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DYNAMICS OF METEOR STREAMS

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At present, the overwhelming majority of meteor streams are generally assumed to be formed due to the decay of comets. The most effective process of the release of solid particles from a cometary nucleus is their ejection by sublimating gases when the comet approaches the Sun.

It seems that some asteroids may also be progenitors of meteor streams if we assume these asteroids to be crumby, porous, fragile bodies disintegrating into numerous small fragments upon collision. The possible formation of meteor streams from asteroids, for example, of groups of Apollos, Amors and Atens is often based on the assumption that some fraction of these asteroids are defunct comets.

In any case, no matter what source of meteor streams we assume the particles must of necessity have small relative ejection velocity ($1-10^3$ ms). This assumption is based on our notion of a meteor stream as an ensemble of particles moving in close orbits as well as on observations of cometary phenomena and theoretical calculations.

The well known 1951 formula (WHIPPLE), for the particle ejection velocity C at a distance r_{AU} from the Sun may be written down as:

$$C_1 = 3.28 \sqrt{\left(\frac{4}{\rho\delta r^{3/4}} - 0.052\, R_c\right) R_c} \quad \text{m/s} \qquad (1)$$

where R_c is the radius of the cometary nucleus in km, ρ = paticle density and δ = particle radius both in CGS units. Then the maximum difference between the semimajor axis $\Delta_1 a$ and the eccentricity $\Delta_1 e$ of ejected particles' orbits from those of the comet's orbit will be:

$$\Delta_1 a = \pm\, 6.72 \cdot 10^{-5}\, a_o^2 c \sqrt{\frac{2}{r} - \frac{1}{a_o}} \quad \text{AU},$$

$$\Delta_1 e = \pm\, 6.72 \cdot 10^{-5}\, r e_o c \sqrt{\frac{2}{r} - \frac{1}{a_o}} \quad , \qquad (2)$$

where r is the heliocentric distance, a_o is the semimajor axis of the comet's orbit in AU and e_o is its eccentricity.

According to RADZIEVSKIJ (1951), variations in the semimajor axis and eccentricity of the released particle's orbit under the radiation pressure are:

$$\Delta_2 a = \pm\, 5.76 \cdot 10^{-5} (\rho\delta)^{-1}\, a_o \left(\frac{2a_o}{r} - 1\right) \text{ AU},$$

$$\Delta_2 e = \pm\, 5.76 \cdot 10^{-5} (\rho\delta)^{-1}\, \rho_o e_o^{-1} \left(\frac{1}{r} - \frac{1}{a_o}\right) \quad . \qquad (3)$$

In the formula (3) $\rho_o = a_o(1 - e_o^2)$ is the parameter of the comet's orbit in AU.

The ejection velocity and radiation pressure define the initial dispersion of the orbital semimajor axes and eccentricity of particles released from the comet. This dispersion is of great importance for the subsequent evolution of meteor streams. The rest of orbital elements of the ejected particles differ only slightly from those of the cometary ones and these differences are of minor importance.

The rate of particle dissipation along the progenitor's orbit is considered a significant characteristic of meteor stream dynamics. The loop formation time T is estimated by the formula (FOX et al., 1983):

$$T = \frac{P^2_{max}}{P_{max} - P_{min}} \qquad (4)$$

where P_{max} and P_{min} are maximum and minimum orbital periods of particles. Table 1 gives values of T for particles with different $\rho\delta$ (for the Geminids and Quadrantids).

Table 1

Loop formation time by stream particles of different mass.

		Geminids (a_o = 1.32 AU)				Quadrantids (a_o = 3.08 AU)			
	m	a_{AU}		T		a_{AU}		T	
g/cm^2	g	max.	min.	yr	per.	max.	min.	yr	per
10^{-2}	4 10^{-6}	2.03	0.85	4	2.6	3.31	3.05	53	10
10^{-1}	4 10-3	1.53	1.14	5	3.3	3.13	3.05	150	28
10^{0}	4 10^{0}	1.39	1.26	12	7.9	3.09	3.07	460	85
10^{1}	4 10^{3}	1.34	1.30	36	23.6	3.083	3.077	2300	425

In calculating the values of Table 1, we have taken into account the joint influence of the ejection velocity and radiation pressure. Masses of particles were calculated for a density of 1 g/cm^3. Radii of the parent comets were considered to be 5 km.

An interesting study of the Geminids was done by FOX et al., (1983). According to their model, the stream has a flat shape at a distance of 1 a.u. The ratio between the stream width and its thickness is about 7:1 which is the theoretical meteor stream cross-section in the ecliptic plane needed to obtain the observed meteor rate profiles with respect to the mass of particles and points where the Earth intersects the stream. The meteor rate profiles obtained explain the asymmetry observed in the Geminids shower. However, FOX et al., taking into account planetary perturbations, ignored the dependence on the value of the orbital semimajor axes. Furthermore, the meteor stream evolution over only a short period of time was considered, so that maxima of the rate of meteors produced by particles of different masses fell at the same solar longitude.

The discovery of the asteroid 1983 TB was an important event in the study of the Geminids origin and evloution. It should be noted that COOK (1973) assumed asteroids to exist in the Geminids stream. The asteroid 1983 TB moves in the orbit which is very similar to the mean orbit of the Geminids so it is natural to assume the asteroid to be a remnant of the Geminid parent body and obviously a "defunct" comet.

The Geminid meteor stream evolution has been dealt with in a number of our papers (BABADJANOV, OBRUBOV, 1971a, 1983, 1984). In the present paper we give new results of investigation of Geminid evolution. We assume that during the formation of the stream the semimajor axes of individual particles of 10^{-3} g might differ from the orbital semimajor axis of the asteroid 1983 TB by ± 0.3 AU, and their eccentricities - by 0.022, these differences being caused by an ejection velocity of 650 ms and by the comet's radius of 6-8 km. These sizes of a cometary nucleus correspond to the present observational data.

According to our calculations the age of the Geminids does not exceed 20 thousand years (BABADJANOV, OBRUBOV, 1979a). So our results are given for a 20,000-year period.

Calculations of secular perturbations of the asteroid 1983 TB were performed by the Halphen-Goryachev method taking into account 5-planet perturbations (Venus-Saturn) and included the secular variations in orbits of the planets themselves. For the Geminid particles with the orbital semimajor axes of 1 AU and 1.65 AU. Secular variations were allowed in the arguments of perihelion, inclination, eccentricities and $\Delta\pi$ (the difference between longitudes of perihelions of particles' orbits and the orbit of the asteroid).

It can be seen that secular variations in the orbital elements of the asteroid and the Geminids are described accurately enough by the following motion integrals:

$$(1 - e^2) \cos^2 i = C_1 = \text{const} \quad , \tag{4}$$

$$e^2 (\frac{2}{5} - \sin^2 i \cdot \sin^2\omega) = C_2 = \text{const} \; . \tag{5}$$

The relation (4) comes from Jacoby's integral when only secular perturbations are taken into account (a = const.) and the relation (5) was obtained by Lidov (1961).

The difference in longitude of perihelion of the orbits of particles ejected from the parent comet nucleus at the velocities of 650 m/s averages 5°-10° over the period under review. Hence, we may assume that the stream precesses around the Sun as a single whole. In order to estimate the stream shape under the influence of planetary perturbations we shall assume the first approximation:

$$\pi = \Omega + \omega = C_3 = \text{const.} \qquad (6)$$

The orbital evolution rate is estimated by the semimajor axis, so as time passes the particles will fill out the total volume in space defined by both the relations (4-6) and differences in a. Plenty of orbits filling out the volume may be obtained in the following way. The values of $C_1 = 0.13$ and $C_2 = 0.29$ correspond to the orbital semimajor axis of 1.65 AU. Giving the argument of perihelion values from 0° to 360° and using (4-6) we are able to derive e, i, and Ω. Plenty of calculated orbits with a = 1.65 AU would define the outer (with respect to the Sun) surface bounding the meteor stream. Using the analogous method for the orbit with a = 1 AU and $C_1 = 0.20$, $C_2 = 0.27$ we obtain the surface restricting the stream on the inside surface. In order to estimate the shape of the volume in space restricted by the derived surfaces, we have constructed cross-sections of these surfaces in a plane perpendicular to the velocity vector at different points of the present orbit of the asteroid 1983 TB. For simplicity, when constructing the cross-sections, the inclination of the asteroid orbit was assumed to be zero. Fig. 1 illustrates some of the calculated cross-sections. Fig. 2 shows the Geminids spatial shape constructed using these cross-sections. This shape differs very much from traditional notions of meteor streams. Eventually, due to planetary perturbations, the Geminid stream takes on a shape most characterized by stream thickness perpendicular to the ecliptic plane. At the distance of 1 AU from the Sun the ratio between the stream's width and its thickness is 1:10.

Let us estimate the time during which the Geminids can take the form caused by long-period planetary perturbations. It may be assumed that the particles will fill out the total volume when the nodal lines of orbits with maximum and minimum semimajor axes differ by 180°-270°. According to data presented in Table 1, the nodal lines of orbits with a = 1.00 AU and a = 1.00 AU and a = 1.65 AU will differ by 270° in another 20 thousand years. Hence, the volume in space estimated by the relations (4-6) and by the differences in a is considered to be filled out.

The investigation of secular variations in the radii-vectors of the ascending and descending nodes of the Geminids orbit with semimajor axes from 1 to 1.65 AU shows that at present (i.e., over 20 thousand years after the stream's formation) only four groups of particles could intersect the Earth's orbit. These groups produce meteor showers: the Geminids, Daytime Sextantids, Canisids (a radiant in the Canis Minor constellation) and Daytime δ-Leonides. The orbital semimajor axes of particles responsible for these showers are close to the values of 1.36 AU, 1.15 AU, 1.65 AU and 1.55 AU respectively.

Observation data show that among these four meteor showers at least three are active, namely the Geminids, Canisids [the shower "B" found by

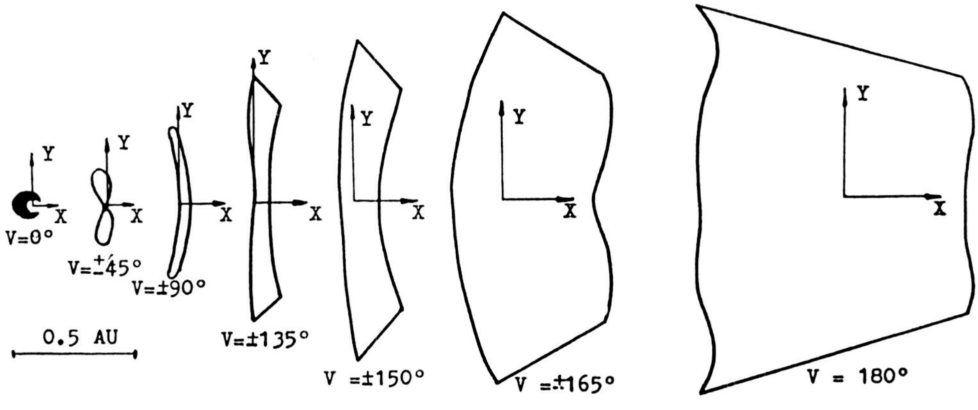

Fig. 1 The model Geminid stream cross-sections in the planes perpendicular to the velocity vector of the asteroid 1983 TB orbit (at i = 0°) at different values of true anomaly V.

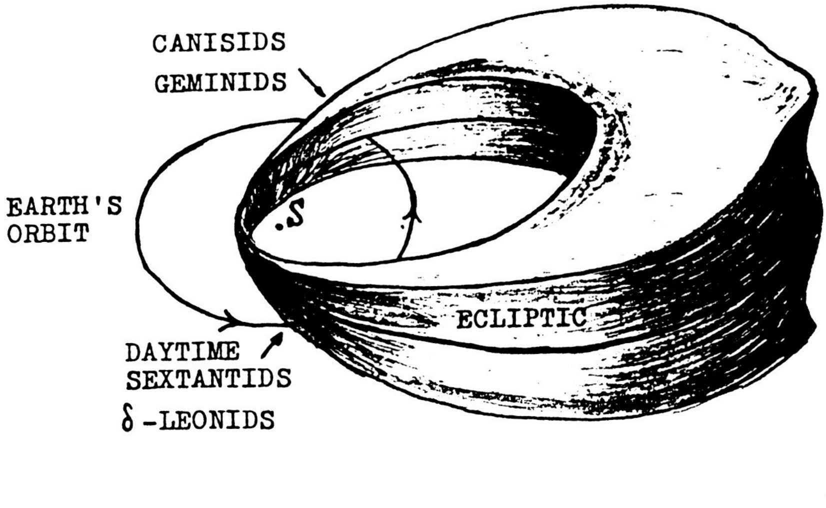

Fig. 2 The Geminid stream shape.

KRESAKOVA (1974)] and Sextantids. The shower "B" was discovered by KRESAKOVA from photographic and visual observations. She also suspected the Canisids and Sextantids to be associated with the Geminids.

At the distance of 1 AU from the Sun, in the region of intersection of the Sextantids orbit with that of the Earth, the stream thickness defined by the observed mean orbits of the Geminids and Canisids is 0.7 AU. This agrees well with the above Geminid stream model.

By the way, it should be mentioned the MCINTOSH and HAJDUK (1984) also came to the conclusion that the stream associated with Halley's comet had a considerable thickness. According to their investigations the stream thickness is 0.44 AU and its width - 0.044 at a distance of 1 AU from the Sun.

As is known in the case of the Geminids, the Earth first encounters small particles and then later the large ones. In the case of the Sextantids the Earth crosses the stream from the outside, so that we should expect the reverse picture, i.e., meteors having more prolonged radioechoes must occur preferentially at the beginning of the shower activity. In connection with this, a careful study of the Sextantids meteor shower and searches for a northern branch the δ-Leonids are of interest.

Now we shall consider the question of the Quadrantids stream shape assuming from observation that the orbital semimajor axes of particles are in the range of 2.8-3.1 AU. First, it should be noted that for the orbits of this stream the equations (4-5) are satisfied only qualitatively. Calculations of secular perturbations of the orbital elements carried out by the Halphen-Goryachev method as well as by the method of Runge-Kutta (WILLIAMS et al., 1979) give a wider range of variations in inclination (from 12° to 74°) (BABADJANOV, OBRUBOV, 1979b, 1980) as compared to the range obtained from equations (4-5): $28° \leq i \leq 73°$. Longitudes of perihelion of the Quadrantids orbits liberate in small ranges. So, using the equations (4-6) we may derive a lower limit of the volume in space which may be filled out be the Quadrantid particles in time. The result of investigation of the Quadrantid meteor stream evolution by the numerical method of Runge-Kutta show that the particles have differences only in initial positions on the orbit and then under the influence of Jovian perturbations the orbital elements of these particles may differ strongly. Here, in contrast to the Geminids, the evolution rate is estimated not only by the orbital semimajor axis, but the positions of particles on their orbits. This leads to quicker filling out of the stream volume estimate by the long-period perturbations, i.e., to a quicker formation of the stream branches. The cross-section of the Quadrantids on the ecliptic plane is presented in Fig. 3. The distinctive feature of the Quandrantids (in comparison with the Geminids) is a narrow "jet" near perihelion caused by the orbits of the highest inclinations and of the largest perihelion distances. The Quadrantids shower is observed at the intersection of this jet. One other interesting feature of the Quadrantids shape lies in the fact that the Earth crosses the stream three times, i.e., in principle, this stream can produce three pairs of meteor showers. We have calculated theoretical geocentric radiants and velocities for the Earth-crossing orbits at points different from the place where the Earth encounters the Quadrantids. The results showed that the Daytime Arietides (COOK, 1973) and the association No. 78 (KASHCHEJEV et al., 1967) with the radiant near α-Ceti as well as the Southern and Northern δ-Aquarides (COOK, 1973) could result from encounters of the Quadrantids stream with the Earth.

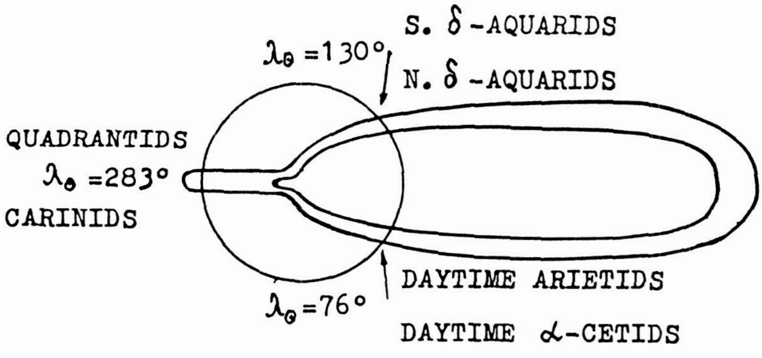

Fig. 3 The model Quadrantid stream cross-section in the ecliptic plane.

Theoretical shower radiants and velocities were obtained from calculations of secular perturbations of the Quadrantids mean orbit by the Halphen-Goryachev method.

Thus, the investigation of the Quadrantids meteor stream evolution and its comparison with observations give evidence of the supposed interrelations between the Quadrantids and δ-Aquarids (HAMID and WHIPPLE, 1963), on the one hand, and between the δ-Aquarids and Daytime Arietids on the other (COOK, 1973). The similarity in the heights of beginning, maximum brightness and end as well as in ablation coefficients and in indices of progressive fragmentation of the Quadrantids, δ-Aquarids and Daytime Arietids meteors (JACCHIA et al., 1965; VERNIANI, 1973) obviously given evidence that these showers are produced by the same stream.

A scantily studied question of the meteor stream dynamics is an estimate of the stream lifetime. The survival time of meteor particles seems to be better studied. Principal mechanisms of meteor stream disintegration are the Poynting-Robertson effect, the exhaustion by large planets and catastrophic collisions with sporadic meteoroids. The most effective mechanism is the last one (DOHNANNY, 1974; TOKHTASJEV, 1982).

Previously, on the assumption that the Geminids and Quadrantids have roughly equal width and thickness according to the calculations of the variation of orbital radii-vectors at the nodes, a conclusion was made that the observable periods of the corresponding showers are short (200-400 yr) (PLAVEC, 1950; BABADJANOV, OBRUBOV, 1980; HUGHES, WILLIAMS, MURRAY, 1980; FOX, WILLIAMS, HUGHES, 1983). In the light of new notions of the streams shape, one may conclude that the observable periods of the Geminids and Quadrantids can be comparable with the life-times of these meteor streams. Arguments in favor of such long observable periods are based on the ancient observations (IV-XII centuries) of fireballs with radiants in constellations of Gemini and Mural Quadrant during periods corresponding to the present active periods of the Geminids and Quadrantids (ASTAPOVICH, TERENTJEVA, 1968).

Thus, the results of investigation of the Geminids and Quadrantids meteor stream evolution show that under the influence of planetary perturbations, the stream may originally be flat but then thicken depending on the variation range of orbital inclinations. Eventually, due to planetary perturbations, a meteor stream may take such a shape as to cause the start of several active showers at different solar longitudes.

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