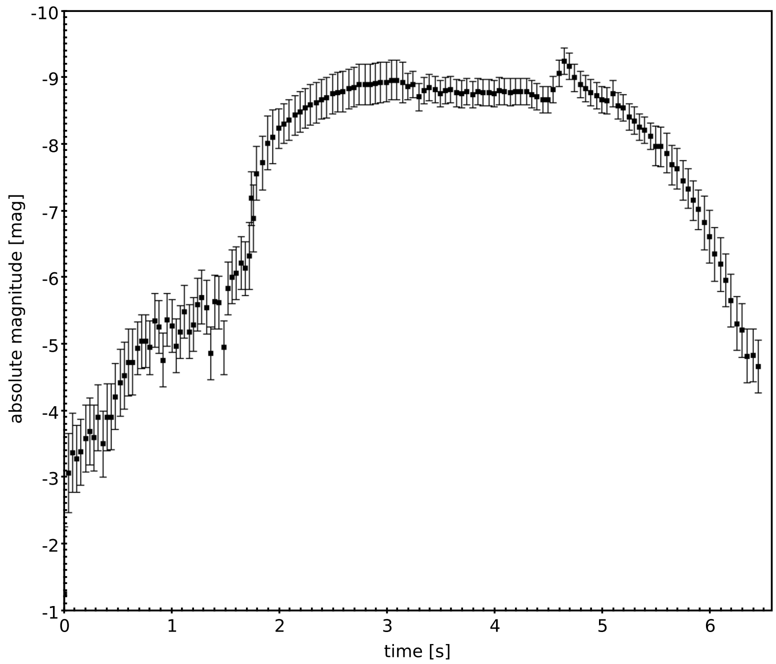

Figure 4. The light curve of the PF120916 Piecki fireball.

The calculations were repeated by modifying the input data within the observed uncertainties. Finally, the potential rectangular area of the fall with 100-200 meters of width and a length of up to four kilometers was obtained. It is located about 4 km south of Reszel city and couple hundred meters east of Leginy village, overlapping partially with Legińskie and Kławój lakes (see Fig. 6).

The light curve of the Piecki fireball indicates that the meteoroid fragmented during the atmosphere passage. Thus, it is highly unlikely that a single 15 kg meteorite hit the ground. Most probable impactors have the mass of around 5 kg.

The bolide event occurred in the northern part of the Warmia and Masuria region, in the south-western part of the Kętrzyn district in the mezoregion of Mrągowo Lakes. It is part of the Mazurian Lake District with an undulating character of surface, locally hilly with the inclination towards the north-west. The calculated strewn-field obtained from the data is situated south of the town of Reszel. The land there are meadows and wastelands with two lakes placed in the middle and south of the area - the Kławój Lake and Legińskie Lake. The surface basement consists of a continuous Quaternary layers of clays, silts and sands lakeside, silts and peats.

Several expeditions to the strewn-field took place in the period of September

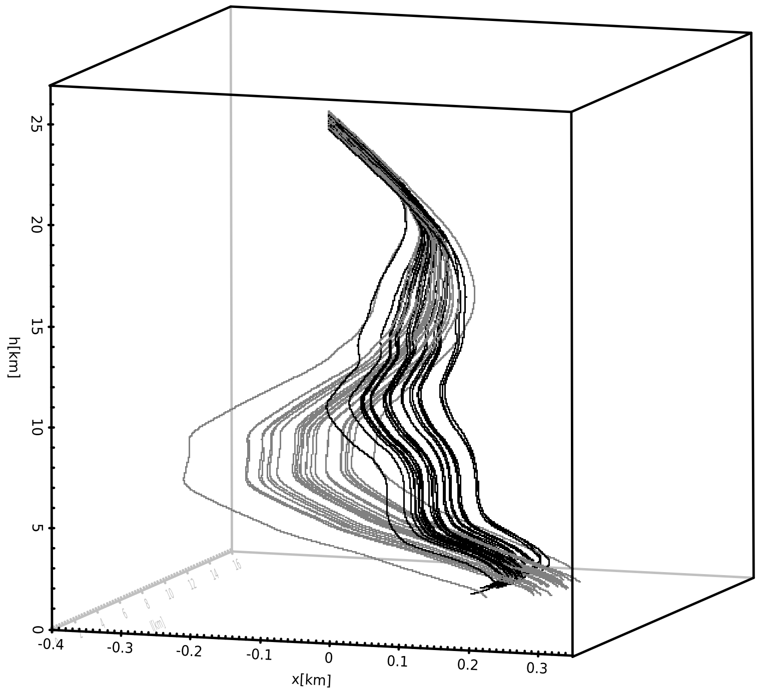

Figure 5. The dark flight tracks for $2-15$ kg meteorites. Different colors of the tracks are used to distinguish the atmosphere profiles from Kaliningrad and Łeba.

to November 2016, involving more than 20 volunteers who searched the area and walked a total of over 1,200 km. Because the meteorite fall was in the late summer, part of the arable land was already plowed and the fertile black soil made it difficult to recognize the meteorite on its surface. Also the most promising area was not searched enough because of lack of access - the most likely drops of 5 kg meteorite were in the lush swamp suited south of Kławój Lake.

One of the search goals was to cover also the region of the smallest mass strewn-field in order to increase the probability of meteorite find. Unfortunately, the lack of a larger number of searchers, the bad weather and the diminishing by cultivating still available area did not allow us for the efficient prospection. The searched out area is marked by tilted stripes in Fig. 6.

In the spring time at least one large search campaign is planned by a group of volunteers. We plan to use metal detector prospection to check the most probable impact points in the skipped areas during the autumn campaign. Some volunteers also declared a willingness to individually scan for meteorites the strewn-field next year.

Figure 6. The computed impact area of Reszel meteorite caused by the PF120916 Piecki fireball. The impact points for 15, 5 and 2 kg meteorites and the trajectory axis are also shown. The area searched by our expeditions is marked by tilted stripes.

3.5. Orbit

Based on the observational data we were able to determine the radiant of the PF120916 Piecki fireball, its geocentric velocity and orbital parameters of the meteoroid which entered the Earth's atmosphere. The orbital parameters of the meteroid which caused the fireball are listed in Table 3.

Table 3 lists also the orbital elements (taken from the NEODyS-2 database) of asteroids with orbits similar to PF120916 Piecki fireball. We selected only bodies with the Drummond criterion $D' < 0.05$ (Drummond 1981). The largest body from this group is (85640) 1998 OX4 whose size is estimated to be 300-600 meters. It is an Apollo group asteroid and a Mars crosser. It is included in the Minor Planet Center list of Potentially Hazardous Asteroids (PHAs) as it comes to within 0.05 AU of the Earth periodically.

Similarity of the orbit of the Piecki fireball to almost all mentioned asteroids seems to be rather accidental. Orbits of such size and shape, and with a slight inclination to the ecliptic, are characteristic for the whole group of Apollo type

Table 3. Orbital elements of the PF120916 Piecki fireball and asteroids with similar orbits ($D' < 0.05$). Both the orbital elements of the NEOs and their errors are taken from the NEODyS-2 database.

	a [AU]	e	q [AU]	ω [deg]	Ω [deg]	i [deg]	D'
PF120916	1.520(7)	0.476(2)	0.795(1)	249.50(6)	170.3150(1)	0.72(2)	
2014 DA	1.5056(4)	0.4848(2)	0.7757(2)	110.192(2)	313.662(1)	2.464(1)	0.0264
2013 BY2	1.593(1)	0.476(1)	0.834(1)	298.7(9)	114.01(6)	2.265(4)	0.0324
1998 OX4	1.58043(1)	0.48572(1)	0.8128(1)	117.114(1)	299.704(1)	4.513(1)	0.0347
2014 SH224	1.5766(1)	0.4657(3)	0.8424(1)	345.86(4)	80.41(4)	0.346(1)	0.0353
2004 RU109	1.5325(7)	0.4894(3)	0.7825(5)	250.588(2)	171.395(2)	5.849(3)	0.0355
2013 BR27	1.5516(2)	0.4594(8)	0.8388(2)	120.72(2)	296.97(2)	2.565(4)	0.0373
2014 SS143	1.485(1)	0.4577(4)	0.8054(9)	259.919(3)	174.596(1)	1.727(2)	0.0438
2013 CV83	1.4346(4)	0.4533(2)	0.7843(1)	86.934(8)	339.417(7)	4.572(2)	0.0444
2015 RU36	1.636(8)	0.486(2)	0.8412(9)	75.74(2)	349.963(7)	4.02(2)	0.0446
2013 RN9	1.560(3)	0.466(1)	0.8325(5)	105.988(9)	324.51(2)	3.50(1)	0.0456

asteroids. The only interesting case is the 20-40 meter size 2014 SH224 asteroid, which passed close to the Earth ($\sim$ 0.1 AU) on 2016 September 18.94605 UT i.e. only six days after the appearance of the Piecki fireball, which indicates that both bodies might be related. Still it is not a decisive argument. To be more certain one needs to do a numerical integration of the orbital parameters backwards in time in order to test the link between the fireball and the asteroid.

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References

Ceplecha, Z., McCrosky, R.E.: 1976, *Journal of Geophys. Research* **81**, 6257

Ceplecha, Z.: 1987, *Bulletin of the Astronomical Institutes of Czechoslovakia* **38**, 222

Drummond, J.D.: 1981, *Icarus* **45**, 545

Molau, S.: 1999, in *Meteoroids 1998*, eds.: W.J. Baggaley and V. Porubčan, Tatranská Lomnica, Slovakia, 131

Olech, A., Żołądek, P., Wiśniewski, A. et al.: 2006, in *Proceedings of the International Meteor Conference*, eds.: L. Bastiaens, J. Verbert, J.-M. Wislez and C. Verbeeck, Oostmalle, Belgium, 53

Olech, A., Żołądek, P., Wiśniewski, A. et al.: 2016, *MNRAS* **461**, 674

SonotaCo: 2009, *WGN* **37**, 55

Spurný, P.: 1997, *Conference Paper, SPIE Proceedings* **3116**, 144

Spurný, P., Borovička, J., Shrbený, L.: 2007, in *Near Earth Objects, our Celestial Neighbors: Opportunity and Risk, Proceedings if IAU Symposium 236*, eds.: G.B. Valsecchi , D. Vokrouhlický and A. Milani, Cambridge, Cambridge University Press., 121

Wiśniewski, A., Żołądek, P., Olech, A. et al.: 2016, in *Proceedings of the International Meteor Conference*, eds.: A. Roggemans and P. Roggemans, Egmond, the Netherlands, 341

Żołądek, P.: 2012, in *Proceedings of the International Meteor Conference*, eds.: M. Gyssens and P. Roggemans, Sibiu, Romania, 53