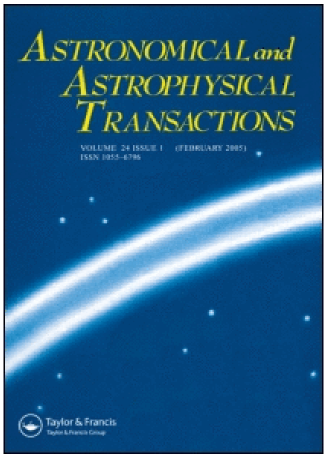

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Disintegration of small bodies and evolution of meteoroid complexes

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Disintegration of small bodies and evolution of meteoroid complexes

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The application of the Southworth–Hawkins, the Drummond, and the Jopek generality criteria has been studied on the basis of the probability–statistical simulation of the disintegration of comets Halley, Temple–Tuttle, Giacobini–Zinner and Pons–Winnecke to establish generality in the origin of isolated meteoroid bodies. The validity and the threshold criteria values for the cometary fragments under consideration are determined.

Keywords: Meteoroid complexes; Comets; Criterions of generality; Probability–statistical simulation

A considerable body of available data on celestial objects entering the Earth's atmosphere, falling on its surface or passing near the sphere of its action has widened our knowledge of the population of the Solar System with small bodies and of the processes influencing the qualitative and quantitative compositions of these objects. The catalogues of meteor, bolide, asteroid and comet orbits are not a collection of characteristics of the isolated objects observed and do not allow researchers to come to unambigous conclusions about the origin and dynamics of the whole class of small bodies and isolated objects (*e.g.* comets, asteroids and meteoroids) and also their expected interconnection.

In the age of space exploration the problem of small bodies in the Solar System seems to be poorly studied and hardly resolved. The available space techniques greatly increase the annual number of newly discovered objects but only records the very fact of their existence and nothing else. On the other hand, space research gives an idea of the complex structure of the Solar System which is populated with natural small bodies and the continuous formation of the interplanetary complex of small bodies.

The reviewed data published in 1996–2003 in this field of science allow some general statements to be formulated.

(i) Most observational data obtained during this period and referred to different classes of celestial bodies are not systematized at all or are only systematized according to one or

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two parameters, for example the time of appearance, the period of observations, and the radiant.

- (ii) There is an increasing number of observed large objects (bolides and large meteoroids), the relation of which with the organizational space structure (comets, asteroids and meteor streams) is difficult to identify.
- (iii) The amount of data confirming the relationship between catastrophic phenomena on the Earth and space factors in the distant past ($1.4 \times 10^9 - 3 \times 10^6$ years) as well as recently from a geological viewpoint (about 2800–3000 years ago) is increasing. Similar data, although on a smaller scale, are found at present. Comets are assumed to be responsible for more than half the terrestrial craters exceeding 10 km in diameter.
- (iv) The numbers of cometary brightness bursts are recorded at great heliocentric distances (more than 2–2.5 AU), which do not fall within the scope of the widespread model of an increase in comet activity on their approach to the Sun.
- (v) Observational data of known meteor streams obtained in 1996–2001 may change our knowledge of the build-up and dynamics of these formations; the Perseids, the Draconids, the Leonids and the α-Capricornids give new peaks in observational data, and new branches in streams; the occurrence of new parent comets is assumed.
- (vi) So far there has been good reasons for supposing that asteroids are dead comets and the number of large bodies observed during meteor streams increases continuously; it is expedient to consider comets as primary sources of an asteroid–meteoroid complex in space.

Recently, a great volume of information has been published about a series of small bodies observed for long periods of time; this information allows a stochastic simulation to be carried out on the basis of more or less reliable (from the viewpoint of human knowledge) input data. First of all, simulation is realized for such objects as comets Halley, Giacobini–Zinner, Tempel–Tuttle and Pons–Winnecke. Simulation is carried out by stochastic methods as substance ejection processes are considered to be stochastic if initial conditions of ejection are unknown *a priori*. A meteoroid stream or an association is formed as a result of this ejection. Orbital similarity is a criterion to establish the genetic relationship between meteoroid formation and the assumed parent body. Theoretical development in combination with computer simulation and a greal deal of observational data allow not only qualitative but also quantitative characteristics to be obtained when considering celestial objects.

It is these objects that were chosen for computer simulation of nuclei disintegration for all known comet appearances in order to study the expected formation of meteoroid complexes and their subsequent evolution, to establish a genetic relationship with certain known meteor streams and showers and to determine the space region of expected encounters with disintegration fragments. Simulation algorithms have been presented by the present author [1] and by the present author together with co-workers [2]. In these cases the process of disintegration is considered as an isotropic ejection of a solid cometary nucleus component at any orbital point of the body studied. Simulation results give both the deviations of orbital ejection fragment elements from the parent-body orbit and the values of the Keplerian orbital elements of ejected fragments. Results of probability–statistical simulation based on the algorithm presented [1] can be supplemented with the data obtained in stochastic simulation by a probability chart method [2]. Two types of chart are plotted according to this method. The first type of probability chart represents statistical images of the Keplerian orbital elements of ejected fragments. This type of chart accumulates information on the dynamics of trajectory orbits in time. In the aggregate, these orbits occupy some space volume in the form of a ‘torus’ or a ‘beam’.

The second type of probability chart is fixed to the reference (parent) orbit and plotted perpendicular to it. This type describes the structure of ‘torus volume’ cross-sections.

Cross-sections represent an unlimited plane area oriented in a three-dimensional space where the crossover points of simulated orbits with this plane are projected to.

As calculations showed, the shape of curves are similar for all orbital elements of ejected fragments determined by two methods. The results obtained allow the main tendencies in the variations of ejected fragment orbits to be established and a general pattern of space filling with studied disintegration products to be developed within the calculated time interval; these confirm the expected relationship between the considered comets and known meteoroid complexes, that is the Leonids, the Draconids, the Orionids and η-Aquarids. The established thin structure of the meteoroid complexes formed is one of the factors essential to safe flights during long-term spacecraft missions.

The most accurate values of orbital elements for all known comet appearances and observations were chosen to simulate substance eruption from cometary nuclei at any orbital point. The data on comet Halley includes 26 appearances from 1404 to 1986 [3], those on comet Giacobini–Zinner 11 appearances from 1910 to 1985 [4], those on comet Tempel–Tuttle ten appearances from 1533 to 1899 [5] and those on comet Pons–Winnecke 19 appearances from 1819 to 1983 [6].

Figure 1 presents the meteoroid situation formed by expected meteoroid complexes of the above four comets during their life cycles. The rates of cometary nucleus disintegration in this case are taken within the limits at which ejected substance particles acquire motion rates corresponding to the meteor streams (Leonids, η-Aquarids, Orinods, Draconids and Pons–Winneckids) referrring to these comets. As a rule, studies of the meteoroid stream structure are based on observations. These data are obtained by radar, television, photographic and visual methods. As each method is informative by degree and its own observational errors, none can be accepted as universal [7].

The available database contains about 62 000 meteors found by radar and about 6000 meteors discovered by photographic and television methods. The accuracy of heliocentric and geocentric paratemers of radar meteors is much lower than that of photographic meteors. The Harvard database includes 865 accurate orbits.

A meteor stream can be determined in terms of geocentric or heliocentric parameters; however, here the degree of meteor orbit closeness is essential. A quantitative degree of generality was first formulated by Southworth and Hawkins [8] by analogy with the orthogonal coordinate system in five-dimensional space, where each heliocentric orbital element is taken as an ordinate. In this case a meteoroid orbit is presented as a point and the distance between two points is considered as the degree of generality between two meteoroid orbits. This method is known as the D criterion; when two bodies are under investigation it is expressed by

$$D_k^2 = (e_2 - e_1)^2 + (q_2 - q_1)^2 + \left[2\sin\left(\frac{I}{2}\right)\right]^2 + \left[\frac{e_2 + e_1}{2}\right]^2 \left[2\sin\left(\frac{\Pi}{2}\right)\right]^2, \qquad (1)$$

where

$$\left[2\sin\left(\frac{I}{2}\right)\right]^2 = \left[2\sin\left(\frac{i_2 - i_1}{2}\right)\right]^2 + \sin i_1 \sin i_2 \left[2\sin\left(\frac{\Omega_2 - \Omega_1}{2}\right)\right]^2$$

and

$$\Pi = \omega_2 - \omega_1 \pm 2\arcsin\left[\cos\left(\frac{i_2 + i_1}{2}\right)\sin\left(\frac{\Omega_2 - \Omega_1}{2}\right)\sec\left(\frac{I}{2}\right)\right].$$

The minus sign is used when $|\Omega_2 - \Omega_1)| > 180°$. For small inclination values,

$$\Pi = (\Omega_1 + \omega_1) - (\Omega_2 + \omega_2).$$

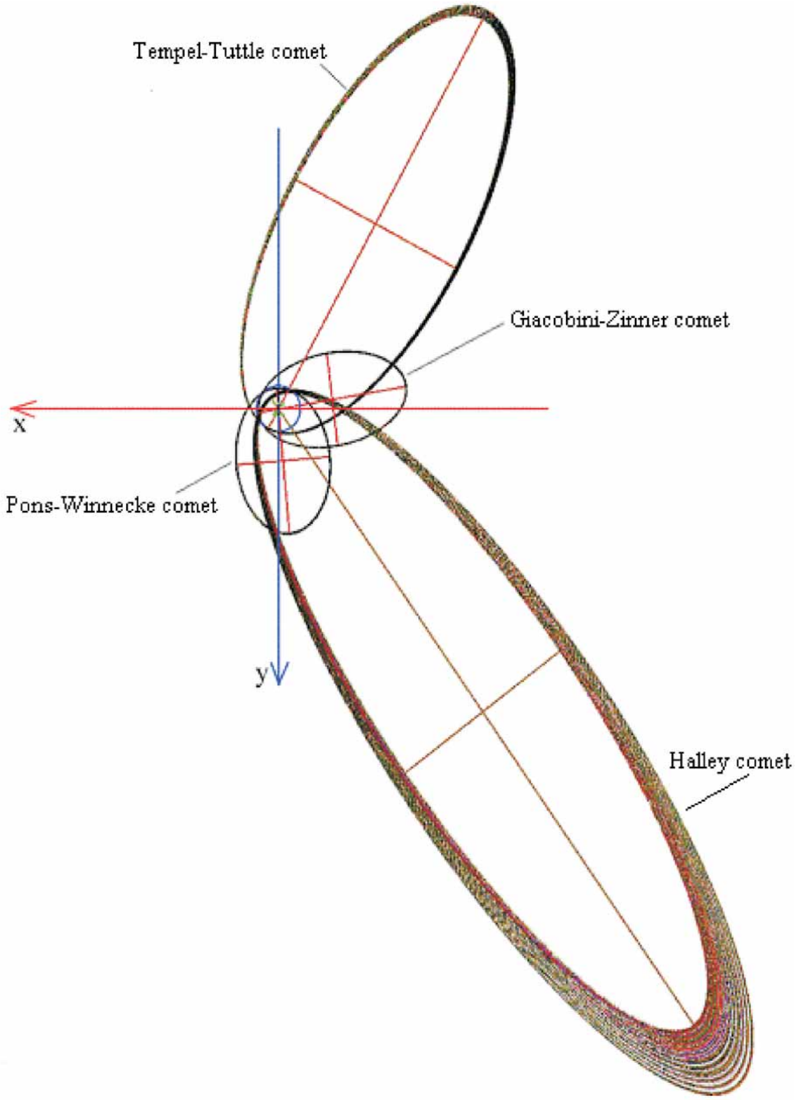

Figure 1. Space situation formed by the expected complexes of the above comets.

e, q, ω, i and Ω are the Keplerian orbital elements. It is accepted that the threshold D_{k}^{n} value for orbit generality is

$$D_{\mathrm{k}}^{n} = 0.2\left(\frac{360}{N}\right)^{1/4},$$

where N is the data sample size.

A modified version D' [9] was suggested later:

$$(D')^2 = \frac{(e_2 - e_1)^2}{(e_2 + e_1)^2} + \frac{(q_2 - q_1)^2}{(q_2 + q_1)^2} + \left(\frac{\Psi}{180^\circ}\right)^2 + \left(\frac{e_2 + e_1}{2}\,\frac{\theta}{180^\circ}\right)^2, \tag{2}$$

where

$$\begin{aligned}\Psi &= \arccos[\cos i_1 \cos i_2 + \sin i_1 \sin i_2 \cos(\Omega_1 - \Omega_2)],\\ \theta &= \arccos[\sin \phi_1 \sin \phi_2 + \cos \phi_1 \cos \phi_2 \cos(\xi_1 - \xi_2)],\\ \phi &= \arcsin(\sin i \sin \omega),\\ \xi &= \begin{cases} \Omega + \arctan(\cos i \tan \omega) & \text{for } 90^\circ > \omega > 270^\circ \\ 180^\circ & \text{for } 90^\circ < \omega < 270^\circ. \end{cases}\end{aligned}$$

In 1987, when considering this criterion [10], however, concluded that it is not completely satisfactory. A high sensitivity to variations in perihelion distance is observed at small q values and variations in the angle of inclination at high values are poorly demonstrated.

It has been shown [11] that functions (1) and (2) are not equivalent. As a result of numerical analysis of the properties of D_{k} and D' an alternative hybride function was suggested:

$$(D''_{\mathrm{J}})^2 = (e_1 - e_2)^2 + \frac{(q_1 - q_2)^2}{(q_1 + q_2)^2} + \left[2 \sin\left(\frac{I}{2}\right)\right]^2 + \left(\frac{e_2 + e_1}{2}\right)^2 \left[2 \sin\left(\frac{\Pi}{2}\right)\right]^2, \qquad (3)$$

where

$$\left[2 \sin\left(\frac{I}{2}\right)\right]^2 = \left[2 \sin\left(\frac{i_2 - i_1}{2}\right)\right]^2 + \sin i_1 \sin i_2 \left[2 \sin\left(\frac{\Omega_2 - \Omega_1}{2}\right)\right]^2$$

and

$$\Pi = \omega_2 - \omega_1 \pm 2 \arcsin\left[\cos\left(\frac{i_2 + i_1}{2}\right) \sin\left(\frac{\Omega_2 - \Omega_1}{2}\right) \sec\left(\frac{I}{2}\right)\right].$$

Equations (2) and (3) are modified functions where the relative weights of different orbital elements have been varied relative to D_{k}. All D functions based on osculating elements, however, possess certain limitations as meteoroid bodies (substance ejection fragments from cometary nuclei?) undergo different disturbances and their orbital elements can vary greatly as a result of long-term secular disturbances (during about 10^4 years). Another approach to assessing the generality of two bodies has been reported by Kholshevnikov and Greb [12]. Unfortunately, the presented algorithms are rather complex and not always suitable.

Recently, a new approach to establishing the generality of meteoroid orbits was suggested [13]. It is based on the geocentric parameters of studied meteors, and the D function is described taking into account the weight factors which can be accepted to be equal to one or estimated on the basis of information about the stream background and dispersion. It is noted that attempts (undertaken from 1963 to 2004) to develop a classic method for determining the generality of meteors and establishing their identity with respect to a particular meteoroid formation with the specific parent body have not been successful in data processing. Under these conditions the presence of a simulated meteoroid complex with its characteristics may serve as the basis on which observational data are superimposed in order to clarify or to determine the genetic relationship of the objects under consideration.

When studying the problem of the identity of an individual object with respect to all the meteoroid bodies the present author stated the following problem: the boundary values for the above criteria and the temporal and space evolution for ejected fragments formed by meteoroid complexes in the parent-body disintegration should be determined. Such calculations have been performed for the whole life period of comets Halley, Giacobini–Zinner, Tempel–Tuttle and Pons–Winnecke. Let us present the calculation parameters and some results obtained for the expected meteoroid complexes to establish the generality with the η-Aquarids, Orionids, Draconids, Orto- and Klino-Leonids, and Pons–Winnickeds.

Firstly, figure 2 shows the D_k curves [8] depending on the ejection rates at different points of the true anomaly. The orbit of comet Halley in 1986 is taken as a reference. If the threshold value of 0.2 is taken for this generality criterion [11], the maximum rate of fragment ejection from the cometary nucleus will be about 150 m s^{-1} at true anomaly points up to 90°. According to the observed ejection phenomena in a cometary nucleus the rate of disintegration is estimated as 400–500 m s^{-1}. D gradually decreases up to $U = 160°$ as the distance from the perihelion increases and then D begins to increase near the aphelion. As ejections near the aphelion are referred to as improbable phenomena, the behaviour of the generality criteria curves in this region should be considered only as theoretically possible. Figure 3 presents D curves [8] within the time interval right from the start of our era until 1986. It should be noted that the shapes of the curves do not change with time; only small variations in values are noted near perihelion for different periods of comet appearances. Table 1 shows three generality criteria determined from simulated ejections in the cometary nucleus at rates of 150 m s^{-1} at any

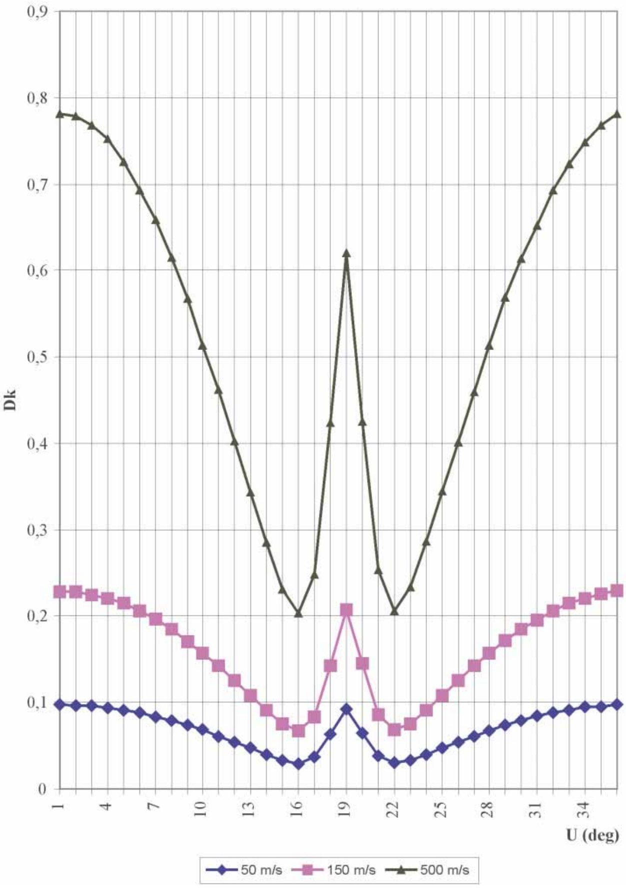

Figure 2. D_k values (comet particle) depending on the ejection rate at different points of the true anomaly of a parent orbit for comet Halley in 1986.

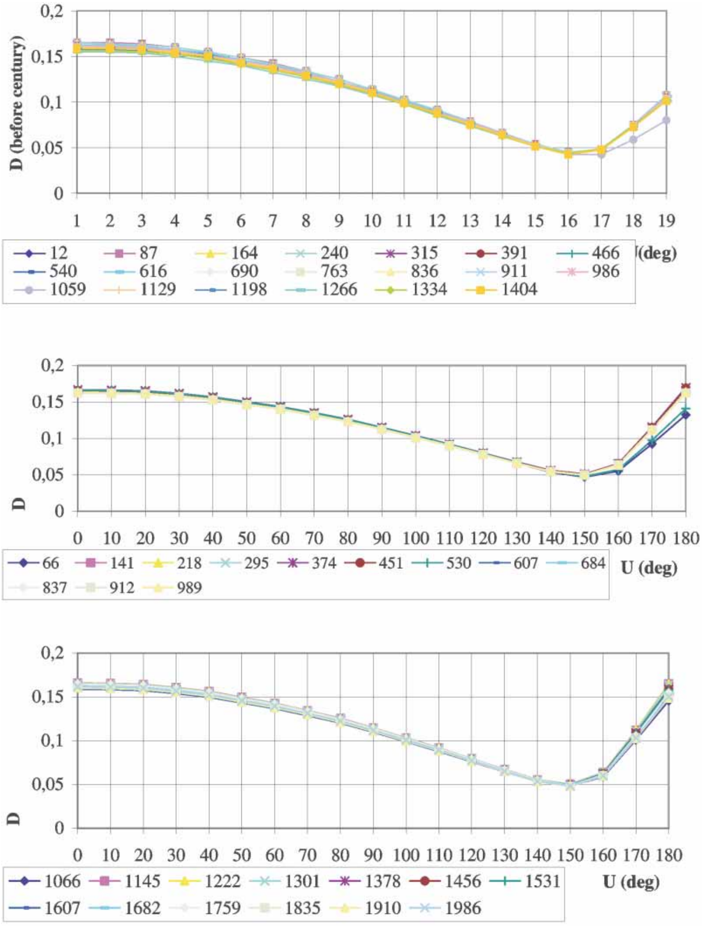

Figure 3. Curves of the D values for the whole lifetime of comet Halley. The rate of disintegration is $100\,\mathrm{m\,s^{-1}}$.

orbital point with the true anomaly point 0–180° for the comet appearance in 1986. Criterion values calculated from Drummond's formula and Jopek's formula differ in the fourth decimal place only; however, the D-criterion values are 1.3 times higher but the forms of the curves for all three criteria are similar (figure 4).

Secondly, table 2 presents three generality criteria for the ejection fragments from comet Tempel–Tuttle on its appearance in 1899 at ejection rates of 5 and $0.25\,\mathrm{m\,s^{-1}}$ at the true anomaly points 0–180°. Ejection rates not exceeding $25\,\mathrm{m\,s^{-1}}$ may correspond to the Orto-Leonids [1]. The above tendencies remain valid; that is the values of the Drummond criterion and the Jopek criterion almost coincide and the values of D are almost twice those of D' and D''. The D values for the appearance of comet Tempel–Tuttle in 1733 at different ejection rates within the range $U \in$ 0–180° are shown in figure 5. The presented rate range is most possible for the Tempel–Tuttle meteoroid complex causing the Leonids. It is seen that at such ejection rates the calculated generality criteria differ greatly from the threshold value of 0.2. Figure 6 illustrates the shapes of the D_{k}, D′ and D″ curves at simulated substance ejection rates of 2.5 for all recorded appearances of this comet from 1533 to 1899. The extreme compactness of the curves considered for D and the rather small displacements of the D' and D'' curves near the true anomaly 0–90° are to be noted.

Table 1. Generality criteria values for the Halley meteoroid complex in 1986 at disintegration rates of 150 m s^{-1}.

True anomaly (deg)	D (Southworth–Hawkins)	D' (Drummond)	D'' (Jopek)
0	0.228 840 987	0.163 080 642	0.163 153 448
10	0.228 760 418	0.163 032 094	0.163 104 289
20	0.224 790 189	0.160 655 584	0.160 725 51
30	0.220 384 977	0.158 002 37	0.158 069 489
40	0.214 525 141	0.154 446 863	0.154 510 366
50	0.206 019 086	0.149 231 605	0.149 289 958
60	0.196 189 562	0.143 123 304	0.143 175 567
70	0.185 334 45	0.136 272 89	0.136 317 801
80	0.170 696 768	0.126 856 326	0.126 890 705
90	0.156 806 643	0.117 719 654	0.117 741 868
100	0.142 101 698	0.107 819 663	0.107 826 118
110	0.125 010 54	0.095 992 467	0.095 974 5
120	0.108 176 604	0.083 926 963	0.083 870 777
130	0.091 112 22	0.071 072 994	0.070 944 687
140	0.074 996 916	0.057 555 442	0.057 253 939
150	0.067 022 392	0.046 616 769	0.045 811 233
160	0.083 106 207	0.045 350 257	0.042 736 271
170	0.142 453	0.064 565 553	0.056 132 823
180	0.207 036 839	0.091 899 391	0.075 311 867

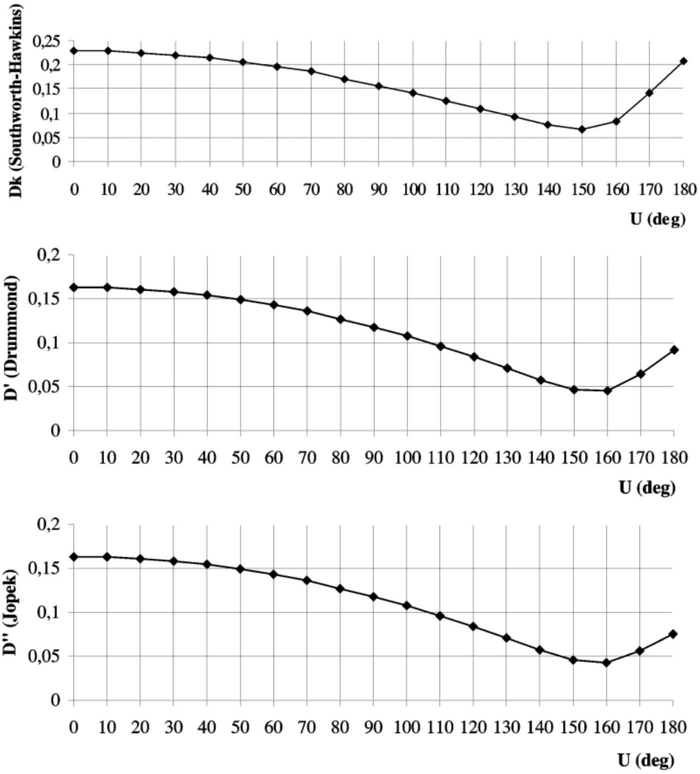

Figure 4. Generality criteria values for Halley meteoroid fragments in 1986 at disintegration rates up to 150 m s^{-1}. U(deg) are the disintegration points from the true anomaly.

Table 2. Values of three generality criteria for Tempel–Tuttle meteoroid fragments in 1899. The ejection rates are 5 and 0.25 m s^{-1}.

True anomaly (deg)	D (Southworth–Hawkins)	D' (Drummond)	D'' (Jopek)
0	0.006 891 3	0.003 530 85	0.003 541
10	0.006 843 6	0.003 506 48	0.003 517
20	0.006 789 9	0.003 479 06	0.003 489
30	0.006 654	0.003 409 74	0.003 42
40	0.006 463 7	0.003 312 57	0.003 322
50	0.006 271 8	0.003 214 66	0.003 224
60	0.005 921 4	0.003 035 69	0.003 044
70	0.005 610 6	0.002 876 99	0.002 885
80	0.005 213 7	0.002 674 14	0.002 681
90	0.004 785 2	0.002 455 12	0.002 461
100	0.004 295 9	0.002 204 74	0.002 21
110	0.003 805 5	0.001 953 52	0.001 958
120	0.003 272 3	0.001 679 51	0.001 682
130	0.002 773 2	0.001 420 87	0.001 422
140	0.002 392 2	0.001 216 8	0.001 212
150	0.002 329 3	0.001 163 04	0.001 146
160	0.002 761 1	0.001 345 56	0.001 305
170	0.003 553 7	0.001 699 62	0.001 626
180	0.004 133 8	0.001 968 43	0.001 88
Ejection rate, 0.25 m s^{-1}			
0	0.000 345	0.000 179 1	0.000 18
10	0.000 342	0.000 177 9	0.000 178
20	0.000 34	0.000 176 5	0.000 177
30	0.000 333	0.000 173	0.000 173
40	0.000 323	0.000 168	0.000 169
50	0.000 314	0.000 163 1	0.000 164
60	0.000 296	0.000 154	0.000 154
70	0.000 281	0.000 145 9	0.000 146
80	0.000 261	0.000 135 6	0.000 136
90	0.000 24	0.000 124 5	0.000 125
100	0.000 215	0.000 111 8	0.000 112
110	0.000 191	9.908×10^{-5}	9.93×10^{-5}
120	0.000 164	8.516×10^{-5}	8.53×10^{-5}
130	0.000 139	7.2×10^{-5}	7.21×10^{-5}
140	0.000 12	6.153×10^{-5}	6.13×10^{-5}
150	0.000 116	5.864×10^{-5}	5.78×10^{-5}
160	0.000 138	6.783×10^{-5}	6.58×10^{-5}
170	0.000 178	8.598×10^{-5}	8.23×10^{-5}
180	0.000 208	9.991×10^{-5}	9.54×10^{-5}

Thirdly, table 3 presents three criteria for the meteoroid complex of comet Giacobini–Zinner in all its known appearances. The substance ejection rate on disintegration is 50 m s^{-1} (the upper limit for the identity of ejected meteoroids to the Draconids); the ejection point is the perihelion. The difference between D' and D'' criteria is insignificant, but the D values are twofold higher. The almost complete stability of the Drummond criterion and the Jopek criterion for the whole observational period is peculiar to this comet. A slight tendency for D to increase is noted between 1900 and 1985. Figure 7 shows the shapes of the curves for the three criteria as functions of the true anomaly of the ejection point for the comet appearances in 1913, 1933 and 1985. In all three appearances the D' and D'' curves merge. The D values for 1933 are somewhat higher than for 1913 and 1985 within the whole range of $U \in 0$–$360°$. The numerical value of all three criteria, however, is an order of magnitude lower than the threshold value of 0.2; that is, to reach such values, the disintegration rate should greatly

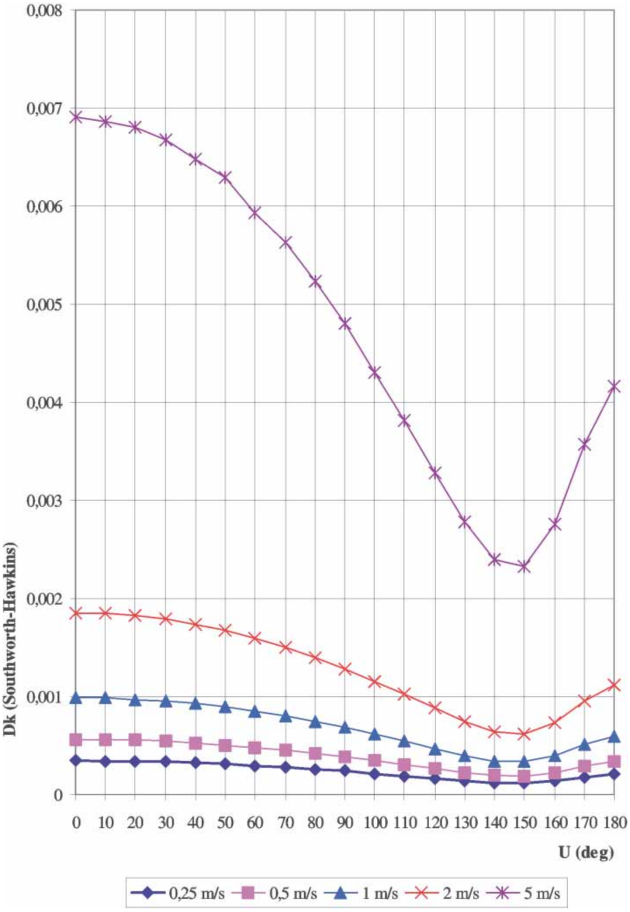

Figure 5. D values for the appearance of comet Tempel–Tuttle in 1733 at different disintegration rates at the true anomaly points from 0 to 180°.

exceed $50\,\mathrm{m\,s^{-1}}$ and should be equal to $5000\,\mathrm{m\,s^{-1}}$ or more. In this case the ejected fragments can hardly be elements of the Draconids.

Fourthly, Similar calculated results for comet Pons–Winnecke are given in figure 8. The substance ejection rate is $50\,\mathrm{m\,s^{-1}}$; the point of ejection is the perihelion. In this case the D' and D'' values are similar for the whole life of this comet; however, there is a tendency for these values to decrease in the whole observational period from 1819 to 1983. The coefficient of decrease is 1.175 for D' and 1.166 for D''. The curve of the D values is upward with a coefficient of increase of 1.335 from 1819 to 1983. Figure 9 shows the variations in the three criteria values as functions of the true anomaly of the ejection point for the three appearances of comet Pons–Winnecke in 1819, 1921 and 1983. The numerical values of D, D' and D'' increase about 1.6-fold with increase in the ejection rates to $100\,\mathrm{m\,s^{-1}}$; however, they are much lower than the threshold value. To reach this value in case of D the ejection rates should increase to $600\,\mathrm{m\,s^{-1}}$ and $500\,\mathrm{m\,s^{-1}}$ for the comet appearances in 1819 and 1983 respectively, that is, in the whole observational period the substance ejection rate tends to decrease and this can be considered as a reduction in comet activity.

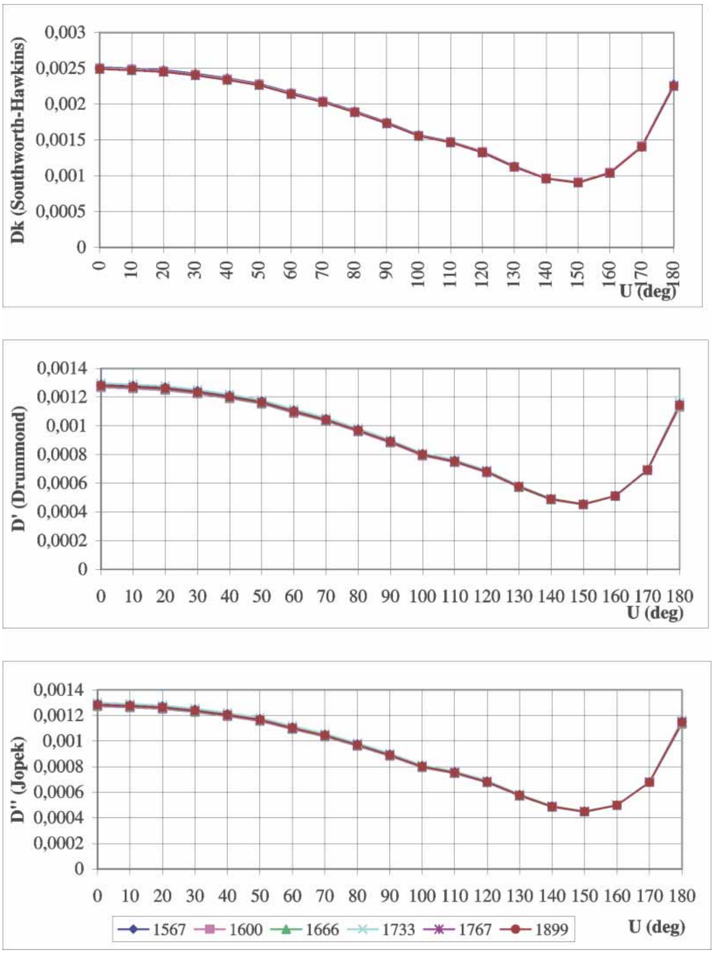

Figure 6. Curves of the generality criteria D, D' and D'' for all recorded appearances of comet Tempel–Tuttle. The rate of disintegration is 2.5 m s^{-1}.

Table 3. Generality criteria values for the Giacobini–Zinner meteoroid complex for all known comet appearances.

Year	D_k (Southworth–Hawkins)	D' (Drummond)	D'' (Jopek)
1900	0.021 778	0.011 638 1	0.011 835
1913	0.022 371	0.011 434 6	0.011 637
1926	0.022 656	0.011 386	0.011 591
1933	0.022 765	0.011 377 4	0.011 583
1940	0.022 694	0.011 384 3	0.011 589
1972	0.022 502	0.011 308 7	0.011 514
1979	0.022 535	0.011 303 2	0.011 508
1985	0.023 008	0.011 197 8	0.011 407

It is also clear that the behaviour of the D' and D'' curves within $U \in$ 0–360° for this comet differ from those of other comets, for example comet Giacobini–Zinner. The Drummond criterion curve corresponding to 1819 within $U \in$ 0–360° lies above the two other curves and for the Jopek criterion this tendency is observed only within $U \in$ 0–130°] and $U \in$ 230–360°.

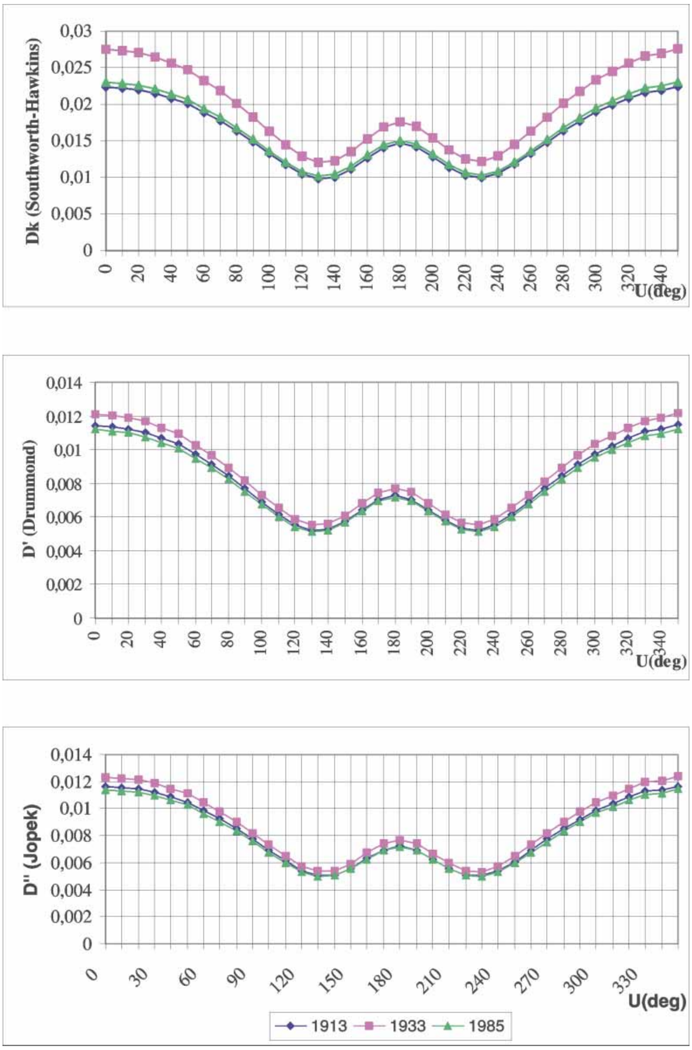

Figure 7. Variations in the three generality criteria as functions of the true anomaly of the substance ejection point for comet Giacobini–Zinner.

All three curves coincide within $U \in 140–220°$. This means that these criteria give ambiguous results for the same objects under similar conditions.

Therefore the following conclusions can be drawn.

(i) Equations (1) and (2) are really not equivalent.
(ii) Equations (2) and (3) give almost similar results.
(iii) The generality criterion values calculated from the Southworth–Hawkins equations are about 1.5–2 times higher than those obtained using the Drummond formula and the Jopek formula.
(iv) In all calculated cases the boundary values of the generality criteria are very low. The obtained values should be increased by an order of magnitude or more to reach the accepted boundary value of the generality criterion.

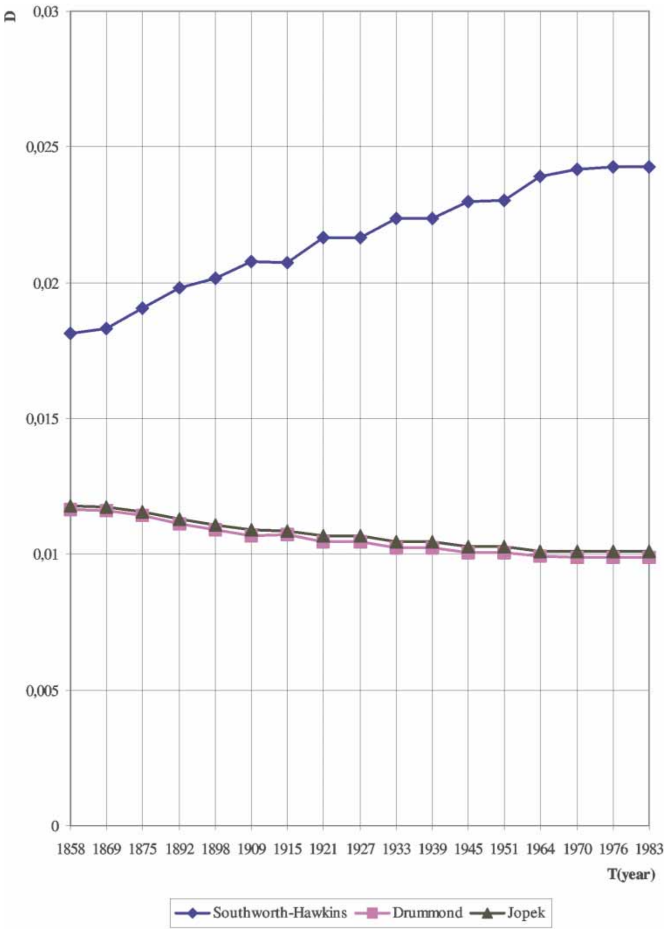

Figure 8. Variations in the generality criteria values for the Pons–Winnecke meteoroid complex for the whole comet lifetime (substance ejection rate, 50 ms^{-1}; $U = \mathbf{C}^{\circ}$).

(v) To reach the boundary generality criterion value calculated from simulation results of cometary nucleus disintegration, much higher ejection rates should be proposed in comparison with those taken in every concrete case.

(vi) Assumptions on the high rates of parent body disintegration call for; firstly, an investigation of the substance eruption mechanism different from the generally recognized process of solid component removal by gas fluxes due to nucleus surface heating as a comet approaches the Sun and/or, secondly, determination of the factors influencing the orbit evolution of ejected fragments which move in space in their own orbits independently of the parent body, form meteor streams and are connected with their parent body only genetically.

In conclusion, there is not yet an accurate and reliable method for data processing which excludes inaccuracies in observations, instrument errors and imperfect processing algorithms. In the present author's opinion this problem can be solved from two different approaches.

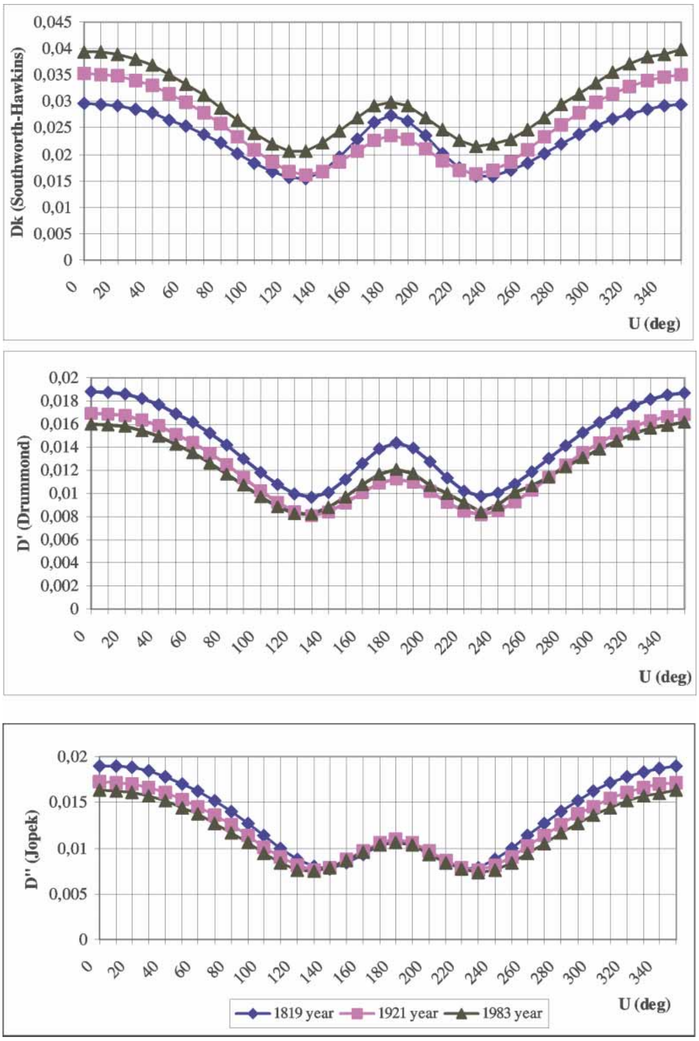

Figure 9. Variations in the three generality criteria as functions of the true anomaly of the substance ejection point for all Pons–Winnecke appearances in 1819, 1921 and 1983.

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