EVOLUTIONARY TRACKS OF SHORT-PERIODIC METEOR SWARMS

E.N.Kramer, I.S.Shestaka, Yu.M.Gorbanev

Abstract. The relations of the meteor streams with comets and asteroids are determined by means of the physical and dynamic properties of these bodies. The mathematical model is considered for the short-periodic meteor stream, the particles of which are ejected from the asteroid 3200 Phaeton with the velocities of about 700 m/s. It is shown, that in this case, the original comparatively compact meteor stream is dispersed gradually under the influence of the secular perturbations. At present, after 20000 years, the streams' orbits are crossing the ecliptic plane along the nearly closed narrow band, the distribution of their arguments of perihelia turning to the uniform one as well as the sporadic background. Owing to this, the opportunity arises to observe simultaneously the very faint meteor showers only at the Earth and other terrestrial planets. The existence of the abundant annual Geminid meteor shower doesn't agree with the considered model and test the suggestion that the particles of this stream were ejected from the Phaeton either not long ago or at small velocities of about tenths of a meter per second, since the meteor stream ejected only at such velocities remains comparatively compact and highly productive one throughout many thousand years. Since the secular perturbations result in the oscillations of the line of apsides of the stream's orbits (with the period of about 30-40 thousands of years) and in changes of the argument of the perihelion of about 360, the stream approached the Earth four times during this interval and produced the corresponding showers. It is shown that such showers are occurring in different epochs, not during the same year, as some scientists erroneously supposed.

Key words: origin and genetical relations of meteor swarms and asteroids.

The similarity of orbits of the well-known meteor swarm Geminids and the object 1983 TB (3200 Phaeton) served as the groundbase of the hypothesis on their mutual genetical relation (Hughes 1983, Whipple 1983). The parent body (PB) of the Geminids, sought for a long time, seemed to be found. Although the considerable scattering of the observed values of the semimajor axes of swarm's orbits ($1,1 \leq a \leq 1,67$ AU) initials us to suggest in this case the improbably large velocities (about 1-5 km/s) of particles' ejections from Phaeton.

There isn't any common opinion on the nature of Phaeton itself. Is hasn't a noticeable coma, rapidly rotates with the period about 4 hours and its brightness varies with the amplitude of about 0.4^m. These properties as well as the too high values of the Tisserand invariant (T=0,8661) and an albedo ($p_v = 0.11$) are the distinctive features of the asteroid origin (Green et al. 1985, Hartmann 1987).

On the other hand, as Green et al.(1985) have shown, Phaeton does not reveal the spectral similarity with the main asteroidal types. In this connection, and on the basis of the infrared observations, which suggest an albedo of Phaeton of 0.11 and its relatively high surface conductivity (Green et al.1985), Davies (1985,1986) concluded that the object is possibly the extinct comet composed of a rocky core. This core was formed as a result of the comet ageing blocking a release of nucleus volatile components and a coma formation.

However, the lifetimes of the comets with the orbits, the perihelion distances of which are as small as that of Phaeton, are not exceeding one or several revolutions around the Sun (Lebedinets, 1984). This may be confirmed by the comets P/Brorsen, P/Tempel-Swift and P/Neujmin-3, which existed at their orbits during 5, 4 and 2 revolutions, respectively, despite their perihelion distances of 0.65, 0.75 and 1.34 AU are much larger than that of Phaeton.

As the estimates show, the equilibrium temperature of a subsolar point of Phaeton at its perihelion amounts to 900 K under the assumption of a blackbody approach. However, the melting temperature (T_m) of cometary ices is much lower, namely:

The ices,	CO,	CH_4,	C_2H_2,	NH_3,	HCN,	H_2O
T_m, K,	74,	91,	192,	196,	260,	272

It may be noted, that the subsolar part of Phaeton finds itself at temperature from 300 to 900 K over a year (about 380 days). Hence it is not worth doubting, that under such conditions, the ice nucleus dooms to evaporate completely during one or several revolutions around the Sun. So, Phaeton is most probable a stone-like fragment of an asteroid, the diameter of which equals to 5-6 km (Green et al., 1985; Hartmann et al., 1985).

The search for an appropriate mechanism of the particles' ejection from an asteroidal body failed to be a successful so far. The collisions at the asteroid belt (Hunt et al.,1986; Riabova, 1989) cannot account for either the observed Geminids aphelia' distribution nor a monomodality of the observed meteor shower.

Apparently it is for this reason, that the majority of scientists use the Phaeton particles' ejection mechanism similar to the disintegration of the comet nucleus (Fox et al., 1983; Jones and Hawkins, 1986; Babadzanov and Obrubov, 1986; Bel'covich and Riabova, 1989), despite the chemical and minerological composition of asteroids is drastically different from those of comets.

Recently a number of papers have been published (Babadzanov and Obrubov, 1986, 1987a, 1987b), in which the possibilities of generating of several (4 or 8) showers by the same swarm are discussed. In the opinion of these authors, the Earth encounters such showers throughout one and the same year. At first, the talk is about Geminids.

From this point of view, Babadzanov and Obrubov supposed that, at first, the ejection velocities from Phaeton had amounted to 670 m/s (owing to that there was an appreciable initial dispersion of semi-major axes) and, at second, the swarm's age had been nearly equals to 20 000 years (such an age was necessary to ensure the dispersion of the arguments of perihelion about 360° for the orbits with the semi-major axes from 1.0 to 1.7 AU).

We carried out the modelling of the Geminids' swarm forming and evolution under the same suggestions as well. In addition, we proceed from facts, that in the spatial twice averaged three-body problem, the system of equations of the perturbed body assumed three integrals (Moiseev,1945):

$$a = const\,, \tag{1}$$

$$\mu = p^{1/2} \cos i = const\,, \tag{2}$$

$$[W] = const\,, \tag{3}$$

where a, i — are the orbital elements, p is its parameter.

Confining ourselves to the first approximation at the Legendre polynomial expansion of the disturbing function $[W]$, M.Lidov (1961) obtained the third integral in the following form:

$$\nu = e^{2}(\,0.4 - \sin^{2} i \cdot \sin^{2}\omega) = const\ . \tag{4}$$

It holds true for bodies' orbit that approach closely the perturbing planet. In the case of the Geminids ($Q \leq 4$ AU), all the above equations are valid.

It is known, that the meteor showers occur, when the swarms generating them are approaching the Earth. Such approaches may be detected by means of the finding positions of the points of the swarm orbits that are crossing the ecliptical plane at present. In general, for this purpose, the secular perturbations of the swarm orbits should have been calculated in the given time interval which is equal to 20 000 years for Geminids.

Since we are interested in the general qualitative trend of the swarm evolution under the influence of secular perturbations, we are decided to imitate the orbital elements' perturbations by the functional dependencies, following the examples of Riabova (1989) and Bel'covich and Riabova (1989).

The perturbations of the argument of perihelion (ω) and the orbital eccentricity (e) can be represented in the following form:

$$\omega = \omega_0 + 360^{\circ}\, t/p\ , \tag{5}$$

$$e = e_b + A\, \sin\,[2(\omega - 45^{\circ})]\ . \tag{6}$$

The e_b and A parameters are found from the system of equations:

$$\begin{cases} e_b - A = e_{\min}\ , \\ e_b + A \sin\,[2(\omega_0 - 45^{\circ})] = e_0\ , \end{cases}$$

where e_{min} and e_0 are given by:

$$e_{\min} = (2.5\,\nu)^{1/2}\ , \qquad e_0 = 1 - q_0/a\ ,$$

and q_0 - is the perihelion distance of the parent body, e_0 is the initial value of the orbital eccentricity of the ejected particle (here and after the index " o " indicates the initial orbital elements at the moment of ejection).

The period P of the oscillations of the argument of perihelion may be expressed by the empirical formula $P = 56800/a^2$ which was obtained from the analysis of the 85 most precisely determined Geminid orbits (Kramer and Shestaka, 1987).

The initial dispersion of the semi-major axes are given by

$$a = a_b + \alpha \cdot C\ ,$$

where a_b - is the parent body semi-major axis, C is a random variation of the semi-major axis, and α_n is a factor, the values of which are in the range from -3.00 to +3.00.

During the modelling of the swarm orbits' evolution, the following elements of the Phaeton orbit were chosen as the initial ones (Babadzanov and Obrubov, 1987b):

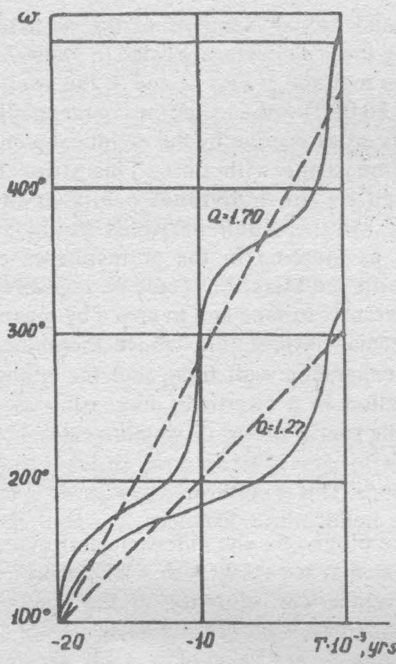

Fig. 1 The argument of perihelion ω vs time for the semi-major axes 1.27 and 1.70 AU (solid curves - the results of the numerical integra-tions, dased lines - the results of calculations by means of eq. (5).

$$a_0 = 1.271\,AU,$$
$$e_0 = 0.898,$$
$$\omega_0 = 100.0^o,$$
$$\pi = \omega_0 + \Omega_0 = 220.0^o,$$
$$i_0 = 16.7^o.$$

These values were obtained by means of calculations of the secular perturbations 20 000 years ago. An inclination of the osculating orbit can be obtained easily from (2):

$$i = \arccos\left\{\mu / [a\,(1-e^2)]^{1/2}\right\}.$$

The quasistationary parameters μ and ν were obtained for each orbit from the equations (2) and (4) and the initial values e_0, i_0, ω_0 and a.

In the modelling process, the certain values of α_n in the range from -3.00 to +3.00 were ascribed to each orbit. Hence, the semi-major axes will be in the range from 0.67 to 1.87 AU, if the factor C = 0.20.

Such a range of a was chosen in order to take into account the various mechanisms of the ejection, including the ejection as a result of the collisions of the asteroid-like body with the bodies, which are moving in the circumsolar nearly circular orbits.

The velocities of impact ejections amount from 0.5 to 1.5 km/s in the case of the collision velocities equal about 10 ... 30 km/s (Melosh, 1984). It can be clearly seen, that in the case of Phaeton, the collision velocities amount to 29.8 km/s at its perihelion and 12.8 km/s at the aphelion.

We carried out the modelling of orbits' perturbations according to the above-mentioned procedure. The ejection velocities amounted to 2.7 km/s. Such velocities provide an initial dispersion of the major semi-axes ranging from 0.67 to 1.87 AU. In Table 1, the part of the set of the computations is given. Here the present cross-sections of a swarm by the ecliptical plane are given for the semi-major axes of the individual orbits, which values range of an ecliptical longitude L and a heliocentric distance R of a node corresponding to each argument of perihelion. These are

$$L_a = \Omega, \quad R_a = [a\,(1-e^2)] / (1+e\cos\omega)$$

for the ascending node, and

$$L_d = \Omega + 180^o, \quad R_d = [a\,(1-e^2)] / (1 - e\cos\omega)$$

for the descending one.

The structure of the model swarm depends on the accuracy of the approximation of the argument of perihelion by the Eq. (5): Fig. 1 shows the argument of perihelion vs time for the semi-major axes 1.27 and 1.70 AU: the straight lines correspond to ω calculated by (5), and the curves correspond to the 'exact' value ω calculated by the numerical integration of the equations of motion. It is clearly seen, that the differences between the 'exact' values ω and the approximated ones by (5) do not distort a general trend of an argument of perihelion increase with time.

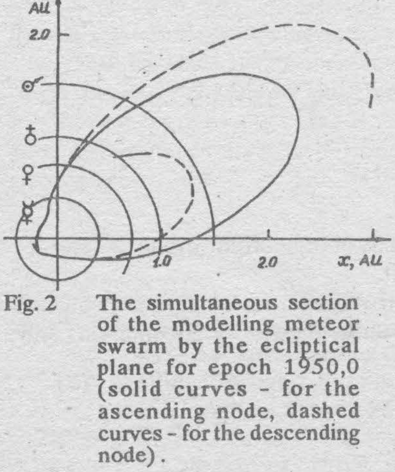

Fig. 2 The simultaneous section of the modelling meteor swarm by the ecliptical plane for epoch 1950,0 (solid curves - for the ascending node, dashed curves - for the descending node).

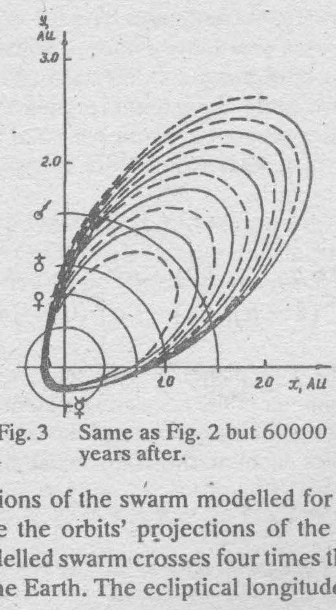

Fig. 3 Same as Fig. 2 but 60000 years after.

At Figs. 2 and 3, the simultaneous cross-sections of the swarm modelled for epoch 1950.0 and 60 000 years later, are shown. Here the orbits' projections of the terrestrial planets are plotted. It is seen, that the modelled swarm crosses four times the orbits of Mercury, Venus and Mars, as well as that of the Earth. The ecliptical longitudes LP of these planets during the expected meteor

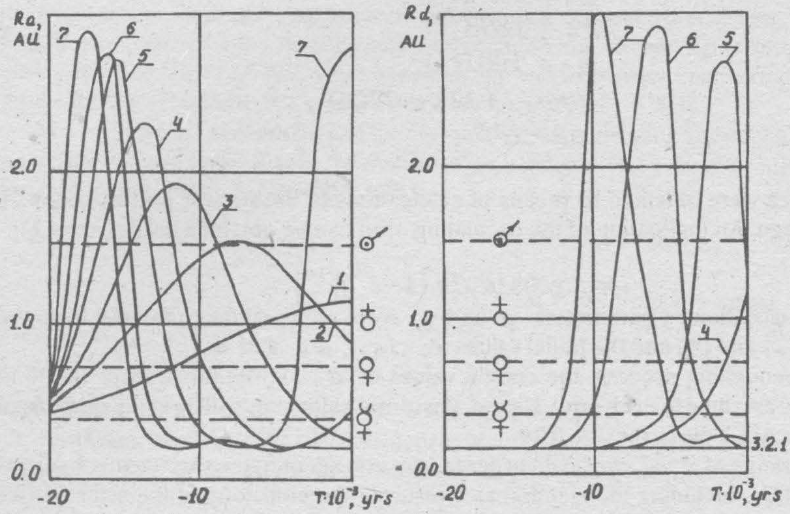

Fig. 4 a The heliocentric distances R_a and R_d vs time for the different semi-major axes: 1- 0.67, 2 - 0.87, 3 - 1.07, 4 - 1.27, 5 - 1.47, 6 - 1.67, 7 - 1.87 AU.

Fig. 4 b Same as Fig. 4a.

showers and orbital elements of the particles generating these showers, are listed in Table 2.

As one may see at Figs. 2 and 3, the swarm modelled 20 000 years ago has the characteristic feature: its cross-section by the ecliptical plane forms some stripe with time. This stripe is penetrated by the individual orbits of the particles' swarm. Such particles could be observed as meteors in the atmospheres of Venus, Earth and Mars, and could be registered on the Mercury' surface and in space by means of the special devices. The above-mentioned stripe is expanding with time, and the orbits' concentration in a swarm is decreasing as a result of the spatial orbits' dissipation caused by their initial dissipation and the secular perturbations. This is confirmed by Figs. 4 (a, b), where the heliocentric distances R_a and R_d vs time are plotted for the different semi-major axes. As one may see at Figs. 4ab, a kind of orbits' sorting by the semi-major axes takes place under the influence of the secular perturbations, namely: its own set of perturbed elements e, i, ω, Ω and its own point of the intersection with the ecliptical plane corresponds to each value of a. However, the repeated encounters (four and more) during the same year of the same swarm with the Earth, take place for the orbits, which have strictly definite and different semi-major axes, hence different geocentric velocities. In the case of the Geminids, the modelled the semi-major axes were equal to 0.68, 0.95, 1.31, 1.55 and 1.76 AU (1950.0).

Thus, the supposed high velocities of particles' ejections from the parent body shall have to result inevitably in the sharp decreasing of the simulated meteor showers productivity as far as to even their merging with the sporadic meteor background. In addition, the definite and different values of semi-major axes should correspond to each of the shower. In fact, only one Geminids' shower is observed, the semi- major axes of which range from 1.1 to 1.7 AU.

As for three other showers, which, according to Babvadzanov and Obrubov (1987b), are originated by the same swarm of meteor particles ejected from Phaeton, one of them - the Daytime Leonides - was not detected at all, the second one - the 11 Canis Minorids - was found in 1964 by means of the telescope observations (in the photographic catalogues there are only 4 meteors with the velocities from 35 to 40 km/s, which belong this shower), and finally the third shower - the Daytime Sextantids - displays an insignificant activity too. All that more contradicts with the model of the unique meteor swarm originating four annual showers than confirms it.

The steady swarm of fragments is forming in the case, when the velocities of particle ejection from the parent body's surface don't exceed tens of meters per second. In such a swarm the fragments have the orbits similar to those of the parent body. The swarm itself approaches the terrestrial planets one time over some thousand years.

Probabilities of such approaches were studied by Kramer and Shestaka (1987). They obtained the equations for the determination of the parameters of the meteoroids' orbits at the moment of their approaching an orbit of the j-th planet:

$$p^2 + \varepsilon_j p + \eta_i = 0, \qquad (7)$$

where

$$\varepsilon_j = a_j (0.6\, a_j / a - 2) - \mu^2,$$
$$\nu_j = a_j \mu^2 (2 - a_j / a) + a_j^2 (0.4 - \nu),$$

a_j - is an average value of the semi-major axis of the j-th planet, a - is a semi-major axis of meteoroid' orbit, μ and ν - are the parameters given by (2) and (4), p is a parameter of the osculating meteor' orbit.

Solving the equation (7), one may find two values of the parameter p of the orbit approaching the orbit of the j -th planet. It should be noted, that the probability of these bodies encountering is not equal to zero under the following conditions only:

$$\Delta = 1/4\, \varepsilon_j^2 - \eta_j \geq 0, \qquad (8)$$

$$p_K < p_{\max} = a(1 - 2.5\nu), \qquad (9)$$

where k is equal to 1 or 2.

It is clearly seen that three cases are possible: a) discriminant Δ of the equation (7) is negative ($\Delta < 0$); then the body's orbit and that of the planet are never crossed and the probability P_j of their encountering is equal to zero: b) $\Delta \geq 0$, but only one value p_K satisfies the condition (9); in this case the probability $\bar{p}_j$ is given by

$$P_j = \frac{\tau_j^2}{\pi a^{3/2} \sin i} \left(3 - \frac{a_j}{a} - \frac{2\mu}{a^{1/2}}\right)^{1/2} \left(2 - \frac{a_j}{a} - \frac{P_k}{a_j}\right)^{-1/2}, \tag{10}$$

where τ_j - is the radius of a sphere of capture of the j-th planet, k is equal to 1 or 2;

c) $\Delta \geq 0$ and both values p_K satisfy the condition (9), then P_j is given by

$$P_j = \frac{\tau_j^2}{\pi a^{3/2}} \left(3 - \frac{a_j}{a} - \frac{2\mu}{a^{1/2}}\right)^{1/2} \times$$
$$\times \left[\left(2 - \frac{a_j}{a} - \frac{\bar{p}_1}{a_j}\right)^{-1/2} \frac{1}{\sin i_1} + \left(2 - \frac{a_j}{a} - \frac{\bar{p}_2}{a_j}\right)^{-1/2} \frac{1}{\sin i_2}\right]. \tag{11}$$

It is obvious, that four values of the argument of perihelion of a disturbed body's orbit correspond to each p_K. In consequence of this, in the second case this orbit four times approaches the orbit of the j-th planet during one revolution of the line of apsides; in the third case, such approaches take place eight times. And they occur at different times, but not during the same year.

It should be noted, that according to the accepted expression for the collision probability (Opik, 1951), it is equal to zero when the perihelion distance fixed for a given epoch of an osculation exceeds an average semi-major axis of a perturbing planet, i.e. $q > a_j$. But a probability given by (10) or (11) can be not equal to zero in this case too.

The convincing example of this is the asteroid 1580 Betulia with the following orbital elements : a = 2.194 AU, e = 0.4901, and q = 1.1119 AU. According to Opik (1951), the collision probability of this asteroid with the Earth cannot be calculated, since the expression $(2 - 1/a - \bar{p}) < 0$. Nevertheless, in this case the equation (7) has two real roots: $\bar{p}_1 = 1.482$ and $\bar{p}_2 = 0.872$. Both roots satisfy the condition (9), in consequence of which the probability of Betulia collision with the Earth prove to be equal to $1.1 \cdot 10^{-8}$. This result is confirmed by the numerical integration of the equations of motion of Betulia: according to these calculations, the orbit of Betulia crosses the Earth's orbit eight (!) times during the complete period of the changing of ω.

One more example is the asteroid 1866 Sysiphus. It moves in the orbit with the perihelion distance q = 0.871 AU. According to the classic Opik's formula, the probability of encountering Sysiphus and the Earth is equal to $9.52 \cdot 10^{-10}$. However, the numerical integration of the asteroid's motion equations, if taking into account the major planets' perturbations, shows that the Sysiphus and Earth orbits did not cross during last 40 000 years. Using the equations (7)-(11), we obtained the same result: since the discriminant of equation (7) is less than zero, one may say that the encounter does not occur.

Betulia, Sysiphus and Phaeton are the typical representatives of the Aten-Apollo-Amor asteroids, the number of which exceeds 120 at present. Above 70 of them move in orbits with the perihelion distances $q < 1.0167$ AU, and over 20 asteroids approach the Earth closer than $d_{ph} = 0.026$ AU (d_{ph} is the minimum distance between Phaeton and the Earth). It should be expected, that such asteroids generate more intensive showers, than the Geminids do. Recently even the theoretical radiants of the AAA-asteroids were calculated (Drummond 1981,1982; Olsson-Steel 1987,1988). However, up to now, no shower related to the asteroids has been detected.

Nevertheless, Babadzanov and Obrubov (1989,1991) and Babadzanov et al.(1990,1991) continue to allege that many short-period swarms as well as the Geminids and the Quadrantids originate from four to eight meteor swarms. Moreover, they believe, that such showers must be observed during the same year. However, we have shown earlier, that their hypothesis is not substantiated.

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Table 1. The points of the intersection of the orbits of the meteor particles ejected from Phaeton with the ecliptical plane (a model)

a, AU	ω	L_a	R_a, AU	L_d	Rd, AU
0.97	219.5	0.5	0.886	180.5	0.204
0.99	224.5	355.5	0.775	175.5	0.202
1.01	229.6	350.4	0.670	170.4	0.200
1.05	240.0	340.0	0.491	160.0	0.197
1.09	250.9	329.1	0.360	149.1	0.200
1.13	262.1	317.9	0.274	137.9	0.254
1.17	273.8	306.2	0.225	126.2	0.335
1.21	285.9	294.1	0.204	114.1	0.493
1.25	298.4	281.6	0.203	101.6	0.493
1.29	311.3	268.7	0.214	88.7	0.775
1.33	324.6	255.4	0.231	75.4	1.237
1.41	352.4	227.6	0.262	47.6	2.465
1.45	6.9	213.1	0.266	33.1	2.555
1.49	21.8	198.2	0.259	18.2	2.017
1.53	37.1	182.9	0.242	2.9	1.287
1.57	52.8	167.2	0.222	347.2	0.731

Table 2. Ecliptical longitudes of the planets during the expected meteor showers and their orbital elements

Planet	L_P	Orbital elements of particles, that generating the meteor showers on the planets					
		ω	Ω	i	e	q	a
	(degrees, 1950.0)					AU	
Mars	69.0	331.0	249.0	45.1	0.833	0.226	1.350
	75.4	144.8	75.4	45.7	0.866	0.240	1.787
Earth	61.0	159.0	61.0	38.4	0.729	0.185	0.682

	5.4	214.6	5.4	41.2	0.850	0.189	0.951
	81.6	318.4	261.4	41.2	0.850	0.197	1.313
	355.7	44.3	175.7	42.1	0.870	0.202	1.549
	86.2	133.8	86.2	42.8	0.883	0.206	1.763
Venus	353.1	226.9	353.1	35.5	0.828	0.172	1.001
	90.7	309.3	270.7	37.5	0.863	0.176	1.285
	346.9	53.2	166.8	38.4	0.866	0.180	1.572
	94.3	125.7	94.3	38.9	0.182	0.180	1.744
Mercury	331.7	248.3	331.7	28.1	0.870	0.140	1.082
	109.2	290.8	289.2	28.2	0.885	0.141	1.227
	329.3	70.7	149.3	28.6	0.912	0.141	1.615
	111.0	109.0	111.0	28.7	0.917	0.142	1.706

Table 3. The asterois approaching the Earth within the distances about 0.1 AU

Asteroids	r , AU	Asteroids	r , AU
12101 Oljato	0.0001	1984 KD	0.034
1981 Midas	0.0008	1954 XA	0.036
1937 UB Hermes	0.0010	1620 Geographus	0.037
1982 DB	0.0053	1566 Icarus	0.040
2340 Hathor	0.0064	1979 VA	0.046
1986 JK	0.0069	1959 LH	0.046
2135 Aristaeus	0.0078	3122 1981 ET3	0.054
2101 Adonis	0.013	1980 AA	0.054
3361 1982 HR	0.013	1685 Toro	0.057
3362 Khufu	0.018	1985 PA	0.066
6343 P-L	0.020	1983 TF2	0.067
1986 PA	0.021	2063 Bachus	0.068
1982 XB	0.022	1984 KB	0.070
1983 LC	0.023	2606 Seneca	0.071
1978 CA	0.024	1917 Cuyo	0.073
3200 Phaeton	0.026	1943 Anteros	0.074
1862 Apollo	0.027	1915 Quetzalcoatl	0.076
6344 P-L	0.027	1983 TO	0.078
2102 Tantalus	0.028	1866 Sisyphus	0.092
1979 XB	0.033	1973 NA	0.095
		2062 Aten	0.098