PF131010 Ciechanów fireball - the body possible related to Near Earth Asteroids 2010 TB54 and 2010 SX11

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Accepted 2015 March 15. Received 2015 February 20; in original form 2015 January 31

ABSTRACT

On 2010 October 13, the Apollo type 20-meter asteroid 2010 TB54 passed within 6.1 lunar distances from the Earth. On the same date, but 11.4 hours earlier, exactly at 02:52:32 UT, the sky over central Poland was illuminated by -8.6 magnitude PF131010 Ciechanów fireball. The trajectory and orbit of the fireball was computed using multi-station data of *Polish Fireball Network (PFN)*. The results indicate that the orbit of the meteoroid which caused the PF131010 fireball is similar to the orbit of 2010 TB54 asteroid and both bodies may be related. Moreover, two days before appearance of Ciechanów fireball another small asteroid denoted as 2010 SX11 passed close to the Earth-Moon system. Its orbit is even more similar to the orbit of Ciechanów fireball parent body than in case of 2010 TB54.

The PF131010 Ciechanów entered Earth's atmosphere with the velocity of 12.8 ± 0.2 km/s and started to shine at height of 82.5 ± 0.3 km. Clear deceleration started after first three seconds of flight, and the terminal velocity of the meteor was only 5.8 ± 0.2 km/s at height of 29.3 + 0.1 km. Such a low value of terminal velocity indicates that fragments with total mass of around 2 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 near Grabowo village south of Ostrołęka city.

Key words: meteorites, meteors, meteoroids, asteroids

1 INTRODUCTION

On 15 February 2013 at about 03:20 UTC 17-meter asteroid entered the Earth's atmosphere and exploded while travelling at a speed of 19 km/s. The body became a superbolide meteor, which was seen over the southern Ural region. At the moment of maximum brightness, which occurred near the city of Chelyabinsk, the meteor was brighter than the Sun. The several small fragments of meteorite (ordinary chondrite) were quickly found on the west of Chelyabinsk, with the largest fragment of total mass of 654 kg raised from the bottom of the Chebarkul lake on 16 October 2013 (Popova et al. 2013, Brown et al. 2013, Borovicka et al. 2013, Kohut et al. 2014).

About 16 hours after Chelyabinsk fireball occurrence

the 45-meter asteroid 367943 Duende (2012 DA14) approached the Earth and missed it by about 27 700 km. This was striking coincidence but subsequent analysis of the data clearly indicated the two objects could not have been related because they had widely different orbits (Wlodarczyk 2012, Moskovitz et al. 2013)

What is more interesting similar situation occurred over two years earlier. On the night of 2010 Oct 9/10, Mt. Lemmon Survey reported a discovery of a new 20-meter Apollo type asteroid designated as 2010 TB54 (Hergenrother 2010). The asteroid has been expected to pass only 6.1 lunar distance (0.011 AU) from the Earth. Over 11 hours earlier sky over central Poland was illuminated by -8.6 magnitude fireball. What is even more interesting these both bodies, contrary to Chelyabinsk meteorite parent body and Duende asteroid, seem to be related.

In this paper we report an analysis of the multi-station

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Figure 1. The video images of PF131010 Ciechanów fireball captured in Nowe Miasto Lubawskie (upper panel) and Gniewowo (lower panel).

observations of the PF131010 fireball made by cameras of the *Polish Fireball Network*. Both the trajectory and orbit are calculated indicating that the fireball was related to 2010 TB54 asteroid. Even closer resemblance of orbits is found for 2010 SX11 asteroid.

2 OBSERVATIONS

The Polish Fireball Network (PFN) is the project whose main goal is regularly monitoring the sky over Poland in order to detect bright fireballs occurring over the whole territory of the country (Olech et al. 2005, Żołądek et al. 2007, 2009, Wiśniewski et al. 2012). It is kept by amateur astronomers associated in Comets and Meteors Workshop (CMW) and coordinated by astronomers from Copernicus Astronomical Center in Warsaw, Poland. Currently, there are over 20 fireball stations belonging to PFN which operate during each clear night.

The PF131010 Ciechanów fireball was observed by five

PFN video stations (Table 1): two of the recordings allowed us to determine the trajectory of the phenomenon, one recording includes observations made from a distance of over 400 km, another one features an initial part of the trajectory, and the last one noticed a bright reflection on clouds layer only.

The most detailed and valuable recording comes from the PFN37 station in Nowe Miasto Lubawskie, positioned 80 km north-east of Toruń (see Fig. 1). A camera with a 70-degree field of view registered its path in the southern direction diagonally through the field of view. The bolide appeared between the constellations of Orion and the Gemini as a point-like structure of about 2 magnitude. The brightness of the meteor increased quickly, and after 1.2 seconds the wake appeared. Until about 3 seconds the bolide continued its luminous path as an object of about -4 magnitude. The fireball started to lose its brightness in the middle of the visible trajectory, reaching a local minimum at about 4.6 second of the flight.

Just after the minimum, a sudden increase of brightness to about -8.5 magnitude was registered. It means that the bolide most probably fell apart. However, on the basis of the video data, it would be difficult to describe the whole process in more details. The image of the moving fireball is strongly overexposed at that moment, one can notice only an elongated structure following the bolide and disappearing after less than 0.2 of a second. From that point the brightness of the bolide decreases constantly and evenly, without any visible fluctuations. After over 9.5 seconds of the luminous trajectory of the bolide, becoming an object with a brightness lower than 0 magnitude, hiding behind a bough of a tree visible near the horizon and could not be seen again on the other side of that obstacle.

The second recording, pertinent to the analysis of that phenomenon, was obtained from the PFN24 Gniewowo station, situated 15 km north-west of Gdynia (see the second panel of Fig. 1). Because of the station's technical problems we got just a static image, without any possibility of recovering data from video frames. However, a file with the XY coordinates was saved along with it, and on that basis one can reconstruct the position of the bolide. The image of that phenomenon is similar to that, registered by the Nowe Miasto Lubawskie station but, in this case, the distance is notably larger; its position is much closer to the horizon with lower elevation angles.

The third of the stations – PFN38 Podgórzyn – was situated on the opposite side of Poland, 10 km of Jelenia Góra. From a distance of several hundred kilometers the phenomenon was visible just over the horizon. It is interesting that there is a persistent train which does not disappear for about 0.5 of a second in the place of the flare. That train can be connected to the elongated structure, visible after the flare in the Ciechanów station images. The recordings of the Podgórzyn station show that the bolide ended right over the horizon, on the edge of the camera's field of view.

A very small fragment of the fireball was registered by the PFN32 Chełm station. The PFN13 Toruń station managed to notice a distinct bright reflection on a thin clouds layer covering the sky. The fireball was not observed by other fireball networks in central Europe.

On the basis of all records, we determined the momentum of the phenomenon. The moment of maximum bright-

Table 1. Basic data on the PFN stations which recorded PF131010 Ciechanów fireball.

Code	Site	Longitude [°]	Latitude [°]	Elev. [m]	Camera	Lens
PFN13	Toruń	$18.6209 \ {\rm E}$	53.0252 N	65	Siemens CCBB1320-MC	Ernitec 4 mm $f/1.2$
PFN24	Gniewowo	18.3042 E	54.5779 N	130	Siemens CCBB1320-MC	Ernitec 4 mm $f/1.2$
PFN32	Chełm	23.4982 E	51.1355 N	194	Mintron 12V8HC-EX	VM2312 2.3-6 mm 4 mm
PFN37	Nowe Miasto Lubawskie	$19.5922 \ \mathrm{E}$	53.4349 N	95	Tayama C3102-01A1	Computar 4 mm f/1.2
PFN38	Podgórzyn	15.6817 E	50.8328 N	360	Tayama C3102-01A4	Evatar 3.5-8 mm 4 mm

ness was at 02:52:32 UT ± 2 seconds. The beginning of the phenomenon observed by PFN37 station was recorded at 02:52:28 UT, while the last point of the bolide was visible at 02:52:38 UT.

The observations were made using CCTV cameras with comparable parameters. All the cameras worked in PAL resolution 786×584 with 25 frames per second offering 0.04 second temporal resolution. The monochrome CCD detectors equipped with fast CCTV lenses of focal length of around 4 mm were used. A typical limiting magnitude of that kind of equipment amounts to +2. The details concerning coordinates all the stations and equipment used are summarized in Table 1.

3 DATA REDUCTION

Using the data gathered by the PFN network cameras an analysis of the phenomenon was conducted. Because of the huge differences in distance from the fireball and, in consequence the quality of the images, only two best recordings were taken into account: from the PFN37 Nowe Miasto Lubawskie station and from the PFN24 Gniewowo station, as both videos show the most complete flight of the bolide. The data from these stations, after a previous conversion, were further reduced astrometrically by the UFO ANALYZER program (SonotaCo 2009). Initially only automatic data were taken into account but during the further processing it became obvious that significant overexposures, the presence of the wake and a possible fragmentation after the flare caused quite serious errors concerning the correct position of the points of the phenomenon. The measurement precision improved noticeably when the bolide's position was determined using UFO Analyzer astrometric solution with manual centroid measurement UFO ANALYZER.

The position of the meteor was recognized on 241 frames of the video from PFN37 station, which means that the time of the flight lasted 9.64 seconds. The photometry of the phenomenon was done with the help of the IRIS program, using reference stars, Jupiter and the Moon at phase close to New Moon as comparison objects. The trajectory of the phenomenon was determined using the PyFN software (Żołądek 2012).

4 RESULTS

4.1 Trajectory of the fireball

The Ciechanów fireball moved from west to east following moderately steep trajectory. The trajectory azimuth and



Figure 2. The luminous trajectory of the PF131010 fireball over eastern Poland and the location of the PFN stations which data were used in calculations.

the trajectory slope were 261 degrees and 29 degrees, respectively. The beginning of the bolide was situated in a place with the following coordinates: $\phi = 52.831(2)^{\circ}$ N, $\lambda = 19.901(1)^{\circ}$ E at the height of 82.5 ± 0.3 km. That location is 33 km north of Plock. In next seconds the bolide traveled east and flew 2 kilometers north of Ciechanów, reaching its maximum brightness at the height of 54.4 ± 0.1 km. Then it went 10 km south of Przasnysz, 9 km north of Maków Mazowiecki and it reached its ending point 10 km north-west of Różan. It was situated then at the height of 29.3 ± 0.1 km over the following coordinates: $\phi = 52.962(2)^{\circ}$ N, $\lambda = 21.275(5)^{\circ}$ E. The trajectory of the PF131010 fireball is shown in Fig. 2 and all important parameters are summarized in Table 2.

4.2 Velocity

Based on those observations the velocity of the phenomenon was determined for different points of its trajectory. In the initial part of the trajectory the velocity did not change in a noticeable way. The initial velocity of the bolide was close to the lower limit of meteoroids entering the atmosphere of the Earth and amounted to 12.8 ± 0.2 km/s. After the third second of the flight the velocity decrease became clearly visible, by t = 6.5 seconds amounting to 12 km/s; from about 7 seconds the intensive slowing down of the residue of the me-

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Table 2.	Characteristics	of the	PF131010	Ciechanów	fireball

2010 October 13, T = $02^h 52^m 32^s \pm 2.0^s$ UT							
Atmospheric trajectory data							
Beginning Max. light Terminal							
Vel. $[km/s]$	12.9 ± 0.2	12.7 ± 0.2	5.8 ± 0.2				
Height [km]	82.5 ± 0.3	54.4 ± 0.1	29.3 ± 0.1				
Long. [°E]	19.901 ± 0.001	20.622 ± 0.002	21.275 ± 0.005				
Lat. [°N]	52.831 ± 0.002	52.902 ± 0.001	52.962 ± 0.002				
Abs. magn.	-1.6 ± 0.5	-8.6 ± 0.5	1.5 ± 1.0				
Slope [°]	29.2 ± 0.1	28.8 ± 0.1	28.4 ± 0.1				
Duration	9.4 sec						
Lenght	$110.5\pm0.8~\mathrm{km}$						
Stations	Nowe Miasto Lubawskie, Gniewowo, Podgórzyn, Chelm, Toruń						
Radiant data (J2000.0)							
	Observed	Geocentric	Heliocentric				
$RA [^{\circ}]$	19.93 ± 0.24	6.17 ± 0.36	-				
Decl. [°]	17.68 ± 0.04	0.41 ± 0.42	-				
Vel. $[km/s]$	12.9 ± 0.2	6.9 ± 0.3	32.2 ± 0.3				



Figure 3. The evolution of the velocity of the PF131010 Ciechanów fireball. Initial velocity given by observations was assumed as a preatmospheric velocity, initial velocity was nor fitted due to limited data precision. Error bars has been determined by repeating calculations with various input values according to astrometry errors.

teoroid with more or less constant value of about 2700 m/s² can be noticed. The fireball stopped being visible (disappearing behind trees near the horizon) at the velocity of 5.8 ± 0.2 km/s. The time of its further flight was very short, most possibly far below 1 second; otherwise the phenomenon would have been observed through a crack between trees on the extension line of the phenomenon visible part. The evolution of the velocity of PF131010 Ciechanów fireball is shown in Fig. 3.

4.3 Brightness

The light curve of the Ciechanów fireball is shown in Fig. 4 and has some interesting features. It should be emphasized especially the fact that there are two separate parts of the curve, distinctly differing in luminosity. Between its initial phase and the final phase you can notice a flare of a maximum absolute magnitude amounting to -8.6 ± 0.5 .

Both parts of the curve themselves have gentle characteristics. In the initial phase there were no brightness oscillations. The luminosity increases from the border of the camera limit to about -4 magnitude in about 1.5 seconds. The further increase is a bit slower, after 3.5 seconds the bolide reaches a local maximum amounting to -5.8 magnitude. For the next second the brightness of the bolide decreases to a value of -4 magnitude. By t = 4.5 seconds one can see a sudden increase of brightness when the luminosity increases by five magnitudes in several tenths of a second. The flare takes place at 55 km with the dynamic pressure being rather low and amounting to 0.05 Mpa. The dynamic pressure has been calculated using formula $p = \Gamma \rho v^2$, using $\Gamma = 0.921$ (Carter et al. 2009) and air density given by MSISE-90 atmospheric model (calculated for the exact moment of the event).

The second part of the curve starts with a brightness increase; then the luminosity decreases slowly during next seconds but keeping a very high level, reaching the value before the flare only in the next 3 seconds. For the decreasing part of the light curve some luminosity changes of 0.5 magnitude can be seen at t = 7.8 second and the dynamic pressure of 0.35 Mpa. A small fragmentation in that place is possible. In the final phase of the phenomenon the curve is very gentle, the fireball is fading down slowly, reaching a brightness of +2 magnitude in the last frame. A light curve with such properties as the ones shown above might indicate some interesting properties of the meteoroid. Observed flare and brighter part of lightcurve may by caused by large number of small fragments separating from the main body after t = 4.5 second. There were no clearly visible fragments on any video record but bright feature visible on the video



Figure 4. The light curve of the PF131010 Ciechanów fireball. Brightness has been determined using aperture photometry with bright stars and the Moon images registered by the same camera used as a reference objects. Errors has been determined by repeating measurements with various reference objects and settings.

from PFN38 camera may suggest that the large number of small fragments ablated shortly after t = 4.5 second. Further meteoroid erosion may be responsible for the brightness increase in second part of the trajectory. Such mechanism of meteoroid erosion has been recently modeled for Kosice fireball (Borovička et al. 2013). Another possibility is a distinct change of the properties of material undergoing ablation. The meteoroid may be covered with some kind of a shell with lower ablation coefficient.

4.4 Dark flight and a possible fall of the meteorite

The observed final velocity of 5.8 km/s at the height of 29 km (which most probably could descend even lower) indicates a possible meteorite fall near Grabowo, south of Ostolęka. An estimated impact point of the single meteorite weighing about 2 kilograms is about 22 kilometers of the final trajectory point, about 3.5 km to the left of the trajectory axis (see Fig. 5). The exact coordinates of the impact point are $\phi = 52.961(5)^{\circ}$ N, $\lambda = 21.624(30)^{\circ}$ E. Calculations have been performed with assumption that only one fragment survived the ablation. The dynamic mass has been calculated using parameters observed at the end of the visible trajectory. The mass is given for chondrite body with bulk density of 3.7 g \cdot cm³ and calculated using standard formulas (Ceplecha 1987).

Because of huge trajectory uncertainties concerning the parameters observed in the final part of the trajectory the precision in determining the final place of impact amounts to about 3 km.

An atmosphere profile, obtained during atmospheric probing performed on October 13, 2010 at 00:00 UT (the Legionowo meteorological station located 65 km south of the terminal point), was used for the computations.



Figure 5. Map with computed impact area of meteorite caused by the PF131010 Ciechanów fireball. The final part of the trajectory is also shown.



Figure 6. Plot of the inner Solar System with orbits of the PF131010 Ciechanów fireball and two asteroids: 2010 TB54 and 2010 SX11.

A searching expedition was launched soon after the first rough estimates of results was determined, but their efforts were fruitless. After another manual measurement of the meteor position there was a new result (presented here), slightly different from the previous one. The second expedition took place at the end of March 2015, though without positive results either. The area (with active agriculture) is not easy to search, with at least half of it not easily accessible.

4.5 Orbit

Based on the observational data we were able to determine the radiant of Ciechanów fireball, its geocentric velocity and orbital parameters of the meteoroid which entered the

	$1/a$ $[1/{ m AU}]$	е	q [AU]	ω [deg]	Ω [deg]	i[deg]	P year	D'
PF131010	0.837(3)	0.263(3)	0.880(3)	64.14(82)	19.5248(1)	0.45(5)	1.304(10)	
$2010 \ \mathrm{TB54}$	0.8680(3)	0.2791(3)	0.8308(2)	82.566(4)	14.2330(3)	6.62(1)	1.2366(7)	0.058
2010 SX11	0.8703(3)	0.2495(2)	0.8703(3)	266.873(4)	182.524(1)	5.17(1)	1.2487(5)	0.043

Table 3. Orbital elements of the PF131010 fireball compared to the orbits of 2010 TB54 and 2010 SX11 asteroids.

Earth's atmosphere. The orbital parameters are listed in the first row of Table 3, and the diagram showing orbit of the fireball in the inner Solar System is displayed in Fig. 6.

The orbit of Ciechanów fireball is located almost in the ecliptic plane and has low eccentricity. The meteoroid hit the Earth less than two months before perihelion passage which was expected on December 4, 2010 at distance of $q = 0.880 \pm 0.003$ AU.

Comparison of the orbit of Ciechanów fireball to orbits of Near Earth Objects (NEO) allowed us to select several asteroids with Drummond criterion $D_D < 0.109$ (Drummond 1979). Two of them are especially interesting. The 2010 TB54 asteroid has D_D criterion value as small as 0.058. What is more interesting this object passed within the distance of only 0.016 AU from the Earth on October 13, 2010 at 14:14 UT, i.e. only 11.4 hours before the occurrence of the Ciechanów fireball. This asteroid has been discovered by Mount Lemnon Survey on October 9, 2010, its observing arc is 3 day long and based on 30 optical measurements. 2010 TB54 has absolute magnitude +26.8 magnitude, and its diameter is less than 29 meters.

Even lower Drummond criterion value ($D_D = 0.043$) was noted for 2010 SX11 asteroid. The close encounter with this body occurred on October 11, 2010 at 13:10 UT at the distance of 0.025 AU. In this case the time difference amounts to 37.7 hours. 2010 SX11 is a larger body, with absolute magnitude +24.8 magnitude and diameter between 33 and 73 meters. Observing arc span is 21 days, 33 optical measurements were used to determine orbital elements. Uncertainties of orbital elements for both asteroids are similar but slightly smaller for 2010 SX11.

Our results indicate the possibility that in period of October 11-13 there is an activity of meteor shower of asteroid origin with radiant located in the border of Pisces and Aries constellations.

5 MODELING

A numerical integration of the orbital parameters backwards in time has been performed in order to test the link between the fireball Ciechanów and two NEOs: 2010 SX11 and 2010 TB54. For the integrations of the asteroids and test particles representing fireball, the RADAU integrator in the Mercury software was used (Chambers 1999). The model of the Solar System used in integrations included: 8 planets, four asteroids (Ceres, Pallas, Vesta, and Hygiea), and the Moon as a separate body. The positions and velocities of the perturbing planets and the Moon were taken from the DE406 (Standish 1998). The initial orbital elements of asteroids 2010 SX11 and 2010 TB54 were taken from JPL HORIZONS website¹. Together with initial orbital elements of asteroids, the test particles were integrated to the same epoch of the beginning of the integration. Next, the backward integration was continued for 5000 yr.

During the evolution, the ascending and descending nodes of theoretical particles are dispersed within heliocentric distances from 0.8 to 1.8 AU, with a concentration around Earth's orbit. The generated stream has been widely dispersed in longitude, mostly by perturbation from the Earth. Therefore, application of a conventional similarity functions: D_{SH} (Southworth and Hawkins 1963), D_D (Drummond 1981), or D_J (Jopek 1993), would be strongly influenced in the longitude term in the D-criterion. Due to it, we used (Steel 1991) criterion, D_S , where the longitude term is not included. Figures 7 and 8 show that the evolution of the D_S criterion reveals a link between the Ciechanów fireball and NEOs, with the values of D_S being less than 0.15 through the whole integration time (except one test particle when we compare orbits with 2010 TB54 and 2010 SX11, respectively).

The theoretical geocentric radiants of the asteroids has been determined using Fortran code which is able to calculate radiant coordinates and theoretical stream orbit (Neslusan et al. 1998). Theoretical radiants of asteroids and Ciechanów meteoroid doesn't match if calculated from present orbital elements. However similarity of the radiant is visible for back integrated orbital elements. Distance between 2010 SX11 radiant and Ciechanów radiant was close to 8.5 degrees 5000 years ago. Also the theoretical radiant of 2010 TB54 was located in the same sky area, 7.5 degrees from the Ciechanów radiant. Five thousands years ago all theoretical radiants were closer than 10 degrees each other with geocentric discriminants $D_D = 0.044$ for 2010 SX11, $D_D = 0.087$ for 2010TB54 and $D_D = 0.010$ for Ciechanów. Change of radiant distances in time may suggest that age of possible stream is probably larger than 10000 years.

6 SUMMARY

In this paper we presented an analysis of the multi-station observations of a bright fireball which occurred over eastern Poland. Our main conclusions are as follows:

• the meteor appeared on 2010 Oct 12/13 at 02:52:32 UT over the eastern part of Poland was detected by five video stations of *Polish Fireball Network*,

• the maximum brightness of the fireball reached $-8.6\pm$

¹ http://ssd.jpl.nasa.gov/?horizons



Figure 7. Evolution of the D_S criterion calculated by comparing the orbit of 2010 SX11 and those of test particles. The red dashed line shows the threshold value ($D_c = 0.15$)



Figure 8. Evolution of the D_S criterion calculated by comparing the orbit of 2010 TB54 and those of test particles. The red dashed line shows the threshold value ($D_c = 0.15$)

0.5 mag and was observed at height of 54.4 ± 0.1 km over Ciechanów city,

• the entry velocity was only 12.8 ± 0.2 km/s and after three seconds of flight the meteoroid was significantly decelerated with the rate of 2700 m \cdot s⁻² resulting with final velocity of only 5.8 ± 0.2 km/s,

• low value of final velocity indicates a possible 2 kg meteorite fall near Grabowo, south of Ostołęka,

• the low eccentric orbit of the fireball, positioned almost in the ecliptic plane, is similar to orbits of 2010 TB54 and 2010 SX11 asteroids, which passed the Earth 11.4 and 37.7 hours before the occurrence of the fireball, respectively,

• numerical integration of the orbital elements backwards in time indicates that Ciechanów fireball and 2010 TB54 and 2010 SX11 asteroids may have common origin. This work was supported by the NCN grant number $2013/09/{\rm B}/{\rm ST9}/02168.$

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