SOME FEATURES OF EVOLUTION OF METEOR STREAMS

P.B. Babadzhanov and Yu.V. Obrubov
Astrophysical Institute, Dushanbe, 734670, USSR

ABSTRACT. It is shown that a number of features of meteor showers such as the correlation of orbital semimajor axes and longitudes of the ascending nodes with meteor magnitudes, the restriction of visibility periods and the displacement of maximum activity dates is explained by the joint influence of planetary perturbations, the Poynting-Robertson effect and its corpuscular analogue, light pressure and ejection velocities of different mass meteoroids from cometary nuclei.

Among the major meteor showers the Geminids and Quadrantids attract special attention for several reasons. The main reasons are high hourly rates, prolonged series of observations and high stability of their annual activity. The Geminids were first observed in 1862 and the Quadrantids in 1830. The annual display of their activities indicates that sufficient time has passed between stream formation and shower detection. This time is necessary to account for the meteoroid distribution along the orbits of their parent comets (unknown to us) and for the formation of the observed correlations of orbital semimajor axes and longitudes of nodes with meteoroid masses. It has been established (Babadzhanov and Obrubov 1980; Hughes et al. 1980) that the detection of the Geminids and Quadrantids became possible due to the change of these stream orbits under the perturbing actions of planets.

Recently several papers have appeared, discussing the theory of formation and evolution of the Geminid and Quadrantid meteor streams. In these papers attempts are made to explain certain meteor shower features. For example, to explain the year to year variation (up to 30 %) of the Geminid rate, Jones (1982) assumes that a parent comet with the radius 0.9 km disrupted into several parts and each part subsequently formed a streamlet. This would explain the variations of the Geminid rate. However, the model does not take into account the influence of gravitational and nongravitational perturbations which could cause the observed variations. The model cannot explain the measured stream width and, moreover, the correlations of the orbital semimajor axes and longitudes of the ascending nodes with meteoroid masses. In order to explain the observed correlations of the longitudes of ascending nodes with meteoroid masses for

Richard M. West (ed.), Highlights of Astronomy, Vol. 6, 411–419.

https://doi.org/10.1017/S1539299600005414 Published online by Cambridge University Press

the Quadrantid meteor stream Hughes et al. (1981) assume that large and small particles were ejected from the nucleus of a parent comet at different epochs when the comet had orbits of various sizes and was spiraling towards the Sun under the action of nongravitational effects. This theory of stream formation is not well-founded. Besides, most papers do not take into account the intensification of the Poynting-Robertson effect in the past with decreasing perihelion distance of the Quadrantid orbit. It was shown (Babadzhanov and Obrubov 1980) that the rate of variation of the semimajor axis of the Quadrantid orbit for minimum and maximum values of the perihelion distance differ by a factor of up to 50.

Apparently, a comprehensive theory of the formation and evolution of a meteor stream must involve the following considerations:
a) estimation of the stream age;
b) initial distribution of the orbital elements of meteoroids according to their masses;
c) estimation of the joint influence of gravitational and nongravitational perturbations in the motion of meteoroids of different masses;
d) investigation of encounter conditions of a meteor stream with the Earth;
e) comparison of the theory with observations.

METEOR STREAM AGE

The G e m i n i d s. Nongravitational effects associated with solar radiation exert an essential influence on the evolution of Geminid meteoroid orbits since the perihelion distance is only 0.14 a.u. and the orbital period 1.5 yr. Indeed the orbital semimajor axes of meteoroids producing meteors of 6^m and -4^m differ by 0.1 a.u. In addition there is a correlation of longitude of the ascending node with meteor magnitude (Jones 1978; Fox et al. 1982). Let us assume that particles of different masses initially had identical orbital semimajor axes. Then, assuming that the difference in semimajor axes of large and small particles is the result of the Poynting-Robertson effect we can compute the time necessary for the formation of this difference, i.e. estimate stream age. Age estimates for different meteoroid densities are presented in Table 1, where T_1 is the estimated age without regard to secular perturbations of the perihelion distance, and T_2 the age including these pertrubations. The mass of a particle producing a meteor of 6^m was assumed to be 10^{-3} g.

Table 1. Estimated ages of the Geminid and Quadrantid meteor streams.

	Geminids				Quadrantids			
δ g/cm^3	$\rho\delta$ g/cm^2	$T_1 \cdot 10^{-3}$ yrs	$T_2 \cdot 10^{-3}$ yrs	T_1/T_2	$\rho\delta$ g/cm^2	$T_1 \cdot 10^{-3}$ yrs	$T_2 \cdot 10^{-3}$ yrs	T_1/T_2
0.3	0.028	1.7	1.6	1.1	0.017	20	3	6.7
1	0.062	3.9	3.5	1.1	0.038	44	10	4.4
3.5	0.143	9.0	8.5	1.1	0.086	102	25	4.1
7.6	0.243	15.1	19.0	0.8	0.149	172	40	4.3

https://doi.org/10.1017/S1539299600005414 Published online by Cambridge University Press

The Q u a d r a n t i d s. At present the perihelion distance of the mean orbit of the Quadrantid meteor stream is 0.98 a.u. (Cook 1973) and the influence of nongravitational forces on the evolution of meteoroid orbits is negligible. But the computations of secular perturbations of the orbital elements by the Halphen-Goryachev method (Babadzhanov and Obrubov 1980) show that approximately $1.5 \cdot 10^3$ yrs ago the perihelion distance reached the minimum value 0.08 a.u. If the meteor stream existed at that time then its particles would suffer strong nongravitational perturbations which at present must show up as correlations of semimajor axes and longitudes of the ascending nodes with meteoroid masses. So an estimate of a lower limit to the stream age is of interest as well. According to Hindley (1972) the difference of semimajor axes of the orbits of meteoroids producing meteors of $1^m.5$ and $6^m.5$ ($m=2.4 \cdot 10^{-4}$ g) is 0.2 a.u. Although this difference does not exceed the bounds of observational errors and seems to be overestimated, it is of interest to consider it as a result of the Poynting-Robertson effect. Taking into account the secular variations of the perihelion distance we arrive at a value of 3000 yrs for the lower limit to the Quadrantid stream age (Table 1). The lower limit of stream age can also be estimated as follows: Following Hamid and Youssef (1963) let us assume that the Quadrantids were formed as a result of the decay of a cometary nucleus, captured by Jupiter. After capture the comet must have moved in the orbit corresponding to the osculating one of the Quadrantid meteor stream, if we assume that particle ejection velocities from the cometary nucleus were small. Suitable moments for cometary capture were those when distances between Jupiter and the stream were minimal. For instance, $3 \cdot 10^3$ - $3.6 \cdot 10^3$ yrs ago a minimum distance was 0.1 a.u. Since that time and up to the present, according to the calculation of the perturbations, a comet could not pass in the vicinity of Jupiter at a distance less than 0.2 a.u. Hence the comet was captured not later than $3 \cdot 10^3$ yrs ago. Thus, $3 \cdot 10^3$ yrs can be taken as a lower limit to the Quadrantid stream age.

INITIAL DISTRIBUTION OF ORBITAL ELEMENTS OF METEOR STREAM PARTICLES

The most probable mechanism of meteor stream formation is disintegration of cometary nuclei. We lack information about the actual conditions of formation of the Quadrantid and Geminid streams including data on orbits and physical properties of their parent comets. So it may be assumed that during the formation of these streams their parent comets were moving in osculating orbits corresponding to those parts of the streams which are observed at present. Using the above estimates of Geminid and Quadrantid ages, and calculating the secular perturbations of the mean stream orbits in the past we have determined possible orbits of the parent comets at the time T of stream formation. (See Table 2 where T is in millennia and $T=0$ corresponds to 1950.0).

Table 2. Possible orbits of the Geminid and the Quadrantid parent comets.

Stream	T	a	e	q	i	Ω	ω
Geminids	-3.5	1.36	0.8966	0.141	24.3	14.8	213.2
Geminids	-19.0	1.36	0.8968	0.140	22.7	172.0	41.1
Quadrantids	-3.0	3.08	0.6732	1.008	73.4	99.4	5.2

To determine the orbital elements of an ejected particle it is necessary to know the cometary position and the velocity vector of particle ejection. The ejection velocity of a particle from the nucleus of a comet is determined by the distance from the Sun, the size of the cometary nucleus, the radius ρ and the density δ of the particle (Whipple 1951). According to Plavec (1957) the entire mass of the Geminid stream is 10^{15} g. Assuming the comet to be wholly disintegrated with a dust/gas ratio equal to 1:3, and a nucleus density of 1 g/cm^3, the corresponding radius of the cometary nucleus will be 1 km. We adopted the same parameters for the hypothetical parent comet of the Quadrantid meteor stream.

In the vicinity of perihelion an intensive decay of the cometary nucleus undoubtedly occurs during tens or hundreds of revolutions around the Sun. For some orbits (such as the Geminids) the secular variations of elements under the action of planetary perturbations may be neglected for the time intervals involved. For other orbits changes of elements during this period may be essential (as is the case for the Quadrantids). Probably, they should be taken into account. We assumed that ejection of particles of different masses and densities from the nuclei of the hypothetical comets occurred isotropically. We further assumed that the ejection occurred at perihelion and at true anomalies of $\pm 30^{\circ}$ in the orbits corresponding to the ages of the Geminid and Quadrantid streams. For Geminid meteoroids with $\rho\delta$ from 0.6 to 0.05 g/cm^2 we obtained ejection velocities from 70 to 260 m/s. For Quadrantid meteoroids in the same interval of $\rho\delta$ the velocities were 12 - 37 m/s. It turned out that the angular orbital elements (i, Ω, ω) differ little from the cometary ones, and only slightly depend on the position of the ejection point and the direction and absolute value of the ejection velocity. Only the orbital semimajor axes of particles ejected in the direction of motion of the nucleus and in the opposite direction differ strongly from the cometary ones. The calculations of the orbital elements of ejected particles included corrections for radiation pressure. The intersection of the resulting Geminid stream with the ecliptic plane is shown in Fig. 1a (Obrubov 1980). The Quadrantid stream intersection has the same form.

JOINT INFLUENCE OF GRAVITATIONAL AND NONGRAVITATIONAL PERTURBATIONS

As a rule planetary perturbations change the semimajor axes of meteoroid orbits in a periodic manner. However, in case of a close encounter the semimajor axis can suffer a variation greatly exceeding the amplitude of the periodical oscillation. It is important to note that the semimajor axes suffer variations which depend on the passage conditions of the particles in the vicinity of a perturbing planet and which are independent of meteoroid mass. So the correlation of semimajor axis a with mass (m) may be caused by the absorption and re-emission of solar radiation, the ejection of particles from cometary nuclei and other effects. But the deceleration caused by the re-emission of radiation and light pressure does not change the orbital plane. If these effects explain the correlation of a with m, then the nature of the correlation of longitude of ascending node Ω with mass is not very clear. The different ejection velocities for different particle masses from cometary nuclei do not explain the correlation of Ω with *m* because of negligible variations of longitudes Ω at the assumed ejection velocities.

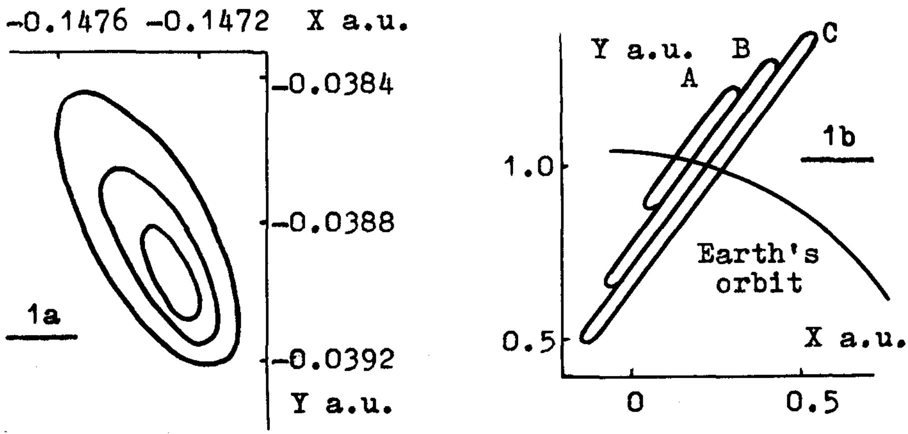

Fig. 1 The intersection of the Geminid meteor stream with the ecliptic plane at the descending node. 1a - at the moment of the stream formation. 1b - after 3500 yrs. Curves A, B and C show the limits for particles with $\rho\delta$ equal to 0.6, 0.1 and 0.05 g/cm^2, respectively. The positive X-axis is directed toward the vernal equinox.

The most probable reason for the correlation of Ω with *m* is the following. The Poynting-Robertson effect and its corpuscular analogue decrease the size of the orbit according to the masses and densities of the particles and thus change the geometrical conditions of their passage in the vicinity of a perturbing planet. These differing conditions lead to different planetary perturbations on particles of different masses, i.e. to the appearance of correlations between the angular elements (i, ω, Ω) and the particle masses.

We have determined the secular variations of the orbital elements of the Geminid and Quadrantid model streams with regard to the joint influence of planetary perturbations, the Poynting-Robertson effect and its corpuscular analogue. Fig. 1b shows the intersection of the model Geminid stream with the ecliptic plane corresponding to the present time. We note that a segregation of meteoroids in $\lambda_\odot$ according to the parameter $\rho\delta$ is evident. This segregation satisfactorily conforms to the observations both qualitatively and quantitatively. It turned out that an interval of 3000 yrs is quite sufficient for the formation of the correlation of Ω with *m* in the Quadrantid shower. We conclude that the main reason for the correlation of longitudes Ω with *m* is the joint influence of such factors as particle ejection from cometary nuclei at various speeds, light pressure, planetary perturbations, and radiative and corpuscular drags.

https://doi.org/10.1017/S1539299600005414 Published online by Cambridge University Press

ENCOUNTER CONDITIONS OF METEOR STREAMS WITH THE EARTH

i. Period of meteor shower visibility. The observations show that within the last 50 yrs 30 % of known meteor radiants have disappeared and the same quantity of new radiants have appeared. These changes may be related to variable stream encounter conditions with the Earth. We showed earlier (Babadzhanov and Obrubov 1980) that planetary perturbations change the Geminid and Quadrantid orbits. The intersection points of the mean stream orbits with the ecliptic plane retreat from the Earth's orbit at the rate of $7.5 \cdot 10^4$ km/yr. Thus, if the extent of the Geminid intersection along the radius-vector of the descending node is equal to 0.1 a.u., then the shower will be observed from the Earth for only 200 years. Assuming that the corresponding intersection size of the Quadrantids is 0.15 a.u., they might be observed for about 300 yrs.

ii. Displacement of date of shower maximum activity. In addition to the heliocentric distances of the orbital stream nodes, their directions are also changed under the action of planetary perturbations. In some cases this leads to a variation of shower maximum activity date, in other cases there are no noticeable displacements of this date. As reported earlier (Babadzhanov and Obrubov 1982) there are two possible cases involved:

1. The observed displacement of shower maximum activity is equal to the secular variation of the longitude of the ascending node, that is: $\Delta T_{obs} = \Delta\Omega$ if the heliocentric distance of the node in which the stream crosses the Earth's orbit is nearly constant. This condition is satisfied for the Leonids, Quadrantids, Bielids and Perseids.

2. For a meteor stream with an orbit slightly inclined to the ecliptic plane, the rate of the displacement in date of maximum activity will be determined by secular variations of the perihelion longitude and eccentricity.

Table 3. Orbital elements of meteor streams.

Shower	a	e	q	i	Ω	ω
Leonids	10.3	0.905	0.977	162.6	234.5	170.9
Quadrantids	3.08	0.683	0.977	72.5	282.7	170.0
Perseids	28.0	0.965	0.953	113.8	139.0	151.5
Bielids	3.52	0.756	0.861	12.6	247.3	223.2
Geminids	1.36	0.896	0.142	23.6	261.0	324.3
η-Aquarids	13.0	0.958	0.560	163.5	42.4	95.2
Orionids	15.1	0.962	0.571	163.9	28.0	82.5

The orbital elements of several meteor streams according to Cook (1973) are given in Table 3. Our calculations of secular variations of the orbital elements and variations of maximum activity dates per 100 yrs are given in Table 4. We obtained the observed displacements ΔT_{obs} of the η-Aquarid and Orionid maximum activities from data by Imoto and Hasegawa (1958) and the displacement of the Bielids from Cook (1973).

The data for the Leonids are taken from Adams (1867); for the Quadrantids and Perseids from Hughes (1972) and Hughes and Emerson (1982); for the Geminids from Hajduk et al. (1974) and Porubčan et al. (1980). We note from Table 4 that the calculated displacements of meteor shower maximum activity are in good agreement with observations.

Table 4. Secular variations of orbital elements and changes of the dates of maximum activity of meteor showers per 100 years.

Shower	Δe	Δi	$\Delta\omega$	$\Delta\Omega$	ΔT_{obs}	ΔT_{cal}
Leonids	0.0002	-0.036	1.57	1.39	1.45	1.39
Quadrantids	-0.024	0.53	1.80	-0.37	-0.36	-0.37
Perseids	-0.00005	0.004	0.001	0.034	0.038	0.034
Bielids	0.008	-2.89	16.6	-17.9	-17.9	-17.9
Geminids	-0.001	0.77	1.58	-1.62	0	0.04
η-Aquarids	0.00008	-0.05	1.64	1.94	0.16	0.18
Orionids	0.00009	0.07	1.29	1.54	0.59	0.41

iii. Mass segregation of meteor streams. If the stream orbit lies inside the orbit of a perturbing planet (for example, the Geminids and Jupiter) then to a first approximation the following integrals of motion are valid (Lidov 1961):

$$(1-e^2)\cos^2 i = C_1 = \text{const.}; \qquad e^2(0.4-\sin^2 i \sin^2\omega) = C_2 = \text{const.} \qquad (1)$$

If we add to these integrals the intersection conditions of the stream orbit with the Earth's orbit $a(1-e^2) = 1 \pm e\cos\omega$, then using known values of a, C_1 and C_2 we can determine the elements e', i', ω' for the epoch of intersection of any given orbit with the Earth's orbit. In some cases we can assume that the perihelion longitude varies linearly with time and practically does not depend on the value of the orbital semimajor axes a of particles belonging to the stream. We then have:

$$\Delta\lambda_\odot \approx \Delta\Omega = -\Delta\omega \,\mathrm{sign}(\cos i)$$

In a young meteor stream C_1 and C_2 are practically similar for all particles, since the changes in e, i, ω as a result of particle ejection from cometary nuclei are small. It follows that the difference in e', i', ω' for the intersection epoch of the particle orbit with the Earth's orbit will be basically conditioned by the difference of the semimajor axes. In particular, for the Geminids introducing the values $a = 1.31$ and 1.41 a.u. ($a_0 = 1.36$) we can compute e', i', ω' and by differences in a we can determine how the particles will be segregated according to $\lambda_\odot$. The results of these calculations (Table 5) are in satisfactory agreement with observations.

Thus, if we know the difference in meteoroid semimajor axes we can estimate the amount of meteoroid segregation with respect to solar longitude for the meteor stream orbit satisfying conditions (1). The inverse assertion, that we can estimate the difference in meteor semimajor axes

https://doi.org/10.1017/S1539299600005414 Published online by Cambridge University Press

from their segregation according to the longitude of the Sun at the moment of their observation is valid as well.

Table 5. Estimation of magnitude segregation of Geminid meteors.

M	a	C_1	C_2	e	i	ω	$\Delta\lambda_o$
6	1.31	0.165	0.275	0.8943	24.7	325.5	-0.9
1	1.36	0.165	0.275	0.8951	24.3	324.6	0
-4	1.41	0.165	0.275	0.8954	23.9	325.9	1.3

It should be noted that in order to explain meteor shower features it is necessary to apply an individual approach to each meteor stream. We must take into account the secular variation of radii-vectors of the nodes of observation, qualitatively possible stream intersections with the ecliptic plane and the particle distribution along, and across, the stream.

Apparently, other properties of meteor showers may be explained by the joint influence of planetary perturbations, the Poynting-Robertson effect and its corpuscular analogue, the light pressure and differing ejection velocities of different mass meteoroids from cometary nuclei. Kramer and Timchenko-Ostroverkhova (1981) investigate the evolution of the Geminid and Taurid meteor streams. It is shown that under the influence of planetary perturbations the initial slight differences of orbital elements of stream particles lead to a secular broadening of the stream, to an increase of the period of shower activity and also to a decrease of meteor rates. In a number of papers by Kiev astronomers (Kruchinenko and Sherbaum 1980; Sherbaum and Kazantsev 1980; Kazantsev and Sherbaum 1981) the possible deformations of meteor streams of different orbital sizes and inclinations under the perturbing gravitational action of Jupiter and Saturn are considered. Their results show that regions of both condensation and dearth of meteoroids may arise in an initially homogeneous stream. Probably, this explanation is valid for the year to year variation of meteor shower rates (for example in the Geminids). It is known that some meteor streams have both northern and southern branches. Galibina and Terent'eva (1981) try to explain the origin of these branches by planetary perturbations.

For the correct solution of these and other problems connected with the formation, evolution and structure of meteor streams it is necessary to obtain new exact data on meteor showers for a long period of time. Meteor observations which will be carried out from stations which differ considerably in longitude may render essential assistance.

REFERENCES

Adams, J.C.: 1867, Month. Not. Roy. Astron. Soc. 27, pp. 247-252.
Babadzhanov, P.B. and Obrubov, Yu.V.: 1980, *Solid Particles in the Solar System*, (eds) I. Halliday and B.A. McIntosh, D. Reidel Publ. Co. Dordrecht, Holland, pp. 157-162.
Babadzhanov, P.B. and Obrubov, Yu.V.: 1982, *Sun and Planetary System*, (eds) W. Fricke and G. Teleki, D. Reidel Publ. Co. Dordrecht, Holland, pp. 401.
Cook, A.F.: 1973, NASA SP-319, pp. 183-191.
Fox, K., Williams, I.P. and Hughes, D.W.: 1982, Month. Not. Roy. Astron. Soc. 200, pp. 281-291.
Galibina, I.V. and Terent'eva, A.K.: 1981, Astron. vest. 15, pp. 180-186.
Hajduk, A., McIntosh, B.A. and Šimek, M.: 1974, Bull. Astron. Inst. Czech. 25, pp. 305-313.
Hamid, S.E. and Youssef, M.N.: 1963, Smiths. Contr. Astroph. 7, pp. 309-311.
Hindley, K.B.: 1972, Sky and Telescope 43, pp. 162-164.
Hughes, D.W.: 1972, The Observatory 92, pp. 41-43.
Hughes, D.W. and Emerson, B.: 1982, The Observatory 102, pp. 39-42.
Hughes, D.W., Williams, I.P. and Murray, C.D.: 1980, *Solid Particles in the Solar System*, (eds) I. Halliday and B.A. McIntosh, D. Reidel Publ. Co. Dordrecht, Holland, pp. 153-156.
Hughes, D.W., Williams, I.P. and Fox, K.: 1981, Month. Not. Roy. Astron. Soc. 195, pp. 625-637.
Imoto, S. and Hasegawa, I.: 1958, Smiths. Contr. Astroph. 2, pp. 131-144.
Jones, J.: 1978, Month. Not. Roy. Astron. Soc. 183, pp. 539-546.
Jones, J.: 1982, Month. Not. Roy. Astron. Soc. 198, pp. 23-32.
Kazantsev, A.M. and Sherbaum, L.M.: 1981, Problemy cosmicheskoy physiki, Kiev, 16, pp. 30-33.
Kramer, E.N. and Timchenko-Ostroverkhova, E.A.: 1981, Astron. vest. 15, pp. 50-54.
Kruchinenko, V.G. and Sherbaum, L.M.: 1980, Astron. vest. 14, pp. 176-181.
Lidov, M.L.: 1961, Iskusst. Sputniki Zemli, No. 8, pp. 5-45.
Obrubov, Yu.V.: 1980, Doklady Acad. Nauk Tadzh. SSR 23, pp. 175-179.
Plavec, M.: 1957, Czech. Acad. Sci. Astron. Inst. Publ. No. 30.
Porubčan, V., Kresáková, M. and Štohl, J.: 1980, Contr. Astron. Observ. Skalnaté Pleso, 9, pp. 125-144.
Sherbaum, L.M. and Kazantsev, A.M.: 1980, Vestnik Kievskogo Universiteta, Astron. 22, pp. 61-65.
Whipple, F.L.: 1951, Astrophys. J. 113, pp. 464-474.