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Looking for the Geminids structure in the range of photographic meteors

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Abstract.
249 out of 387 selected Geminids are formally grouped into one of the 16 determined orbital filaments. A structure of the filaments is studied. As it was expected, the Geminids seem to be a relatively compact stream. Only a weak conception of 4 branches of filaments can be found. It is hardly cognizable only on the basis of the space visualisation and with the low numerous filaments included. According to our analysis, the two observed maxima of Geminids (e. g. Ryabova, 2001a) are product of the activity of two different groups of filaments. These parts of Geminids might appear to be as two different meteor streams, unless the similarity of their orbits was so high.
Key words: Geminids – structure of the meteoroid stream – photographic meteor orbits

1. Introduction

Geminids are one of the most active annual meteor showers. The maximal Zenithal Hourly Rate of the visual meteors is about 100. The stream is peculiar due to several aspects:
1.) It has an extremely short orbital period of about 2.6 years. The orbit of Geminids is located far from the orbits of the giant planets. Table 1 lists the orbital parameters of the Geminids and asteroid (3200) Phaethon according to several authors.
2.) The parent body is probably an asteroid or an extinct comet.
3.) The activity profile is distinctly asymmetrical (e. g. Jones and Morton, 1982); or with two maxima according to some authors (e. g. Ryabova, 2001a).
4.) Some observed features of the stream (e. g. the activity profile; the mass distribution of the particles in the stream) still have not been clarified.

The stream became observable relatively recently – it appeared rather suddenly, during the 60-ies of the 19^{th} century. The appearance of the stream is a consequence of secular gravitational planetary perturbations, mostly those of Jupiter. The ascending node of the Geminids orbit is shifting retrogradely approximatelly 1.6° per 100 years (Plavec, 1950; Fox et al., 1982; Babadzhanov and Obrubov, 1980), however, this drift has not been observed yet (Hajduk, 1974; Fox et al., 1982). The explanation is hidden in the shape of the cross section of

Table 1. The orbital parameters of photographic Geminids and the small body (3200) Phaethon; (2000.0). (1) Kresák and Porubčan, 1970; (2) Williams and Wu, 1993; (3) Porubčan and Cevolani, 1994; (4) Kaňuchová and Svoreň, 2006; (5) Gibson and Marsden, 1984.

	q(AU)	e	$\omega(°)$	$\Omega(°)$	$i(°)$	No.	Ref.
Geminids	0.129	0.906	325.8	261.0	24.9	81	1
	0.141	0.898	324.2	260.7	23.6	100	2
	0.143	0.891	324.7	261.0	23.7	191	3
	0.141±.016	0.894±.023	324.6±1.8	261.9±1.0	23.6±3.2	387	4
Phaethon	0.139570	0.890215	321.6581	265.7572	22.0314		5

the intersection of the meteor stream with the ecliptic plane. The ascending nodes of the meteoroids are moving retrogradely, however, the cross section is skew and thus the maximum of the activity is observed at the constant solar longitude. In 1862 the Geminids orbit was inside the Earth's orbit and it has subsequently moved outwards, crossing over the Earth's orbit (for details see Fox et al., 1982; 1983).

2. A note about the parent body of Geminids

Altough the stream and its characteristics are rather well known, the question of its origin is still open.

The first possible parent body - comet C/1917 F1 Mellish (formerly 1917 I) - was suggested by Kresáková (1974). She proposed a chain association among the Geminids and two minor streams, which were identified with Monocerotids (Whipple, 1954; Lindblad, 1971a; Lindblad, 1971b) and Southern Geminids or 11 Canis Minorids (Hindley and Houlden, 1970). At present, this theory is considered to be obsolete. Many new facts and relationships point at other parent body - the small body (3200) Phaethon, which was discovered by the Infrared Astronomical Satellite in 1983.

On the basis of the similarity and evolution of the orbital parameters of Phaethon and Geminids, the small body (3200) Phaethon seems to be the parent body of Geminids with a high probability. The question is, if Phaethon is an extinct comet, or, vice versa, an "activated" asteroid. It turned out shortly after its discovery that it is an Apollo-type object, but with a very small perihelion distance $q = 0.1376$ AU (Gibson at al., 1983). In accordance with the results of several spectral analyses (e. g. Cochran and Barker, 1984; Green et al., 1985; Licandro et al., 2007) 3200 Phaethon seems to be an "activated" asteroid rather than an extinct comet.

The results of the analyses of the Geminids fireballs are ambiguous. Halliday (1988) concluded that Geminid meteoroids had too low density to associate them with meteorites or normal asteroids. Frequent exposure to intense solar radiation near the perihelion (0.14 AU) may lead to a loss of volatiles and may produce relatively tough meteoroids that resemble the crust of a comet rather than its interior. On the other hand, the theory of stony - asteroidal material of Geminids is supported by smaller number of fireballs observed with long persistent trains in comparison with Perseids and Orionids (Evans and Bone, 2001); the value of an ablation coefficient (Spurný, 1993) and the density of hydrated minerals (Licandro et al., 2007).

Despite the fact that the spectrum of Phaethon resembles an asteroidal one, many authors assume that Phaethon is the core of an extinct comet, because its actual orbit with a high eccentricity is of a cometary type (e. g. Halliday, 1988; Gustafson, 1990; Porubčan et al., 2004).

A transformation of a long-period cometary orbit into a short-period one with the aphelion located deep inside the Jupiter's orbit and the perihelion near the Sun (Geminid and Arietid type) is a bit disputable. Such a transformation could be possible as a consequence of close encounters of the body with the Earth or Venus (Andreev et al., 1990; Terentjeva and Bayuk, 1991) or as a result of the decelerating reactive ejection of cometary gas (Lebedinets, 1985).

The Tisserand invariant T of Phaethon with respect to Jupiter is 4.18, a value typical for the orbits of the Main Belt asteroids. The treshold value which separates the cometary and asteroidal orbits is $T = 3$. According to the dynamical model of Bottke et al. (2002), Phaethon originates from the $\nu 6$ resonance area (with a probability of 52%); eventually from the 3:1 resonance area (24%) or from the area of the Mars-crossing objects (24%) (Weissman et al., 2002).

In contrast to the well-known theory of the cometary meteoroid streams creation (on the basis of Whipple's model of cometary nucleus), the question of the asteroid stream origin is exactly still not answered.

Hirayama asteroid families (Hirayama, 1918), which are supposed to be the products of destructive encounters of the Main Belt asteroids, could be regarded as little numerous asteroidal streams. Some of the Hirayama families could be associated with the dust belts discovered in the Main Belt of asteroids (Dermott and Nicholsson, 1989). Hence, it could be supposed that a great number of small dust particles are produced when the asteroids collide - the asteroidal streams of particles are created in this manner. A dust cloud consists of the regolith, which is likely the common crumbled material, covering the surface of asteroids (the thickness of the regolith on the asteroids Ida and Gaspra is ≥ 10 m, for example (Sullivan et al., 1996)).

The idea of the asteroidal streams is coming more acceptable as new facts about the amount and structure of regolith are growing. As well, the Geminid meteoroids could be made from this material.

3. Acivity of the stream

The Geminid shower is active for about 10 days (Williams and Wu, 1993). The weak, radar meteors are active in the interval of December 2–15 (Jones and Morton, 1982); the interval of activity of the photographic meteors is a bit shorter (Jones, 1985). However, some bright meteors can be detected at the beginning of the activity interval - on 3^{rd} and 5^{th} of December, respectively (Svoreň et al., 1997; Evans and Bone, 2001). The activity curves confirm that Geminids is a concentrated stream and the Earth crosses its dense central part during about two and a half days (Pupillo et al., 2004).

The maximum of activity occurs regularly around December 13–14 ($\lambda_\odot \approx 261°$). According to Jones and Morton (1982), the Geminid shower shows a gradual increase in activity from $\lambda_\odot = 255°$ to 261.3° and a rather shift drop-off thereafter, so the activity profile is seen as asymetric.

There was detected a secondary maximum of the activity of the visual meteors. It occurs 0.8° after the primary one (Spalding, 1982). The secondary maximum of visual and also the radar Geminids was analysed by Ryabova (2001b). The time interval between the primary and the secondary maxima depends strongly on the mass of meteoroids - it is about 0.5° for 0.1 g particles and $\approx 6°$ for meteoroids in the mass range of 10^{-5}–10^{-6} g (Ryabova, 2001b). There were indicated even more maxima in the wide and asymetric profiles of the activity of the radio meteors (Pupillo et al., 2002; Pupillo et al., 2004). The shape of the activity curve may exhibit the filamentary structure of the stream.

The Hourly Rates of Geminids differ in time depending on the brightness of meteors (and consequently the mass of meteoroids) investigated. It is well known for many years that the activity of small particles culminates earlier than the activity of bigger ones (Plavcová, 1962; McIntosh, 1966; Šimek, 1973). The skewness of the activity profile is also dependent on the particles' mass (Jenniskens, 1994; Pecina and Šimek, 1999).

The stream has been widened into the structure which can be described as follows: the solar longitude of the maximum activity is changing with the brightness of meteors according to the formula $\lambda_\odot = 261.3 - 0.135M$ (1950.0), where M is the magnitude in the range of radar meteors (McIntosh and Šimek, 1980). The similar formula valid for visual meteors is: $\lambda_\odot = (261 \pm 0.05) - (0.078 \pm 0.025)M$ (1950.0) (Spalding, 1984).

The mass distribution index s tends to become smaller as the Earth moves through the shower: $s = 1,667 - 0,0219(\lambda_\odot - 260°)$ [for the $\lambda_\odot$ in the interval of 248° – 264°] (Webster et al., 1966). This conclusion was confirmed by an analysis of radar observations achieved during 6 years (Pupillo et al., 2004). For many years, the facts mentioned above were interpreted as a consequence of the Poynting-Robertson effect, which pushes small particles back to the region of inner orbits of the stream (Plavcová, 1962; Šimek, 1975; Jones, 1978). In fact, the stream of faint meteors "wraps up" the stream of brighter meteors (Webster et al., 1966; Lokanadham, 1980; Fox et al.,1983). The activity of faint meteors does not finish before the end of the activity of bright meteors. The intervals of all six orbital parameters are narrower for the photographic meteors compared to the radar ones (Williams and Wu, 1993). It means that the stream of small particles is wider than the stream of bigger meteoroids. Bright Geminids are active just for 2–3 days, while the faint radar meteors are detected for 10 days (McIntosh and Šimek, 1980; Fox et al.,1983; Williams and Wu, 1993). On the basis of the shower duration, the minimal lenght of the cross-section in the 1 AU distance from the Sun is estimated to be 0.12 AU for 1 mm particles and about 0.05 AU for 1 cm meteoroids (Olsson-Steel, 1987).

4. Input Data and Method used

A fine structure of the Geminid stream is studied using the method of indices (Svoreň et al., 2000). For the study, a 2003 version of the IAU Meteor Data Center Catalogue of 4581 precise photographic orbits (Lindblad et al., 2003) is used. The meteors with heliocentric velocities higher than $48\,\mathrm{km\,s^{-1}}$ were omitted from this analysis (Porubčan et al., 1995) and thus the final set consisted of 4526 orbits. The Geminid stream is the second most abundant stream in the database.

In the method, the 5 orbital elements appearing in the Southworth-Hawkins D-criterion (Southworth and Hawkins, 1963), the coordinates of the radiant and the geocentric velocity are used as the input data. The basic ideas of the method are as follows: the observed range of each parameter is divided into a few equivalent intervals; each meteor is assigned by a group of indices according to the intervals pertinent to its parameters. A philosophy of the method says that grouping of the meteors with the same indices reflects a similarity (and with a high probability a relationship) among the orbits. A detailed description of the method used was published before by Svoreň et al. (2000) and Kaňuchová et al. (2005).

The method enables a study of the fine structure of streams and their filaments. The filaments (mainly those less numerous) can be hardly separated by any iterative method. If a meteor stream has some complicated structure, the meteors are separated into a few related groups - filaments - using a sufficient fine division of the intervals of parameters in the method. The small differences between the corresponding indices mean the similarity of the orbits within one group. The efficiency of the procedure is supported by the positive results of the analysis of the Perseid stream structure (Kaňuchová et al., 2005; Svoreň et al., 2006). It was found that the structures of this stream found by the method of indices can be interpreted as a product of gravitational perturbations of the giant planets on particles of the stream.

The method of indices was applied to acquire a basic data set for the Geminids - totally 387 orbits were selected from the catalogue. The selected Geminids cover the interval from December 8$^{\mathrm{th}}$ to December 15$^{\mathrm{th}}$. Ranges of parameters for 387 Geminids are listed in Table 2 and the mean orbit is in the last row (Kaňuchová and Svoreň, 2006).

Table 2. The ranges of parameters for 387 selected Geminids and the mean orbit.

parameter	q(AU)	e	$\omega(^\circ)$	$\Omega(^\circ)$	$i(^\circ)$	$\alpha(^\circ)$	$\delta(^\circ)$	$v_\mathrm{g}(\mathrm{km\,s^{-1}})$
Lowest value	0.085	0.743	318.1	256.8	12.1	107.4	29.3	24.40
Highest value	0.234	0.981	334.4	263.8	43.2	121.7	35.3	44.20
Mean orbit	0.141	0.894	324.6	261.9	23.6			
	±0.016	±0.023	±1.8	±1.0	±3.2			

5. Filaments of Geminids

5.1. Groups of similar orbits

We applied the method of indices to 387 separated meteors for the study of the fine structure of Geminids. According to the rules of the method, the individual numbers of intervals were used in the division of each parameter. Table 3 lists: the parameters considered in the method of indices; the errors of the parameters for the Geminid stream; the ranges of parameters of the selected Geminids; the ratios of given ranges to the mean errors, which moreover divided by the empirical value (2.27) fulfilling the condition of mimimal sum of squares of differences between the real values and closest integers; and the coresponding nearest integers serving as a basic set of numbers for the division of the parameters into the equidistant intervals.

We found, for the investigated Geminids, that the basic numbers of division of parameters and its doubles and triples (with relative high numbers of selected meteors) give considerably different numbers of associations (18, 30 and 20) - groups of meteors which contain minimally 3 similar orbits (see Kaňuchová et al., 2005). We took into account the compactness of associations and a proportion of the meteors from the whole amount which they are compound of.

We prefer a double of the basic division, based on which 242 meteor orbits are selected and 182 of them are grouped into 30 associations, numbered 1–30. We note that the preference of some multiple of the basic number of division of parameters doesn't influence the final results (number of filaments found), in principle. Using a higher multiple of the basic division, the individual filament will be compound of more, less numerous associations.

The number of meteors within the individual associations differ considerably. Only 3 out of 30 associations consist of a higher number of meteors (assoc. Nos. 4, 11 and 25 consist of 15, 14 and 18 meteors), hovewer, 12 associations consist only of 3 meteors, what is a treshold value for denoting them as an "association".

Table 3. The mean errors (MEs) and the numbers of intervals of the basic division.

parameter	q(AU)	e	$\omega(^\circ)$	$\Omega(^\circ)$	$i(^\circ)$	$\alpha(^\circ)$	$\delta(^\circ)$	$v_{\rm g}({\rm km\,s^{-1}})$
ME.	0.016	0.023	1.8	1.0	3.2	1.6	0.8	1.78
Range	0.149	0.238	16.3	7.0	31.1	14.3	6.0	19.80
Range/ME/2.27	4.03	4.60	3.97	3.03	4.26	3.96	3.43	4.90
Intervals	4	5	4	3	4	4	3	5

5.2. Structure of the Geminid meteoroid stream

A clustering of orbits in space means a clustering of their orbital parameters. If we deal with the associations of orbits, this is true for their mean parameters (for details see Svoreň et al., 2001). We studied a grouping of orbits in the following parameters q, e, ω, Ω and i. We try to determine the borders of the intervals of the individual parameters with any subjective influence.

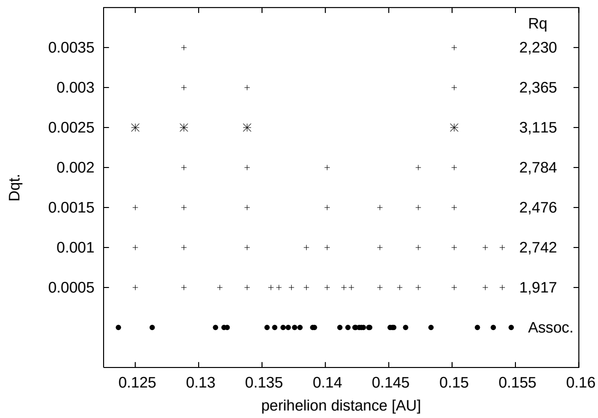

Figure 1. Grouping of the associations by q. Dots in the lowermost row correspond to the values of q for 30 associations. For details see the text.

We analyse theoretical cases in which the groups of associations are more or less numerous. We clarify the principle of groups formation using one parameter q as an example (see Fig. 1). The difference between the neighbouring values of the mean q of the associations was denoted as Δq. $\Delta q_{\rm t}$ (in Fig. 1 labeled as Dqt.) is the smallest Δq available. If Δq of two successive associations is $< \Delta q_{\rm t}$, these associations are included into one group, but if $\Delta q > \Delta q_{\rm t}$, these two associations are separated into two neighbouring groups. We calculate the $q_i = (q_{\max} - q_{\min})/(n-1)$ for each group and, consequently, the mean q_i ($< q_i >$) of all groups; where $q_{\max}$ is maximal and $q_{\min}$ minimal q in the group of n associations. In the next step, we take the closest higher value of Δq as a new

Table 4. The limits of parameters q, e, ω, and Ω separating the groups of associations. *d.r.* – designation of range.

d.r.	range (AU)	*d.r.*	range	*d.r.*	range (°)	*d.r.*	range (°)
$q1$	0.123–0.125	$e1$	0.864–0.872	$\omega1$	322.8–324.1	$\Omega1$	260.7–260.9
$q2$	0.125–0.129	$e2$	0.872–0.885	$\omega2$	324.1–325.3	$\Omega2$	260.9–261.4
$q3$	0.129–0.134	$e3$	0.885–0.910	$\omega3$	325.3–326.3	$\Omega3$	261.4–262.6
$q4$	0.134–0.150	$e4$	0.910–0.917	$\omega4$	326.3–327.3	$\Omega4$	262.6–263.4
$q5$	0.150–0.156	$e5$	0.917–0.924	$\omega5$	327.3–327.9		

$\Delta q_{\rm t}$ and repeat the whole procedure till the highest available $\Delta q_{\rm t}$. Finally, the determination of the ratio $R_q = \Delta q_{\rm t}/ < q_i >$ for each considered $\Delta q_{\rm t}$ is done (R_q is labeled as Rq in Fig. 1). The division of a parameter characterized by the higher R_q is considered as optimal ($R_q = 3.115$ in this example).

Concerning the inclination, all possible groups were equivalent. The corresponding rate R_i remained approximately constant for all values of $\Delta i_{\rm t}$. So we decided not to take some "artificial" division in this element into account so as not to influence final results. The derived limits of parameters are listed in Table 4 and depicted in corresponding Figures 2 and 3.

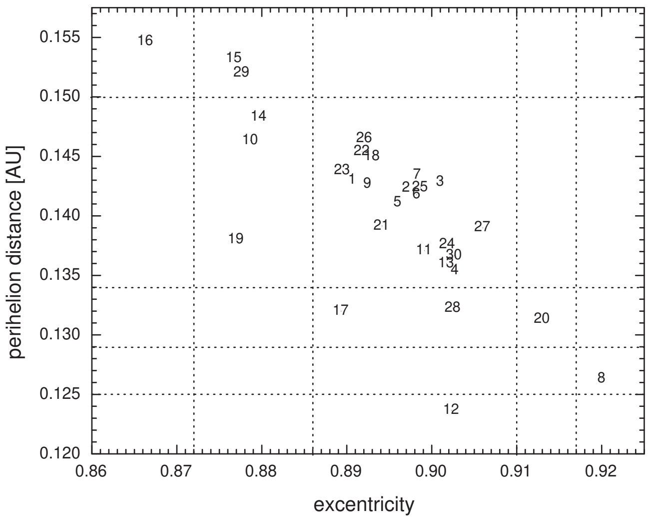

Figure 2. The dependence of $q = q(e)$ for the associations selected. The associations are identified by the serial numbers. The position of a given number corresponds to the mean values of q and e of the respective association.

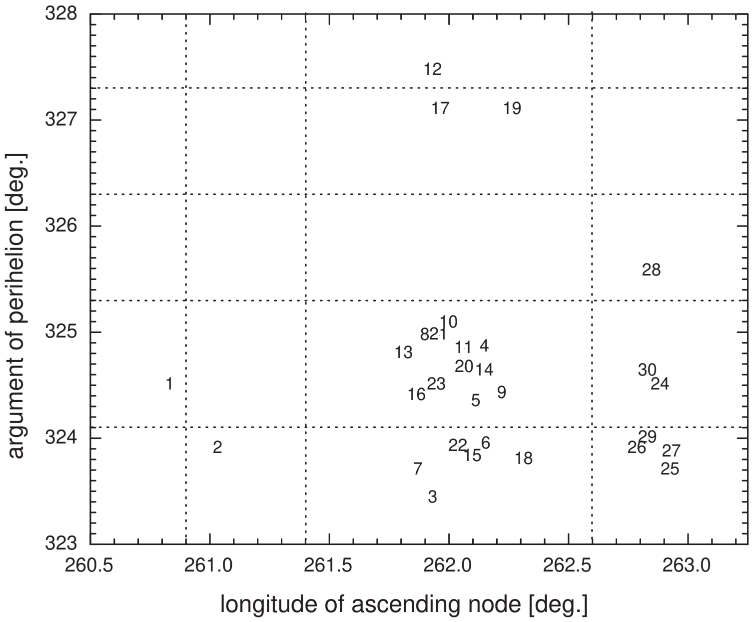

Figure 3. The dependence of $\omega = \omega(\Omega)$ for the associations selected. The associations are identified by the serial numbers. The position of a given number corresponds to the mean values of ω and Ω of the respective association.

Clustering of associations in 4 considered elements led to an operational definition of 16 filaments consisting of 182 individual orbits. The definition of filaments seems to be just formal, and it is hard to see any relation with real structures at first sight.

The derived limits are, in the next step, used to search in the datafile of remaining 205 Geminids, which were not assigned to one of 30 associations. Finally, 249 (64% of 387) Geminid orbits are selected to 16 filaments, which are listed in Table 5.

Associations don't make groups in more elements simultaneously, that's why many low-numerous individual filaments are defined. Many filaments represent just one association. It is possible that this low-numerous filaments are just random clusters of orbits with no statistical significance. Just 6 out of 16 filaments – C, D, F, G, N and O - seem to be real structures in space. In spite of the several facts mentioned above, we try to apply further procedures and analysis to the set of 16 filaments found.

Table 5. Mean orbits of the filaments. *d.rs.* - designation of combination of ranges, Q - designation of filament, N - number of orbits.

$d.rs.$	Q	N	α	δ	$v_{\rm g}$	q	e	ω	Ω	i	$1/a$
$\Omega1, \omega2, q3, e4$	A	6	112.4	32.3	33.96	0.142	0.891	324.7	260.8	22.9	0.766±0.006
$\Omega2, \omega1, q3, e4$	B	4	111.9	32.4	34.41	0.144	0.896	323.8	261.1	23.0	0.727±0.006
$\Omega3, \omega1, q2, e5$	C	10	113.5	32.4	33.08	0.153	0.879	323.6	262.1	22.1	0.793±0.006
$\Omega3, \omega1, q3, e4$	D	51	113.1	32.4	34.68	0.143	0.898	327.3	262.0	23.8	0.712±0.004
$\Omega3, \omega2, q1, e5$	E	3	113.9	32.2	32.00	0.155	0.866	324.6	261.9	20.8	0.864±0.007
$\Omega3, \omega2, q2, e4$	F	12	114.1	32.0	32.99	0.147	0.880	324.9	262.0	21.8	0.820±0.005
$\Omega3, \omega2, q3, e4$	G	80	113.6	32.1	34.49	0.139	0.897	324.7	262.0	23.5	0.739±0.003
$\Omega3, \omega2, q4, e3$	H	6	113.8	32.8	36.11	0.131	0.913	324.8	261.9	27.2	0.665±0.006
$\Omega3, \omega2, q5, e2$	I	3	113.4	32.4	36.60	0.126	0.920	325.0	261.9	26.6	0.633±0.018
$\Omega3, \omega4, q3, e3$	J	3	115.5	32.0	33.58	0.132	0.889	327.1	262.0	23.9	0.838±0.006
$\Omega3, \omega4, q2, e4$	K	3	117.0	33.0	32.83	0.138	0.877	327.1	262.3	25.7	0.891±0.004
$\Omega3, \omega5, q3, e1$	L	3	115.5	32.0	34.72	0.124	0.902	327.5	261.9	25.5	0.790±0.025
$\Omega4, \omega1, q2, e5$	M	4	114.2	32.0	32.98	0.152	0.878	323.9	262.8	21.3	0.802±0.009
$\Omega4, \omega1, q3, e4$	N	39	113.9	32.0	34.56	0.143	0.897	323.8	262.9	23.0	0.715±0.004
$\Omega4, \omega2, q3, e4$	O	16	114.4	32.0	34.57	0.139	0.898	324.6	262.8	23.4	0.731±0.007
$\Omega4, \omega3, q3, e3$	P	6	115.3	32.1	34.98	0.132	0.903	325.6	262.9	25.1	0.736±0.011

6. Analysis of the structure of the stream

6.1. Time dependence

The activity curve of the 387 selected Geminids (Fig. 4) has two distinctive maxima: at $\lambda_\odot = 261.9°$ and $262.8°$. The interval of $\lambda_\odot = 0.1°$ is considered. The profile with two peaks is known from visual, photographic and radar observations (Jenniskens, 1986; Rendtel and Arlt, 1997, Ryabova, 2001a; Spalding, 1982). There are some smaller peaks also, but only 2 of them are at least 10% of the primary one. The occurrence of the peaks with difference in $\lambda_\odot \approx 1°$ (one day), could seem to be just an observational effect.

To prove this, the observed meteors are classified into 4 classes as consistent with the location of the observational station (the meteor codes of the stations presented in the IAU MDC catalogue are used). In the 4 groups there are meteors observed from: 1. Japan; 2. central Asia; 3. Europe and 4. America.

As it can be seen from Fig. 4, the groups are not equivalent considering the number of meteors which they are consisted of. In spite of this fact, there can be seen the relative maxima of the activity curve for three series of meteors. The less numerous set of meteors observed from the central Asia is an exception. This set consists of meteors being observed at just one station - Dushanbe.

The first, second and third maximum consists of meteors which originate from Europe and America. That is why we consider them as real, not just a

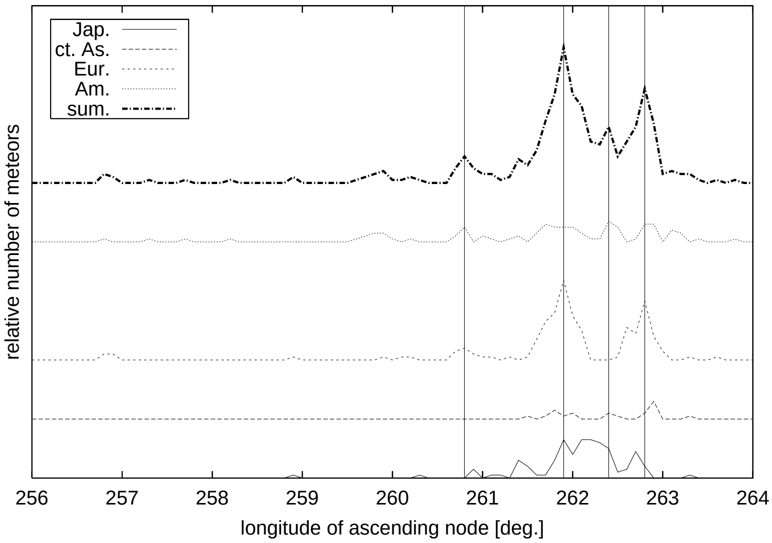

Figure 4. The activity profiles of 4 meteor groups, which are selected considering the location of the observational station. The upper curve represents the actvity profile of all 387 Geminids selected. For details, see the text.

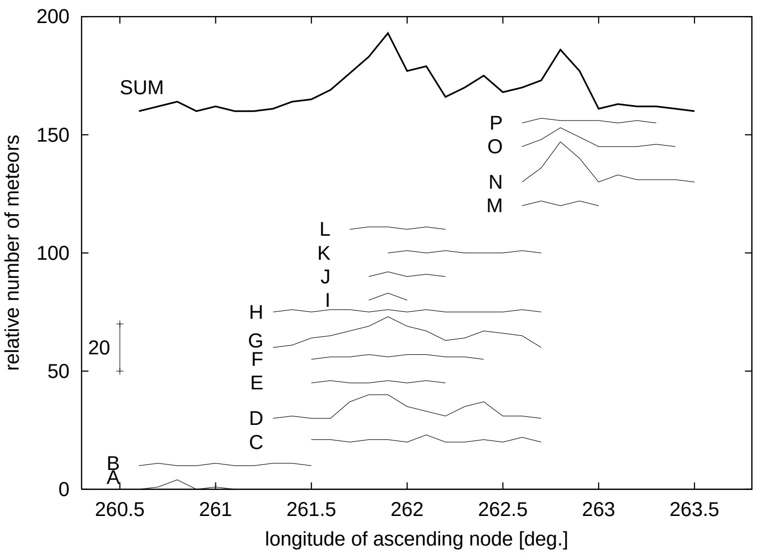

Figure 5. The activity profiles of 16 Geminid filaments and their superposition (SUM).

product of the observation timing. As an expected observational effect, a small shift of pertinent maxima of individual series of data would be seen.

As it can be seen in Fig. 5, the contributions of individual filaments to the whole activity differ considerably. At the beginning, just two filaments - A and B - are active. The first maximum consists mainly of meteors of G and D filaments, but the majority of filaments are co-active. During the second maximum, the isolated group of 4 filaments - M, N, O, P - is active. We can say that the Geminids activity curve has two parts which can be cut at $\lambda_{\odot} = 262.7°$. In this point, most of the filaments terminate their activity, whereas the activity of another ones begins. These parts of Geminids might appear to be as two different meteor streams, unless the similarity of their orbits was so high. According to Ryabova (2001a; 2007), this discontinuity could be caused by prior and post perihelion ejections.

6.1.1. Positions of perihelia

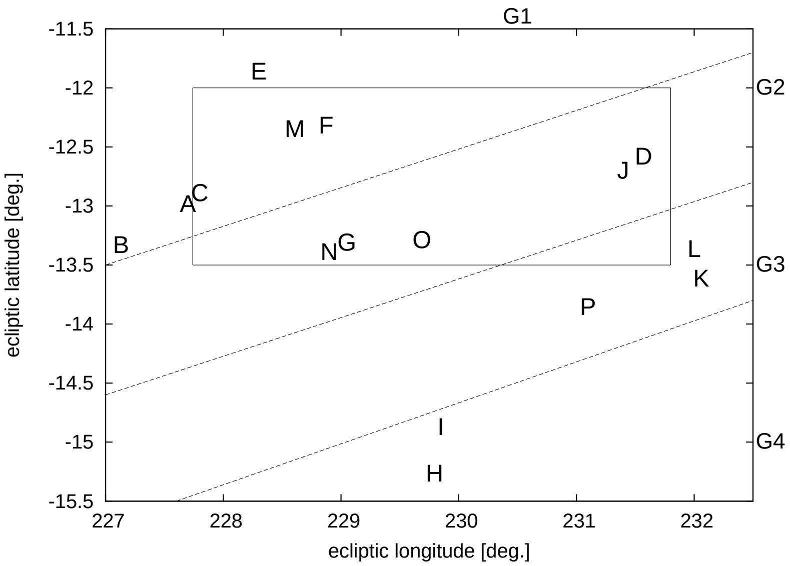

Figure 6. The positions of perihelia of 16 Geminid filaments in the ecliptic coordinate system.

Considering the directions to perihelion of filaments (Fig. 6), no significant and explicit grouping was found. At the picture, there are filaments which consist of more than 6 meteors (except for M and J), bordered. The 4 meteor groups denoted as G1–G4 will be described later.

6.1.2. Distribution of radiants

An analysis of the distribution of the radiants of selected filaments is done (see Fig. 7). The positions of almost all filaments (with exception of low numerous filament K) are consistent with the mean radiant motion according to Kaňuchová and Svoreň (2006):

$$\alpha = 0.837(\lambda_\odot - 261.9) + 113.7 \quad [^\circ] \tag{1}$$

$$\delta = -0.196(\lambda_\odot - 261.9) + 32.4 \quad [^\circ] \tag{2}$$

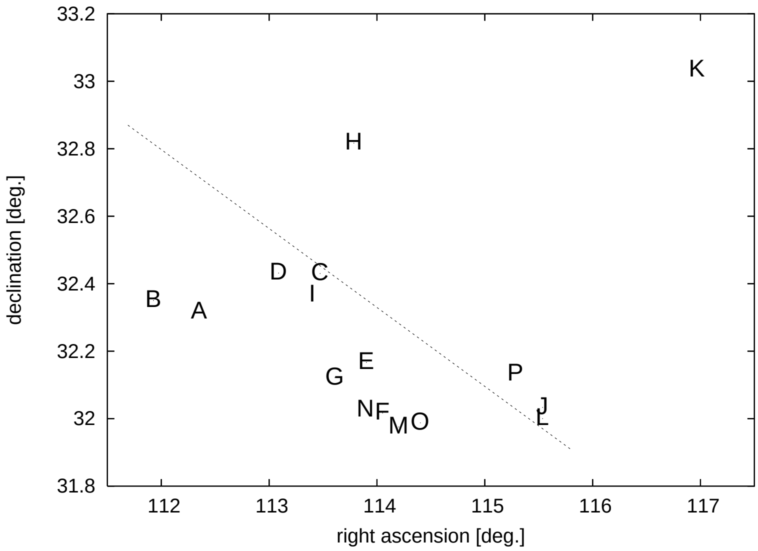

Figure 7. The positions of radiants of 16 Geminid filaments in the equatorial coordinate system.

6.1.3. Space visualization

A distribution of the filaments in space is interesting. On the basis of Figs. 8a); b), the stream seems to have no notable structure. The filaments could be described as tangled. The stream splits into three parts in the Earth-approaching area - the central part (I): C, D, E, F, G, H, I, J, K, L filaments; and two adjacent parts - more abundant part (II): M, N, O, P and part (III) which consists of just A and B filaments. The filaments in group II are more concentrated than those in I - the scatter in the main axis is just 0.152 AU; whereas it is the whole observed interval - 0.458 AU - in the case of group I. The angular elements of the filaments of both groups I and II differ notably.

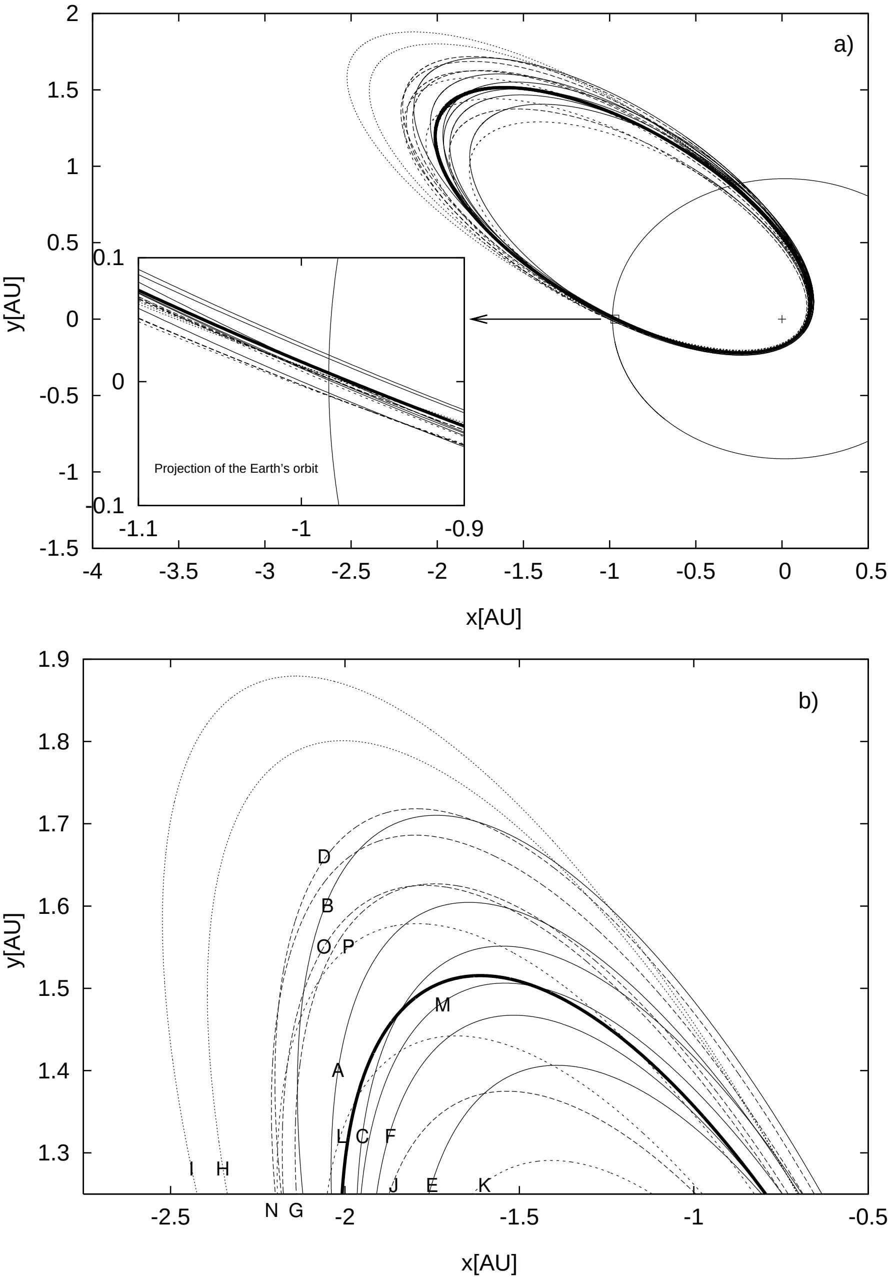

Figure 8. A projection of the mean orbits of the filaments into the plane of the mean orbit of 249 Geminids. a) a global view; b) an aphelion region. The orbit of Phaethon is marked with a bolder line.

We can distinguish 4 zones of the orbital area denoted as G1 – G4 (Fig. 9). Zone G1 consists of filaments A, B, C, E, F, M; G2 - filaments D, G, J, N, O; G3 - filaments K, L, P and G4 - filaments I, H. It was found that G1 zone change continuously into G2 zone and, G3 and G4 zones consist of just low numerous filaments.

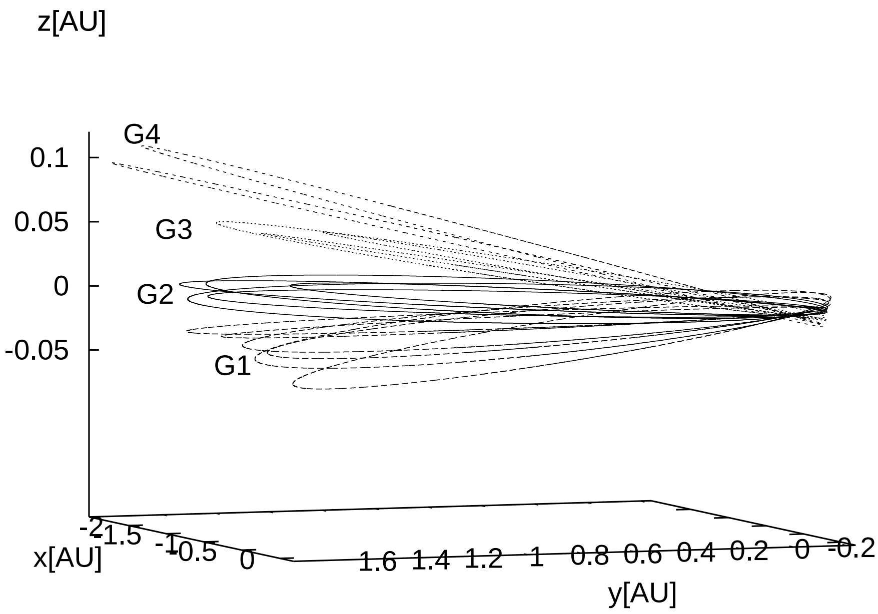

Figure 9. The filaments A-P depicted relatively to the mean orbit plane of 249 Geminids.

6.1.4. D-discriminant analysis

In the last step, the Southworth-Hawkins D-discriminants of all the pairs of 16 selected filaments and the potential parent body Phaethon were calculated (Table 6). A searching for the pairs closer than others was not successful, as all the orbits are very similar to each other - values of the D-discriminat range from 0.01 to 0.12. Such small differences are a very poor argument for supporting grouping of the filaments into separated clusters.

Table 6. The values of D-discriminant (multiplied by 100) among the mean orbits of filaments and (3200) Phaethon (Ph.).

	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Ph.
A	1	2	2	5	3	2	8	8	6	8	8	4	2	3	6	4
B		3	2	5	4	3	8	8	7	9	9	5	3	4	7	5
C			4	3	2	4	10	10	7	9	9	2	3	4	8	4
D				6	4	2	7	6	5	7	7	5	2	3	5	5
E					2	6	12	12	7	10	11	2	5	6	9	5
F						3	10	10	5	8	8	1	3	4	7	3
G							7	6	4	6	6	4	1	1	4	4
H								1	7	6	6	11	8	7	5	10
I									7	6	5	11	7	6	4	9
J										4	3	6	5	3	3	5
K											3	9	7	6	3	8
L												9	7	5	2	8
M													4	5	8	3
N														2	5	3
O															4	3
P																6

7. Conclusion

On the basis of our analysis, Geminid stream seems to be a relatively homogenous system of meteor orbits. These results are suspected due to a short activity interval of the stream and its space orientation relative to the giant planets. Four individual clusters can be recognised more or less using the space visualisation only, involving the low numerous filaments. The clusters also differ in the positions of perihelia (see Fig. 6). The analysis of a more quantitative dataset and/or a numerical simulation of the stream evolution remains to be done.

The shift of 2 significant maxima in the activity profile of Geminids is $0.9°$. This finding is in a good agreement with the results of various authors (e. g. Spalding, 1982; Ryabova, 2001a). The first maximum is a superposition of the activity of populous filaments D and G; the second maximum consists mainly of O and N filaments. All four filaments are very similar each other (they are parts of one proposed cluster G2). Therefore, it is difficult to discuss their different dynamics and support one of the theories of the Geminids double maximum origin.

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References

Andreev, G.V., Terentjeva, A.K., Bayuk, O.A.: 1990, in *Asteroids, Comets, Meteors III*, eds.: C.I. Lagerkvist, H. Rickman, and B.A. Lindblad, Uppsala Universitet, Uppsala, 493

Babadzhanov, P.B., Obrubov, Yu.V.: 1980, In *Solid Particles in the Solar System*, eds.: I. Halliday and B.A. McIntosh, Reidel, Dordrecht, Holland, 157

Bottke, W.F., Morbidelli, A., Jedicke, R., Petit, J.M.; Levison, H.F.; Michel, P.; Metcalfe, T.S.: 2002, *Icarus* **156**, 399

Cochran, A.L., Barker, E.S.: 1984, *Icarus* **59**, 296

Dermott, S.F., Nicholsson, P.D.: 1989, *Highlights of Astronomy* **8**, 59

Evans, S.J., Bone, N.M.: 2001, *J. British Astron. Assoc.* **111**, 33

Fox, K., Williams, I.P., Hughes, D.W.: 1982, *Mon. Not. R. Astron. Soc.* **199**, 313

Fox, K., Williams, I.P., Hughes, D.W.: 1983, *Mon. Not. R. Astron. Soc.* **205**, 1155

Gibson, J., Marsden, B.G.: 1984, *IAUC* 3994

Gibson, J., Skiff, B., Shoemaker, C.S., Bardwell, C.M.: 1983, *IAUC* 3879

Green, S.F., Meadows A.J., Davies J.K.: 1985, *Mon. Not. R. Astron. Soc.* **214**, Short Comunication, 29

Gustafson, Bo A.S.: 1990, in *Asteroids, comets, meteors III*, eds.: C.I. Lagerkvist, H. Rickman, and B.A. Lindblad, Uppsala Universitet, Uppsala, 523

Hajduk, A.: 1974, *Bull. Astron. Inst. Czechosl.* **25**, 305

Halliday, I.: 1988, *Icarus* **76**, 279

Hindley, K.B., Houlden, M.A.: 1970, *Nature* **225**, 1232

Hirayama, K.: 1918, *Astron. J.* **31**, 185

Jenniskens, P.: 1986, *Radiant* **8**, 58

Jenniskens, P.: 1994, *Astron. Astrophys.* **287**, 990

Jones, J.: 1978, *Mon. Not. R. Astron. Soc.* **183**, 539

Jones, J.: 1985, *Mon. Not. R. Astron. Soc.* **217**, 523

Jones, J., Morton, J.D.: 1982, *Mon. Not. R. Astron. Soc.* **200**, 281

Kaňuchová, Z., Svoreň, J.: 2006, *Contrib. Astron. Obs. Skalnaté Pleso* **36**, 181

Kaňuchová, Z., Svoreň, J., Neslušan, L.: 2005, *Contrib. Astron. Obs. Skalnaté Pleso* **35**, 135

Kresák, Ľ., Porubčan, V.: 1970, *Bull. Astron. Inst. Czechosl.* **21**, 153

Kresáková, M.: 1974, *Bull Astron. Inst. Czechosl.* **25**, 20

Lebedinets, V.N.: 1985, *Sol. Syst. Res.* **19**, 101.

Licandro, J., Campins, H., Mothé-Diniz, T., Pinilla-Alonso, N., de León, J.: 2007, *Astron. Astrophys.* **461**, 751

Lindblad, B.A.: 1971a, *Smithson. Contr. Astrophys.* **12**, 14

Lindblad, B.A.: 1971b, *Space Ressearch* **11**, 287

Lindblad, B.A., Neslušan, L., Porubčan, V., Svoreň, J.: 2003, *Earth, Moon, Planets* **93**, 249

Lokanadham, B.: 1980, in *Solid Particles in the Solar System*, eds.: I. Halliday and B.A. McIntosh, Reidel, Dordrecht, Holland, 163

McIntosh B.A.: 1966, *Can. J. Phys.* **44**, 2729

McIntosh, B.A., Šimek, M.: 1980, *Bull Astron. Inst. Czechosl.* **31**, 39

Olsson-Steel, D.: 1987, *Mon. Not. R. Astron. Soc.* **226**, 1

Pecina, P., Šimek, M.: 1999, *Astron. Astrophys.* **344**, 991

Plavcová, Z.: 1962, *Bull. Astron. Inst. Czechosl.* **13**, 176

Plavec, P.: 1950, *Nature* **165**, 362
Porubčan, V., Cevolani, G.: 1994, *Nuovo Cimento* **17**, 243
Porubčan, V., Kornoš, L., Cevolani G., Pupillo, G.: 2004, *Nuovo cimento* **27**, 395
Porubčan, V., Svoreň, J., Neslušan, L.: 1995, *Earth, Moon, Planets* **68**, 471
Pupillo, G., Grassi, G., Cevolani, G., Trivellone, G.: 2002, *Mem. S. A. It.* **73**, 756
Pupillo, G., Porubčan, V., Bortolotti, G., Cevolani, G., Franceschi, C., Hajduk, A., Kornoš, L., Trivellone, G., Zigo, P.: 2004, *Nuovo cimento*, **27**, 301
Rendtel, J., Arlt, R.: 1997, *WGN The journal of the IMO* **25**, 75
Ryabova, G.O.: 2001a, in *Meteoroids 2001*, ed. B. Warmbain, ESA-SP **495**, Nordvijk, 77
Ryabova, G.O.: 2001b, *Sol. Sys. Res* **35**, 151
Ryabova, G.O.: 2007, *Mon. Not. R. Astron. Soc.* **375**, 1371
Southworth, R.B., Hawkins,G.S.: 1963, *Smithson. Contrib. Astrophys* **7**, 261
Spalding, G.H.: 1982, *J. British Astron. Assoc.* **5**, 227
Spalding, G.H.: 1984, *J. British Astron. Assoc.* **94**, 109
Spurný, P.: 1993, in *Meteoroids and their parent bodies.*, eds.: J. Štohl and I.P. Williams, Astronomical Inst., Slovak Acad. Sci., Bratislava, 1193
Sullivan, R., Greeley, R., Pappalardo, R., Asphaug, E., Moore, J.M., Morrison, D., Belton, M.J.S., Carr, M., Chapman, C.R., Geissler, P., Greenberg, R., Granahan, J., Head, J.W. III, Kirk, R., McEven, A., Lee, P., Thomas, P.C., Veverka, J.: 1996, *Icarus* **120**, 119
Svoreň, J., Kaňuchová, Z., Jakubík, M.: 2006, *Icarus* **183**, 115
Svoreň, J., Neslušan, L., Porubčan, V.: 1997, *Planet. Space Sci.* **45**, 557
Svoreň, J., Neslušan, L., Porubčan, V.: 2000, *Planet. Space Sci.* **48**, 933
Svoreň, J., Porubčan, V., Neslušan, L.: 2001, in *Proc. Meteoroids 2001 Conf. ESA SP-495*, eds.: B. Warmbein, ESA Publ. Div., ESTEC, Noordwijk, 105
Šimek, M.: 1973, *Bull. Astron. Inst. Czechosl.* **24**, 213
Šimek, M.: 1975, *Bull. Astron. Inst. Czechosl.* **26**, 1
Terentjeva, A.K., Bayuk. O.A.: 1991, *Bull. Astron. Inst. Czechosl.* **42**, 377
Webster, A.R., Kaiser, T.R., Poole, L.M.C.: 1966, *Mon. Not. R. Astron. Soc.*, **133**, 3
Weissman, P.R., Bottke, W.F. Jr., Levison, H.F.: 2002, in *Asteroids III*, eds.: W.F. Bottke Jr., A. Cellino, P. Paolicchi and R.P Binzel, University of Arizona Press, Tuscon, 669
Whipple, F.L.: 1954, *Astron. J.* **59**, 201
Williams, I.P., Wu, Z.: 1993, *Mon. Not. R. Astron. Soc.* **262**, 231