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Analysis of the Upper Limit of the Southworth–Hawkins *D* Criterion for the Pons–Winneckid and Perseid Meteoroid Streams

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Abstract—The value of the upper limit of the Southworth–Hawkins *D* criterion for the Pons–Winneckids (June Bootid) and Perseids meteor streams is analyzed on the basis of the comparison of the parent comet orbit with the model orbits of meteoroids ejected at different points of the comet orbit with the most likely ejection velocities. The change of the *D* values is investigated depending on the dynamic evolution of the streams by integrating forward the orbital elements of the model particles using the Cowell method taking into account the perturbations from all planets. It is shown that after ten rotations, for Pons–Winneckids the upper limit of the *D* criterion is higher than 0.5 and for Perseids the *D* criterion does not exceed 0.2.

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INTRODUCTION

The identification of small Solar System bodies with parent bodies is of extreme importance for the study of their evolution and possible encounter with the Earth. The fall of a cosmic body with a size of about 10–100 m onto the Earth will result in a local catastrophe similar to that observed on June 30, 1908 during the explosion of the Tungus meteorite. It is supposed that the size of the Tungus body was about 50 m (Kozin, Korotkov, 2000). The problem of its origin (a piece of a comet, asteroid, or meteoroid) has attracted the attention of researchers up to now. Comic bodies of such sizes have a mass of about 10^2–10^6 g and their spatial density in the near-Earth space is 10^{-16}–10^{-14} m^2/s (Bagrov et al., 2003). It is difficult to observe small bodies of this mass range by optical methods, since their brightness is low, the apparent motion velocity is high, and the direction of their approach is indefinite. The probability of the collision of the Earth with such large meteoroids is high enough and their danger is enhanced by the difficulty to detect and follow them. Some researchers even propose to single out this class of objects into a separate group, "inasans," a group intermediate between asteroids and bolids (Bagrov et al., 2003).

All inasans observed up to now belong to meteor streams. The genetic identification of an observed meteoroid with a meteor stream can be performed by various means. The comparison of radiants is the most reliable way when the coordinates of the meteor stream radiant are well known, i.e., for well-studied and comparatively young meteoroid swarms. The *D* criteria are a more universal way to identify genetically cosmic objects with any group of small bodies of asteroid–comet and meteor complexes. The proximity of the distance between the orbits of the bodies in a five-dimensional phase space is taken as a measure of the genetic generality (Southworth, Hawkins, 1963). For two studied bodies, the *D* criterion has the form

$$D^2 = (e_2 - e_1)^2 + (q_2 - q_1)^2 + (2\sin(I/2))^2 + ((e_2 + e_1)/2)^2(2\sin(W/2))^2, \quad (1)$$

where $(2\sin(I/2))^2 = (2\sin((i_2 - i_1)/2))^2 + \sin i_1 \sin i_2 \times (2\sin((\Omega_2 - \Omega_1)/2))^2$, $W = \omega_2 - \omega_1 \pm 2\arcsin(\cos((i_2 + i_1)/2)\sin((\Omega_2 - \Omega_1)/2)\sec(I/2))$, I is the mutual angle of the inclination of orbits; W is the angle between the directions at the perihelion; and e, q, i, ω, and Ω are the orbital elements. The minus sign is introduced when $|\Omega_2 - \Omega_1| > 180°$. It is assumed that the bodies have a common origin if the distance between their orbits in the given five-dimensional space provides a value of the *D* criterion less than the definite given value.

The main problem in using the *D* criterion is the determination of the upper limit of the *D* value as a measure of the common origin of the two bodies. When studying if the meteoroids belong to this or that stream or when determining the average orbit of the stream, as a rule, the *D* value is assumed to be 0.2. However, the *D* value depends on the initial dispersion of the ejection velocities of the fragments during the disintegration of the parent body and the features of their future dynamic evolution. Therefore, the authors agree completely with the conclusions in the paper on the investigation of the

D values for the meteor complex of Halley's comet (Kulikova et al., 2003) that the same limiting *D* value for each meteor stream can be used only as the first approximation. For more reliable identification, it is necessary to study the upper limit of the *D* criterion for each meteor swarm, since this quantity is the evolutional characteristics of the given swarm.

To determine the upper limit of the criterion, we selected and studied two meteor streams with known parent comets which relate to different planet groups. Comet Pons–Winnecke belongs to the Jupiter group; its aphelion distance is 5.615 AU. A meteor stream called Pons–Winnekids is related to comet Pons–Winnecke. It is also called June Bootids by the name of the constellation hosting the stream radiant. The meteoroid streams of this planet group experience strong perturbations from Jupiter due to the small inclinations of their orbits, the semimajor axes being multiple of the Jupiter orbit, and small perihelion distances close to 1 AU. Another object, comet Swift–Tuttle, refers to Halley-type comets and has an aphelion distance of 55.7 AU, i.e., the aphelion is out of the orbit of Neptune. The orbit of this comet is less affected by gravitation perturbations from the planets. It is the parent comet of the Perseid meteor stream relating to the annual streams that are well observed. It should be noted that both comets are active and their return to the Sun is accompanied by the ejection of the dust component.

At the disintegration of the comet nucleus, the orbits of the ejected fragments are still closely connected with the parent body, and the *D* value (1), first of all, depends on the initial conditions of the ejection (the ejection velocity and the ejection point on the orbit). For each meteoroid stream, the ejections of meteor matter from the parent comet in different orbit points with the most likely velocities were modeled. The orbital elements of the model particles according to formula (1) were compared with the orbital elements of the parent comet. In addition, to follow the dynamics of the *D* values, depending on the dynamic evolution of the swarm the orbital elements of the comet for the ejection epoch were compared with the perturbed orbital elements of the model particles integrated forward by the Cowell method taking into account the perturbation from all planets.

ANALYSIS OF THE *D* CRITERION FOR THE PONS–WINNECKID STREAM

The Pons–Winneckid meteor stream refers to periodic streams with low annual activity hardly exceeding the activity of the sporadic background. However, lately the stream has attracted the attention of researchers by its unusually high activity in 2004, when on June 23 at 14:30 UT the zenithal hourly rate (ZHR) of meteors was recorded as 30–10 (Vaubaillon et al., 2005). A similar increase in the stream activity was recorded previously as well, for example, in 1916, 1927, and 1998. The study of the dynamics of the stream shows that with time the swarm particles ejected from the comet in various years are located beyond the orbit of the Earth due to a close encounter with Jupiter and become inaccessible for the observations (Kondrat'eva, Reznikov, 1976; Asher, Emel'yanenko, 2002; Vaubaillon et al., 2005).

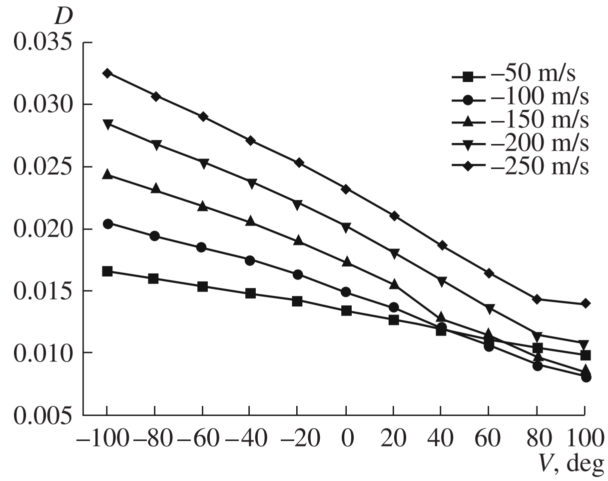

Fig. 1. The value of the *D* criterion for Pons–Winneckids depending on the ejection velocity and the position of the ejection point on the orbit (the ejection of 1869).

According to the data of photometric observations at the European Southern Observatory (Snodgrass et al., 2005), it was obtained that the radius of the Pons–Winnecke comet nucleus is 2.24 km and its minimal density is 0.23 g/cm^3. The change in the comet brightness is noted, which might presume dust ejection from the nucleus. The ejection of particles from the nucleus was modeled on the orbit arc from the point with the true anomaly $V = -100°$ to the point with the true anomaly $V = +100°$ in the direction opposite to that of the motion of the comet, since in this case the orbit of the ejected particle differs from the orbit of the comet itself most strongly. As noted above, the comet nucleus is rather friable; therefore, one can suppose that the ejection velocities of the particles are not high and in the model assume they do not exceed modulo 250 m/s. The orbits of the hypothetical particles ejected from the comet nucleus in 1869 were analyzed. The elements of comet Pons–Winnecke to the moment of the modeled ejection taken from the catalog (Belyaev et al., 1986) have the following values: a = 3.150432 AU; e = 0.751932; $\Omega = 115.6280°$, $i = 10.655°$, $\omega = 162.5639°$; and T = June 1869, 30.4417 UT (the angular elements are given to the 1950.0 epoch)

The change of the *D* value calculated according formula (1) depending on the ejection velocity of the hypothetical particles and the position of the ejection point of the comet orbit at the moment of their ejection from the nucleus is shown in Fig.1. It is seen that the *D* value in this case does not exceed 0.035. There is a distinct dependence of the dispersion of the orbital ele-

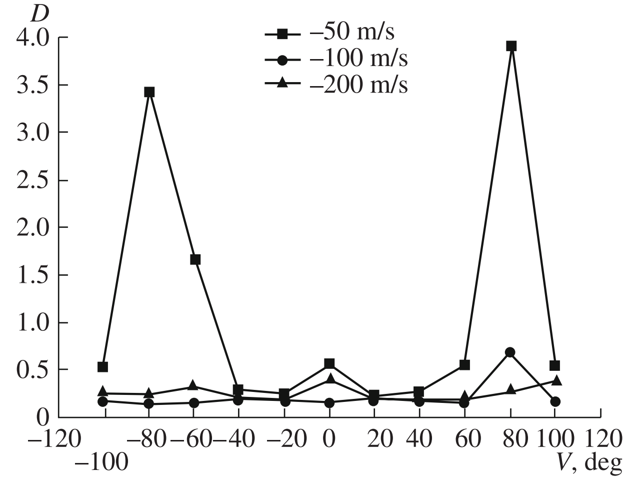

Fig. 2. The value of the *D* criterion for Pons–Winneckids depending on the ejection velocity and the position of the ejection point on the orbit 50 years after the ejection.

ments of the ejected particles on the ejection point on the comet orbit. If the ejection occurs on the orbit arc after the perihelion, a more compact swarm is formed.

To study the variation of the *D* criterion due to the dynamic evolution of the stream, the orbital elements of the model particles ejected from the comet in 1869 were integrated forward up to 1920, taking into account the perturbations from all of the planets. Figure 2 shows the changes of the *D* value for the comet orbit and the perturbed orbits of the model particles. It is seen that the *D* criterion changes in a wide range. A close encounter with Jupiter results in considerable changes of the orbits of the stream particles in an interval of 50 years (ten rotations). As a result, the *D* value for Pons–Winneckids exceeds the upper limit of 0.2 accepted for the meteoroid streams. It is very important to note that the particles ejected from the nucleus with the most likely velocities up to 50 m/s, including those in the orbit perihelion where the possibility of dust ejection is the most probable, experience the strongest gravitational perturbations (Fig. 2).

A *D* value exceeding unity is provided by the perturbed orbits with the semimajor axes after five rotations, reaching 10.5 AU. The minimal value of the semimajor axis for the model particles after ten rotations is 2.7 AU. The conclusion that the particles with such orbits are present in the Pons–Winneckid stream indeed and can cross the Earth's orbit is supported by TV observations of this stream performed in Japan (Okamoto et al., 2005). For three Pons–Winneckid meteors registered in June 2004 at 23.47339, 23.50487, and 23.57530 UT, the following geocentric velocities and semimajor axes of the orbits are obtained: 13.3 km/s, 2.81 AU; 17.4 km/s, 10.02 AU; and 13.7 km/s, 2.98 AU.

The large scatter of the *D* values (Fig. 2) indicates that all of the modeled orbital elements are subjected to strong perturbation, since it is not the semimajor axes of the comet and the meteor particle, but rather the differences of their eccentricities, perihelion distances, and angular elements that enter formula (1) directly. Even if one determines the value of the upper limit of the *D* criterion by using the average orbit of the stream, for example, modeled in this case to the 1920 epoch, a value of 0.5 is obtained. Moreover, it is necessary to note that the meteoroid streams are mainly formed from several dust ejections in different epochs. In (Vaubaillon et al., 2005), the evolution of Pons–Winneckids ejected from the comet during each of its perihelion passages starting from 1714 is considered. Therefore, the real dispersion of the orbits in the stream is most likely higher than that which we obtained on the basis of modeling the stream in the interval of 50 years.

ANALYSIS OF THE *D* CRITERION FOR THE PERSEID SWARM

Let us analyze the values of the *D* criterion for the Perseid meteoroid stream related to the Neptune family. Earlier, modeling the Perseid formation was described in detail (Ishmukhametova, Kondrat'eva, 2005). Let us use the results of modeling the ejection of matter from the parent comet Swift–Tuttle in 1348 and consider only the retrograde ejection analogous to that performed above for the Pons–Winneckid stream. For modeling, the following elements of comet Swift–Tuttle were used (Marsden, 1995): a = 25.87025 AU; e = 0.9627980; Ω = 139.3714°; i = 113.5664°; ω = 152.7737°; and T = August 1862, 23.4229 UT (the angular elements are given to the 2000.0 epoch). The ejection of particles was modeled in the range of velocities of 300–2100 m/s in the points of the comet orbit with the true anomaly V being as follows: before perihelion, –90°, –60°, –30°; in perihelion, 0°; and after perihelion, +30°, +60°, and +90°.

The change of the *D* value calculated according to formula (1) depending on the ejection velocity of the hypothetical particles and the position of the ejection point on the comet orbit at their ejection from the nucleus are shown in Fig. 3. It is seen that the *D* value remains practically the same for the particles ejected at the different points of the orbit with the same velocity. The *D* value of 0.2 is achieved only for the particles ejected with velocities higher than 2000 m/s. Earlier, the authors studied the most likely range of the ejection velocities of Perseids being supposedly from 0 to 300 m/s (Ishmukhametova, Kondrat'eva, 2005). Even if it is assumed that the ejection velocity reaches 600 m/s (the maximal ejection velocity of dust according to the modern gas-dynamic ideas about the disintegration of the comet nucleus at its encounter with the Sun), at the moment of the ejection of Perseid model particles the upper limit of *D* does not exceed 0.075, independent of the ejection point on the orbit.

To study the changes of the *D* criterion due to the evolution of the stream, the orbital elements of the model particles ejected from the comet in 1348 were

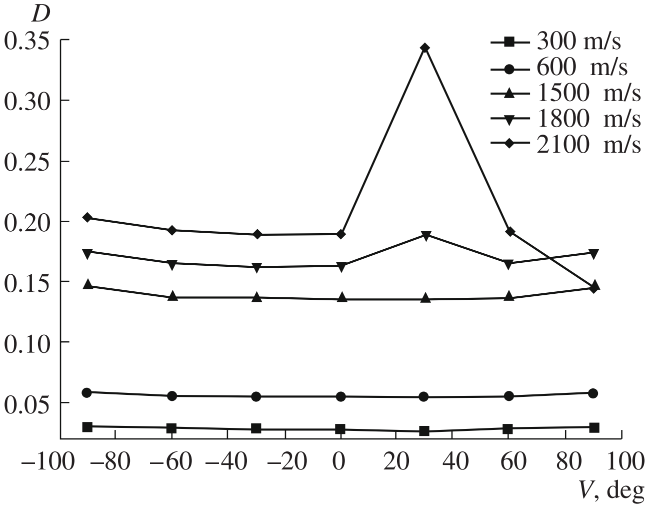

Fig. 3. The value of the *D* criterion for Perseids depending on the ejection velocity and the position of the ejection point on the orbit (the ejection of 1348).

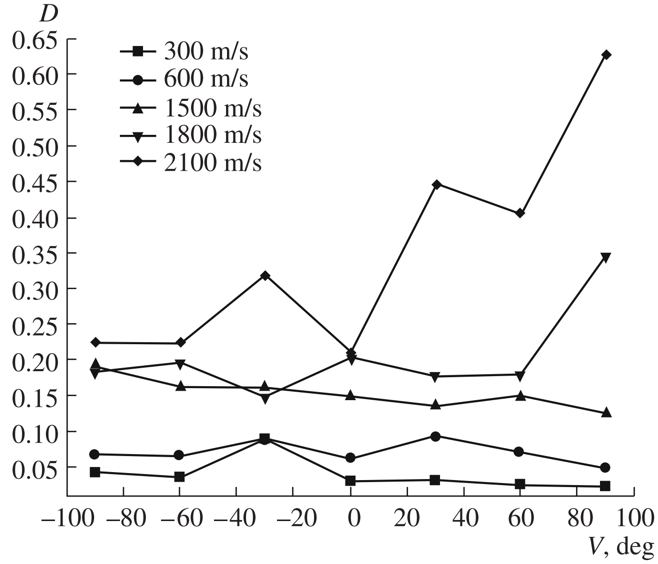

Fig. 4. The value of the *D* criterion for Perseids depending on the ejection velocity and the position of the ejection point on the orbit 500 years after the ejection.

integrated forward to 1862, taking into account the perturbation of all planets. The *D* values calculated from the orbital elements of the comet and the perturbed orbital elements of the model particles are shown in Fig. 4. The *D* value above 0.3 is provided by the perturbed orbit of the particle ejected with a velocity of 2100 m/s in the orbit point with a true anomaly of +30°. This is due to the encounter of the particle and Jupiter: a close one (a mutual distance of 0.27 AU) and two at the border of the sphere of its action. At the same ejection velocity but in the orbit point with a true anomaly of –30°, the main perturbation of the particle orbit is due to the Earth. There are a number of its close encounters with the Earth: in 1469, 1497, 1525, 1590, 1730, 1758, 1786, and 1842. During the encounter, the minimal mutual distance is 0.093 AU and the maximal is 0.16 AU. However, the changes of the *D* value are analyzed only for the range of the most likely ejection velocities up to 600 m/s; the *D* value does not exceed 0.11 (Fig. 4).

A feature of Perseids is the large scatter of the semimajor axes with respect to the semimajor axis of the orbit of the parent comet. The observational errors taken into account, the values of the semimajor axes of the orbits of the meteors observed are mostly likely in the interval of 10–35 AU (Ishmukhametova, Kondrat'eva, 2005). The *D* criterion is most often used to identify the meteoroids with this or that stream in order to further find the elements of its average orbit. Let us determine the average orbit of the Perseid stream from the data of the Czech TV catalogue of the meteor orbits (Koten et al., 2003) using the Southworth–Hawkins *D* criterion (1) with its upper limit of 0.11. The elements of the Perseid average orbit calculated in this manner are as follows (the 2000.0 epoch):

$$1/a = 0.083 \pm 0.053 \text{ AU}, \quad e = 0.921 \pm 0.149, \quad q = 0.952 \pm 0.0.010 \text{ AU}.$$

$$i = 112.8° \pm 0.6°, \quad \omega = 150.7° \pm 0.8°, \quad \pi = 291.1° \pm 0.8°$$

For the comparison, let us present the data on the Perseid average orbit given in (Betlem et al., 1997): according to the TV observation of the Nippon Meteor Society (NMS),

$$1/a = 0.055 \pm 0.019 \text{ AU}, \quad e = 0.948 \pm 0.018, \quad q = 0.947 \pm 0.002 \text{ AU},$$

$$i = 113.40° \pm 0.27°, \quad \omega = 151.5° \pm 0.5°, \quad \pi = 290.7° \pm 0.5°,$$

according to the photographic observations of the Dutch meteor Society (DMS)

$$1/a = 0.014 \pm 0.011 \text{ AU}, \quad e = 0.961 \pm 0.007, \quad q = 0.953 \pm 0.002 \text{ AU},$$

$$i = 113.22° \pm 0.19°, \quad \omega = 151.3° \pm 0.4°, \quad \pi = 291.9° \pm 0.5°.$$

The angular elements and the perihelion distances of all the above orbits agree well within the experimental error; however, the orbit sizes considerably differ by 12.05, 18.18 (NMS), and 74.1 AU (DMS), respectively. The average orbit of the stream we calculated from the catalogue data (Koten et al., 2003) was less elongated. The minimal value of the semimajor axis of the considering Perseid orbits was 7.1 AU and the minimal value was 35.0 AU. The same as for the NMS data (Betlem et al., 1997), in our version the value of the semimajor axis of the average orbit of the stream of 18.18 and 12.05 AU, respectively, was less than the value of the semimajor axis of the parent comet of 25.87 AU. In

(Oppolzer, 1867), (Sekanina, 1981), and (Fomenkova et al., 1995), it was shown that at the perihelion passage of comet Swift–Tuttle both in 1863 and 1992, the main ejection of the dust matter from the nucleus was in the direction perpendicular to the radius vector and opposite to that of the motion of the comet. At this ejection direction, the ejected particles move on orbits smaller than that of the parent comet. Therefore, the lower value of the semimajor axis of Perseids is quite understandable and probably characterizes the feature of the disintegration of the Swift–Tuttle comet.

CONCLUSIONS

The studies of the upper limit of the Southwirth–Hawkins *D* criterion for two meteoroid streams related to different planet groups showed that it is not possible to artificially transfer the same *D* value as the measure of the common origin of the two bodies to all meteoroid streams. The upper limit of the *D* criterion has to be studied individually for each meteoroid stream as its dynamic, evolutional characteristics.

For the Pons–Winneckid stream related to the Jupiter group, it is hardly correct to use the *D* criterion to determine the generality of the origin of the meteoroids or the meteoroids and the parent comet. In this case, the value of the upper limit of the criterion rather characterizes the velocity of the dispersion of particles in space. Small bodies of the comet–meteor complexes of the Jupiter group at each rotation around the Sun experience considerable perturbations. Meteoroids ejected from the comet during its different encounters with the Sun can have a considerable scatter of orbital elements already after several rotation periods. Thus, to identify the meteoroids belonging to the streams, comets, or asteroids of the Jupiter group and most dangerous from the point of view of their falling on the Earth, it is necessary to use other methods of the determination of the genetic generality of the small bodies.

As to the meteoroid streams with orbit sizes reaching the vicinity of Neptune, for example, Perseids, in this case the Southworth–Hawkins *D* criterion could be used. However, in this planet group the small bodies depending on the orientation of their orbits with respect to the ecliptic experience different perturbations from the planets as well. Therefore, to determine the generality of the small bodies or the average orbits of the meteoroid streams, it is necessary to study the usage of the *D* criterion for each of them and to justify the value of its upper limit.

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