2015 Southern Taurid fireballs and asteroids 2005 UR and 2005 TF50

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ABSTRACT
On the night of October 31, 2015 two bright Southern Taurid fireballs occurred over Poland, being one of the most spectacular bolides of this shower in recent years. The first fireball – PF311015a Okonek – was detected by six video stations of Polish Fireball Network (PFN) and photographed by several bystanders, allowing for precise determination of the trajectory and orbit of the event. The PF311015a Okonek entered Earth’s atmosphere with the velocity of 33.2 ± 0.1 km s⁻¹ and started to shine at height of 117.88 ± 0.05 km. The maximum brightness of −16.0 ± 0.4 mag was reached at height of 82.5 ± 0.1 km. The trajectory of the fireball ended at height of 60.2 ± 0.2 km with terminal velocity of 30.2 ± 1.0 km s⁻¹. The second fireball – PF311015b Ostrowite – was detected by six video stations of PFN. It started with velocity of 33.2 ± 0.1 km s⁻¹ at height of 108.05 ± 0.02 km. The peak brightness of −14.8 ± 0.5 mag was recorded at height of 82.2 ± 0.1 km. The terminal velocity was 31.8 ± 0.5 km s⁻¹ and was observed at height of 57.86 ± 0.03 km. The orbits of both fireballs are similar not only to orbits of Southern Taurids and comet 2P/Encke, but even closer resemblance was noticed for orbits of 2005 UR and 2005 TF50 asteroids. Especially the former object is interesting because of its close flyby during spectacular Taurid maximum in 2005. We carried out a further search to investigate the possible genetic relationship of Okonek and Ostrowite fireballs with both asteroids, that are considered to be associated with Taurid complex. Although, we could not have confirmed unequivocally the relation between fireballs and these objects, we showed that both asteroids could be associated, having the same origin in a disruption process that separates them.

Key words: meteorites, meteors, meteoroids – minor planets, asteroids: general – planetary systems.

1 INTRODUCTION
The Taurids are an annual meteor shower active in October and November with maximum Zenithal Hourly Rates of about 5. The orbit of the shower has low inclination and thus, due to the gravitational perturbations of planets, swarm of particles is diffuse and separated into two main branches i.e. Northern Taurids and Southern Taurids.

The parent body of Taurid complex is comet 2P/Encke (Whipple 1940), however both 2P/Encke and Taurids are believed to be remnants of a much larger object, which has disintegrated over the past 20 000–30 000 yr (Asher, Clube & Steel 1993; Babadzhanov, Williams & Kokhirova 2008). Recently, Porubčan, Krončov & Williams (2006) identified as many as 15 Taurid complex filaments and found possible association with nine near earth objects (NEOs). Most recently, Jopek (2011) identified as many as 14 parent bodies of the Taurids stream.

It has been widely recognized that the Taurid complex, despite its moderate activity, produces a great number of bright fireballs.

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Asher (1991) suggested that a swarm of Taurids being in 7:2 resonance with Jupiter produces occasional enhanced activity. It was later confirmed by Asher & Izumi (1998) who predicted observed swarm encounters in 1998, 2005 and 2008. In period 2009–2014 activity of Taurid shower was typical but still some fireballs were observed (Madiedo, Toscano & Trigo-Rodriguez 2011; Madiedo et al. 2014). The return in 2005 was spectacular with both enhanced global activity and maximum rich in fireballs (Dubietis & Arlt 2006). In 2008 the activity of the shower was lower but still it may be considered as enhanced (Jenniskens et al. 2008; Shrenby & Spurný 2012). According to the Asher’s model, the next swarm encounter year was expected in 2015.

Additionally, most recently, the Taurid shower was suspected to have ability to produce meteorites (Brown et al. 2013; Madiedo et al. 2014). On the other hand, Tubiana et al. (2015) found no spectroscopic evidence for a link between 2P/Encke, the Taurid complex NEOs and CM type carbonaceous chondrite meteorites which felt recently in Denmark and were suspected for origin from the Taurid-Encke complex. Moreover, there is still no consensus concerning origin of the complex while the spectral data of its largest objects do not support a common cometary origin (Popescu et al. 2014).

In this paper we report the results of observations and data reduction of two very bright Taurid fireballs which were detected on 2015 October 31 over Poland. Afterwards we discuss their connection with the asteroids 2005 UR and 2005 TF50, and comet 2P/Encke. This is the pilot study preceding more comprehensive analysis devoted to an enhanced fireball activity of 2015 Taurid meteor complex and its comparison to 2005 Taurid return.

2 OBSERVATIONS

The Polish Fireball Network (PFN) is the project whose main goal is to regularly monitor the sky over Poland in order to detect bright fireballs occurring over the whole territory of the country (Olech et al. 2006; Zoładek et al. 2007, 2009; Wiśniewski et al. 2012). It is kept by amateur astronomers associated in Comets and Meteors Workshop and coordinated by astronomers from Copernicus Astronomical Center in Warsaw, Poland. Currently, there are almost 30 fireball stations belonging to PFN that operate during each clear night. It total over 60 sensitive Closed-Circuit TeleVision (CCTV) cameras with fast and wide angle lenses are used.

During last ten years typical setup of the PFN station consisted of 2 to 3 Tayama C3102-01A4 cameras equipped with 4 mm f/1.2 Computar or Ernitec lenses. Tayama C3102-01A4 is cheap CCTV camera with 1/3 arcsec Sony SuperHAD CCD detector working in PAL interlaced resolution with 25 frames s⁻¹. The field of view of one camera with 4 mm lens is 69.8 × 55.0 deg with scale of ~10 arcmin pixel⁻¹. This setup allows detection of the atmospheric entries of debris (both natural and artificial) with accuracy of trajectory determination below 300 m.

Almost each station is equipped with a PC computer with Matrox Meteor II frame grabber. The signal from each camera is analysed on-line. Our video stations use the METREC software (Molau 1999) which automatically detects meteors in frames captured by Matrox Meteor II frame grabber. The frames containing meteors are stored into BMP files. Additionally, information about basic parameters of the event such as its time of appearance and (x, y) coordinates on the frame are saved into METREC INF files. In case of some new stations containing higher resolution cameras, UFO CAPTURE software is used (SonotaCo 2009).

On the evening of 2015 October 31 at 18:05 UT a very bright fireball appeared over north-western Poland. The International Meteor Organization received almost 70 visual reports concerning this event from Austria, Czech Republic, Denmark, Germany, Netherlands, Poland and Sweden. Good weather conditions that night in central Europe and the high brightness of the fireball were the main factors for receiving so many reports. However, there are two other reasons for it as well.

First, the fireball appeared almost exactly at the moment of the close flyby of large 2015 TB145 asteroid. Such events attract not only the attention of astronomy amateurs but also general public, encouraging people for observations. What is more interesting, the asteroid was passing across the Ursa Major constellation at that time, which was exactly the same region of the sky where the fireball was visible for observers situated in central and southern Poland, Czech Republic and Slovakia. Finally, the date of the appearance of the fireball was the date of the All Saints’ Eve. This is a public holiday in Poland, when in the evening people gather in cemeteries lighting the candles at the graves of their relatives. The scenery of candles after dusk creates nice landscapes which many people try to photograph. It is thus no surprise then that one of the most beautiful images of this fireball was captures in the cemetery in Czernice Borowe, Poland by Aleksander and Grzegorz Ziełeniecki. This image, kindly shared by the authors, was used for analysis in this work.

The fireball reached its maximum brightness over Okonek city, and therefore received designation PF311015a Okonek. It was observed by six regular PFN video stations, where from the PFN38 Podgórzyn station the fireball was recorded by two cameras. Basic properties of the stations that recorded the event are listed in Table 1. Fig. 1 shows images of the fireball captured by the Podgórzyn and Rzeszów stations. Additionally, the bolide was accidentally photographed in Czernice Borowe (location of the former PFN22 station). Here the Nikon D3300 digital single-lens reflex camera with Nikkor AF-S 18–55 mm f/3.5-5.6 lens was used. The lens

![Table 1. Basic data on the PFN stations which recorded PF311015a Okonek fireball.](https://academic.oup.com/mnras/article-abstract/461/1/674/2595259)

### Table 1. Basic data on the PFN stations which recorded PF311015a Okonek fireball.

| Code   | Site          | Longitude (°) | Latitude (°) | Elev. (m) | Camera                        | Lens               |
|--------|---------------|---------------|--------------|-----------|-------------------------------|--------------------|
| PFN38  | Podgórzyn     | 15.6817 E     | 50.8328 N    | 360       | Tayama C3102-01A4             | Computar 4 mm f/1.2|
| PFN38  | Podgórzyn     | 15.6817 E     | 50.8328 N    | 360       | KPF-131HR                     | Panasonic 4.5 mm f/0.75|
| PFN43  | Siedlice      | 22.2833 E     | 52.2015 N    | 152       | Mintron MTV-23X11C             | Ernitec 4 mm f/1.2  |
| PFN48  | Rzeszów       | 21.9220 E     | 50.0451 N    | 230       | Tayama C3102-01A4             | Computar 4 mm f/1.2|
| PFN52  | Stary Sielce  | 21.2923 E     | 52.7914 N    | 90        | DMK23GX236                    | Tamron 2.4–6 mm f/1.2|
| PFN61  | Piwnice       | 18.5603 E     | 53.0851 N    | 85        | Tayama C3102-01A4             | Ernitec 4 mm f/1.2  |
| PFN67  | Nieznaszyn    | 18.1849 E     | 50.2373 N    | 200       | Mintron MTV-23 X11E           | Panasonic 4.5 mm f/0.75|

1 http://imo.net/node/1645

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was set at 18 mm focal length with relative aperture of f/3.5. The exposure time was 20 s with ISO equal to 800.

Five hours after the PF311015a Okonek appearance another very bright fireball appeared passed through the sky at 23:13 UT. It was only slightly fainter than Okonek fireball but due to the late hour (after midnight of local time) it was not observed by any bystanders. Fortunately, it was detected by six PFN stations which are listed in Table 2 and the images of the fireball captured by the Urzędów and Podgórzyn stations are shown in Fig. 2. The maximum brightness of the meteor was observed over Ostrowite village and thus its designation is PF311015b Ostrowite.

All analogue video cameras contributing to this paper work in PAL interlaced resolution of 768 × 576 pixels, with 25 frames s⁻¹ offering 0.04 s temporal resolution. While, the digital camera DMK23GX236 used in PFN52 station has resolution of 1920 × 1200 pixels and works with 20 frames s⁻¹.

3 DATA REDUCTION

The data from all stations, after a previous conversion, were further reduced astrometrically by the UFO ANALYZER program (SonotaCo 2009). Initially only automatic data were taken into account. However, 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 trajectory and orbit of both fireballs was computed using PYFN software (Zoładek 2012). PYFN is written in PYTHON with usage of SCIPY module and 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

Table 2. Basic data on the PFN stations which recorded PF311015b Ostrowite fireball.

| Code | Site     | Longitude (°) | Latitude (°) | Elev. (m) | Camera          | Lens                |
|------|----------|---------------|--------------|-----------|----------------|---------------------|
| PFN20| Urzędów  | 22.1456 E     | 50.9947 N    | 210       | Tayama C3102-01A1 | Ernitec 4 mm f/1.2   |
| PFN38| Podgórzyn | 15.6817 E     | 50.8328 N    | 360       | Tayama C3102-01A4 | Computar 4 mm f/1.2  |
| PFN38| Podgórzyn | 15.6817 E     | 50.8328 N    | 360       | KPF 131HR       | Panasonic 4.5 mm f/0.75 |
| PFN43| Siedlce   | 22.2833 E     | 52.2015 N    | 152       | Mintron MTV-23X11C | Ernitec 4 mm f/1.2   |
| PFN48| Rzeszów   | 21.9220 E     | 50.0451 N    | 230       | Tayama C3102-01A4 | Computar 4 mm f/1.2  |
| PFN52| Stary Sielc | 21.2923 E    | 52.7914 N    | 90        | Watec 902B      | Computar 2.6 mm f/1.0 |
| PFN57| Krotoszyn | 17.4416 E     | 51.7018 N    | 150       | Tayama C3102-01A4 | Computar 4 mm f/1.2  |
4 RESULTS

4.1 Brightness determination of the fireballs

The photometry of both fireballs was not trivial because of the strong saturation observed. On every camera both fireballs looks like strongly overexposed bulbs of light. Video cameras in the northernmost stations were completely overexposed with whole image saturated. Only the most distant stations can be usable to any kind of photometric measurements. The best results have been obtained using PFN48 Rzeszów video recordings. Both fireballs were recorded completely and from the large distance. The Ökon fireball has been observed from the distance of 525 km (point of maximum brightness), the Ostrowite fireball from the distance of 380 km. From such large distance both fireballs appeared as overexposed objects with only slightly different brightness. The same camera recorded also the Full Moon image and its brightness was used as a primary reference point.

Two independent methods have been applied to estimate the real brightness of fireballs. The first one was based on the measurements of the sky brightness during the fireball flight. These measurements have been compared with the sky brightness caused by the Full Moon in the same camera. As a result we had observed maximum magnitude for Ökon fireball reaching −12.5 and −12.3 mag for the second fireball. Due to low sensitivity of the cameras used and severe light pollution in the PFN48 site the resulted light curve is incomplete and contains only brightest part of the fireball. The second method used several comparison objects recorded by cameras of different types with the same optics as used in PFN48 and working in similar sky conditions. The only available comparison objects were bright planets like Jupiter and Venus (magnitudes in the range −2.5 to −4.5) and the Moon in the different phases (magnitudes from −8 do −12.6). We used two sets of reference objects – one set recorded by the same camera configuration as for both fireballs and one set recorded by camera with two magnitude higher sensitivity. This second set can be treated as a set of reference objects which are brighter by two magnitude and it is helpful to fill the gap between −4.5 and −8 magnitude objects. Some trial and error photometric tests led us to choose the best measure method. Good results has been obtained using aperture photometry on the images with overexposed pixel only visible (pixel with value below 255 on eight bit exposed pixel). Further refinements lowered reject value to 230. From such measurements the \( I(m) \) function has been derived (see Fig. 3). It is an exponential function empirically defined in the form:

\[
I = A^{-0.45 m}
\]

where \( I \) is intensity, \( m \) magnitude and \( A \) constant.

In case of our measurements this function is valid for magnitude range from −4.5 to −12 and is a bit different for higher magnitudes. This method has been used for both fireballs. The light curves have been determined. Measurements have been repeated using different sets of reference points, different results have been used to magnitude error determination. Maximum magnitudes measured using this method were −12.4 for Ökon fireball and −11.9 for Ostrowite fireball, respectively. These results are consistent with measurements of the sky brightness mentioned before. Difference between two methods is less than 0.5 mag. Both fireballs observed from PFN48 Rzeszów, from the distance of hundreds kilometres, looked as very bright objects with brightness comparable to the Full Moon. Reduction to the standard absolute magnitude (fireball visible 100 km directly overhead) gives significantly higher brightness values. Resulting absolute brightness for Ökon fireball is −16 ± 0.4 mag. The Ostrowite fireball was fainter and its absolute magnitude was −14.8 ± 0.5. Both fireballs illuminated the southern parts of the country comparable to the Full Moon. In the north-western part of Poland these fireballs were observed as extremely bright objects which lit the sky with bright blue-greenish light.

4.2 Observational properties of the fireballs

The PF311015a Ökon fireball appeared over Western Pomerania moving almost directly from east to west. The beginning of the meteor was recorded 117.88 km over the Radotzierz Lake. The entry velocity was 33.2 ± 0.1 km s\(^{-1}\) and was slightly higher than the mean velocity of Southern Taurids of 28 km s\(^{-1}\).\(^2\) The peak brightness was observed at the height 82.5 km about 10 km east over Ökon city. The fireball travelled its 181.2 km luminous path in 5.62 s, ending at the height of 60.2 km over Zloczowic. The basic characteristics of the PF311015a Ökon fireball are summarized in Table 3 and its luminous trajectory is shown in Fig. 4.

The PF311015a Ökon fireball appeared as a meteor with absolute magnitude of −0.8 ± 0.5. The brightness was increasing slowly by about 2 mag throughout the first second of the flight. While during the next 1.5 much more steep increase of brightness was observed, ending with plateau lasting about one second when the peak brightness reaching −16.0 ± 0.4 mag was recorded. The plateau finished abruptly at around 3.8 s of the flight with steep and almost linear decrease of brightness. At the terminal point the brightness of the meteor was −2.3 ± 0.5 mag. At the end of the plateau phase a bright persistent train appeared. It started to shine with absolute

\(^2\) Meteor Data Center: http://www.astro.amu.edu.pl/~jopek/MDC2007/
The PF311015a Okonek fireball appeared over the central Poland moving almost from south to north. It started its luminous path at the height of 108.05 km over place located about 5 km west of Konin. The entry velocity was 33.2 ± 0.1 km s⁻¹ and ended at height 57.86 km with terminal velocity equal to 31.8 ± 0.5 km s⁻¹. The PF311015b Ostrowite fireball appeared as object with absolute magnitude of −15, and it slowly faded to −13 mag during almost two seconds. After that moment its brightness started to decrease much faster. Fig. 5 shows the light curve of the PF311015a Okonek fireball and its persistent train.

The PF311015b Ostrowite fireball appeared over the central Poland moving almost from south to north. It started its luminous path at the height of 108.05 km over place located about 5 km west of Konin. The entry velocity was 33.2 ± 0.1 km s⁻¹ and was identical to the velocity of Okonek fireball. The peak brightness was observed at height of 82.2 km over the place located 5 km east of Ostrowite. The fireball travelled its 62.77 km luminous path in 2.0 s and ended at height 57.86 km with terminal velocity equal to 31.8 ± 0.5 km s⁻¹. The basic characteristics of the PF311015b Ostrowite fireball are summarized in Table 4, while its luminous trajectory is shown in Fig. 4.

The PF311015b Ostrowite fireball appeared as object with absolute magnitude of −0.3 ± 1.2. During the first second of the flight its brightness was increasing almost linearly to the value of −9 mag. After that, within a period of about 0.2 s, the brightness of the fireball increased by a factor of 100, reaching the plateau phase lasting for about 0.5 s. During this plateau the maximum absolute magnitude of −14.8 ± 0.5 was recorded. While starting from 1.7 s of the flight the sudden drop of brightness was observed. So that the luminous path ended after about 2 s of the flight, with the terminal magnitude equal to −3.6 ± 0.4.

As in case of Okonek fireball, the bright persistent train was observed as well. It started to be visible just after the plateau phase with brightness of −13 mag, and within over one second it faded to −3 mag. The light curve of the PF311015b Ostrowite fireball and its persistent train is plotted in Fig. 6.

### 4.3 Orbits of the fireballs

The orbital parameters of the Okonek and Ostrowite fireballs as computed from our observations are shown in Table 5. For comparison the orbital parameters of comet 2P/Encke are listed as well. The orbits of both fireballs are located almost in the ecliptic plane and have high eccentricity with perihelion distance slightly less than...
The light curve of the PF311015b Ostrowite fireball (squares) with the distance of 1981 e8 i1998 http://ssd.jpl.nasa.gov criterion shows similarity through shorter period of times: MERCURY 4 1981 2006 D 1993 http://Newton.dm.unipi.it/neodys/index.php lists the Drummond criterion UT 8 D shows orbits of both fireballs in the inner Solar system to- < 2006 D 1999 RCriterion re- 1963 (Drummond 7 2006 3 Arlt moment as outburst of fireball activity of 2005 Taurids (Dubietis & Fig. TF50 Near Earth Asteroids and comet 2P/Encke. Additionally, Okonek and PF311015b Ostrowite fireballs, 2005 UR and 2005 TF50 allowed us to select couple of asteroids with Drummond criterion describing the similarity of the orbit of PF311015b Ostrowite fireball to the orbit of 2005 UR asteroid is its close approach to Earth on 2005 October 30 at 13:11 UT with the distance of 0.041 au. The time of the close passage is at exactly the same moment as outburst of fireball activity of 2005 Taurids (Dubietis & Arlt 2006).

Table 6 lists the Drummond criterion $D_h$ values for PF311015a Okonek and PF311015b Ostrowite fireballs, 2005 UR and 2005 TF50 Near Earth Asteroids and comet 2P/Encke. Additionally, Fig. 7 shows orbits of both fireballs in the inner Solar system together with the orbits of 2005 UR and 2005 TF50 asteroids and comet 2P/Encke.

4.4 Modelling

A numerical integration of the orbital parameters backwards in time has been performed in order to test the link between the fireballs PF311015a Okonek and PF311015b Ostrowite, two NEOs: 2005 UR, 2005 TF50 and comet 2P/Encke. For the integrations of the asteroids and test particles representing fireball, the RADAU integrator in the MERCURY software was used (Chambers 1999). The test particles means a series of clones of the radiant position and geocentric velocity of a fireball generated within the measurement uncertainties, that were later converted into orbital elements and propagated in the backward integration together with orbits of NEOs. We generated 100 massless clones of the fireballs individually.

The model of the Solar system used in integrations included: eight planets, four asteroids (Ceres, Pallas, Vesta, and Hygiea), and the Moon as a separate body. Additionally, we included the radiation pressure here as well. The positions and velocities of the perturbing planets and the Moon were taken from the DE406 (Standish 1998). The initial orbital elements of asteroids 2005 UR and 2005 TF50 and comet 2P/Encke were taken from JPL Solar system dynamics web site. Together with initial orbital elements of asteroids and comet, 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 generated stream has been widely dispersed in longitude, therefore, we used Steel, Asher & Clube (1991) criterion, $D_s$, instead of a conventional similarity functions (Southworth & Hawkins 1963; Drummond 1981; Jopek 1993). With the values being less than 0.15, the evolution of the $D_s$ criterion reveals a link between Okonek fireball and 2P/Encke, 2005 TF50, and 2005 UR, through 2300, 1600, and 1600 yr, respectively (left-hand panels in Fig. 8). In case of Ostrowite fireball, the evolution of the $D_s$ criterion shows similarity through shorter period of times: 2000, 450, and 400 yr with 2P/Encke, 2005 TF50, and 2005 UR, respectively (right-hand panels of Fig. 8). If there is a link between two bodies then the value of the dissimilarity criterion is very low at the moment of their separation, and increases with time. In theory, analysing results of the backward integration, we start in a moment when some time passed since the separation. Therefore, we start with a higher value of the dissimilarity criterion, then it decreases reaching a minimum value (at the possible moment of the separation). And then it increases again because in the integration two bodies are still treated as separate objects, as if the separation did not occur – unless we tell the program to stop integration when a given condition is fulfilled. We would see more complex image when involved in a study are objects which undergo a stronger perturbation and are in resonance with a planet (particularly Jupiter). The distance of an asteroid from the Jupiter’s orbit, characterized by the semi-major axis and aphelion distance, influences the amplitudes and rates of changes of the perihelion distance ($q$), eccentricity ($e$), and inclination ($i$). Moreover, all of used by us in the study asteroids are close to 7/2 resonance with Jupiter. All of this has its reflection in amplitudes and rates of changes of the dissimilarity criterion as well. Thus, instead of a stable, linear decreasing in going back in time to the possible separation moment we observe sinusoidal curve.

Figure 6. The light curve of the PF311015b Ostrowite fireball (squares) and its persistent train (crosses).

3 http://Newton.dm.unipi.it/neodys/index.php

4 http://ssd.jpl.nasa.gov
Table 6. Drummond criterion $D_S$ values for PF311015a Okonek and PF311015b Ostrowite fireballs, 2005 UR and 2005 TF50 near Earth asteroids and comet 2P/Encke.

| Object          | 2P/Encke | 2005 UR | 2005 TF50 | PF311015a Okonek | PF 311015b Ostrowite |
|-----------------|----------|---------|-----------|------------------|---------------------|
| 2P/Encke        | –        | 0.119   | –         | 0.093            | 0.099               |
| 2005 UR         | 0.119    | –       | 0.052     | 0.044            | 0.036               |
| 2005 TF50       | 0.072    | 0.052   | –         | 0.045            | 0.042               |
| PF311015a Okonek| 0.093    | 0.044   | 0.045     | –                | 0.011               |
| PF311015b Ostrowite | 0.099 | 0.036   | 0.042     | 0.011            | –                   |

Table 5. Orbital elements of the PF311015a Okonek and PF311015b Ostrowite fireballs compared to the orbits of 2005 UR and 2005 TF50 near Earth asteroids and comet 2P/Encke.

|                | $1/a$ (AU) | $e$    | $q$ (AU) | $\omega$ (deg) | $\Omega$ (deg) | $i$ (deg) | $P$ (yr) |
|----------------|------------|--------|---------|-----------------|-----------------|----------|----------|
| PF311015a Okonek | 0.4440(55) | 0.8690(21) | 0.2948(17) | 120.8(2)     | 37.76723(1)    | 4.73(12) | 3.379(73) |
| PF311015b Ostrowite | 0.4408(50) | 0.8720(17) | 0.2930(15) | 121.2(2)     | 37.98982(1)    | 5.636(51) | 3.51(7)  |
| 2005 UR         | 0.4420(36) | 0.8797(15) | 0.2723(1)  | 141.0(3)     | 19.555(14)     | 6.972(26) | 3.40(4)  |
| 2005 TF50       | 0.4401(5)  | 0.8689(3)  | 0.2978(3)  | 159.898(8)   | 0.666(23)      | 10.699(14) | 3.425(6) |
| 2P/Encke        | 0.45144(1) | 0.84833(1) | 0.33596(1) | 186.546(1)   | 334.5682(1)    | 11.7815(1) | 3.29698(1) |

Figure 7. Plot of the inner Solar system with orbits of the PF311015a Okonek and PF311015b Ostrowite fireballs, two asteroids – 2005 UR and 2005 TF50 and comet 2P/Encke.

Additional outcome of our work concerns the relation between asteroids themselves. Fig. 9 shows the time evolution of semi-major axis ($a$), eccentricity ($e$), perihelion distance ($q$), inclination ($i$), argument of perihelion ($\omega$), and longitude of ascending node ($\Omega$) of NEAs and the comet. Our results show orbital similarity between 2005 TF50 and 2005 UR in the interval of almost 4000 yr applying both $D_S$ and $D_{SH}$ (see Fig. 10 for $D_S$ plot). The lower values are obtained around 2600 yr, which corresponds with low values of $D_S$ and $D_{SH}$ when comparing asteroids’ orbit with orbit of 2P/Encke. This may suggest that around that time separation of both asteroids might have occurred.

We generated 100 clones of asteroids 2005 UR and 2005 TF50, using their orbital covariance matrix taken from the JPL Horizon. Analysing results of the backward integration of those objects and their clones shows, as expected, that an orbit calculated from a short data-arc span (6 d for 2005 UR) would produce orbits with higher dispersion in time than for a longer data-arc (26 d for 2005 TF50). However, the amplitudes and rates of changes of orbital elements of clones have similar range and pattern, especially for 2005 TF50, for which orbital uncertainties of their nominal orbit are smaller.

The current and past $D_S$ values for each NEO and 2P/Encke are not extremely low indicating that real separation of all these three bodies might took place 20 000–30 000 yr ago in one catastrophic event which created the whole Taurid complex (Asher et al. 1993; Babadzhanov et al. 2008). Leaving for a while a connection with 2P/Encke comet, we can speculate about both NEOs and both MNRAS 461, 674–683 (2016)
The orbits of 2005 UR and 2005 TF50 are very similar through a period of last 3600 yr. Almost zero values of $D_S$ criterion are observed at moments of $-700$, $-1300 \div -1500$ and $-2700$ yr (Fig. 10). What is interesting is that the deep minimum of $D_S$ around the moment of $-1500$ yr was obtained for each NEO–fireball orbit combination (see Fig. 8). This epoch might be suspected as the time when larger body was disrupted creating both NEOs and meteoroids which caused the fireballs. Still we have taken into account earlier minimum observed at epoch around $-400$ yr. This is the first deep minimum of $D_S$ observed for all NEO–fireball origin.
Figure 9. The time evolution of orbital elements of 2005 UR (green), 2005 TF50 (red), and 2P/Encke (blue).

Figure 10. Evolution of the $D_S$ criterion calculated by comparing the orbit of NEAs and the comet. The red dashed line shows the threshold value ($D_S = 0.15$).
combinations. In case of the disruption at that moment further backward integrations for earlier epochs have no physical sense.

5 SUMMARY

In this paper we presented an analysis of the multi-station observations of two bright Southern Taurid fireballs which occurred over Poland on 2015 October 31. Moreover, we investigated their connection with two NEOs and comet 2P/Encke. Our main conclusions are as follows:

(i) both meteors are similar with many aspects including brightness higher than Full Moon, shape of the light curve, entry velocity, persistent train and orbital parameters ($D_0$ of only 0.011),

(ii) among over dozen of NEOs identified as possible parent bodies of Taurid complex two, namely 2005 UR and 2005 TF50, have orbits which are very similar to the orbits of observed fireballs (with $D_0 < 0.045$),

(iii) similarity of orbits of both fireballs and 2005 UR asteroid is especially interesting due to the fact that the close flyby of this NEO was observed exactly during last high maximum of Taurid complex shower in 2005,

(iv) the numerical backward integration of the orbital parameters of both fireballs and NEOs backwards in time, which has been performed in this work, indicates many similarities between orbits of these objects during past 5000 yr. However, about 1500 ago, $D_0$ criterion has close to zero values for each of NEO–fireball, NEO–NEO and fireball–fireball pair suggesting at that moment a disruption of a larger body might took place,

(v) although, we could not have confirmed unequivocally the relation between fireballs and 2005 UR and 2005 TF50, we showed that at least both asteroids could be associated, having the same origin in a disruption process that separates them.

The Taurid complex is certainly one of the most interesting objects in the Solar system. It is able to produce both impressive meteor maxima and extremely bright fireballs (Dubietis & Arlt 2006; Spurný 1994). Additionally, it can be connected with catastrophic events like Tunguska (Kresak 1978; Hartung 1993) and can affect the climate on Earth (Asher & Clube 1997). Accurate observations and analysis of all kind of bodies associated with the Taurid complex are then very important tasks, demanding to continue and affecting the safety of our planet.

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