Enhanced activity of the Southern Taurids in 2005 and 2015

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ABSTRACT

The paper presents an analysis of Polish Fireball Network (PFN) observations of enhanced activity of the Southern Taurid meteor shower in 2005 and 2015. In 2005, between October 20 and November 10, seven stations of PFN determined 107 accurate orbits with 37 of them belonging to the Southern Taurid shower. In the same period of 2015, 25 stations of PFN recorded 719 accurate orbits with 215 orbits of the Southern Taurids. Both maxima were rich in fireballs which accounted to 17% of all observed Taurids. The whole sample of Taurid fireballs is quite uniform in the sense of starting and terminal heights of the trajectory. On the other hand a clear decreasing trend in geocentric velocity with increasing solar longitude was observed.

Orbital parameters of observed Southern Taurids were compared to orbital elements of Near Earth Objects (NEO) from the NEODYS-2 database. Using the Drummond criterion $D'$ with threshold as low as 0.06, we found over 100 fireballs strikingly similar to the orbit of asteroid 2015 TX24. Several dozens of Southern Taurids have orbits similar to three other asteroids, namely: 2005 TF50, 2005 UR and 2010 TU149. All mentioned NEOs have orbital periods very close to the 7:2 resonance with Jupiter’s orbit. It confirms a theory of a "resonant meteoroid swarm" within the Taurid complex that predicts that in specific years, the Earth is hit by a greater number of meteoroids capable of producing fireballs.

Key words: meteorites, meteors, meteoroids, asteroids

1 INTRODUCTION

The Taurids are two ecliptic meteor showers active every autumn. They have been observed since the second half of 19th century and they were examined using photographic methods for the first time in the mid-20th century (Whipple 1940, Wright and Whipple 1950). At that time they were divided into two segments, the Northern Taurids and the Southern Taurids, and now they are recognized as two separate showers. During those studies the Taurids were found out to be a part of a bigger complex which includes also smaller swarms with ecliptic radiants positioned nearby. A very complicated structure of the Taurids complex along with a long period of their activity make the problem of their origin and evolution anything but trivial. Actually it is thought that the 2P/Encke comet is the source and parent body of the Taurids (Whipple 1940), however both 2P/Encke and Taurids might be the remnants of a much larger object, which has
disintegrated over the past 20000 to 30000 years (Clube and Napier 1984, Asher et al. 1993, Babadzhanov et al. 2008).

A wide analysis of the Taurids swarm based on studies of photographic orbits available in the IAU database was conducted Porubčan et al. (2006). While examining orbital similarities among the Taurids registered in photographs the authors singled out 15 filaments belonging to the Taurid complex. For 7 substreams they found 9 Near Earth Objects (NEOs) which can be connected to them. Among those worth listing there are the 2004 TG10 (similarity to the Northern Taurids) and the 2005 TF50 situated near 7:2 resonance with Jupiter. The conducted retrograde orbit integration shows a possibility of common source of many discovered filaments which date of creation is thought to be about 4500 years ago.

Most recently, analysis of Porubčan et al. (2006) was followed by Jopek (2011) who identified as many as 14 possible parent bodies of the Taurids stream. Additionally, Kaňuchová and Svoreň (2014) used the method of indices to study the autumn part of the Taurid complex and identified as many as 13 associations.

The analysis of the activity of the Taurids over decades and centuries is a matter of separate studies. Usually that swarm is characterized by Zenithal Hourly Rate not exceeding 5 but while studying their activity for last several decades the scientists managed to notice years in which the activity of the Taurids was higher than average; particularly they managed to connect the noticeably higher activity of fireballs with the swarm of the Taurids (Asher 1991, Asher and Clube 1993, Asher and Izumi 1998). The increased activity of the shower was connected with the existence of a stream of particles which remains in 7:2 resonance with Jupiter. An increased activity of the swarm was predicted for years 1995, 1998, 2005 and 2008.

The return in 2005 was spectacular with both enhanced global activity and maximum rich in fireballs (Dubietis and Arlt, 2006). In 2008 the activity of the shower was lower but still it may be considered as enhanced (Jenniskens et al. 2008, Shrbený and Spurný 2012).

According to the Asher’s model, the next swarm encounter was expected in 2015. Other points of meeting with the 7:2 resonance stream were computed and the increased activity was predicted also for years 2019, 2022, 2025, 2032 and 2039.

In the following paper we described the peaks of the Taurids’ activity observed in 2005 and 2015. According to predictions, in 2015 the observed maximum was characterized by a high number of bright fireballs. Among them there were two very bright events which detailed description might be found in a separate paper (Olech et al. 2016). Many orbits of fireballs were found similar to the orbits of the 2005 UR and the 2005 TF50 objects (Olech et al. 2016) as well to the asteroid 2015 TX24 (Zołądek et al. 2016). In the following paper we are examining the activity of the Taurids and their orbital similarities to NEO objects for years 2005 and 2015.

2 OBSERVATIONS

The 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. 2006, Wiśniewski et al. 2016). 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 35 fireball stations belonging to PFN that operate during each clear night. It total over 70 sensitive CCTV cameras with fast and wide angle lenses are used.

2.1 Observations in 2005

The PFN was created a bit over one year earlier so at the end of 2005 it consisted of less than 10 active cameras positioned in different parts of the country. The Tayama C3102-01A1 cameras combined with the Ernitec 1.2/4mm lens were the basic set for video observations - one of the faster non-enhanced video sets in those times, allowing to observe meteors up to +2 magnitude. Also other cameras with similar parameters - the Mintron MTV-23X11C and the Siemens CCBB 1320 - were used. During the analysis of the Taurids in 2005 and 2015 we focused on solar longitudes ($\lambda_\odot$) from 206 to 228 degrees (from October 20 to November 10). In 2005, for the aforementioned period, the weather conditions were changeable. From October 23 to 25 we had no data due to bad weather conditions and then it was repeated on November 5 and 7-8. Between 2005 October 26 and November 4 the weather conditions at night were quite good for a change. The New Moon on November 2 offered good conditions for observations of not only fireballs but also fainter meteors.

In the Table 1 we present a list of stations observing the peak activity of the Taurids in 2005. These observations were conducted using video sets described above and the output was controlled by the MetRec software (Molau 1999). Additionally, we conducted photographic observations in the Żabików PFN09 station.

| Code   | Site     | Longitude [°] | Latitude [°] | Elev. [m] | Camera             | Lens     |
|--------|----------|---------------|--------------|-----------|--------------------|----------|
| PFN03  | Złotokłos | 20.9086 E     | 52.0062 N    | 128       | Tayama C3102-01A1  | Ernitec 4mm f/1.2 |
| PFN05  | Poznań   | 16.9098 E     | 52.4280 N    | 89        | Tayama C3102-01A1  | Ernitec 4mm f/1.2 |
| PFN06  | Kraków   | 19.9424 E     | 50.0216 N    | 250       | Mintron MTV-23X11C | Ernitec 4mm f/1.2 |
| PFN09  | Zabików  | 22.5498 E     | 51.8068 N    | 154       | Praktica L2        | Vivitar 28mm f/2.5 |
| PFN13  | Toruń    | 18.6209 E     | 53.0252 N    | 66        | Siemens CCBB1320   | Ernitec 4mm f/1.2 |
| PFN17  | Gdynia   | 18.5473 E     | 54.5609 N    | 34        | Mintron MTV-23X11C | Ernitec 4mm f/1.2 |
| PFN19  | Kobiernice | 19.2018 E    | 49.8377 N    | 345       | Mintron MTV-23X11C | Ernitec 4mm f/1.2 |
Figure 1. Fireballs from the Southern Taurids shower registered on 30.10.2005 (left) and on 31.10.2005 (right) by the PFN05 Poznań station using PAVOS camera.

Figure 2. Fireball of $-15$ mag registered on 4.11.2005 at 20:19:42 UT with the Pegasus constellation in the background. Photo taken by D. Dorosz in PFN09 Żabików station (Praktica L2, Vivitar 28 mm f/2.5, Konica VX200).

A fireball network consisting of just one photographic station and six video ones was not able to deliver a lot of data. What is more, stations using early version of MetRec software analyzed data in half PAL resolution so a huge percentage of double-station phenomena was rejected because of poor quality astrometry. In the analyzed period we managed to get from more than two to a dozen or so orbits every night. At the beginning the majority of observed phenomena were the Orionids with just a vestigial number of the Taurids. After 2005 October 27 we noticed the increase of the Taurids activity with a local peak on October 31. When it comes to the number of the Taurids as a percentage of all registered phenomena their peak was observed on November 4. In the analyzed period we determined orbits of 44 Taurids: 37 Southern and 7 Northern ones. The Northern Taurids constitute just 18% of the number of the Southern Taurids. Overall we determined 107 orbits for shower and sporadic meteors.

On 2005 October 27 a fireball from the shower of the Southern Taurids was observed with an apparent magnitude close to $-5$. On October 28 a similar phenomenon was seen as well. On 2005 October 30, at 22:59 UT there was a fireball and its brightness in the peak of its flare exceeded $-8$ mag. The next night we observed a fireball as bright as $-6$ mag which belonged to the shower of the Southern Taurids. The same night we registered the highest number of phenomena belonging to that shower. On November 4, at 20:19:42 UT, there was visible a spectacular fireball, as bright as $-15$ mag. It was registered using the photographic technique by the Żabików PFN09 station. We did not manage to determine a precise trajectory or orbit of that fireball but it seems it also belonged to the Southern Taurid shower. We base our assumption on comparison between eyewitnesses’ reports and also the photographic observation. Its maximum brightness was observed over the town of Pulawy. The last bright fireball, a phenomenon of $-7$ mag, was observed on 2005 November 6. The fact that in the same period we registered several very bright phenomena not connected in any way to the Taurids shower is also worth noticing. Among them there was a sporadic $-10$ mag fireball, visible in the evening on 2005 October 28 or a similar event on November 30, with an orbit being an equivalent of the 00241 OUI October Ursae Minorids stream (Molau and Rendtel 2009).

2.2 Observations in 2015

Like in 2005, our research included solar longitudes ranging from 206 to 228 degrees. This time the Moon phases were not as perfect as in 2005 with Full Moon on October 27 and New Moon on November 11. From October 20 to 22 our stations did not provide any data due to heavy clouds. Between October 24 and November 4 good weather allowed the PFN to work at its fullest; nights from November 5 to 7 were partially or completely cloudy but the nights between November 8 and 9 were clear in most of the country.

Compared to 2005 the number of stations and the quality of our equipment increased significantly. We were able to gather data from 25 stations covering a period of time from October 20 to November 10. We used a quite diverse
were determined for fireballs brighter than
the night from October 31 to November 1 four other orbits
Apart from these two extremely bright phenomena during
1920
and a resolution of
on October 27 (similarly to 2005). Three bright fireballs wer e
T aurids.
belonged to the Southern T aurids and 39 to the Northern
showers and sporadic centers. Out of that number 215 orbits
termined 719 orbits. They corresponded to different meteor
PFN cameras registered 6970 meteors out of which we de-
second. T able 2 summarizes a list of our stations active in
Table 2. Basic data on the PFN stations which observed Taurid shower maximum in 2015.

| Code   | Site                  | Longitude [◦] | Latitude [◦] | Elev. [m] | Camera          | Lens                  |
|--------|-----------------------|---------------|--------------|-----------|-----------------|-----------------------|
| PFN03  | Złotokłos             | 20.9086 E     | 52.0062 N    | 128       | Tayama C3102-01A1 | Ernitec 4mm f/1.2      |
| PFN06  | Kraków                | 19.9424 E     | 50.0216 N    | 250       | Mintron 12V6HC-EX | Panasonic 6mm f/0.75   |
| PFN13  | Toruń                 | 18.6209 E     | 53.0252 N    | 66        | Siemens CCBB1320 | Ernitec 4mm f/1.2      |
| PFN19  | Kobiernice            | 19.2018 E     | 49.8377 N    | 345       | Tayama C3102-01A1 | Panasonic 4.5mm f/0.75 |
| PFN20  | Urzędów               | 22.1456 E     | 50.9947 N    | 210       | Tayama C3102-01A1 | Ernitec 4mm f/1.2      |
| PFN32  | Chełm                 | 23.4982 E     | 51.1356 N    | 345       | Mintron 12V6HC-EX | Panasonic 6mm f/0.75   |
| PFN37  | Nowe Miasto Lub.      | 19.5922 E     | 53.4349 N    | 95        | Tayama C3102-01A1 | Ernitec 4mm f/1.2      |
| PFN38  | Podgórzyn             | 15.6817 E     | 50.8328 N    | 360       | KPF 131 HR       | Panasonic 4.5mm f/0.75 |
| PFN40  | Otwock                | 21.2494 E     | 52.1078 N    | 100       | Watec 902 H2    | Computar 3.8mm f/0.75  |
| PFN41  | Twardogóra            | 17.4589 E     | 51.3762 N    | 178       | Tayama C3102-01A1 | Ernitec 4mm f/1.2      |
| PFN42  | Błonie                | 20.6215 E     | 52.2147 N    | 95        | Watec 902B      | Ernitec 4mm f/1.2      |
| PFN43  | Siedlce               | 22.2835 E     | 52.2015 N    | 152       | Mintron MTV-23X11C | Ernitec 4mm f/1.2      |
| PFN45  | Łańcut                | 22.3333 E     | 50.1039 N    | 190       | Tayama C3102-01A1 | Ernitec 4mm f/1.2      |
| PFN46  | Grabniak              | 21.7015 E     | 51.7131 N    | 176       | Tayama C3102-01A1 | Computar 2.9-8.2mm f/1.0 |
| PFN48  | Rzeszów               | 21.9220 E     | 50.0451 N    | 230       | Tayama C3102-01A1 | Computar 4mm f/1.2     |
| PFN49  | Helenów               | 22.3316 E     | 52.1155 N    | 168       | Siemens CCBB1320 | Ernitec 4mm f/1.2      |
| PFN51  | Zelów                 | 19.2332 E     | 51.4698 N    | 200       | Tayama C3102-01A1 | Ernitec 4mm f/1.2      |
| PFN52  | Stary Sielc           | 21.2925 E     | 52.7914 N    | 90        | DMK23GX236       | Tamron 2.4-6mm f/1.2   |
| PFN53  | Bełećcy Nowy           | 16.8564 E     | 51.8907 N    | 114       | Tayama C3102-01A1 | Ernitec 4mm f/1.2      |
| PFN54  | Legowo                | 18.6430 E     | 54.2253 N    | 20        | Tayama C3102-01A1 | Ernitec 4mm f/1.2      |
| PFN57  | Krotoszyn             | 17.4416 E     | 51.7014 N    | 150       | Tayama C3102-01A1 | Ernitec 4mm f/1.2      |
| PFN60  | Bystra                | 19.1892 E     | 49.6215 N    | 444       | Mintron 12V6    | Panasonic 6mm f/0.75   |
| PFN61  | Płenicze              | 18.5603 E     | 53.0950 N    | 85        | Tayama C3102-01A1 | Ernitec 4mm f/1.2      |
| PFN67  | Nieznaszyn            | 18.1848 E     | 50.2373 N    | 200       | Mintron MTV 23x 11E/1/3 | Panasonic 4.5mm f/0.75 |
| PFN72  | Koźmin Wlkp.          | 17.4548 E     | 51.8283 N    | 139       | Tayama C3102-01A4 | Lenex 4mm f/1.2        |

observation equipment, the sets of the highest speed based
on the Mintrons 12V6 which allowed us to observe meteors as faint as 3 − 4 mag. For the first time we used the
digital DMK23GX236 megapixel camera and the Tamron
2.4-6 mm f/1.2 lens. Such a set allows you to observe field of
128.3 × 80.2 deg with a limiting magnitude of about +1 + −2
and a resolution of 1920 × 1200 pixels with 25 frames per
second. Table 2 summarizes a list of our stations active in
2015.

In a period from 2015 October 20 to November 10 all
PFN cameras registered 6970 meteors out of which we de-
termined 719 orbits. They corresponded to different meteor
shower and sporadic centers. Out of that number 215 orbits
belonged to the Southern Taurids and 39 to the Northern
Taurids.

The first phenomena of high brightness were observed
on October 27 (similarly to 2005). Three bright fireballs were
seen on October 30 as well. The night of October 31 brought
two other incredibly bright phenomena. At 18:05 UT a fire-
ball from the Southern Taurids shower appeared over the
western Poland at 23:13 UT. Its brightness was esti-
mated to −14.8 mag and its flight lasted just 2 seconds.
Apart from these two extremely bright phenomena during
the night from October 31 to November 1 four other orbits
were determined for fireballs brighter than −4 mag. A fire-
ball of an absolute magnitude of −7.3 mag was the third
brightest object which appeared during that night and was
registered at 22:02 UT above the border between Latvia and
Belarus. The next night brought as many as 10 Taurid or-
bits of objects brighter than −4 mag. At 21:13 a fireball of −7 mag appeared on the sky, then at 00:57 UT another
fireball of −8.5 mag was observed. The night November 2/3
brought 4 fireballs; the next night another 8 fireballs includ-
ing 3 with brightness close to −6 mag. In the evening of
November 4 the PFN cameras detected 3 fireballs with one
phenomenon as bright as −7 mag among them. During the
following nights the weather worsened and it did not im-
prove until November 8. On November 8/9 the activity of
the Taurid complex was still very high, with 6 fireballs ob-
served. On November 9, at 01:00 UT, the cameras of PFN42
and PFN48 stations registered a very distant fireball flying
over the eastern part of Belarus, near Komaje. Its absolute
magnitude reached −9 mag. While describing the activity
of fireballs you should emphasize the high brightness of phe-
nomena registered on October 31/November 01 night and
also high number of fireballs observed during the following
nights.

Taking into account all events which belonged to the
Southern and Northern Taurids up to October 28 the regis-
tered numbers of all the phenomena from both showers were
small and comparable. Starting from October 28 the South-
er Taurids started to dominate. Their peak was observed
on November 2 when 48 orbits were recognized and they
constituted 47% of all orbits registered that night. During
the following nights there was a decrease of the number of
the Taurids compared to the number of other registered me-
tors. After a spell of bad weather the night of November

Table 2. Basic data on the PFN stations which observed Taurid shower maximum in 2015.
Selection of fireballs registered during the peak of activity of the Taurids in 2015.

Amount of Southern and Northern Taurid orbits registered during each night of 2015 maximum. A clear peak is visible for solar longitude of 219°.

8/9 was very interesting as the Southern Taurids constituted 51% of all registered orbits.

Fig. 4 shows an amount of Southern and Northern Taurid orbits registered during each night of 2015 maximum with a clear peak which is visible for $\lambda_\odot = 219°$.

3 DATA REDUCTION

Video data constitute most of information gathered during the Taurids activity in 2005 and 2015. Most of them are saved in PAL standard. Data from 2005 were primarily analyzed by MetRec software (Molau 1999). The first versions of MetRec analyzed images in half PAL resolution; what’s more, in astrometry they used only stars visible directly in the camera’s field of view.

Later on, better tools were developed so we could use stars from many detections in order to improve the precision of astrometry. A converter was also constructed which allows you to analyze data from MetRec with UFO Analyzer software (SonotaCo 2009). Such tools made it possible to analyze data from 2005 for the second time, with paying proper attention to the quality of astrometry. The 2005 data were taken in the form of raw MetRec output because the contemporary versions of that program use an appropriate number of stars as points of reference and are able to generate astrometry of high quality. For several brightest phenomena astrometric measurements were taken manually with the help of the UFO Analyzer. That way we were able
to eliminate errors due to overexposures or fragmentation of fireballs.

Photographic data were measured using AstroRecord software (de Lignie 1997).

Positional data were downloaded to the PyFN software (Zołądek 2012). For all nights all meteors constituting double-station or multi-station events were recognized. Input data for particular detections were checked in order to eliminate astrometric errors. Points differing in a distinct way were rejected, events with grave astrometric mistakes were eliminated from calculations. Using the PyFN software the trajectories and orbits were determined for all meteors registered between October 20 and November 10 of 2005 and 2015. The orbits were classified and assigned to particular meteor showers by comparing them to the average orbit of a given stream taken from IAU Meteor Data Center. Phenomena which belonged to Southern and Northern Taurids were selected. Orbital similarities were researched for that group of objects using the NEODYS-2 database with Drummond criterion - $D'$ (Drummond 1981). Initially we selected asteroids for which $D' < 0.105$.

Photometry of registered phenomena was based on automatic measurement from the MetRec program. Because of overexposures and a different characteristic of converters used by particular cameras those brighter areas come with errors of 1 mag. For the brightest events the photometry was conducted manually, with such comparison objects as the Moon and planets registered in the same settings by the equipment of the same parameters. The details of this procedure are given in Olech et al. (2016).

4 RESULTS

4.1 The brightest phenomena

Both peaks of Taurids activity, in 2005 and in 2015, were full of very bright phenomena. For 2005 data there were 5 events with magnitude over $-5$ mag out of 44 for which orbits and trajectories were determined. It constitutes 11% of all phenomena. In 2015 the number of events brighter than $-6$ mag was 43 out of 243 determined orbits which constitutes 17% of all phenomena. Both peaks were characterized by occurrences of extremely bright events. In 2005 a fireball of $-15$ mag from the Taurid shower was observed but, unfortunately it was detected by only one station. During the 2015 peak two fireballs with a magnitude of $-16$ and $-14.7$ were registered. In the case of both peaks the first very bright events appeared for $\lambda_0 = 214^\circ$ (around October 27), in 2015 very bright fireballs were observed at $\lambda_0 = 218^\circ$ and during the following nights the number of bright events remained significant, with a strong emphasis on the evening of 2015 November 8 ($\lambda_0 = 226^\circ$) when, averagely, every hour a very bright phenomenon was observed. Table 3 presents basic parameters of double-station fireballs observed both in 2005 and 2015 with its errors. Almost all phenomena brighter than $-4$ mag belong to the Southern Taurid shower and only one observed on 2015 October 30 belongs to the Northern Taurids.

A downward trend of geocentric velocity is clearly noticeable when it comes to observed fireballs - at the beginning of their activity a typical geocentric velocity exceeded 31 km/s but for the night of November 8 it was closer to 28 km/s. The starting and final altitudes of observed fireballs are also quite interesting. As the velocities were very similar to each other in the examined sample the dimension of the body entering the atmosphere should be a decisive factor, influencing the altitudes. Of course the brightest fireballs had initial altitudes higher than average, for the fireball visible on 2015 October 31 at 18:05 UT it was 117 km and for the fireball at 23:12 UT it was 108 km. In the case of the majority of fireballs observed during both peaks the initial altitude ranges from 97 to 103 km. The final altitude does not depend on brightness. When it comes to the brightest October 31 fireballs the final altitudes were, respectively, 62 and 58 km which does not differ from the rest of events, presented in the table. The phenomena which end with a flare usually have the final altitudes exceeding 70 km. The $-5$ mag fireball seen on 2015 November 3 was a special case - its initial altitude was 97 km and final altitude only 48 km. When it comes to orbital parameters and the entry velocity that fireball does not differ in any way from other Taurids. Most likely that phenomenon was triggered by a meteoroid with a smaller ablation tendency which suggests in turn that the Taurids shower can contain also bodies with higher density and resistance (Madiedo et al. 2014).

The errors in geocentric velocity and trajectory determination shown in Table 3 result in errors in orbital parameters determination. It is worth to note that typical errors for semimajor axis $a$, perihelion distance $q$, eccentricity $e$ and inclination $i$ in observed fireballs are around 0.01 AU, 0.001 AU, 0.002 and 0.1 deg, respectively. In case of argument of periastron $\omega$ the error is around 0.3 deg, and for longitude of the ascending node $\Omega$ it is lower than $10^{-4}$ deg. The errors in orbital elements of NEOs discussed in the text are typically one order of magnitude lower than errors for fireballs.

Similarities between fireball orbits and all asteroid orbits from the NEODY2 catalogue were examined (in fact the PyFN software compares orbits of fireballs not only to NEO orbits but also to the orbits of comets from JPL and meteoroids recorded by other fireball networks). The last column of the Table 3 includes marking of the body which similarity in orbital parameters to the studied fireball is the greatest. Fireballs from the very beginning of the activity period are like the asteroid 2005 UR (and, in the second order, like the orbit of the 2015 TX24). Fireballs registered at the end of October and the beginning of November had orbits very similar to 2015 TX24. In the case of the 2015 October 31, 23:12 UT fireball the similarity to that asteroid amounts to $D' = 0.0055$ only and for the 18:05 UT phenomenon $D' = 0.0144$. Fireballs with orbits very similar to the orbit of 2015 TX24 were observed between October 28 and November 2 both in 2005 and in 2015. Between November 3 and 6 the similarity to orbits of the 2003 UV11 and the 2007 RU17 becomes dominant; still it is not as clear as in the case of the 2015 TX24 and typical $D'$ values are around 0.05. The night of November 8/9 was dominated by bright Taurids with orbits similar to orbits of the 2007 UL and the 2010 TU149. In that case the orbits look very much the same, with low $D'$ values ranging from 0.02 to 0.03.

https://www.ta3.sk/IAUC22DB/MDC2007/
Below you can find a short description of the most interesting phenomena.

- **2005 October 30, 22:59 UT and 2005 October 31, 23:38 UT.** Two similar fireballs with brightness of −8 and −6 mag. In both cases the maximum brightness was reached in the final flare which was connected with a disintegration of the meteoroid. The beginning altitudes are the same and equal to 97 km, the terminal points are at the heights of 70 and 67 km, respectively. Both fireball were observed near Opole and both are similar in orbital elements to the asteroid 2015 TX24.

- **2005 November 04, 20:20 UT.** The fireball was registered by only one PFN station using the photographic method so there are no precise data concerning the trajectory and orbit. The photo and visual observations allowed us to confirm that the fireball belonged to the Southern Taurids shower. The phenomenon’s magnitude was −15 and it was the brightest fireball observed during the 2005 peak. The light curve was typical for very bright Taurids, with a distinct maximum and numerous flares in the final part. After the flight of the fireball the persistent trail lasted several minutes. The trajectory was most likely over the town of Pulawy, about 150 km south from Warsaw.

- **2005 November 11, 22:48 UT.** A fireball of −7 mag
observed over northern Poland. That brightness was reached during one of two strong flares at the end of its trajectory; for most of trajectory the magnitude of the fireball did not exceed \(-2\) mag. The end of trajectory was at 76 km and the orbit is similar to the orbit of the 2010 TU149.

- **2015 October 27, 22:07 UT.** A fireball of a magnitude of \(-7\) mag in its flare. Observed over southwestern Poland. Its initial altitude was 101 km; then there was a single flare at 70 km, after that a small part continued the flight to an altitude of 60 km. Orbital similarity to the 2005 UR.

- **2015 October 28, 02:15 UT.** A \(-6\) mag fireball with a relatively flat light curve and with \(h_{\text{beg}} = 101, h_{\text{end}} = 58\) km. Brightening visible in the final part Orbital similarity to the 2005 UR.

- **2015 October 31, 18:05 UT.** An exceptionally bright fireball from the Southern Taurids swarm registered soon after the sunset. The phenomenon reached its highest magnitude of \(-16\). The trajectory was located over northwestern Poland, it had a length of 181 km and lasted 5.6 seconds. The light curve in the initial part of trajectory was flat, after the peak there were many flares and brightenings. The persistent train was visible for about 50 min (practically until the Moon rise). The peak of brightness over a town called Okonek. Orbital similarity to the 2015 TX24 (for more details see Olech et al. 2016).

- **2015 October 31, 22:03 UT.** A very distant detection of a fireball from the Southern Taurids. Its absolute brightness was over \(-7\) mag, the trajectory was located over the border between Latvia and Belarus and the peak of its brightness near Borysov in Belarus. The radiant of the phenomenon was in accordance with the radiant of the Southern Taurids but, due to distinct velocity errors, we did not use it in further analysis.

- **2015 October 31, 23:12 UT.** A fireball of \(-14\) mag registered over Ostrowite in northern Poland. The event was characterized by a steep trajectory with inclination amounting to 53 degrees and lasted 2 seconds. The maximum brightness reached in a strong, distinct peak. PFN34 Siedlce station managed to get a low-resolution spectrum of the fireball. The orbit is almost identical with the orbit of the asteroid 2015 TX24 with \(D' = 0.0055\) (for more details see Olech et al. 2016).

- **2015 November 02, 00:57 UT.** A \(-8\) mag fireball registered over central Poland with a flare ending the trajectory at 61 km. The beginning of the fireball was observed at 98 km. Orbital similarity with the 2015 TX24.

- **2015 November 03, 21:20 UT.** A fireball of \(-5\) magnitude registered about 40 km south-west from the city of Lublin. A phenomenon of a length of 65 km and an atypically flat light curve, completely devoid of any flares, with a gradual brightness decrease in the final part. Its initial altitude amounted to 97 km and final altitude was far from typical values of the rest of the Taurids and amounted to just 48 km. Very distinct braking visible on the velocity curve, the final speed almost twice slower than the speed at the beginning (about 16 km/s). Despite quite different traits the orbit of the fireball was typical for the Southern Taurids and similar to the orbit of the 2007 RU17 (other fireballs with orbits similar to the 2007 RU17 have not had such properties).

- **2015 November 04, 01:11 UT.** A fireball with an initial altitude of 101 km and a strong flash at 65 km. The flash did not cause complete disintegration; the fireball was visible, its brightness almost unchanged, till 58 km. The brightness of the flash exceeded \(-6\) mag, for the rest of trajectory the magnitude reached \(-3\) mag. Orbital similarity to the 2015 TX24.

- **2015 November 04, 20:38 UT.** A \(-7\) mag fireball which trajectory ran near Złoczew. The light curve with three noticeable brightenings and small flares near the end (\(h_{\text{beg}} = 101, h_{\text{end}} = 67\) km). Orbital similarity to the 2003 UV11.

- **2015 November 08, 21:45 UT.** One of the brightest phenomena that night. A \(-6\) mag fireball with three flares, registered over northern Poland with \(h_{\text{beg}} = 100\) and \(h_{\text{end}} = 69\) km. Similarity to the 2007 UL and the 2010 TU149 asteroids.

- **2015 November 09, 01:00 UT.** A fireball observed by two FFN cameras but only from a great distance, the brightest event of that night. The trajectory over Komajee in eastern Belarus. Absolute magnitude of \(-9\) mag, the radiant overlapping with the radiant of the Southern Taurids. Due to the significant distance there were significant velocity errors so the phenomenon was not used in further analysis.

### 4.2 Determining a threshold while studying the similarity of orbits

The meteoroid orbits which belonged to the Southern and Northern Taurids were initially compared to orbits of NEO objects from the NEODYS-2 database. The comparison was made with the help of the Drummond criterion. It turned out that, within the limits of the usual threshold \(D' < 0.105\) originally suggested by Drummond (1981), for every meteoroid orbit there were many comparable objects. Few of them were situated on very similar orbits; for most of them the probability value was close to the threshold. There was a risk that, with such a database as the NEODYS-2, including so many objects, with orbits compared to those situated in the ecliptic plane a coincidental similarity of orbits is possible. There was a need to determine a new threshold for the NEODYS-2 base and orbits of such type.

In order to do that 360 clones were created, with their orbits based on those belonging to the typical Southern Taurids. The orbit of reference was an average Southern Taurids orbit from the IAU MDC database according to Jenniskens et al. (2016). The clones were modified in the orbital node \(\Omega\) as its value was changed gradually by one degree and so an even distribution of the value of the node was reached (the argument of perihelion \(\omega\) was kept fixed in this procedure). The resulting orbits had shapes and dimensions identical with those characteristic of the Taurids; also their inclination to the plane of ecliptic was identical but they were moved in the node every one degree, creating a ring of evenly spread orbits. Clones defined in such a way were compared to the NEODYS database. For every one of them there were bodies found which met the \(D' < 0.105\) criterion. Figure 5 presents similarity values for all 360 clones. The X axis shows the value of the ascending node for the simulated object, the Y axis includes orbital probability for all bodies which meet the \(D' < 0.105\) condition. Points of similarities create local maxima where the similarity between a NEO asteroid and a clone is the most obvious.

The graph at Fig. 5 shows many local maxima which...
represent similarities of the clones to different NEODYS-2 database objects. Most of the similarities create a quite unanimous background which meets the \( D' > 0.06 \) criterion in its majority. Below the 0.06 value you find just few asteroids or small groups of them. The highest peak, visible at 40 degrees is an equivalent of the longitude of the Southern Taurids node. That peak is created by several asteroids. The biggest similarity in that group is visible for the 2003 UV11, 2007 RU17, 2007 UL12 and 2010 TU149 asteroids. The similarity to these objects had been found earlier for fireballs observed after November 3, 2005 and 2015. At 299 degrees there is a single peak visible connected to the asteroid 2013 NE19. We did not manage to connect that object with any big stream of meteors. Also we did not find any corresponding meteor showers for other bodies which similarity \( D' \) is lower than 0.06. The presence of a distinct maximum, created by several asteroids for the ecliptic longitude close to 40 degrees, is the proof that there is a group of asteroids on orbits very similar to the orbit of the Southern Taurids. The probability of accidental coincidence is minimal. Following the comparison of Taurid orbits and NEO objects, presented above, it seems that \( D' < 0.06 \) threshold eliminates successfully similarities with accidental NEO objects.

### 4.3 Similarity between asteroid and observed meteors

In Table 3 we presented orbital similarity for events brighter than \(-4 \) mag. In the next step we researched orbital similarity for all Southern Taurids, registered in the given period of time. Only cases of the Southern Taurids meeting the \( D' < 0.06 \) criterion when compared to a NEO object were taken into account. Table 4 presents a list of all asteroids which were found similar to the studied orbits. The asteroids were sorted according to their maximum orbit similarity.

Definitely the biggest similarity was found for the 2015 TX24 asteroid. It is an object similar to many bright fireballs from 2005 and 2015, including two brightest fireball of October 31, 2015. It is also an object for which most of meteoroid orbits meet the \( D' < 0.06 \) condition. The following places are occupied by the 2005 UR, the 2007 UL12 and the 2010 TU149 asteroids. The asteroid 2005 TV15 is also worth your attention. We found only 15 Taurids which \( D' \) was lower than 0.06 for this object but most of Taurids in this group are similar to the 2005 TB15 on a level of 0.02-0.04.

Sorting the NEO objects in semi-major axis (and, what follows, in the orbital period) you can notice a group with a semi-major axis close to 2.25 AU and the orbital periods close to 1240 days (see Table 5). The 2015 TX24 and the 2005 UR asteroids are situated on almost identical orbits; the 2005 TF50 has a distinctly higher orbit inclination but the perihelion distance, semi-major axis and orbital period are also very similar. The 2010 TU149 with a similar semi-major axis has a noticeably higher perihelion value. The orbital periods of the objects, mentioned here, are close to a period typical for the average 7:2 resonance with Jupiter which lasts 1238 days.

The orbit of the 2005 TB15 has a much smaller semi-major axis, with the orbital period of 891 days. The object is characterized by a quite high perihelion distance and the smallest eccentricity. The 2003 UV11 which was found similar to as many as 97 Southern Taurid orbits has an orbit distinctively different than the others with semi-major axis of 1.45 AU and the orbital period which is equal to only 639 days.

Fig. 6 shows the eccentricity-perihelion value graph for all Taurids for which precise orbital elements were determined and for NEOs from Table 5. The majority of registered Taurids have perihelions ranging from 0.26 to 0.44 AU. The eccentricity of the orbit is between 0.44 and 0.88 and you can notice a clear relation between the perihelion distance and the eccentricity. The same relation is, approximately, seen for most asteroids with orbits similar to orbits of the Taurids. Fig. 6 shows that objects similar to the brightest Taurids of October 31, 2015 concur with the NEOs with the smallest perihelion distance and highest eccentricity - these are the 2005 UR, the 2015 TX24 and the 2005 TF50. The second group is found for perihelion distances from 0.34 to 0.38 and it includes such

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**Table 4.** The NEODYS-2 catalogue objects with \( D' < 0.06 \) similarity to the Southern Taurids. For each object its absolute magnitude \( H_0 \) and size \( D \) are given. The sizes are computed from \( H_0 \) or taken from Mainzer et al. (2016).

| Asteroid | \( H_0 \) [mag] | Size [m] | Number of meteors | Lowest \( D' \) |
|----------|----------------|---------|-------------------|----------------|
| 2015 TX24 | 151 – 337 | 102 | 0.0055 |
| 2005 UR | 144 – 322 | 51 | 0.0158 |
| 2007 UL12 | 199 – 445 | 59 | 0.0222 |
| 2010 TU149 | 603 | 86 | 0.0222 |
| 2005 TB15 | 379 – 848 | 15 | 0.0236 |
| 2003 UV11 | 260 | 97 | 0.0249 |
| 2007 RU17 | 722 – 1616 | 70 | 0.0296 |
| 2005 TF50 | 262 – 586 | 86 | 0.0407 |
| 2011 UD | 218 – 488 | 10 | 0.0432 |
| 1999 VK12 | 54 – 122 | 1 | 0.0524 |

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**Figure 5.** Values of Drummond criterion similarities to the NEODYS-2 catalogue bodies for meteoroid clones which were based on average orbit of the Southern Taurids, modified in the ascending node.
Table 5. Orbital parameters of selected asteroids taken from NEODYS catalogue and sorted according to semi-major axis.

| Asteroid     | $a$ [AU] | $q$ [AU] | $e$  | $i$  | $\omega$ | $\Omega$ | $P$ [days] |
|--------------|----------|----------|------|------|----------|----------|------------|
| 2005 TF50    | 2.272    | 0.2978   | 0.8689 | 10.69 | 159.9    | 0.664    | 1250       |
| 2015 TX24    | 2.2688   | 0.2896   | 0.8723 | 6.044 | 127.01   | 33.007   | 1248       |
| 2005 UR      | 2.262    | 0.2723   | 0.8976 | 6.972 | 141.03   | 19.553   | 1243       |
| 1999 VK12    | 2.2358   | 0.4998   | 0.7764 | 9.504 | 103.06   | 48.635   | 1221       |
| 2010 TU149   | 2.2016   | 0.3778   | 0.8283 | 1.972 | 91.712   | 59.717   | 1193       |
| 2007 RU17    | 2.0400   | 0.3507   | 0.8281 | 9.081 | 129.83   | 17.469   | 1064       |
| 2011 UD      | 2.0324   | 0.4454   | 0.7808 | 8.823 | 146.81   | 357.31   | 1058       |
| 2007 UL12    | 1.9666   | 0.3815   | 0.806  | 4.185 | 95.626   | 67.148   | 1007       |
| 2005 TB15    | 1.8122   | 0.4425   | 0.7558 | 7.291 | 139.08   | 9.549    | 891        |
| 2003 UV11    | 1.4527   | 0.3444   | 0.7629 | 5.928 | 95.626   | 31.931   | 639        |

Figure 6. Perihelion and eccentricity of orbits of studied Taurids (marked by crosses) and NEOs (marked with black squares).

Figure 7. Perihelion distance and orbital periods of studied Taurids (marked by crosses) and NEOs (marked with black squares).

astereids as the 2007 RU17, the 2010 TU149 and the 2007 UL12.

Among few Taurids having the perihelion distance higher than 0.4 AU we can find the 2015 TB15 and the 2011 UD asteroids. You should notice the position of the asteroid 2003 UV11 on the graph. It is an object very similar to many Taurids but the orbital elements of the observed asteroids differ from orbital elements of that asteroid.

Fig. 7 shows perihelia and orbital periods of observed Taurids and NEO objects. Asteroids like the 2005 UR, the 2015 TX24, the 2005 TF50 and the 2010 TU149 are the nearest of 7:2 resonance with Jupiter. A bit shorter orbital periods are found for the 2007 RU17, the 2007 UL12 and the 2005 TB15 asteroids. Also in this case we think the 2003 UV is situated on the orbit with a shorter orbital period. In this place you can find a small number of Taurids with a great orbital resemblance to the 2003 UV11. Most of the objects, with the perihelion distance characteristic for the 2003 UV11 feature much longer orbital periods. Orbital periods of most of observed Taurids range from 1000 to 1300 days, with a noticeable cut-off over 1300 days. Among observed Taurids there is a quite homogeneous distribution of orbital elements which do not create any noticeable groups. The NEO objects orbiting inside the Taurids’ stream do not seem to be responsible for the existence of the current activity; they can be considered as the biggest among objects which belong to the stream of the Southern Taurids.

Fig. 8 shows similarities between observed Taurids and NEO objects in the function of solar longitude ($\lambda_\odot$). Taurids observed around $\lambda_\odot = 215^\circ$ seem to be most similar to the 2005 UR. The similarity is significant here, reaching $D' = 0.015$. At $\lambda_\odot = 218^\circ$ you can observe a very distinct peak due to similarity to the 2015 TX24. In the $216^\circ - 219^\circ$ range one can find many objects which similarities to the 2015 TX24 within $D' < 0.015$. For the fireball of October 31, 2015 seen at 23:12 UT. A similarity to the 2005 TF50 is observed in the $215^\circ - 220^\circ$ range without a noticeable maximum. For the majority of the Taurids from that range a simultaneous similarity to the 2015 TX24, the 2005 UR and the 2005 TF50 seems to be typical; those objects move on quite similar orbits but the 2005 TF50, as an object with a noticeably higher orbit inclination, is distinctly less like the observed Taurids.
RU17 at the $\lambda_\odot = 220^\circ$, the high similarity is noticeable but the majority of objects similar to 2003 UV11 show also a very close similarity to the 2007 RU17. The events observed during further nights were characterized by similarity to the 2010 TU149 and the 2007 UL12. Most of the phenomena observed around $\lambda_\odot = 226^\circ$ have orbits similar to the ones of those two objects.

For the 2005 TB15 there were only 15 objects with $D' < 0.06$. The period in which observed objects with similar orbits are situated is very wide, encompassing practically the whole range of solar longitudes. For $\lambda_\odot = 219^\circ$ there were two meteors for which $D'$ compared to the 2005 TB15 was 0.0236 and 0.0246, respectively. Taurus similar to the 2005 TB15 differ distinctly from others when it comes to different parameters. The average geocentric velocity for that group is 25.7 km/s that is about 5 km/s lower that in case of rest of the Taurids. The mean geocentric radiant for this group is $\alpha = 49^\circ$ and $\delta = 12^\circ$, whereas an average radiant for all registered Taurids is $\alpha = 51^\circ$ and $\delta = 14^\circ$. Fig. 9 shows positions of radiants for objects similar to 2005 TB15. These are meteors with the highest perihelion distance among all examined Taurids.

4.4 Comparison of activity in 2005 and 2015

A big part of fireballs in 2005 and 2015 showed a very pronounced similarity to the orbit of the 2015 TX24. That similarity is especially clear for $\lambda_\odot = 218^\circ$. The similarity of data gathered in 2005 and in 2015 was checked separately. Despite the fact that in 2005 we had definitely less data you still can perceive a distinct peak, reflecting the similarity with the 2015 TX24. The height and solar longitude of the peak for 2005 and 2015 fit each other almost completely. It means the presence of the Taurids on orbits very similar to the orbit of an object which orbital period is very close to the 7:2 resonance with Jupiter. Fig. 10 presents that similarity very clearly.

Similarly for the objects connected to the 2003 UV11 and the 2007 RU17 a comparable activity was found in 2005 and in 2015. When it comes to nights after November 4, in
2015 you could observe the Taurids which brightness exceeded the brightness of Full Moon; there were also many bright fireballs visible during several nights after the maximum. For all Taurids observed in a period of 20 days starting at the end of October and ending at the beginning of November 2005 and 2015 we determined trajectories and orbits. The majority of Taurids’ orbits is similar to NEO objects which orbital periods which are in 7:2 resonance with Jupiter. It concerns especially the 2015 TX24, the 2005 UR and the 2005 TF50 as well as the 2010 TU149 which orbit is very similar to orbits of the Southern Taurids observed at solar longitude of $\lambda_{\odot} = 226^\circ$. The NEO objects with orbits close to resonance orbits have also perihelions distinctly different than the perihelion of the 2P/Encke comet (noticeably smaller for the 2015 TX24, 2005 UR and 2005 TF50 objects, noticeably bigger for the 2010 TU149 and the 2007 UL12 objects). These NEO objects should not be treated as parent bodies of the 7:2 filament, it is more correct to treat them as the most massive remnants of the larger body fragmented in the past. It is worth to note that larger numbers of such bodies may exist in the Southern Taurid stream creating a kind of asteroidal core of the 7:2 stream.

Among the observed Taurids the spread of orbital elements is quite even no matter whether there are NEO objects in the stream or not. There is very little chance of an accidental coincidence of those orbits with the swarm of the Taurids and their presence is undoubtedly a result of a long and complex evolution of the Taurid complex. Currently these are the biggest objects circulating in the Taurid stream; what’s more, the list of NEO objects with orbits similar to those of the Taurids most likely remains incomplete and it depends on the possibility of detection from Earth.

This paper is another proof that 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) attracting the attention of the media and ordinary people. 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 task, demanding to continue and affecting the safety of our planet.

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