On the ejection and dispersion velocities of meteor particles

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Received: March 16, 1992

Abstract. This paper is a reaction to the attempts to determine the ejection velocities of meteor particles from cometary nuclei using the statistics of photographic meteor orbits. It is argued that this is essentially impossible. The original dispersion velocities are masked completely by much larger measuring errors, and for all permanent meteor showers also by the accumulated effects of planetary perturbations. The perturbations, appearing after a sufficient spread of the particles along the orbit, are on the average about 25-times more effective in the direction perpendicular to the orbital plane than in the direction of motion, and they are about 50-times more effective for typical comets of Jupiter family than for those of Halley type. The latter disproportion is responsible for the widely different distribution of the revolution periods of comets, annual meteor showers, and temporary meteor storms. In addition to direct spacecraft measurements, the only feasible sources of information on the ejection velocities are meteor storms, like the Draconids or Leonids, appearing only several times per century, and the cometary dust trails discovered by IRAS. Both of them indiciate incomparably lower velocities than the meteor data - only a few meters per second - and a substantial role of the solar radiation pressure in the initial dispersion.

Key words: comets - meteors

1. Introduction

The dispersion of orbits within meteor streams bears signatures of the ejection velocities of their members from their parent objects. However, these original velocities are masked by a number of overlapping effects:

A. The differential effect of the solar radiation pressure, appearing immediately after the separation of the particle and depending on its size, shape, and bulk density.

Contrib. Astron. Obs. Skalnaté Pleso **22**, (1992), 123- 130.

B. The differential effect of planetary perturbations, appearing after a sufficient spread of the particles along the orbit, and increasing substantially after each encounter with a major planet.

C. The Poynting-Robertson and Yarkovsky-Radzievsky effects, appearing until in later phases of evolution, and also depending on the physical properties of individual particles.

D. The deceleration by the atmospheric resistance, appearing shortly before the meteor becomes observable, and increasing afterwards. This can be only approximately extrapolated from the decelerating trend along the recorded trajectory.

E. The errors in the determination of the velocity and direction of motion in the atmosphere, introduced by the short duration of meteor phenomena and limited accuracy of positional measurements. Even the best of them are made with instruments of short focal length and limited resolution. The measured segments are not clearly separated due to the wakes; the object may consist of a number of separate fragments; and sometimes there is also a significant uncertainty in timing.

For the widely dispersed annual meteor showers, point **B** is a definite obstacle; and for all meteor showers also point **E**. The uncertainties resulting from them are, as a rule, two to three orders of magnitude larger than the real ejection velocities, making their discrimination by direct velocity measurements hopeless.

2. The accuracy of velocity measurements

In his recent paper, Pittich (1991) estimates the ejection velocities at 0.3 to 2.0 km/s, using the published photographic double-station meteor orbits, but without taking into account any of the disturbing effects mentioned above. He also refers to similar results by Kresák and Porubčan (1970), but this is a clear misunderstanding. That paper uses photographic meteor data, in particular the dispersion of individual radiant points, to estimate the current relative velocities within the evolved meteor streams, without searching for any relation to the original ejection velocities from the parent comets. A long process of dynamical evolution can indeed increase the relative velocities up to $>$ 10 km/s (see the Taurids or δ Aquarids), and make them easily discernible.

Pittich (1991) uses only the dispersion of the velocity component along the orbit, basing on the computed values of the binding energy $1/a$. The relation between $1/a$ and the heliocentric velocity V_H at the precisely known heliocentric distance r is unambigously defined by the energy integral $V_H = V_0(2/r - 1/a)^{1/2}$, when the solar radiation pressure is neglected. The determination of V_H from meteor observations, however, is a stepwise process: from the measured atmospheric velocity V through the velocity of entry V_∞ (adding the loss by progressive deceleration) and the unperturbed geocentric velocity

V_G (subtracting the acceleration by the Earth's attraction), to the vectorial decomposition of V_G into the heliocentric velocity of the Earth V_T and that of the meteoroid V_H. Each of these steps tends to increase the inaccuracy of the starting data. At the end the error of V_H can easily exceed 1 km/s, which corresponds to about 0.08 - 0.09 AU^{-1} in $1/a$. For the comets of Halley type such large positive errors transfer the orbit over the parabolic limit.

The resulting hyperbolicity cannot be attributed at all to the ejection velocity. In that case the backward extrapolation of the meteor orbit would have to cross exactly the orbit of the parent comet and, moreover, both would have to pass through this crossing point at the same time. For the annual showers this is evidently out of question. The only alternative is a close accelerating encounter with a major planet after the last aphelion passage. This is not only irreconcilable with the annual reappearance of such objects, but also extremely improbable from the statistical point of view - and for almost all of the major showers impossible due to the location of their nodes. Such a process can accelerate only very rare meteor particles approaching the Earth from inside its orbit (members of daytime showers), because they have to encounter the perturbing planet before the perihelion passage and the Earth afterwards, within the same revolution.

For the annual meteor showers produced by parent objects with shorter revolution periods, like the Taurids or Geminids, the situation is a little different. Their binding energies $1/a$ are so high that the errors do not reflect in a spurious hyperbolicity as an unambiguous evidence of their presence. At the same time, the differences in V_H are much less representative than the dispersion of nodes and radiant points. The complex structure of the stream associated with P/Encke (see, e.g., Porubčan and Štohl 1987), and considerable minimum distances of the meteoroid orbits from that of their parent comet, make it clear that there must be also significant differences in V_H tied with the past dynamical evolution. Contrary to the comets of Halley type, the main factor smearing out all traces of the original ejection velocities is the influence of planetary perturbations, rather than the inaccuracy of the velocity measurements.

The mean errors and dispersions of V_H are different for different orbit catalogues and meteor showers; for more details see Kresáková (1974) and Porubčan (1978). Another insight into this problem is presented by Table 1. It lists for eight major showers the names and revolution periods P (in years) of their parent objects. The next columns give the following quantities, all in km/s: the difference between the parabolic velocity and the heliocentric velocity of the parent object at $r = 1$ AU, i.e. the escape velocity V_E; the standard deviation of V_H corresponding to the standard deviation of $1/a$ as listed by Pittich (1991), σ_1; the same for the selection of best Super-Schmidt meteor orbits by Jacchia and Whipple (1961), σ_2; and the entry velocity (or perturbed geocentric velocity), V_∞. The data base used for the determination of σ_1 includes 429 meteors, and that used for σ_2 73 of them. When the subsample referring to a particular

Table 1.

Shower	Parent object	P	V_E	σ_1	σ_2	V_∞
Andromedids	P/Biela	6.6	3	0.4	0.5	20
Draconids	P/Giacobini-Zinner	6.6	3	0.7	0.0	23
Taurids	P/Encke	3.3	5	0.87	1.47	30
Geminids	3200 Phaethon	1.4	8	1.16	0.44	36
Lyrids	1861 I Thatcher	415	0.19	0.74	0.4	48
Perseids	P/Swift-Tuttle	120	0.44	1.63	0.37	60
Orionids	P/Halley	76	0.59	2.20	0.23	68
Leonids	P/Tempel-Tuttle	33	1.04	2.58	0.2	72

shower is statistically significant (at least 8 objects), σ_1 and σ_2 are given to two decimal digits, otherwise to one.

For the streams produced by comets of Halley type (lower half of the table, $P > 20$ years), there is double evidence that the dispersion of V_H is almost entirely due to measuring errors. First, σ_1 exceeds the escape velocity V_E by a factor of 2.5 to 4; and second, it is very closely correlated with the geocentric velocity V_∞. This is exactly what one has to expect from the measuring errors, because an increase of V_∞ implies a shortening of the optical meteor phenomena and reduction of the number of shutter breaks on the photographic exposures. The list of orbits by Jacchia and Whipple (1961) is limited to bright meteors with long trails, warranting a higher accuracy of the velocity and deceleration measurements. And indeed, σ_2 is much smaller than σ_1, in particular for the streams of high geocentric velocity, where the difference reaches one order of magnitude. Even these low values of σ_2 include measuring errors and accumulated perturbations, which makes them substantially larger than the actual ejection velocities. Indirect evidence indicates that a majority of the Perseids has revolution periods between 100 and 170 years (Kresák and Kresáková 1974), which corresponds to $\sigma = 0.07$ km/s. At the same time, only 8% of their photographic orbits (but 33% of those listed by Jacchia and Whipple) fall within this range, and 29% are formally hyperbolic.

σ_2 is higher than σ_1 only for the Taurids, but this depends on the classification of shower membership within the widely dispersed meteor complex associated with P/Encke, and perhaps also with other objects moving in similar orbits (Porubčan and Štohl 1987). For the Geminids σ_2 is relatively large, but still smaller than the mean velocity difference of 0.7 km/s between the meteors ($P = 1.60$) and their parent Phaethon ($P = 1.43$). Only two out of the 20 Geminids listed by Jacchia and Whipple have $P < 1.43$. This asymmetry points to a long evolution of the stream in its rather stable orbit, situated deep inside the orbit of Jupiter (aphelion distance $Q = 2.6$ AU).

3. The effects of planetary perturbations

The effects of planetary perturbations on meteor orbits can be statistically evaluated using the long-term integrations of their parent objects. The data prepared for the next edition of the catalogue by Carusi et al. (1985) were used to reconstruct the absolute changes of the velocity, ΔV_A along the orbit and ΔV_P perpendicular to its plane, at $r = 1$ AU, and the changes of the nodal longitude $\Delta\Omega$ over periods of 10 subsequent revolutions of each comet. Only those periods were taken into account during which the perihelion distance remained less than 1 AU.

The objects were divided into three classes : I. Typical comets of Jupiter family (P = 5 to 10 years; 10 objects with a total of 840 revolutions). Atypically stable comets P/Encke and P/Machholz (P = 3 to 6 years, small q; a total of 390 revolutions). III. Comets of Halley type (P = 20 to 80 years; 10 objects with a total of 130 revolutions). Halley type comets with $P > 80$ years were omitted, as there are less than 10 revolutions covered by the integrations. The results are presented in Table 2, listing in succession the lower 10% limit - the median - the upper 10% limit for each parameter and orbital class. ΔV_A, ΔV_P (both in km/s) and $\Delta\Omega$ (in degrees) characterize not only the typical values of these quantities, but also their broad non-Gaussian distributions.

Table 2.

Class	ΔV_A	ΔV_P	$\Delta\Omega$
I	0.018 - 0.060 - 0.210	0.22 - 1.63 - 5.90	1.1 - 8.6 - 45.0
II	0.001 - 0.007 - 0.022	0.05 - 0.16 - 0.37	0.3 - 0.6 - 2.6
III	0.002 - 0.008 - 0.024	0.09 - 0.26 - 0.56	0.4 - 1.5 - 7.2

From the table it is apparent that all of these quantities are substantially larger for class I than for classes II and III. This implies a much faster progressive dispersion. Note that the time is scaled by the revolutions around the Sun, so that for a time scale in years the evolution of class I proceeds nearly 100-times faster than that of class III ! This difference is the main reason why no major permanent meteor shower belongs to the most abundant comet class I, all of them having relatively stable orbits characteristic for class II (Geminids, Taurids, Beta Taurids, Quadrantids) or III (Perseids, Orionids, Eta Aquarids, Leonids). On the contrary, comets of class I are parents of the densest temporary meteor storms (Andromedids, Draconids).

Another important point is that ΔV_P is, on the average, about 25-times larger than ΔV_A. This is mainly due to the stability of the Tisserand invariant with respect to Jupiter, and to the low inclinations of the comets of class I. Strong perturbations concentrate near their aphelia and more distant nodes.

After a close perturbing encounter, the inner node is usually removed from the intersection with the Earth's orbit, or the perihelion even recedes outside it ($q > 1$ AU). When this happens to a new stream or to a section of an old streams, the meteor activity is discontinued.

The perturbations make the cross sections of evolved meteor streams rather complicated, and widely different from the simple model of cylindrical isodensity envelopes around the central orbit. The Earth does not cross the centre of the stream, and especially the wings perpendicular to the main orbital plane remain unnoticed (see Kresák 1968, Fox et al. 1983, McIntosh and Hajduk 1983, Hunt et al. 1986, McIntosh 1991).

The disproportion between ΔV_A and ΔV_P has important, and not yet generally acknowledged, implications for the study of the structure and evolution of meteor streams. There is a widespread opinion that double-station photographic velocity measurements represent the fundamental source of information on this problem. In fact, the distribution of meteor radiants and the curves of hourly rates (the determination of which does not require expensive instrumentation, and is open to experienced amateur observers) have the great advantage that they reveal the principal component of the dispersion, perpendicular to the orbital plane.

4. Conclusions and implications

In the annual meteor showers, all traces of the original ejection velocities are smeared out by other effects. For the streams associated with comets of Halley type they are two to three orders of magnitude smaller than the measuring errors, and comparable with the dispersion produced by planetary perturbations integrated over several revolutions. For the comets of Jupiter family the measuring errors and perturbing effects are comparable, and exceed the ejection velocities by two orders of magnitude. The observed velocity dispersion indicates very long ages for the streams associated with P/Encke and 3200 Phaethon.

The only opportunities to determine the ejection velocities by ground-based meteor observations are encounters of the Earth with narrow streams of recent origin, which did not yet have time enough to spread over a substantial fraction of the parent comet orbit, and to undergo comparable differential perturbations. Unfortunately, there are only a few such events per century. As a rule, they are visible only from 20 to 30 % of the Earth's surface, where the night-time hemisphere overlaps with that centered against the geocentric radiant. In this century these were: the Draconids associated with P/Giacobini-Zinner (1933, 1946 and 1985), the Leonids associated with P/Tempel-Tuttle (1965 and 1966), and the less conspicuous Tau Herculids associated with P/Schwassmann - Wachmann 3. For more details see Kresák (1980).

The main source of information on the dispersion velocities is the lag behind the comet (deviation in mean anomaly) and, in particular, the curve of hourly rates which reflects the stream width. From the time lag the effect of solar radiation pressure must be separated, but this cannot be determined exactly without an accurate knowledge of the particle properties.

Another limitation is that there may be some secondary disintegrations of larger objects between their separation from the parent comet and the observation. This possibility is supported by circumstantial evidence in several respects.

The strongest meteor shower of the Ursids, which has led to the discovery of this stream in 1945 (Bečvář 1946), appeared at the time when its parent comet P/Tuttle was near its aphelion, behind the orbit of Saturn. After the perihelion passage of P/Tempel-Tuttle in 1965 and a meteor storm in 1966, there was no exceptional activity in 1967 and 1968, but a strong shower appeared again in 1969. The time lag was 4.5 years (50° in mean anomaly), and also in this case the comet was already behind the orbit of Saturn. The distribution of radio echoes in time deviated very significantly from randomness in the central region 14 000 km across, while around it, and in extensive data on other meteor showers, no such deviation was found (Porubčan 1974). The size distribution of the Leonids was also quite different at their individual returns (McIntosh 1973), but this may be associated with the solar radiation pressure.

The curves of meteor rates of the 1946 Draconid storm, recorded from three different locations using different observing techniques (Jodrell Bank, radio - Lovell et al. 1947; North Bay, photographic - Jacchia et al. 1950; Skalnaté Pleso, visual and summary - Kresák and Slančiková 1975), exhibit three maxima appearing simultaneously at all three places, but of widely different relative strength. These can be interpretted as filaments or layers separated by about 20 000 km from each other, and composed of particles of different size distribution.

An attractive alternative approach to the problem of ejection velocities was opened by the discovery of the IRAS cometary dust trails (Sykes et al. 1986, Sykes and Walker 1992). In many respects these appear identical with the streams producing exceptional meteor storms. The asymmetry of these trails, stretching much farther behind the comets than in front of them, agrees perfectly with the statistics of temporary meteor showers (Kresák 1980, Yeomans 1981, Williams et al. 1986). The measured trail width and identification of its disconnection with the responsible planetary encounter can provide reliable information on the range of ejection velocities, again coupled with the effects of solar radiation pressure. Of course, the planned cometary rendezvous missions promise most reliable data for a broader size range.

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