SEARCH FOR INTERSTELLAR METEOROIDS

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A possibility is discussed that there are interstellar meteoroids among those detected by ground based instrumentation. It appears that about 0.2–10% of the total number of the meteoroids have hyperbolic orbits. There are different points of view on possibility to detect a meteoroid having an infinite orbit. One may expect theoretically that many of the recorded hyperbolic meteoroids are interstellar. Hence, some hyperbolic orbits may be either erroneous or belong to the meteoroids which were born in the Solar System. A criterion of selection of the real interstellar particles is given in the present paper. The Kharkiv catalogue of orbits of meteoroids with the masses greater than 10^{-6} g, which produce faint radiometeors, was used.

DATA ON HYPERBOLA AND THE ACCURACY OF THE ORBITS DETERMINATION

The most of meteors observed instrumentally belong to the Solar System. Nevertheless, the Solar System is not closed. It is permeable for the particles and even large bodies flying inward and outward. Since a meteoroid with a hyperbolic heliocentric velocity may have an usual geocentric velocity [1, 11] then a possibility to record a hyperbolic meteor is no more connected with a great error of determination of its velocity. Presence of interstellar particles in the observation data is not proved till now because the accuracy of measurements and calculations is not good enough to check the reliability of these data. This problem is known as the problem of hyperbolic meteoroids but really it is the problem of hyperbolic orbits of dust grains in the Solar System. No one exact enough orbit of a small body is distinctly classified as really hyperbolic.

It is supposed that 80% of the particles recorded by the Pioneer-8 and Pioneer-9 spacecrafts caused by a stream of the β-meteoroids with the masses $10^{-15}-10^{-12}$ g. Unfortunately, the accuracy of determination of orbits was rather poor because the speed was determined with an accuracy $\pm10\%$ and direction of the velocity with that of $\pm27\%$ [22]. Nevertheless, the dust experiments on board of the Ulysses and other spacecrafts detected a significant flux of the β-meteoroids with interstellar hyperbolic orbits in the mass range $10^{-16}-10^{-8}$ g [17]. Effect of accuracy of the data on the percentage of hyperbola was investigated in the papers [1, 15, 21]. It occurs that there are 1–2% of hyperbola in precise photographic data [8] and up to 10% in less precise ones as well as in radio meteor catalogues [5, 6, 11]. There are hyperbolic orbits in television meteor catalogues: almost 15% in the Japanese one that includes the observations in 1990–1994 and 12% in the Canadian catalogue.

The root-mean-square errors of photographic and radio measurements are given in Table 1. The values for radio meteors [11] are averaged taking into consideration the tails of error distribution functions. The accuracy of individual orbits is sometimes better. One can meet such minimal values as follows: $\sigma V_g < 1.5$ km/s, $\sigma Z < 0.^\circ5$, $\sigma A < 0.^\circ5$, $\sigma V_h < 1$ km/s. It is shown in the papers [11, 16, 23] that the accuracy of catalogues of the orbits of radio meteors is not worse than that of photographic catalogues and sometimes exceeds it. The accuracy of catalogued orbits can be improved by increasing the accuracy of computations (if initial parameters are known), *i.e.*, taking better algorithm and constants [1, 11].

An error may be either positive or negative. Therefore, hidden hyperbola may be present among the near parabolic ellipses ($e < 1$ and $e \sim 1$). The work [1] shows the dependence of the number of hyperbola on the accuracy of computations. It occurred that 24.8% (1975) and 24.3% (1976) hyperbolic orbits became elliptic after a recalculation with the changed constants. The type of an orbit may be changed because the root-mean-square error of eccentricity σe increases with decreasing of e [23].

The growth of the number of hyperbolic orbits with increasing of the volume of data may be either real or a result of accumulation of erroneous data. Analysis of formation of hyperbolic orbits in the Solar System shows that their number cannot exceed some percent. The less is the mass of a meteoroid the more mechanisms to transform its orbit into a hyperbola exist but it is more difficult to detect such a body. Having more data one can study the distribution of hyperbolic orbit even each orbit is not very precise. Unfortunately, the accumulated at present time observation data on bodies with hyperbolic orbits are very non-uniform and insufficiently comprehensive to make any ultimate significant conclusions. According to Öpik the Pultusk famous meteorite

Table 1: Root-mean-square errors of meteoroid velocities, coordinates of the radiants and orbital elements obtained by different techniques

Technique of observation	σVg km s^{-1}	σA °	σZ °	$\sigma\alpha$ °	$\sigma\delta$ °	σe	$\sigma(1/a)$ AU^{-1}	σi °	$\sigma\omega$ °
1. Photographic in Odesa [3]	0.6	–	–	0.5	0.5	0.052	0.054	2.12	2.46
2. Radar in Kharkiv (observations of the Geminids meteor stream) [9]	2.0	–	–	2.7	2.4	0.028	0.15	5.6	4.3
3. Radar in Kharkiv (calculation with analytical formulas, average values for elliptic orbits) [23]	1.4	–	–	–	–	0.25	0.12	6.6	–
4. Radar in Kharkiv (individual hyperbolic orbits) [11]	2.4	1.8	4.2	–	–	0.205	0.253	7.0	7.6
5. Radar in Obninsk [16]	–	–	–	–	–	0.04	0.08	3.0	4.0

is a single body with confidently determined hyperbolic velocity. It is also worthy to mention 98 hyperbolic comets of the Marsden's catalogue and hyperbolic orbits in other comet catalogues. Several catalogues of hyperbolic meteoroids have been published. There are among them the Vsekhsvyatsky's catalogue consisting of 78 orbits [24] and the Simakina's catalogue consisting of 38 hyperbolic orbits [20]. There are also observed data on hyperbola determined by photographic and radio techniques in Kyiv, Kazan and Kharkiv. The radar system AMOR is working daily in the Southern Hemisphere and gives a possibility to study the characteristics of groups of non-bound particles in the inner Solar System. Meteor investigation with Arecibo radar system in 1997 confirmed the existence of hyperbolic meteoroids with masses $10^{-11}-10^{-6}$ g.

MECHANISMS OF THE HYPERBOLIC ORBIT FORMATION OF METEOROIDS

Since both interstellar particles and those leaving the Solar System can have hyperbolic orbits it is rather complicated to analyze data on such orbits. The problem of interstellar meteoroids has already become a component of the problem of hyperbolic orbits. So, it is difficult to reveal the peculiar motion of the Sun in distributions of all hyperbolic orbits. According to the theory of capture [18] the captured into the Solar System bodies will have elliptic and near parabolic orbits. It makes the search of interstellar particles more complicated. When processing cometary orbit data one often can succeed in passing from an observed oscillating hyperbolic orbit to the primary elliptic one after accounting planetary perturbations. The observational selection is an additional difficulty when studying of distributions of cometary orbits.

The density of the interstellar comets in the Galaxy disk is estimated as one comet per cube with a side of 9 AU. It is not far from that density which ensure a noticeable probability to observe an interstellar comet. According to the Vsekhsvyatsky's estimates an interstellar meteor must be observed practically every day. In this case the meteoroids with $e \gg 1$ must be present among the observed bodies [24]. According to other estimates [4, 12], on the contrary, the eccentricities of gravitationally focused interstellar meteor orbits must be concentrated around unity. The orbits, which became hyperbolic due to perturbations from the nearest planets [21], are expected to have eccentricities $e \sim 1$ as well. A possible mechanism of the origin of hyperbolic meteoroids is a collision of two asteroids [1]. Meteoroids born in explosions caused by such collisions can get hyperbolic orbits. It is supposed in the work [13] that such meteoroids ($10^{-3}-10^{-4}$ g) could have their orbital inclinations $i < 90°$ and heliocentric velocities $V_h > 57$ km/s.

There are many other criteria to evaluate the efficiency of a hyperbolic orbit formation mechanism in the Solar System. One of the criteria is the number of nodes of the testing orbit. A hyperbolic orbit on the contrary to an elliptic one can cross the ecliptic plane only once. For the hyperbolic meteoroids having two nodes one can find the perturbation forces in the ecliptic plane, which could transform into hyperbola their initial, probably a non-hyperbolic orbit. In Kharkiv it is proposed to use the radius vectors of ascending and descending nodes when applying this criterion. The results of measurements in Kharkiv has been checked in this way. Such suspicious orbits have been found among the data of 1975–1976. They are transformed by planetary perturbations of Mars (4 orbits), Jupiter (3 orbits) and Saturn (2 orbits). The idea that any planet of the Solar System is able to transform an orbit into hyperbola is proved in [2] by estimation of the incoming flux of the particles whose hyperbolic orbits are the result of transformation of their initial orbits in spheres of influence of planets.

There are another mechanisms which can change an orbit of a meteor body (especially of a small mass $M \ll 1$ g) in the Solar System: non-gravitational effects (*e.g.*, light pressure), perturbations from the Sun and the Moon within the sphere of the Earth attraction. Recent astronomical discoveries qualitatively confirmed the hypothesis on origin hyperbolic meteoroids by volcanic eruption on satellites of planets as well as elsewhere in the Galaxy [14, 17, 24]. Data available on Geminga show a direct connection between the matter released during the Supernova explosion and discovered micrometeoroid streams of the Arecibo particles and the Ulysses ones.

There is a hypothesis on a possibility to detect the interstellar particles by a kinematic considerations. If interstellar bodies are present among the observed meteoroids with hyperbolic orbits, then their interstellar velocity distribution must correspond to the distribution of radial velocities of the nearest stars. The velocity of the Sun is about 19.4 km/s. Parabolic velocity of bodies in the Solar System is believed to be 42.1 km/s. It gives 46.6 km/s as the lowest limit of the heliocentric velocity of interstellar meteoroids. Therefore, if the heliocentric velocity of a meteoroid exceeds the parabolic velocity more than by 10 km/s this body may be of interstellar origin. Moreover, a concentration of meteor radiants to the apex of the Sun ($\lambda = 272°$, $\beta = 57\overset{\circ}{.}5$) should be observed for interstellar meteoroids. For a particle entering the Solar System from interstellar space and coming to the Earth (*i.e.*, moving from the apex) the distributions of interstellar meteoroids on the orbital eccentricity and the perihelion distance have been calculated in the paper [12] for different longitudes of the Earth (observation dates). It has turned out that the most convenient observation periods for detection of interstellar meteoroids were in March and September. Eccentricities of such interstellar particles' orbits should not exceed the value 1.1.

ANALYSIS OF THE KHARKIV RADIO METEOR OBSERVATIONS

More than 230 thousand orbits of the meteoroids with the masses $> 10^{-6}$ g have been registered in Kharkiv [23] with the Meteor Automatic Radar System (MARS) form January 1972 till December 1978. In order to enhance reliability of further analysis we carefully select 159787 orbits according to the special technique. The hyperbolic meteoroid orbits in Kharkiv were studied by samples of different volumes selected of the mentioned multitude by a criterion $a < 0$, $e \geq 1$ and $a > 0$, $0.9 < e < 1$. All the 7911 selected orbits cover a 6 year period with the following numbers of orbits: in 1972 – 475; in 1973 – 1802; in 1974 – 1884; in 1975 – 1448; in 1976 – 1004; in 1977 – 752; in 1978 – 546. Other samples of orbits observed in 1975–1976 have also been studied [1, 2, 10, 11, 15]. There have been selected 1350 hyperbolic orbits among the 54000 orbits observed during 1975 and 950 hyperbolic orbits among the 46000 ones observed during 1976. The orbits selected according to this criterion in the Kharkiv works [1, 2, 10, 11, 15] were called near parabolic and those selected by an additional criterion $e > 1+2\sigma e$ were called hyperbolic. This selection gave 436 hyperbolas of the total number of 1350 orbits of 1975. Among all the near parabolic orbits there are orbits for which analytically determined heights of the meteor trails are in the range of 69–121 km. There were 640 (1975) and 461 (1976) such orbits. A list of 533 elliptical orbits (data of 1975 with $0.9 \leq e < 1$) were used. It was compiled using the Kharkiv elliptical orbit catalogue.

The Kharkiv database contains information obtained for the same period of time and by the same facilities. High statistic representativeness of the data allowed to estimate season variation of the number of observed hyperbolic orbits. The number of such orbits changes during a year approximately as the total number of orbits with a minimum in the first half of the year. The percentage of hyperbolic orbits changes during a year from 1.2 to 4.8, the averaged annual percentage of hyperbolic orbits is 2.8% of the total number of orbits. One should compare the distributions of orbital parameters of meteoroids with that of other bodies (as well as the parameters obtained by different methods) with regard to the above mentioned observational selection. The difference between the distributions of hyperbolic and elliptic meteoroids by their azimuth, zenith distance and the radiant inclination is unessential [11, 23]. The distribution of geocentric velocity V_g for meteoroids with hyperbolic orbits is only slightly shifted to larger velocities in comparison with the distribution V_g for all orbits. The physical factor of noticeability of radio meteors is a function of the observed velocity and the zenith distance of radiant. The geometric form factor is a function mainly of the radiant inclination in continuous day-and-night observations [9]. So, with regard to the stated above analogy of distributions for all the meteors and the meteoroids with hyperbolic orbits, one can conclude that it is possible to use the Kharkiv data to compare different parameters of hyperbolic and elliptic orbits.

Fig. 1 shows the distributions of hyperbolic orbits on some parameters (an example for possible interstellar meteoroids). The distributions of all different samples hyperbolic meteor orbits on the eccentricity are investigated. Among 7911 orbits 28 ones are the eccentricity above 5 and 2300 orbits are $1 < e < 2$, fifteen orbits (1975) have $5 < e < 7$ [11]. The distributions by e both according to the Kharkiv data with $e > 1 + 2\sigma e$ [11] and the catalogue [24] are similar with the main maximum between 1.3 and 1.5. But the distribution on e of all the hyperbolic meteoroids as well as that of the hyperbolic orbits by Fig. 1 are different from them and have the main maximum at $e = 1.0$ to 1.1.

When analyzing a distribution on heliocentric velocity it is worthy to mention that rather many orbits have errors of individual estimates less than the average value of $\sigma V_h = 2$ km/s. According to the Kharkiv data the tail

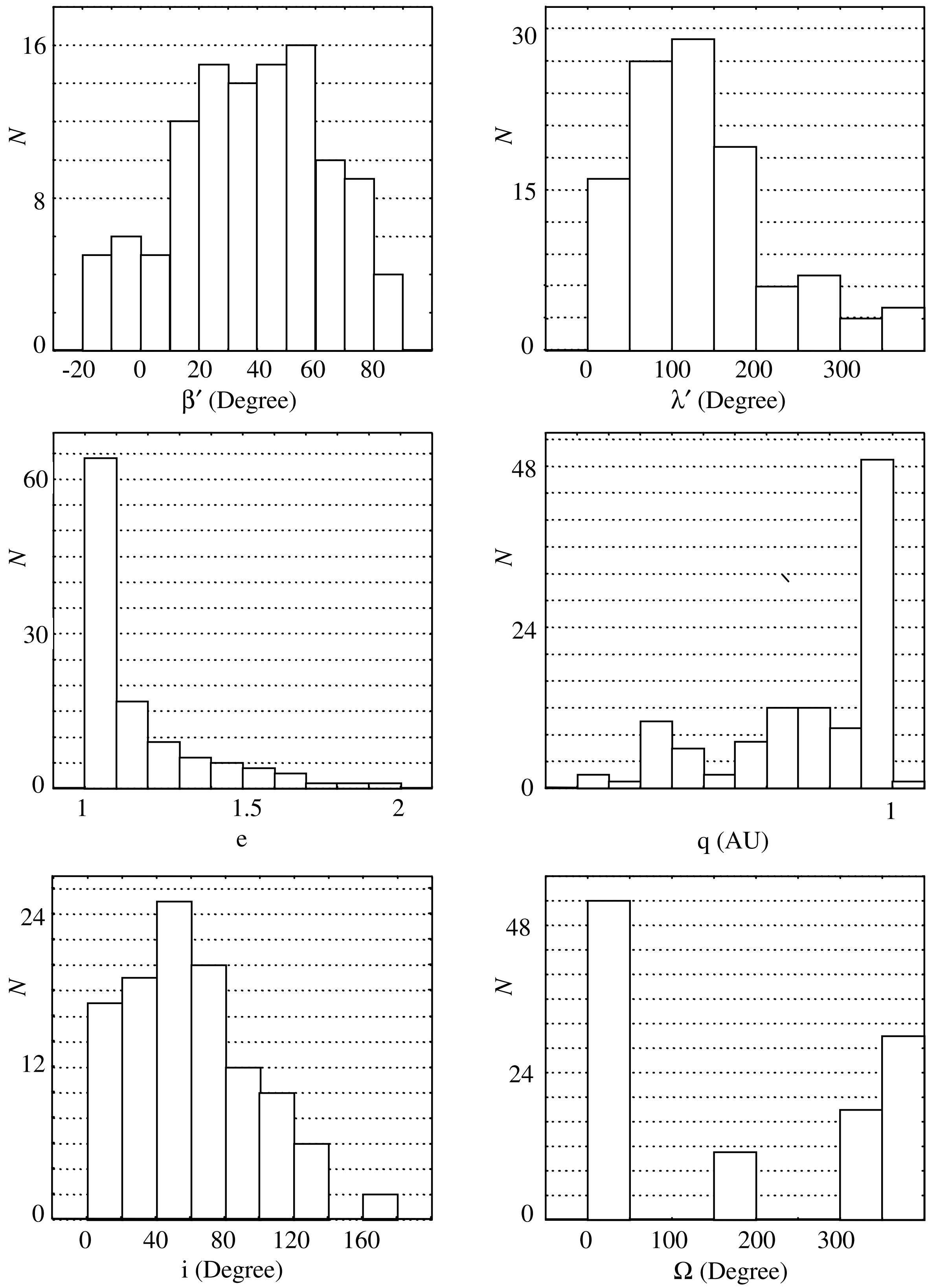

Figure 1: Distribution of a number (N) of hyperbolic meteor orbits ($1 < e < 2$) on heliocentric radiant coordinates (λ', β') and on elements of orbits: the eccentricity e, the perihelion distance q, inclination i, the longitude of the ascending node W

of the velocity distribution function extends up to $V_h \sim 90$ km/s, but the main maximum of distribution of V_h is in the range from 40 km/s to 50 km/s as well as for hyperbolic orbits. The difference between distributions of the Kharkiv data and the Vsekhsvyatsky's catalogue [24] can be explained by the fact that in the catalogue [24] the data is very non-uniform and the selection of observations wasn't taken into account. In the distributions on V_h and e based on the Kharkiv data in 1975–1976 the form and physical factors of selectivity were taken into account by a weighted processing. For hyperbolic and elliptic orbits the distributions of q are different. Elliptic orbits have an almost uniform distribution with a little excess in an interval from $q = 0.9$ to 1.0. Hyperbolic orbits show a sharp increase of the number of orbits when $q \to 1$, the most of orbits are concentrated in an interval of 0.9–1.0. It is known that for parabolic orbits q and ω are connected by the relationship $q = \sin^2(\omega/2)$ and if $q \to 1$ then the argument of perihelion $\omega \to 180°$. The distribution of ω is given in the work [11]. The main maximum lies near $\omega = 180°$. The connection between the distributions of q and ω can be used to test whether the most of orbits are real or the majority of them are a result of errors.

The distributions of near parabolic, hyperbolic and elliptic orbits on longitude of perihelion are compared. The distributions are different that can be an evidence of reality of hyperbolic orbits. The statistics of directions to aphelion and perihelion [10] was used. It was initially assumed that near parabolic and hyperbolic orbits belong to comets. According to celestial mechanics there should be a concentration of perihelion directions of long period comets to a point with the coordinates $\lambda_\pi = 246°$ and $\beta_\pi = 66°$. The search of this feature was carried out. For many hyperbolic orbits of the Kharkiv data $i < 90$. However, the obtained distributions of coordinates of perihelions λ_π and β_π for about parabolic and hyperbolic orbits hardly show the mentioned concentration distinctly. But if the interconnection of aphelion and perihelion directions is taken into account, an analysis only one coordinate of the perihelions permits to suppose that a part of particles on hyperbolic orbits are flying to meet the Solar System and penetrate it.

The distribution of elongation of the radiant from the Sun is a weighty argument in favour of reality of hyperbolic orbits in the Kharkiv data. These distributions for hyperbolas and ellipses with $0.9 < e < 1.0$ are essentially different [1]. The distribution of radiant coordinates (λ', β') of hyperbolic orbits in the ecliptic heliocentric coordinate system can testify for the conclusion about the concentration of meteor radiants to the apex of the Solar peculiar motion.

A possibility to locate interstellar meteoroids according to [12] has been studied as well. It is possible that there are certain number of interstellar meteoroids among those observed 20 days before and 20 days after March 21 during a seven years interval (1972–1978) when 111 meteoroids with the hyperbolic orbits having $1 < e < 2$ was found. Distribution of their parameters is given in Fig. 1.

The research carried out in Kharkiv gave many evidences of existence of hyperbolic orbits. They stimulate us to search for interstellar meteoroids in future. This search today has much more prospects because increasing volume of data but as well as before it is limited by accuracy of meteoroid data. New criteria of choice of interstellar meteoroids are necessary and the problem of such criteria has not been solved yet.

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