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The Taurid complex meteor showers and asteroids

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Abstract. The structure of the Taurid meteor complex based on photographic orbits available in the IAU Meteor database is studied. We have searched for potential sub-streams or filaments to be associated with the complex utilizing the Southworth-Hawkins D-criterion. Applying a strict limiting value for $D = 0.10$, fifteen sub-streams or filaments, consisting of more than three members, could be separated out from the general complex. To confirm their mutual consistence as filaments, rather than fortuitous clumping at the present time, the orbital evolution over 5000 years of each member is studied. Utilizing the D-criterion we also searched for NEOs that might be associated with the streams and filaments of the complex and investigated the orbital evolution of potential members. Possible associations between 7 Taurid filaments and 9 NEOs were found. The most probable are for S Psc(b) – 2003 QC10, N Tau(a) – 2004 TG10, o Ori – 2003 UL3 and N Tau(b) – 2002 XM35. Some of the potential parent objects could be either dormant comets or larger boulders moving within the complex. Three of the most populated filaments of the complex may have originated from 2P/Encke.

Key words: asteroid – meteor streams – parents

1. Introduction

The Taurids are a meteor shower that originates from a stream with very low inclination so that the Earth is almost moving within the complex for a large fraction of its orbit and that meteors are seen on Earth near to both the ascending and descending nodes. This means that the Taurid complex encounters the Earth two times with the duration of each resulting shower being very long. Before perihelion passage it generates the night-time showers called the Northern and Southern Taurids (September 15 – December 1, Cook, 1973) and in postperihelion as the daytime showers recognized by radio observations - Zeta Perseids and Beta Taurids (May 20 – July 6, Sekanina, 1973). In the beginning of the 20th century, Denning (1928) recognized the complex nature of the stream, identifying thirteen active radiants situated in Aries and Taurus.

Porubčan and Štohl (1987) analysed all photographic data on the Taurids available at that date and found a very long activity period of the stream extending in the solar longitude for almost 120 degrees.

It is generally accepted (Olsson-Steel, 1988; Babadzhanov *et al.*, 1990; Štohl, Porubčan 1990; Steel *et al.*, 1991; Babadzhanov, 2001, etc.) that the stream is, in fact, a complex of several small meteor streams. Some are genetically associated with comet P/Encke and several to Apollo asteroids. Whether the Apollo asteroids are associated with the comet is a more profound question that we will not discuss here.

In our analysis we have searched in the current version of the IAU Meteor Data Center catalogue of photographic orbits (Lindblad *et al.*, 2005 - available at *www.astro.sk/~ne/IAUMDC/Ph2003/database.html*) for meteoroid orbits belonging to the complex. We have also searched the available data on NEO's for potential parents.

2. The Taurid stream filaments

The Taurids are rich in bright meteors thus the activity and structure of the stream is best known from photographic observations which provide also the best determined orbits. In his analysis of photographic Taurids, Whipple (1940) used a sample of 14 orbits and suggested a possible relationship between the Taurids and comet Encke. At present, the updated IAU MDC catalogue (Lindblad *et al.*, 2005) lists 4581 orbits compiled from 35 different catalogues in which 240 members of the Taurid complex could be identified (Porubčan, Kornoš 2002).

On the other hand, there is a steady increase in the number of the NEOs that have been discovered, amounting to over three thousand at present. These provide an additional source of potential co-parents of the complex or of individual filaments.

Our approach was in two steps. In the first step a computerized stream-search based on an iteration procedure and Southworth-Hawkins D criterion was applied to the sample of photographic orbits covering the period of activity of the complex, approx. September – January.

D (Southworth, Hawkins 1963) is given by

$$D_{AB}^2 = (e_A - e_B)^2 + (q_A - q_B)^2 + [2\sin(I_{AB}/2)]^2$$
$$+ (e_A + e_B)^2 [\sin(\Pi_{AB}/2)]^2.$$

Here e_A, e_B, q_A and q_B are the eccentricities and perihelion distance of orbits A and B, I_{AB} is the angle between the orbital planes and Π_{AB} is the difference between the longitude of perihelion, measured from the intersection point of the orbital planes (not from either node). Both I and Π can be expressed in terms of the three angular orbital elements, i, ω and Ω, but we do not give these expressions here.

To get the cores or central parts of the streams or sub-streams a strict limiting value of $D \leq 0.1$ was applied. Then only filaments moving in the orbits related to the Taurids considering the geocentric velocity ($\pm 5\,\mathrm{km\,s^{-1}}$ with respect to the mean geocentric velocity of the stream) and position of the radiant ($\pm 10°$ with respect to the Taurid radiant ephemeris allowed for the radiant daily motion) were selected. In this way 23 filaments consisting of 2 to 56 members were identified.

This procedure identified 210 meteors belonging to the complex as a whole, 84 to the Northern branch and 126 to the Southern branch. Fig. 1 shows the radiants of meteors of individual filaments of the Northern and Southern branch (depicted by various symbols – upper plot). One possible way of verifying whether individual filaments can be related to the Taurid complex is to reduce the radiants to a common solar longitude, e.g. corresponding to the maximum of the Taurid stream activity by allowing for their radiant daily motion. For reduction, the Taurid radiant daily motion ephemeris derived by Porubčan and Kornoš (2002) was applied. The radiants reduced to the solar longitude of 220° (lower plot), show the size of the radiant area for the Northern and Southern branch. The radiant areas of both branches are well defined, compact and form a common area of the size of about $25° \times 15°$. The most outlying filament in January (filament no. 23 at right ascension 140° – 150°, upper plot of Fig. 1) is close to 7 : 2 mean-motion resonance with Jupiter and may not belong to the Taurid complex.

Due to a very long period over which the shower is active, about four months (at least 120° in the solar longitude) September – December, the Taurid radiant passes through several constellations. In consequence amongst the meteors identified by the above procedure as belonging to the Taurids are also meteors that have been designated by the authors of other catalogues as members of other minor streams.

By comparing the mean orbits of the N Piscids, the S Arietids and both branches of the Chi Orionids with the orbit of the N and S Taurids it is apparent that these streams can be regarded as extended members of the TC (Porubčan and Štohl, 1987).

In the later work, we have considered only filaments that contain four members at least. This gives 15 filaments and their mean orbits, radiants, geocentric velocities and corresponding Tisserand invariant values (with respect to the Jupiter's orbit) are given in Tab. 1.

3. NEOs in the Taurid meteor complex

It is difficult to find a simple explanation for the long duration and large dispersion of the orbits within the TC and of its origin. Whipple (1940) suggested that in the distant past a giant comet disintegrated gently into a number of smaller comets, one of which was P/Encke while another of these disintegrated

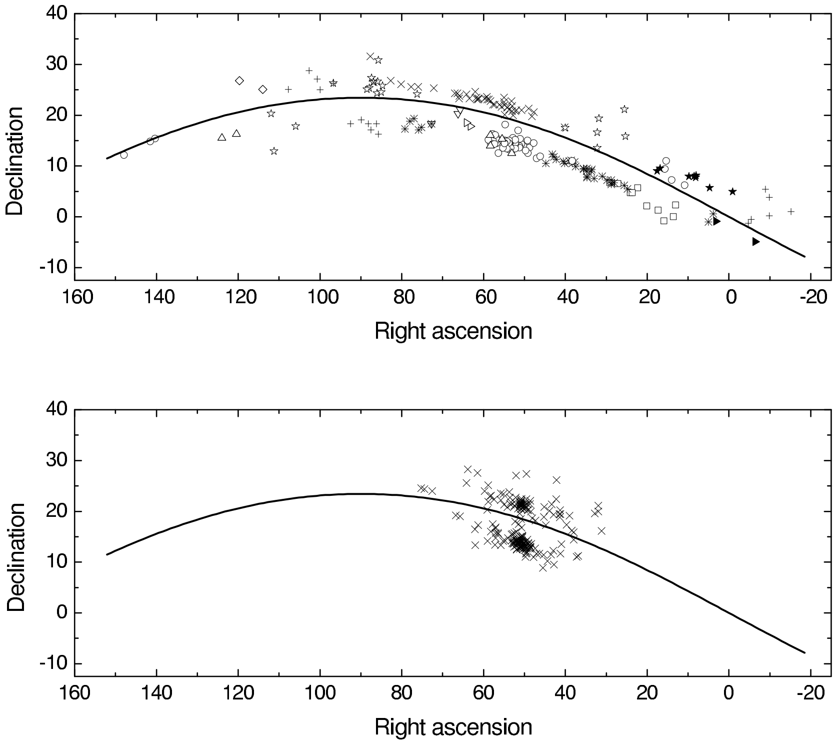

Figure 1. The radiant positions within the Taurid meteor complex (upper plot) and the radiants reduced to the common solar longitude of 220° (lower plot). Meteors of individual filaments in the upper plot are depicted by different symbols.

into the Taurid stream. Whipple and Hamid (1952) calculated the secular perturbations for 9 photographic Taurids and found that some of them had to be ejected from the comet 4700 years ago and others probably from a hypothetical companion about 1400 years ago. At present, as well as P/Encke, several Apollo asteroids are considered possible progenitors (Olsson-Steel, 1988; Babadzhanov *et al.*, 1990; Štohl and Porubčan, 1990; Asher *et al.*, 1993; Steel and Asher, 1996; Babadzhanov, 2001, and others).

Typical asteroids by their nature and structure differ from comets and so the mechanisms for the formation of meteoroid streams from asteroids should be different. The most basic scenarios for meteoroid ejection are collisions (Williams, 1993), disruption of an asteroid through fast rotation, or possible ejections due to thermal tension at close perihelion passages. However, these mechanisms are relatively rare events and are unlikely to provide a steady source for a regular supplying of meteoroids into a stream as is the case of cometary streams.

To find potential associations between Tau filaments and NEOs, we searched

Table 1. The mean orbital elements, radiants and geocentric velocities of the Taurid complex filaments. T is the Tisserand invariant value.

filament	Q	q	a	e	i	ω	Ω	π	n	R.A.	Dec.	V_g	T
	(AU)	(AU)	(AU)		(°)	(°)	(°)	(°)		(°)	(°)	($\mathrm{km\,s^{-1}}$)	
01 N Psc(a)	3.08	.410	1.743	.766	6.7	291.8	160.3	92.1	4	349.0	2.6	25.06	3.73
02 S Psc(a)	3.99	.309	2.148	.855	2.6	120.3	346.6	106.8	4	1.4	-1.6	29.58	3.09
03 N Psc(b)	3.93	.310	2.115	.857	4.6	300.1	177.0	117.1	8	9.1	7.6	29.50	3.12
04 S Psc(b)	2.59	.338	1.465	.770	6.1	121.8	359.5	121.3	5	16.0	1.0	25.77	4.23
05 S Psc(c)	3.54	.318	1.925	.837	5.7	120.1	10.9	131.0	5	25.2	5.7	28.73	3.37
06 β Ari	3.72	.375	2.048	.817	4.8	292.7	203.8	136.5	6	31.2	17.3	27.33	3.26
07 S Psc(d)	3.36	.296	1.826	.839	6.1	123.0	19.8	142.7	28	35.0	9.0	29.12	3.49
08 S Tau(b)	2.85	.225	1.539	.854	8.2	132.9	36.3	169.2	4	56.3	14.5	30.47	3.94
09 S Tau(a)	4.01	.365	2.187	.833	5.3	113.1	43.3	156.4	56	53.6	14.4	28.16	3.09
10 N Tau(a)	3.99	.358	2.174	.835	2.7	293.7	228.6	162.4	38	57.6	22.4	28.30	3.10
11 o Ori	4.34	.429	2.385	.820	5.0	104.8	69.8	174.6	5	77.1	18.0	26.84	2.96
12 N Tau(b)	4.37	.380	2.372	.841	2.9	290.1	255.7	185.8	9	85.3	26.0	28.35	2.92
13 N χ Ori	3.81	.476	2.143	.779	3.3	280.4	256.8	177.2	7	81.6	26.9	24.73	3.23
14 S χ Ori	4.91	.438	2.673	.836	5.6	102.7	81.4	184.2	6	88.3	17.9	27.22	2.73
15 ϵ Gem	3.74	.400	2.071	.808	3.7	289.2	270.6	199.8	5	101.6	26.5	27.05	3.26

the Asteroid Orbital Elements Database (Ted Bowell, Lowell Observatory - *http://alumnus.caltech.edu/˜nolan/astorb.html*) for discoveries up-to mid-June 2005 and found 3380 objects.

Orbital similarity was verified by comparing the mean orbits of the filaments with the orbits of NEOs applying the Southworth-Hawkins D-criterion. Considering that the present orbital similarities based on the osculating elements cannot reflect potential close associations of the TC filaments with NEOs in the past, for the analysis asteroids for which the value of $D \leq 0.30$ were selected and thus 91 NEOs were identified. The theoretical meteor radiants (right ascension α, declination δ) and the geocentric encounter velocity V_g at the approach to the Earth's orbit were then computed (Neslušan *et al.*, 1998).

We have integrated the motion of all the 91 asteroids and the mean orbits of the filaments by using the multi-step procedure of Adams-Bashforth-Moulton's type up to 12th order, with variable step-size and positions of the perturbing major planets were obtained from the Planetary and Lunar Ephemerides DE406 prepared by the Jet Propulsion Laboratory (Standish, 1998).

Though meteoroid streams can be typically recognized over a time scale of 10^3 to 10^4 years (see Arter and Williams, 1997 for formulae and calculations) we followed the orbital evolution of the bodies for 5000 years, the time which could be count for sufficient to indicate on potential associations between the studied objects.

In Tab. 2 we show the resulting list of potential parents obtained by comparing the orbital elements, radiants and velocities of filaments with the potentially associated objects. Besides the filaments listed in Tab. 2 an additional close association between filament no. 6 and four asteroids was identified. However, due to the fact that the orbit of the filament is in a close 4 : 1 resonance with Jupiter and thus the filament particles are on chaotic orbits, no real D value could be obtained and, therefore, this association was not included in Tab. 2.

Tab. 2 lists besides the geocentric radiant and velocity also the absolute magnitude of the asteroid H and the diameter defined for the albedos in the range 0.05 – 0.25. The table also gives the change of D value (D_{SH}) over the period of integration.

Table 2. Taurid complex filaments - NEO

stream	R.A. (°)	Dec. (°)	V_g (km/s)	H (1,0)	Diameter (m)	D_{SH}	Period (yrs)
Tau 01	349	3	25				
2001 HB	330	-7	23	20.50	210-470	0.15-0.25	5000
2003 SF	14	3	24	19.57	320-720	0.12-0.25	2000
Tau 02	1	-2	29				
2001 QJ96	356	-7	27	21.98	110-240	0.15-0.13	3000
Tau 04	16	1	26				
1999 RK45	16	9	26	19.32	360-810	0.19-0.19	5000
2003 QC10	16	2	24	17.83	720-1610	0.07-0.06	5000
Tau 09	54	14	28				
2003 WP21	67	17	25	21.43	140-310	0.20-0.15	5000
Tau 10	58	22	28				
2004 TG10	55	22	30	19.40	350-780	0.25-0.05	5000
Tau 11	77	18	27				
2003 UL3	67	22	26	17.85	720-1600	0.25-0.05	3200
2003 WP21	67	17	25	21.43	140-310	0.25-0.15	4000
Tau 12	85	26	28				
2002 XM35	81	26	28	22.96	70-150	0.25-0.05	3300

The results of integration for probable associations are depicted in Figs. 3-7, where the plots of the orbital elements - a, q, e, i, ω and Ω of the objects as well as of the differences between the lines of apsides $\Delta\pi$, the values of D and their evolution in the last 5000 years are presented. For the integration, the mean orbit of the stream was represented by 18 modeled particles distributed equidistantly along the orbit of the stream in the mean anomaly by 20 degrees.

The mean radiants of the filaments listed in Tab. 1 (open circles) and positions of the theoretical meteor radiants of the associated NEOs (stars) calculated for the osculating orbits are plotted in Fig. 2. The orbital elements of the NEOs are listed in Tab. 3.

Table 3. The orbital elements of Taurid complex asteroids and comet 2P/Encke. T is the Tisserand invariant value.

object	Q (AU)	q (AU)	a (AU)	e	i (°)	ω (°)	Ω (°)	π (°)	T
1999 RK45	2.834	0.363	1.598	0.773	5.9	4.0	120.1	124.1	3.96
2001 HB	2.225	0.402	1.314	0.694	9.3	237.7	196.1	73.7	4.68
2001 QJ96	2.876	0.321	1.599	0.799	5.9	121.3	339.1	100.4	3.92
2002 XM35	4.212	0.378	2.295	0.835	3.1	312.8	229.8	182.6	3.00
2003 QC10	2.379	0.369	1.374	0.731	5.0	120.5	0.3	120.8	4.49
2003 SF	3.842	0.481	2.162	0.778	5.7	31.8	77.6	109.5	3.22
2003 UL3	4.036	0.457	2.246	0.797	14.6	13.0	153.2	166.1	3.09
2003 WP21	4.115	0.489	2.302	0.788	4.3	123.7	38.1	161.8	3.08
2004 TG10	4.169	0.315	2.242	0.860	3.7	310.0	212.3	162.3	2.99
2P/Encke	4.097	0.339	2.218	0.847	11.8	186.5	334.6	161.1	3.03
2005 TF50	4.247	0.292	2.269	0.871	10.7	159.8	0.8	160.5	2.93

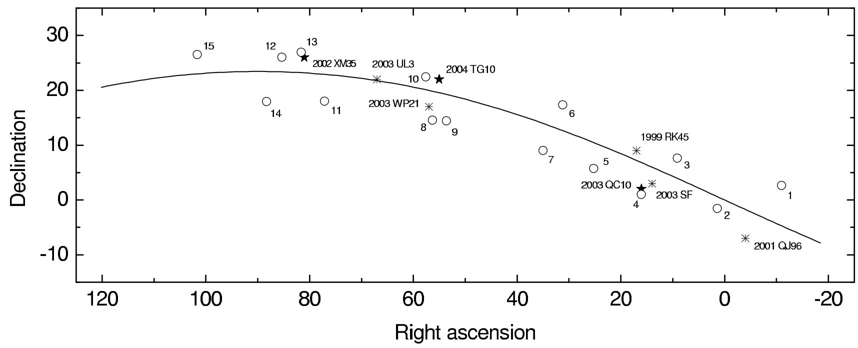

Figure 2. The mean radiants of the TC filaments (open circles) and theoretical meteor radiants of the associated NEOs (stars).

4. Discussion and conclusions

Based on the similarity of the orbital evolution, the TC sub-streams (filaments) can be arranged into four groups, which at the same time correspond to different values of the Tisserand invariant T (with respect to Jupiter's orbit). In order of the increasing T (Tab. 1) can be arranged as: (I) - the first group with $T \leq 3.0$ is formed by filaments 11, 12 and 14; (II) - the second and the most numerous group has T in the interval of 3.09 – 3.26 and consists of filaments 2, 3, 6, 9, 10, 13 and 15; (III) - the third group is formed by two filaments 5 and 7 with T between 3.37 – 3.49; (IV) - the fourth group consisting of filaments 1, 4 and 8, has the largest T between 3.73 – 4.23.

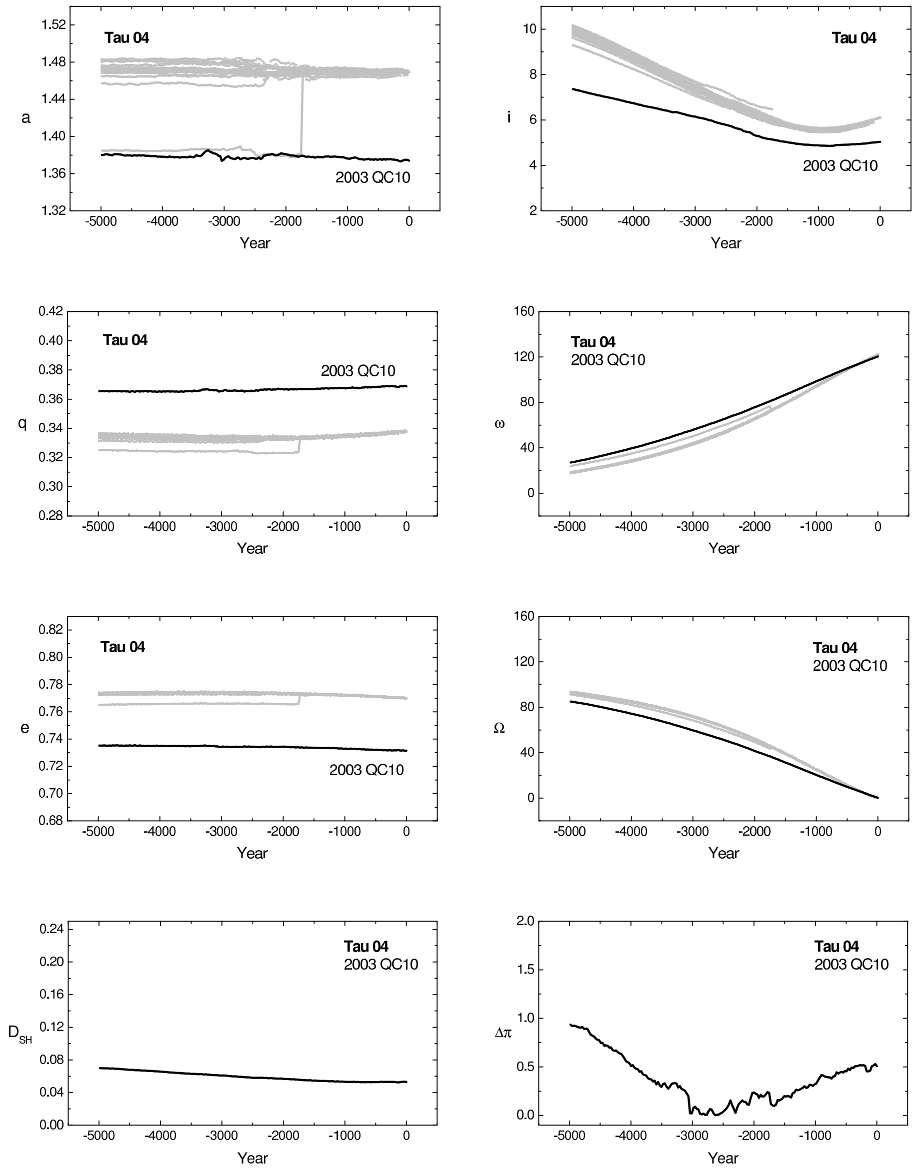

Figure 3. Orbital evolution and D_{SH} of TC filament 04 and 2003 QC10.

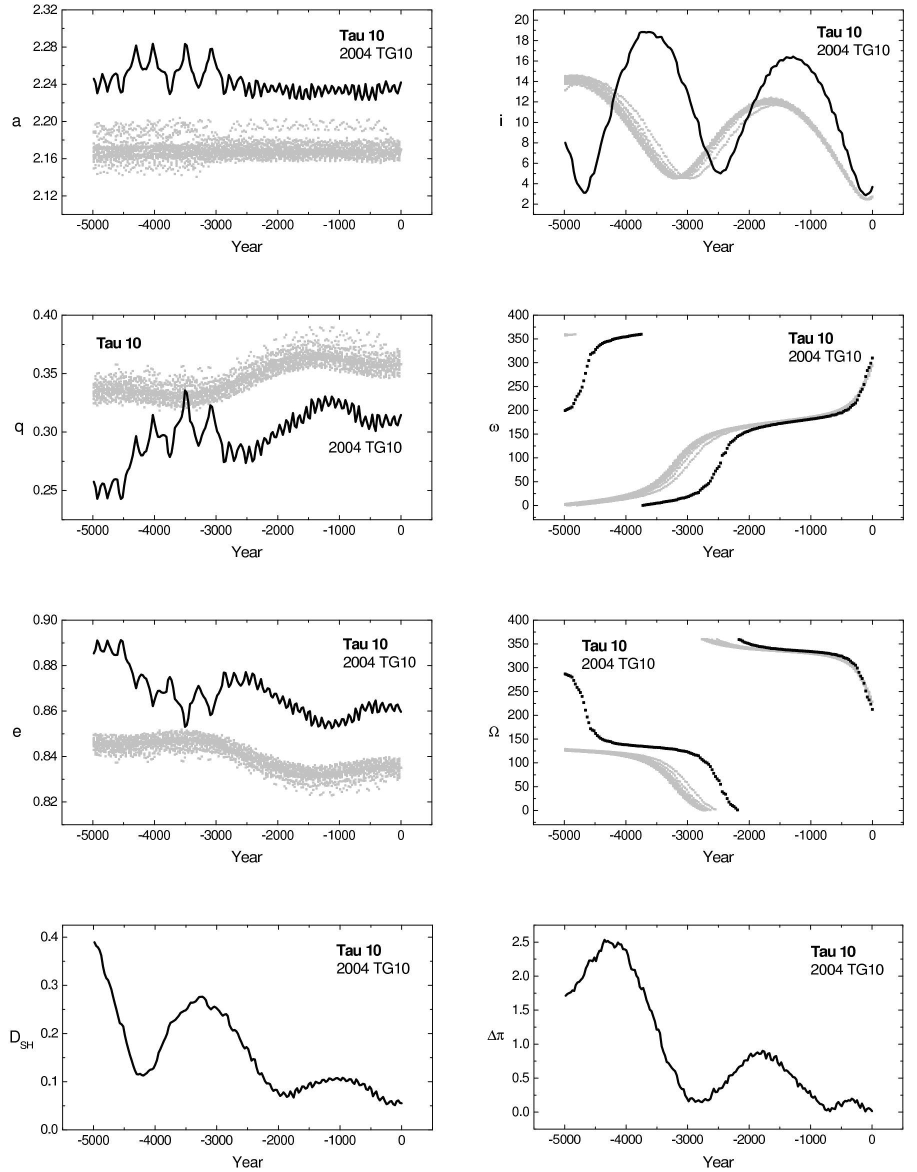

Figure 4. Orbital evolution and D_{SH} of TC filament 10 and 2004 TG10.

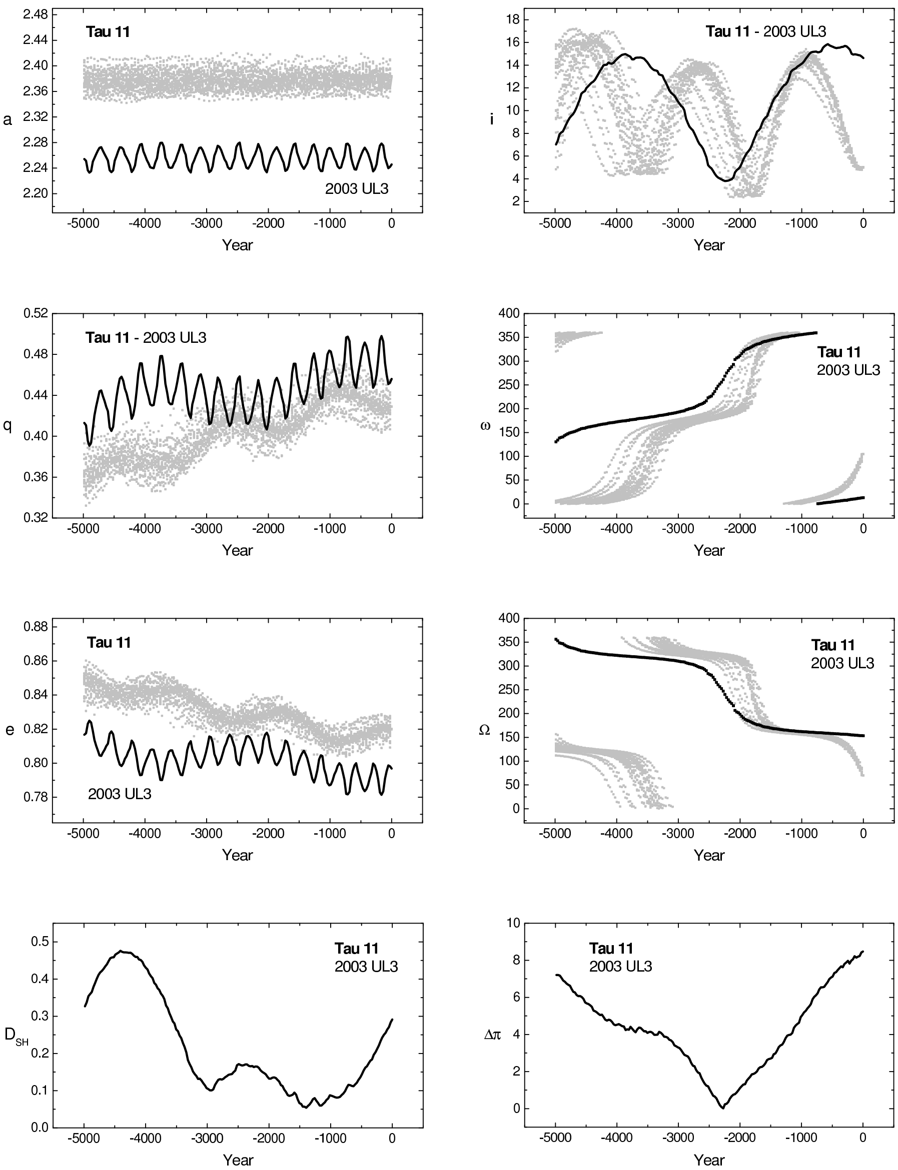

Figure 5. Orbital evolution and D_{SH} of TC filament 11 and 2003 UL3.

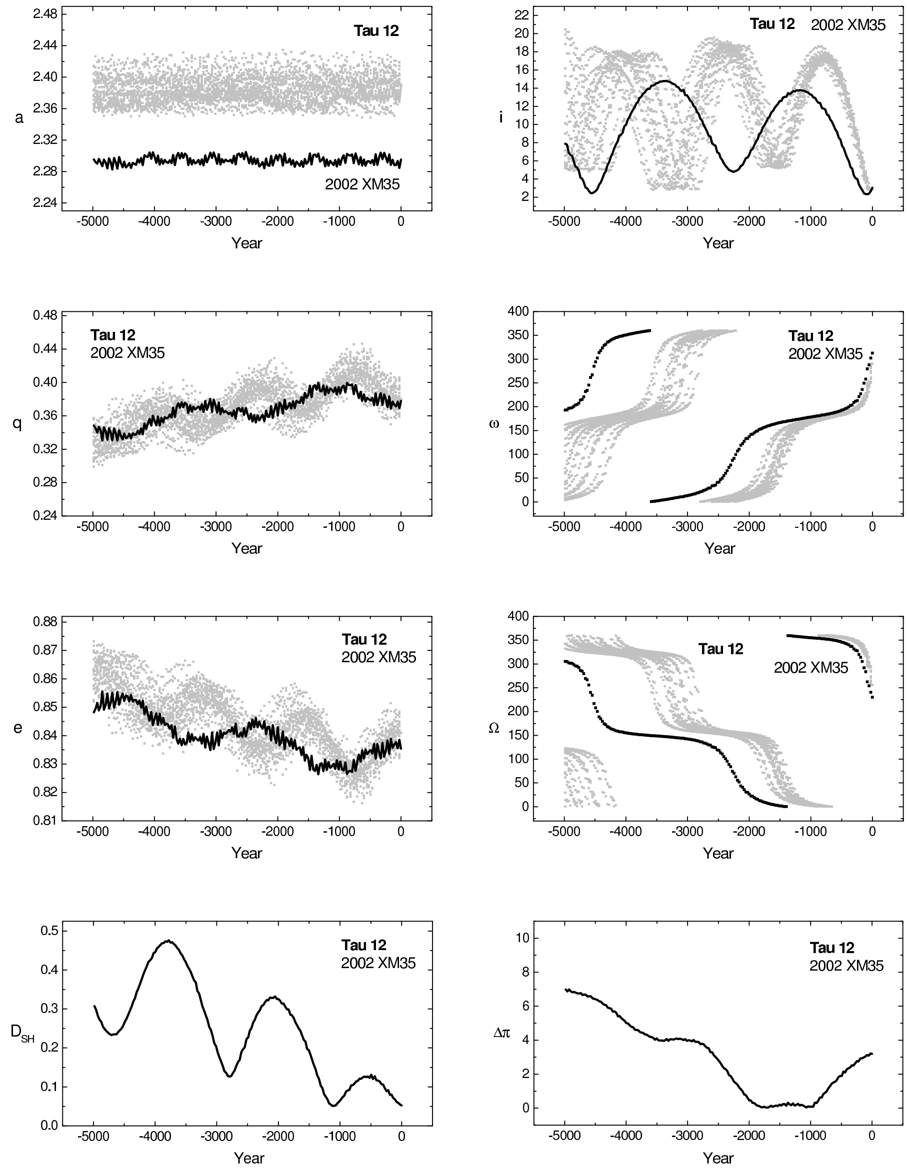

Figure 6. Orbital evolution and D_{SH} of TC filament 12 and 2002 XM35.

The most important of the elements when considering orbital evolution are the semimajor axis a and aphelion distance Q which characterize the distance of the filament from the Jupiter's orbit. These influence the amplitudes and rates of changes of the elements q, e and i during the integration. The first two groups (I and II) have Tisserand invariant close to P/Encke ($T = 3.03$) while the groups III and IV are with their a, Q and T on typically asteroidal orbits.

Filaments 6 and 15 (group II) are close to 4 : 1 mean motion resonance with Jupiter and this causes a large dispersion of the modeled particles in the evolution of both streams. Filament 14 has a very high aphelion distance (4.9 AU), the particles approach Jupiter and many of them are disturbed.

The best defined association is for filament 4 and 2003 QC10 with a very low D for the whole period of integration and the association is on a typical asteroidal orbit. The next one is the association between filament 10 and 2004 TG10 which has $D \leq 0.1$ for the last 2200 years and their lines of apsides are very close for the whole period of integration.

Whipple's suggestion that comet Encke is one fragment of a giant comet which disintegrated in the distant past gained support when in October 2005 asteroid 2005 TF50 was discovered (Spahr, 2005). The asteroid is moving close to Encke (Tab. 3). Though the orbit of 2005 TF50 is still rather uncertain, the orbital evolution of comet Encke and 2005 TF50 (not considering non-gravitational effects) is calculated and shown in Fig. 7 (upper six plots). 2005 TF50 is close to 7 : 2 resonance with Jupiter.

Following the orbital evolution of 2P/Encke and Taurid filaments, the closest similarity in evolution between the comet and filaments is for filaments 7, 9 and 10, which contain 28, 56 and 38 meteors (Tab. 1) the richest filaments of the complex and correspond to the early S Tau (7), main S Tau (9) and main N Tau (10) branches of the complex. All the three filaments have the Tisserand invariant value close to that of Encke. The last two plots of Fig. 7 show comparison of Encke and the filaments as evolution in the differences of D_{SH} and $\Delta\pi$. The orientation of the lines of apsides of filaments 9 and 10 with respect to Encke remains practically the same over the whole period of integration and all three filaments had the same orientation about 4000 − 4500 years ago. At the same time small D_{SH} values for filament 7 and 10 in this period may suggest a possible origin of both filaments from Encke at this time. Another enrichment of filament 10 from comet Encke may have occured about 1200 years ago. Filament 9 could have originated from Encke about 2500 years ago (smallest D_{SH}) but more probably earlier, more than 5000 years ago.

Summarizing, the following conclusions can be drawn:

Applying a strict value of the Southworth-Hawkins D-criterion ($D \leq 0.1$) to photographic orbits of the Meteor Data Center catalogue - version 2003, 23 TC filaments containing from 2 to 56 members (210 meteors) were identified.

15 Taurid meteor complex filaments contain more than three meteors each and these were searched for potential parents. The complex forms a very broad stream active for almost four months (Fig. 2), 120° in solar longitude. The ra-

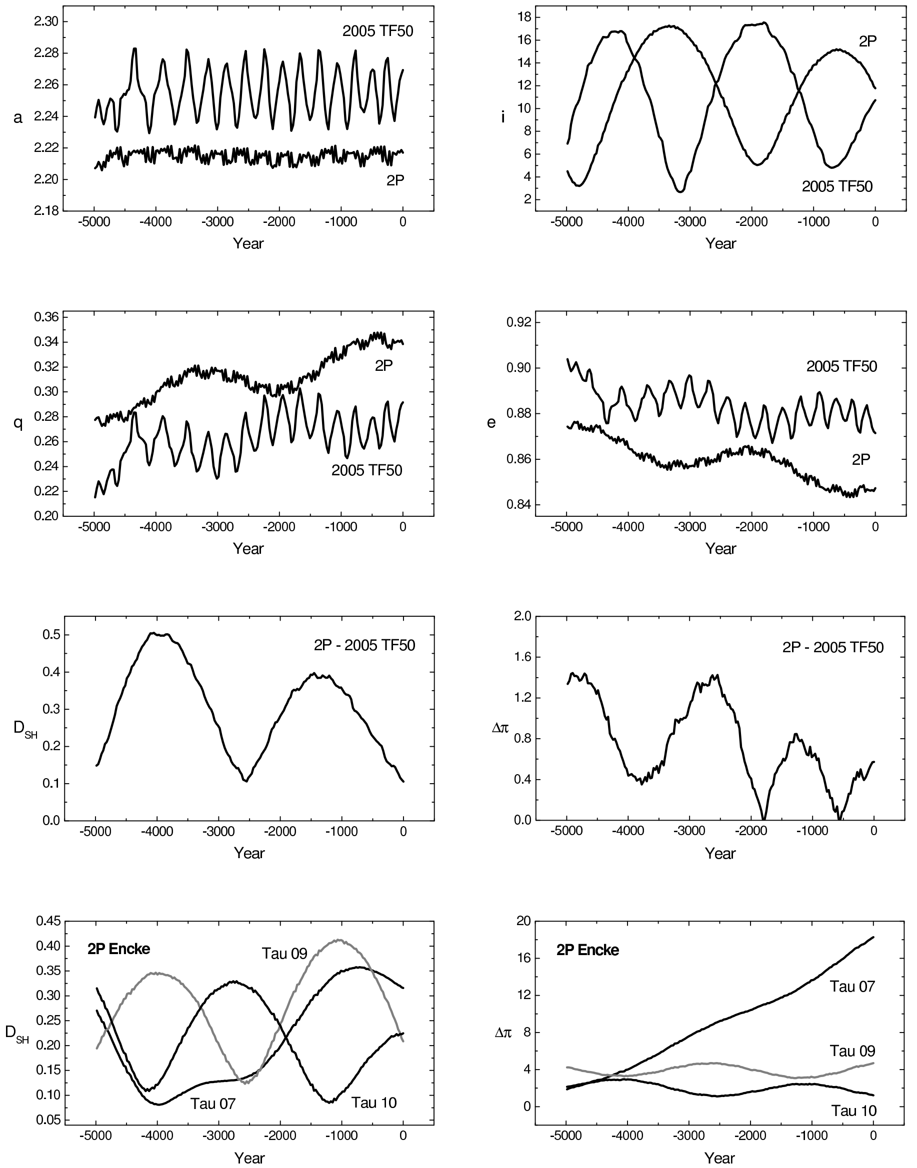

Figure 7. Orbital evolution and D_{SH} of 2P/Encke and 2005 TF50 (upper six plots) and evolution in D_{SH} and $\Delta\pi$ between 2P/Encke and Taurid filaments 7, 9 and 10 (lower two plots).

diant area of the complex reduced to the common solar longitude of 220° is 25° × 15°.

From the data set of 3380 NEO known until June 2005, 91 objects were found to move close to the TC (for $D \leq 0.30$).

Following the orbital evolution backwards over 5000 years, possible associations between 7 TC filaments and 9 NEOs were found and the most probable are for filaments (04): S Psc(b) – 2003 QC10, (10): N Tau(a) – 2004 TG10, (11): *o* Ori – 2003 UL3 and (12): N Tau(b) – 2002 XM35.

All the NEO in the TC are small objects with diameters less than 2 km and may be collisional fragments, dormant cometary nuclei, asteroidal fragments or larger meteoroids.

The most close associations between 2P/Encke and Taurid filaments were found for filaments 7 (the earlier branch of S Tau), 9 (the main branch of S Tau) and 10 (the main branch of N Tau). Filaments 7 and 10 originated from the comet about 4000 – 4500 years ago and filament 10 was enriched about 1200 years ago, filament 9 originated from comet probably still before 5000 years ago.

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