INTERSTELLAR METEORS AND RELATED PROBLEMS

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1. *The Velocity Criterion and the Variation of Meteor Frequency.* A body at the mean distance of the earth from the sun is firmly bound to the solar system when its velocity relative to the sun, or its heliocentric velocity, is less than a certain limiting value, $u = 42.1$ km/sec ; this represents the velocity of escape into interstellar space. By determining the heliocentric velocity of meteors, we can tell whether they belong to the solar system or not. The velocity in interstellar space, w, before entering the solar system, is given by

$$w^2 = v^2 - u^2, \qquad (1)$$

where v is the heliocentric velocity.

The velocities of meteors in interstellar space (relative to the solar system) should be of the same order of magnitude as stellar velocities. The average velocity of a star is around 30 km/sec. In Table 1 the heliocentric velocities (v) of meteors of various interstellar velocities (w) are calculated.

w, km/sec	0	5	10	20	30	40	50	75	100
v, km/sec	42.1	42.4	43.3	46.6	51.7	58.1	65.4	86.0	108.5

From an observed value of v the interstellar velocity, w, may thus be found, but with a very unequal degree of precision ; as shown by Table 1, v is insensitive to small values of w.

Interstellar, or " hyperbolic " * meteors of an original velocity of less than 5, or even 10 km/sec, will be difficult to distinguish from solar meteors moving in very elongated ellipses—the nearly " parabolic " meteors†—as their heliocentric velocity remains close to the " parabolic limit," $u = 42.1$. A velocity around $w =$ 20 km/sec should be rather common among interstellar meteors ; this would be so in the case of objects " at rest " with respect to the surrounding Galactic medium, or of those sharing in the general rotation of the Galaxy without peculiar motion of their own. The heliocentric velocity in such a case would be $v = 46.6$ km/sec, thus exceeding the parabolic limit by only 4.5 km/sec, or 10 per cent. A large class of interstellar meteors cannot, therefore, be well separated from the solar " parabolic " objects without using refined methods of velocity determination. As most of the methods hitherto applied are rather crude, it is no wonder that conflicting results relating to the frequency and properties of interstellar meteors have been obtained ; even the mere existence of such objects has been questioned.

From Table 1 we infer that the velocity criterion works well only for interstellar velocities exceeding 20 — 30 km/sec. All the positive results hitherto

* Their orbits are hyperbolæ with respect to the sun.

† The ellipses being so elongated that, near the sun, they differ very little from arcs of parabolæ.

announced, concerning the observation of hyperbolic meteors, refer to such high velocities and thus tell only part of the whole story.

The diurnal variation of meteor frequency offered the first method of determining the mean heliocentric velocity. Observed meteor velocities are "geocentric," being referred to the moving earth. Knowing the speed, $g = 29.7$ km/sec, and direction of the earth's orbital motion, the heliocentric motion is found from observed geocentric motion according to the "parallelogram" rule. The simplest case is when the motion is in the direction of the orbital motion of the earth. In this case the geocentric velocity (G) is equal either to the sum,

$$G = v + g \quad ,$$

or to the difference,

$$G = v - g \quad ,$$

according to whether the meteors meet the earth or overtake it. For equal space-density the number of meteors striking a given area will be proportional to the geocentric velocity ; the ratio of those meeting to those overtaking the earth will be (putting $v/g = h$)

$$N/n = (h+1)/(h-1) \quad . \qquad (2)$$

Similar, but more complicated, expressions may be written for other (oblique) directions of motion and can be averaged over all possible directions.

The direction of orbital motion of the earth is from the evening point towards the morning point. Therefore, in the morning hours, meteors meeting the earth—in the evening hours, those overtaking the earth—are predominant. This explains why the hourly number of meteors increases from a minimum in the evening to a maximum early in the morning. The explanation was already known to Brandes in 1827. H. A. Newton (1864) and G. V. Schiaparelli (1866) used it to calculate h, the ratio of the mean heliocentric velocity of the meteors to that of the earth, with the aid of formulæ similar to (2). Both found a mean heliocentric velocity close to the parabolic limit ; Schiaparelli's value is $v = 43.2$ km/sec. He disregarded the small difference as compared with 42.1 and assumed that meteors move with nearly parabolic velocities, forming one family with comets and belonging thus to the solar system. Several coincidences of meteor-shower orbits with cometary orbits strengthened this view.

Now we know that only some of the meteors can be identified as belonging to showers, i.e. to groups moving in similar orbits, more or less parallel in space. About 20 per cent are "shower meteors," the rest being "sporadic," moving in random directions (*Ref.* 20). Of the shower meteors, some have elliptical orbits, with a geocentric velocity below the parabolic limit, and many sporadic meteors have been observed with heliocentric velocities down to 30 km/sec and less (*Ref.* 1, 14, 18, 22). Schiaparelli's mean value of slightly above the parabolic limit for *all* meteors would imply, therefore, the existence of a number of velocities considerably above the parabolic limit, to counterbalance the included low-velocity group.

The statistical method of the diurnal (and annual) variation was further developed by Hoffmeister who found values of $v = 60 - 80$ km/sec for the mean heliocentric velocity of sporadic meteors. The interstellar origin of most of them seemed to be indicated.

However, the method contains weak points : (1) the arbitrary assumption of a random distribution of the heliocentric directions, and (2) neglecting the influence of velocity upon the luminosity of the meteor. The second point was severely criticised by Öpik who pointed out that, assuming a constant fraction of the kinetic energy to be converted into visible light, the brightness of a meteor of given mass should vary as the cube of its velocity (*Ref.* 4), and for random directions an expression about

$$N/n = (h + 1/h - 1)^{k} \qquad (3)$$

should have been used with k = 4 (approximately). Higher values of the heliocentric velocity would, however, result, thus leaving the conclusion about the existence of interstellar meteors still valid.

Later on, Öpik (*Ref.* 1) was induced to admit that the assumption in point (2) is less in error than supposed, this being due to the fact that the visible radiation of meteors originates chiefly from the neutral atoms (iron, etc., *Ref.* 24) ; as soon as the atom is ionized, it becomes practically invisible (*Ref.* 1, 2, 3). The theory of ionization and excitation by atomic collisions remaining still valid (*Ref.* 4), the peculiar property of the meteor material with respect to the emission of visible light reduces the visible radiation per unit mass to an almost constant amount, even slightly decreasing with velocity. Of course, even for a constant amount of light per unit mass, this light will be emitted in a shorter interval of time at a higher velocity, and the intensity will be, therefore, directly proportional to the velocity. As a result, the exponent in (3) is estimated to lie somewhere near k = 2.3, thus still differing, but not so very much, from Schiaparelli-Hoffmeister's assumption (*Ref.* 1).

The theory of meteor phenomena is gradually advancing through trial and error. The above-described peculiarity of meteor radiation is one of the definite achievements, influencing not only the theory of meteor frequency but the interpretation of meteor phenomena in the upper atmosphere and the estimates of meteor masses, as well. It applies to photography and to visual observations, but not to radar results where ionization is the determining factor. This " quantization " of meteor radiation, practically independent of velocity, is quite self-evident after it has been discerned. It is regrettable that the cube law of luminous efficiency is still used by many distinguished authors in dealing with the theory of the upper atmosphere and the masses of meteors.

In any case, the basis of the theory of the variation of meteor frequency is not firm enough to provide an unobjectionable velocity criterion. Confirmation by other means is required.

2. *Estimates of Velocities.* On dividing the length of the path by the estimated duration of flight a value for the geocentric velocity can be obtained, but, usually, the estimates of duration (mostly a fraction of a second) are so uncertain that the result indicates only the order of magnitude of the velocity. From such estimates Brandes and Benzenberg, students of Göttingen University, found in 1798 that meteors have velocities comparable to those of planets and are, therefore, extra-terrestrial bodies.

If systematical observations of duration are checked with the aid of meteors of known velocity, corrections to the observed durations can be obtained and average corrected velocities arrived at. The shower meteors, especially those related to comets with known orbits, represent an excellent "yardstick" or standard for comparison. Hoffmeister, some Russians and others have successfully applied this method, an average velocity of the sporadic meteors well above the parabolic limit being indicated. The method is of value only when all the observations are made by a single, experienced observer. The corrections are so large, and so different for different observers that the practice of mixing the records of various observers makes little sense ; unfortunately, as will be seen later on, in some cases such an uncommendable procedure has been used.

Table 2 gives an idea of the kind of systematic error in duration (assuming the length of the trail to be correct) which may occur (from *Ref.* 5). The table quotes the average " true " or calculated duration for a given estimated duration

Table 2

Observer	Estimated Duration : 0.05	0.1	0.15	0.2	0.3	0.4	0.5	0.6	0.8	1.0	1.2
	Aver. True Duration, sec.:										
E.Ö., Arizona	0.042	0.085	0.127	0.170	0.254	0.349	0.424	0.509	0.678	0.848	1.02
E.Ö., Tartu	0.031	0.073	0.118	0.166	0.258	0.368	0.480	0.600	0.80	1.00	1.20
R.W., Arizona	......	0.03	......	0.20	0.70	0.92	1.05	......	1.64	2.20	......
D.H., "	......	0.06	......	0.12	0.22	0.34	0.49	0.66	1.70	2.90	......
R.H., "	......	0.02	......	0.20	0.38	0.89	1.28	......	2.90	......	......
G.P., "	......	0.03	......	0.10	0.24	0.42	0.61	......	1.19	......	2.08

of the shower meteors. From the table it appears that, whereas the estimates of *E.Ö.* compare more or less to a true yardstick, those of the others show a " wild " run and sudden changes, which make them useless ; such estimates cannot be used at all. From these unreliable estimates surprising results are obtained if the " regression curve " is inverted as in Table 3, which quotes the average estimated duration corresponding to a given " true " duration (*Ref.* 5, Figs. 7, 8).

Table 3

	True Duration, sec.: 0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0	1.5	2.0	2.5
	Aver. Estimated Duration, sec.:											
R.W., Arizona	0.13	0.16	0.19	0.22	0.25	0.28	0.31	0.34	0.37	0.43	0.49	0.53
D.H., Arizona	0.08	0.14	0.20	0.24	0.25	0.26	0.27	0.31	0.37	0.47	0.52	0.57

Thus, from Table 3, a true duration 0.8 sec is estimated by *D.H.* on the average as 0.31 ; but from Table 2 we infer that 0.31 estimated by *D.H.* would correspond to an average true duration of only 0.23 sec, which is less than one-third of the figure 0.8 sec assumed at the start. This contradiction between the two " regression curves " is, in itself, not surprising ; it is a logical consequence of the law of accidental errors, and is well known in statistics. However, the size of the discrepancy is such that little or no weight can be attributed to the estimates. The estimated and the true durations for the four observers (except *E.Ö.*) show little "correlation" ; their figures have the appearance of having been written down almost at random, seldom being influenced by the true duration of flight of the meteor. Thus, *D.H.* records, for a slow meteor of 0.7 sec, an average duration of 0.27, while for a fast meteor of 0.4 sec he arrives at 0.24, or practically the same ; anybody using such estimates would conclude that there is almost no difference between the two kinds of meteors, whereas their true velocities may differ in the ratio 1.75 to 1.

It may be added that, whereas their estimated durations could not be used, both *R.W.* and *D.H.* obtained satisfactory results at the Rocking Mirror (*cf.* next section).

Observations by inexperienced, casual observers have been widely used in the case of bright meteors or fireballs. Because of the rarity of these objects they seldom happen to come into the field of view of a regular meteor observer, and most of our statistical knowledge of these bodies is based upon observations by casual eye-witnesses. The situation is, however, made easier here by the very much greater length of the visible trail and the longer duration of the fireballs as compared with "ordinary" meteors ; and by a much larger displacement, or parallax, owing to the larger mass and luminosity of these objects, visible from great distances. The odds are, nevertheless, unfavourable, especially regarding the determination of velocities.

Although the von Niessl-Hoffmeister catalogue (*Ref.* 6) of fireballs ascribes a hyperbolic velocity to the majority of these objects, doubts as to the reliability of these velocity data are well founded. Watson showed (*Ref.* 7) that the heliocentric radiants of the catalogue exhibit a marked concentration towards the ecliptic, which can be explained only if a great proportion of the fireballs belong to the solar system. In fact, a strong ecliptical ("asteroidal" or "zodiacal-light") component exists among meteors (*Ref.* 14, 1, *et alias*) and this may account for the concentration of the radiants in the catalogue. At the same time, it is probable that the velocities determined from such casual observations are exaggerated, *on the average*. Nevertheless, a good proportion of the fireballs may still be hyperbolic, perhaps up to 50 per cent.

A systematic error in the velocities obtained by casual observers is rightly assumed by Wylie (*Ref.* 8). He ascribes the error chiefly to an involuntary tendency to extend the trail backwards. The error effect might be ascribed also to seeing the meteor start early, but by being late in counting the time. This kind of systematic error was already suspected by von Niessl with respect to the fireball of June 17, 1873 ; however, A. V. Nielsen showed, by a very convincing analysis (*Ref.* 13), that the longer path of about 400 km was undoubtedly real, and that the shorter path (150 km) was the section of the trail where a persistent train was formed ; on this occasion, such a conspicuous marking as the planet Mars set the early beginning of the visible path beyond doubt. Not always do such favourable circumstances exist, and this case summons to caution. Now, Wylie is not content with, justly, casting doubts on the value of the velocities derived from casual observations ; he undertakes to correct them *post factum*. The procedure is not justified even where average values of the velocity are concerned, unless systematic errors are derived for all the observers—which is impossible. Wylie, however, corrects individual values: imagine the systematic corrections of *D.H.* (Table 2) applied to *E.Ö.*! There is the case of the Pultusk meteorite of January 30, 1868—one of the observers was an astronomer, another a trained army officer, with a number of other reliable observers—for which the famous German astronomer J. G. Galle found a hyperbolic velocity practically beyond doubt (*Ref.* 11, 10). Wylie, not in possession of Galle's original paper, "curtails" the observations in order to make an elliptic case of it, too. The case has been thoroughly discussed anew by Nielsen (*Ref.* 12) who again arrives at the only possible conclusion—that the Pultusk meteorite had a heliocentric velocity far in excess of the parabolic limit: $v = 56$ km/sec, whence the interstellar velocity $w = 37$ km/sec.

3. *Rocking Mirror Observations.* At Harvard College Observatory the writer devised a mirror which was rocked ten times per second with the aid of a synchronous motor, and in such a manner that the normal to the mirror described a conical surface. The images of stars reflected in the mirror were ellipses. A meteor seen in the mirror described characteristic curves, cycloids as in Fig. 1 (a = slow meteor ; b = medium velocity ; c = fast). By drawing (with reference to a star map or a reticle) the meteor trajectories as they appeared in the mirror, the angular (apparent) velocity of the meteor could be derived, chiefly from the number of loops (which gave the duration, each loop corresponding to 0.1 sec), partly from the shape of the loops. Observations with this apparatus were made in Arizona (1931-33) by the writer and two other observers (*R.W.* and *D.H.*) and in Tartu, Estonia, by *E.Ö.* alone since 1934. The observations were continued until, in the summer of 1941, the observing station in Tartu fell into the front line of the fighting forces, where it was damaged by an artillery shell and essential parts of the apparatus were stolen. For the details of observation and reduction the reader may be referred to the original publications (*Ref.* 1, 5). The linear velocities were calculated from the angular velocities with the aid of average heights, depending upon the luminosity and upon the angular velocity itself (*Ref.* 5, Table III). Systematic corrections, separately for each observer and method, were derived from the shower meteors.

The velocities obtained in such a manner are thus *differential,* referred to the better-known system of the velocities of the shower meteors. Being more accurate than former estimates, they could be used to derive the *probable frequency* of velocities within given limits. The observations give directly only one component, the transverse (tangential) geocentric velocity of the meteor ; this is corrected for the transverse component of the orbital motion of the earth (parallelogram law), heliocentric transverse velocities being thus obtained. The frequency of the latter is corrected for observational error-dispersion with the aid of Öpik's numerical method of solving a certain "integral equation of diffusion" and the true frequency of the transverse heliocentric velocities is obtained, i.e. the probable frequency if the observations were not affected by observational errors (the frequency law of errors is again derived from the shower meteors).

Each of these transverse velocities is smaller than the space-velocity, because the radial component of velocity is not included. From purely geometrical considerations, the frequency of space-velocities can be derived from the frequency of transverse velocities (which again involves the solution of a certain " integral equation ").

There exists a certain span in the assumptions involved, but even extreme assumptions agree in requiring a high frequency of interstellar meteors among the sporadic ones. With the most restrictive assumptions about two-thirds of the sporadic, or one-half of all visual meteors should be interstellar.

Of the three observers, Öpik had the smallest accidental error, about 10 per cent of the observed velocity; his observations are of greater weight in determining the frequency of meteor velocities, although the other two observers (referred to their own system of shower meteors) did not show any systematic difference. On the most restrictive (with respect to high velocities) treatment of Öpik's observations the frequency of heliocentric velocities, freed from the effects of observational errors, is as follows (*Ref.* 5, 3) :

Table 4

" True " Frequency of Heliocentric Velocities for 583 Visual Sporadic Meteors

v, km/sec	0 to 19.5	19.5 to 27.5	27.5 to 39.0	39.0 to 46.2	46.2 to 55.0	55.0 to 65.4	65.4 to 78.1	78.1 to 92.5	Over 92.5
Number	11	27	68	115	153	86	58	39	26
Percentage	1.9	4.6	11.7	19.7	26.2	14.7	9.9	6.7	4.5

Those above $v = 46.2$ are definitely interstellar ; these represent 62 per cent of all sporadic meteors. Those below $v = 39.0$, 18 per cent of the sporadic, should move in elliptical orbits and represent the " asteroidal " or " ecliptical " component. Within $v = 39.0 - 46.2$ there should be partly cometary (nearly parabolic), partly slow interstellar meteors.

Extreme assumptions with respect to the basic " standards " used in the derivation of the above table will not change much in the general picture (*Ref.* 3).

There have been many comments on Öpik's rocking-mirror results and his methods of reduction ; unfortunately it appears that, often, commentators (both for and against) did not read, or have not seen, Öpik's two extensive papers on this subject (*Ref.* 1, 5). The writer can assure them that the general outcome does not depend upon the method of reduction ; for whatever is wrong or right in the broad results, the observations themselves should be made responsible. Only a very strange systematic difference between the observational records of the sporadic and shower meteors, the same for three different observers, could render the hyperbolic meteors non-existent. The writer is personally sure of his own observations.

Table 4 represents the final results for the " true " frequency, obtained after solving certain complicated integral equations. To the bystander the raw, " semi-fabricated " product may be a more eloquent witness. In Table 5 the frequency of the transverse heliocentric velocities, uncorrected for observational error-dispersion, is given ; these data may be considered as observed individual values, only reduced to a certain standard scale of velocities.

The limits of velocity used are " logarithmic " (geometrical progression). In Fig. 2 the percentages of Table 5 are plotted and smooth curves drawn. The difference between the two distributions is clearly visible. There are many velocity records of the shower meteors that exceed the parabolic limit, 42 km/sec ; these records are considered as errors of observation (which follow a logarithmic law), although some of them may be stray meteors not belonging to the shower.

Table 5

Observed Frequency of Transverse Heliocentric Components of Velocity

Öpik's observations

Velocity Limits, km/sec	0 to 14	15 to 21	22 to 29	30 to 42	43 to 59	60 to 84	85 to 119	Over 120
Sporadic Meteors								
Number	26	27	57	162	161	82	44	24
Percentage	4.6	4.6	9.8	27.8	27.6	14.1	7.5	4.1
Shower Meteors								
Number	20	14	24	65	44	24	4	7
Percentage	9.9	6.9	11.9	32.2	21.8	11.9	2.0	3.5

The frequency of the sporadic meteors differs considerably from that of the showers, showing a broader maximum displaced to the right, a greater frequency of high velocities and a lower frequency of small velocities. If the error-frequencies in both cases are similar, the difference between the two curves indicates a difference in the true frequencies of velocities, chiefly the occurrence of a high-velocity group among the sporadic meteors that is absent from the shower meteors.

4. *Porter's Analysis.* Dr. Porter published two papers on " An Analysis of British Meteor Data " (*Ref.* 15, 16) in which he challenged the reality of the hyperbolic meteors and the work of Hoffmeister, Öpik and others. The papers are written in a manner quite unusual in scientific publications. Let us try to look closer at what is behind it.

Let us first compare Porter's statements referring to Öpik's work and the Arizona Expedition with the true state of affairs.

(a) Porter : " Olivier has strongly criticized the results of this expedition, . . ., in particular that they do not include any data for the major showers, and that there is therefore no check upon the results by a simple comparison of shower and non-shower meteors " (*Ref.* 16, p. 267). " The Arizona results are open to other criticisms. . . . The absence of shower meteors prevents the fundamental check on reliability by a comparison of shower and non-shower meteors " (*Ref.* 16, p. 271). Thus, through repetition, Porter emphasizes his statement.

Facts : Of Öpik's series of papers (seven in number) referring to the Arizona Expedition and velocities, Porter cites only one, the " Analysis of Meteor Heights " (*Ref.* 17). If Porter had cared to look into that paper (instead of referring to Olivier's unjustified remarks about quite a different detail, the use of recticles), he might have made the following comparison :

	Number of :		
	Heights, all meteors	Heights, shower meteors	Showers with heights
Arizona Expedition	3540	433	26
Porter	778	298	10

Porter has too great a proportion of shower meteors (chiefly Perseids!) which is by no means representative of the average, and is to the detriment of the statistical fairness of the sample.

As to the " major showers," the figures are equally eloquent :

Shower	Number of Heights	
	Arizona	Porter
Perseids	114	152
Orionids	9	35
Taurids	54	28
Leonids	93	27
Geminids	0	0
Eta Aquarids	4	0
Delta Aquarids	26	15
Quadrantids	15	8
Lyrids	16	6
All	331	271

In Öpik's determination of velocities, these were checked with the aid of shower meteors (*cf.* Section 3), quite contrary to Porter's statement :

Number of Velocities (*Ref.* 1, 5, 16) :

	Öpik	R.W.	D.H.	Porter
All	785	611	546	686
Shower Meteors	202	41	32	260

Conclusion : Porter makes obviously incorrect statements about the only paper he cites, and wrongly criticizes results which he, evidently, has never seen ; these false statements refer, not to details in general, but to points which Porter himself considers as of major importance.

(b) Porter claims (*Ref.* 16, pp. 264-267) that Öpik (*Ref.* 17 again) did not take into account the elongation from the apex, the magnitude, etc., in discussing the difference in height of the sporadic and shower meteors, the seasonal and diurnal variation, etc. If Dr. Porter cares to look into Öpik's paper, he will find that all these effects are considered and that the comparison is made at equal elongation and magnitude ; in fact, the essence of Öpik's paper (*Ref.* 17) consists in the detailed analysis of all these effects, of which Porter gives but vague hints. Conclusion : same as in (a).

These two examples suffice to discard Porter's " Analysis " altogether : what confidence can be placed in his *re-reduction and revision of other people's work,* in view of such lack of responsibility in referring to work done elsewhere? There are other examples of such an attitude in Porter's " Analysis " which would take

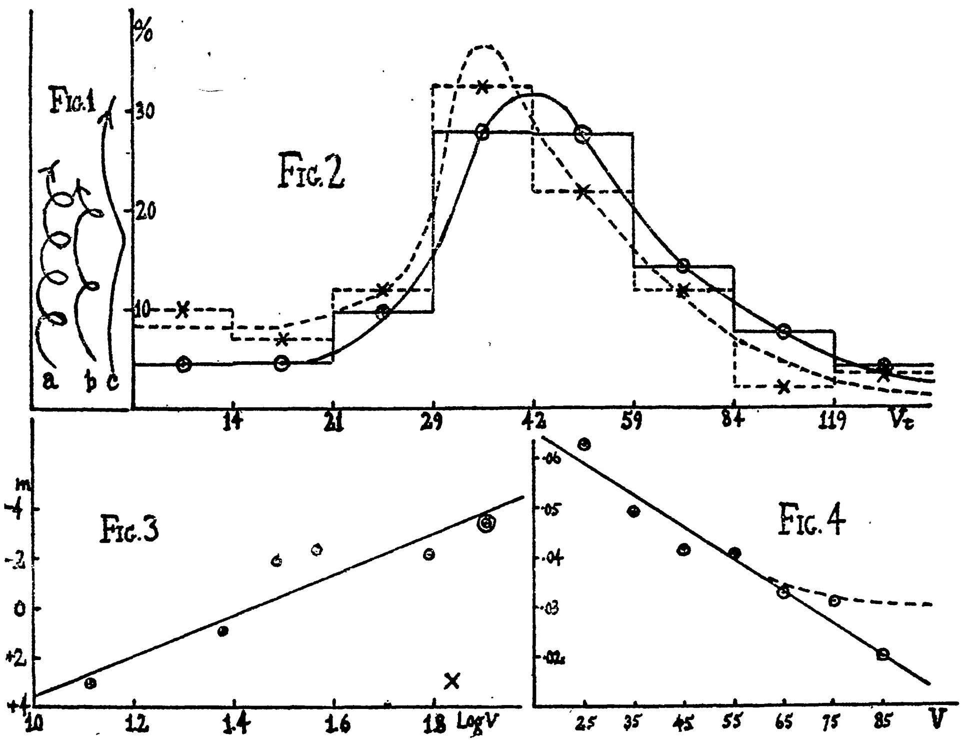

Fig. 1. Cycloid meteor trails at the Rocking Mirror.
Fig. 2. Percentage frequency of transverse heliocentric velocities in Öpik's rocking-mirror observations. Broken line and crosses = shower meteors ; full line and pointed circles = sporadic meteors.
Fig. 3. Correlation of luminosity per unit mass (ordinates in magnitudes) and velocity (abscissae, log of velocity) for Whipple's photographic meteors. Double circle, " hyperbolic " (original) solution, cross—" solar " (changed) solution of No. 663.
Fig. 4. Correlation of the duration of echo (ordinates, seconds) and velocity (abscissae, km/sec), according to Lovell.

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too long to enumerate. But let us, for a moment, take Porter's papers at their face value and inquire into his own results with respect to meteor velocities.

He has a total of 1253 " coincidences," i.e. meteors observed simultaneously from at least two stations ; this list is a compilation of observations between 1877 and 1940, obtained by 13 " first-line " observers and 174 " second-line " observers. The individual systematic errors were not, and could not have been, determined from such a heterogeneous mixture : what a Babylonic confusion of systematic errors in the estimated velocities (length/duration) must be concealed in this material (*cf.* Table 2) ! The revision by Porter could only introduce uniformity in the calculations, without removing the basic heterogeneity of the observations.

Of the 1253 original coincidences, over one-third were rejected by Porter on account of contradictory results, 778 being retained for the analysis. The percentage of rejections is large ; in Arizona, only 6 per cent of the coincidences were rejected as probably not referring to the same meteor (*Ref.* 17, p. 551). Among

Porter's rejections the majority refer undoubtedly to common objects which are distorted by errors of observation. The practice of rejecting discordant observations is open to criticism, and is generally allowed only when those rejected represent but a small fraction of the total ; rejection of 38 per cent in a material subject to statistical use is inadmissible.

Therefore, the material is not homogeneous and is strongly influenced by personal selection. It represents also but a fraction of the British observations available, e.g. of Denning's some 1400 meteor paths, less than 10 per cent are included (the rest were not re-reduced by Porter because it is said that the original notebooks are lost).

The velocities are calculated by Porter simply from the ratio *length/duration;* a " standard " velocity is also calculated, corresponding to the geocentric velocity of a meteor moving in the same direction in a parabolic orbit. The ratio of observed to standard velocity, which we here call R (in Porter's notations $R = S/V$), is the observed velocity criterion. The observations are, of course, too inaccurate to attach any meaning to the individual values of R. Average values and a statistical comparison between shower and sporadic meteors can be used, in a way similar to that used in Table 5 and Fig. 2. This Porter actually does, and finds that large velocities (R exceeding 1) represent 16.5 per cent of the sporadic meteors and 14.2 per cent of the shower meteors. There is a slight preponderance for sporadic meteors, but too small for definite conclusions.

Looking closer into Porter's data we find, however, that the non-homogeneity in velocity estimates is so large that the figures for different epochs show little similarity. Thus, whereas the median value of R for the whole material is 0.60, observations before 1915 yield a median $R = 0.97$. The discrepancy was known to Porter, yet it did not deter him from placing all these conflicting data into the same basket.

Rejecting the 109 early observations, the remaining presumably more accurate data after 1915 yield : sporadic meteors, 12 per cent high velocities (R exceeding 1) ; shower meteors, 7 per cent. For a higher velocity limit, R exceeding 1.2 : sporadic, 8 per cent ; shower meteors, 2 per cent. The figures are now reasonably similar to those of Table 5, indicating a higher percentage of large velocities among sporadic meteors. Thus, Porter's recent material supports Öpik's frequency of high velocities, the exact opposite of what Porter claims to have demonstrated.

The explanation of this unexpected outcome is that most of the high values of R for shower meteors refer to the early period, whereas most of the high values of R for sporadic meteors are recorded after 1915.

Of course, this support from Dr. Porter's material for the existence of hyperbolic velocities has little weight, on account of the large dispersion and heterogeneity of the material. Although the quality of the observations of position may be good, the heterogeneity in the estimates of duration renders the velocities unfit for statistical use.

Now, a word about the accuracy of observations of meteor positions. Porter claims that the observational technique used in obtaining his data " gives superior results to that used in other countries." In the Arizona Expedition, the displacement of the centre of the trail was used in the determination of heights ; this has the advantage of depending little upon the angle between the direction of the parallactic displacement and the meteor. The maximum number of reliable heights can be obtained by this method. The probable error of one observer in the parallactic displacement was 1°.14 in Arizona (*Ref.* 17, p. 599), which corresponds to a standard deviation of ± 1°.70. Porter's figures for the errors (*Ref.* 15, p. 142), for the average case of a meteor making an angle of 45° with the parallactic displacement, give ± 1°.75 as standard deviation of the centre of the trail along the parallactic displacement (" offset " and " sliding " errors summed according to statistical rules). The figures are practically equal and hence the quality of the observations. No doubt, British meteor data are excellent and deserve better treatment than that given them by Porter. The claim of superiority, however, is not borne out by the figures. If the Arizona heights are less accurate, it is not because of inferior observations but because of a smaller base-line, so chosen for other (statistical) reasons.

Porter's claims, in the two above-mentioned papers, as well as in his Presidential Address (*Journ. Br. Astr. Ass.*, 60, pp. 1-17, 1949) about having disproved the existence of hyperbolic meteors, are unfounded. The Address contains a number of misstatements, e.g. the claim that meteors of greater velocity penetrate deeper into the atmosphere (loc. cit., p. 10, lines 8-11 from above).

In view of all this, it sounds rather pathetic (and arrogant, at the same time) to hear the claim, in reference to Porter's work, that it seems " to dispose of the results of the Harvard College Observatory Expedition to Arizona some sixteen years ago ". (Anonymous, *Nature,* November 20, 1948)—the results Dr. Porter did not care to look into—, or " He spent some years in investigating the subject with utmost care, and showed that the methods adopted in the Harvard-Cornell Expedition were unsound " (Anonymous, *Nature,* March 11, 1950)—what the methods actually were Dr. Porter did not know.

5. *Photography.* Excellent photographic velocities have been determined by Whipple, or under his supervision (*Ref.* 18, 19). However, a weak point in these determinations is the indirect method of determining the time : in most cases the time was found by identifying individual irregularities on the two simultaneous meteor trails ; the great circle joining identical details represents the direction of parallactic displacement which, in equatorial coordinates, depends upon time and thus may be used as a " clock ". Whipple states that, in most cases, the determination of time was very satisfactory. However, in such a question as hyperbolic velocities, the degree of uncertainty has turned out to be rather alarming. In the first set of 6 velocities (*Ref.* 18) there was a sporadic meteor, No. 663, which gave a hyperbolic heliocentric velocity, $v = 52$ km/sec (thus interstellar $w = 30$ km/sec). Now, for some reason, Whipple had doubts as to the reality of this result and preferred to change the time (against the existing evidence of the details of the trail) in order to get a velocity just below the parabolic limit. Later on, Jacchia (*Ref.* 19) assumes a third value for the velocity, intermediate between the two (apparently exactly at the parabolic limit). Such a procedure of arbitrarily altering observational data is not commendable. According to the good

old principles of observational astronomy, direct evidence of observations must never be altered. Such direct evidence consisted, in the present case, in the identification of the details in the two simultaneous photographs, which was evidently made without knowing the outcome. The alteration was made after the hyperbolic velocity was obtained and, apparently, on the subjective assumption that the hyperbolic result was spurious (why not change in the opposite direction and increase the velocity?).

Öpik showed (*Ref.* 1, pp. 82, 83) that, in the present case, there exists another kind of evidence supporting the original version of Whipple's No. 663, namely, the correlation between luminosity and velocity. On certain assumptions as to the density gradient of the upper atmosphere, Whipple's data could be used to calculate the luminosity of the meteor per unit mass. The results are represented in Fig. 3. We notice that the original hyperbolic case of No. 663 falls well on the general line of correlation of luminosity and velocity, whereas the arbitrarily-changed case falls 6 mag below the line, or is "out of tune" in a ratio 250:1. For another assumption as to the atmospheric density gradient, the relative arrangement of the points with respect to the straight line remains practically the same, although the inclination of the line is different ; the "changed No. 663" remains invariably "out of tune" by the same tremendous amount.

From this double evidence the writer feels that the hyperbolic nature of No. 663 is practically certain, and that the velocity originally determined by Whipple is close to the correct value.

Since the first publication, there have been many more velocities determined by Whipple and his team. Unfortunately, for the later observations no radiants, heliocentric velocities or other data relevant to the problem of hyperbolic velocities are published for the sporadic meteors, so it is not yet possible to consider critically these later data. In the most complete list (*Ref.* 19) there are altogether 50 items, of which but 19 are sporadic. Of these, in addition to No. 663, there is another apparently-hyperbolic case, No. 1103, with an observed velocity of 75.5 km/sec, which exceeds the possible upper limit for solar meteors (72 km/sec). In a verbal statement Dr. Whipple told the writer that there are more similar cases. It seems that, among the photographed sporadic meteors, there may be up to 20 per cent hyperbolic cases; none, however, has yet been found with a very high velocity.

It appears that these bright objects, by their size far outside the normal range of visual meteors, have a different statistical composition. Already the fact that, among the 50 Harvard photographic meteor velocities (*Ref.* 19), 31 meteors or 62 per cent belong to well-known showers, against 20 per cent for an all-over-the-year sample of visual meteors (Arizona Radiants, *Ref.* 20), indicates that the solar component among the bright objects is strongly enhanced. For the same reason, among the photographic sporadic meteors, a greater number of stray solar objects, of a similar origin to those now traceable to showers, should exist ; this has actually been confirmed by some of Whipple's results.

Another reason for the small number of high velocities is the peculiar photographic selection which favours long exposure, and thus slow motion across the plate.

6. *Manchester Radar Velocities.* On the suggestion of Dr. Whipple and the writer, Dr. Lovell and his team at Jodrell Bank undertook specially devised experiments to check the existence of hyperbolic velocities. In a recent short note (*Ref.* 21) Dr. Lovell states that their results do not confirm the existence of any considerable proportion of hyperbolic meteors among the sporadic objects.

The writer has been in constant touch with Dr. Lovell during this extended experiment. From privately communicated data the writer arrives at a conclusion contrary to that of Dr. Lovell, and finds that the Manchester figures, in spite of being influenced by a tremendous selection in favour of small velocities, agree well with Öpik's rocking-mirror results.

Dr. Lovell's statement (*Ref.* 21) is not accompanied by statistical data. The writer expects Dr. Lovell to publish all the individual determinations of velocity, including those rejected after provisional determination.

We hope to deal with these results in more detail on another occasion and, therefore, the problem will be considered but briefly here.

Because of the specular reflection effect, the Manchester velocities refer to meteors observed at right angles to their direction of flight, or in 90° distance from their radiants. Thus, when the radar beam is directed toward the zenith, only meteors from the horizon can be observed ; the yield will be, however, near zero, as the meteors move horizontally and will not enter the atmosphere. The lower the altitude of the beam, the more meteors will be observed.

In the first experiment at Jodrell Bank (autumn 1948), the radar beam was directed at a low altitude. Observations were made in the morning hours, with the " circle of radiation " passing through the apex. The parabolic limit of velocity along the circle of radiation drops from 72 km/sec at the very apex to 57.6 in 45° from the apex, and to 30 km/sec in 90° from the apex. Thus, hyperbolic meteors may be found within all this range of velocity ; those exceeding 72 km/ sec are certainly hyperbolic. On certain plausible assumptions, the effective statistical limit of hyperbolic velocity, for meteors radiating from the circle which is passing through the apex, may be calculated ; the limit is close to 65 km/sec, i.e. the *number* of meteors (although not each individual) with velocities exceeding this limit should be representative of the number of interstellar meteors.

In a letter dated 12th January, 1949, Dr. Lovell writes :

" You will no doubt remember that we were fairly convinced that all the meteors we observed here had less than parabolic velocities, and we regarded the experiment, which Whipple and yourself urged us to do, as in the nature of a ' negative results ' experiment. However, it has turned out far from being in this category, since we have measured many hyperbolic velocities . . . . so far I have only managed to work out about one-eighth of our total results which have yielded about 30 velocity values. The distribution of these velocities is given in the following table.

Velocity between	30 and 35	35 and 40	40 and 45	45 and 50	50 55	55 60	60 65	65 70	70 75	75 80	80 85	85 90	90 95	95 100
Number	3	1	1	1	2	4	2	4	2	1	2	1	1	2."

This first sample contains a probable number of 46 per cent hyperbolic velocities.

When all the 1500 meteor echoes were reduced, the yield was different, only 83 velocities being obtained :

Velocity	Below 35	35 40	40 45	45 50	50 55	55 60	60 65	65 70	70 75	75 80	80 85	85 90	Over 90
Number	11	7	10	6	9	12	8	8	7	2	1	2	0

A comparison with the preceding table (which refers to a fraction of the same material) indicates that a restrictive procedure of rejecting high velocities (from nearly 65 km/sec up) was applied. The probable number of hyperbolic meteors is now 24 per cent.

The experiment was repeated at Jodrell Bank in autumn of 1949 with a different wave-length. Of the 3,000 echoes about 200 velocities were expected, of which an incomplete list of " 120 good velocities " was as follows :

Velocity	Below 35	35 40	40 45	45 50	50 55	55 60	60 65	65 70	70 75	75 80	80 85	85 90	90 95	95 100
Number	8	9	9	15	25	22	32	20	11	5	0	1	1	0

In this sample the probable number of interstellar meteors is 32 per cent. Dr. Lovell suggests that the high velocities represent only the " tail " of an observational error-curve. Were this true, it would contradict the high precision announced for the method of the diffraction of radio waves (*Ref.* 22), about ± 2 km/sec. From samples which are now published (*Ref.* 22, 23) the writer arranged " experiments " by making " artificial meteor velocity records " using intermittently the 3rd, 4th, etc. pulses, which would correspond to a triple, quadruple etc. velocity. The error turned out to depend on velocity as follows :

Average Velocity, km/sec	35	133	170
Standard Devi. km/sec, ±	2.6	10.7	31
Number of " individuals "	11	11	13
Stand. Devi., per cent, ±	7.4	8.1	18.5

Also, *all* the velocities once recorded turned out to be reliable. It seems that the Manchester velocities are excellent, of a uniform accuracy, about ± 5 per cent (*p.e.*) up to 140 km/ sec, and the procedure of rejecting all cases above 100, or 90 km/sec (as done in the above-mentioned samples) is not justified.

The true distribution could be obtained by freeing the observed distribution from the observational error-dispersion by solving the " integral equation of diffusion." Such a procedure can be applied, however, only to a material where no rejections were made. Rejection of a small proportion of discrepant values is sometimes justified, as when an average measured quantity is sought. In the case, however, where the error function itself is involved, the procedure of rejecting observations which are once obtained means curtailing, at will, the error-deviations at the high velocity end of the distribution. The " integral equation of diffusion " cannot be applied to such a distribution.

Of the above-quoted samples the first, containing 27 velocities, appears to be the least biased ; the number is too small for application of the exact procedure, but it is clear that, with a probable error ± 5 per cent, no substantial change in the distribution will occur, and that almost the same number of cases exceeding the absolute limit (72 km/sec) will remain.

The other two samples are too heavily influenced by the procedure of " rejection " to allow of the exact statistical treatment.

One of Dr. Lovell's recent publications (*Ref.* 23, p. 38) contains indirect proof that the above interpretation is correct. Fig. 4 represents the dependence of the echo duration upon the observed velocity, according to Lovell. The dependence is excellently represented by a straight line. Now, if there are no hyperbolic meteors, the velocity group 85, as suggested by Lovell, would correspond to meteors with a true velocity below 72 km/sec, the high velocities being produced by errors of observation. In such a case, however, the average duration should correspond to this true velocity, not to the erroneously-measured velocity. The correlation curve should bend up at the high velocity end as indicated by the broken line in Fig. 4 (a well-known property of " regression curves "). This is not the case. For 85 km/sec, the duration continues to decrease with the same trend—an indication that the group is made up not so much of errors of observation as of real high velocities.

7. *Crucial Test by Radar.* The above experiments are intrinsically obscured by two major factors : by the variable elongation from the apex, rendering the " parabolic limit " variable along the circle of radiation ; and the observational error-dispersion. The first is by far the greater obstacle.

It is possible to do away with this major impurity in a very simple manner, by directing the radar beam to the apex, or to the antapex. In both cases, the circle of radiation will be, all over its length, at a constant distance of 90° from apex or antapex, and the critical velocity limit constant and low, near 30 km/sec.

Another pre-requisite for successful radar observations is that the altitude of the beam must be low, otherwise the yield in numbers will be too small. Therefore, the best arrangement for a crucial test would be—to observe with the beam in the apex in the mornings of February-April, or in the antapex in the evenings of August-October.

This suggestion was made, indeed, by the writer to Dr. Lovell early in 1950. However, in spite of warnings, Dr. Lovell started the spring observations in the antapex and had, of course, to abandon them on account of insignificant yield. Then Dr. Lovell, instead of directing the beam to the apex, switched over to the old arrangement, except that the circle of radiation now passed through the antapex. Dr. Lovell says this was done in order to meet certain objections " in a decisive manner " (*Ref.* 21). Here, apparently, words have a different meaning from what is commonly agreed. The heterogeneity of the " parabolic velocity limit " in this " decisive " experiment was not less than in the apex experiment, the limit varying from 16 to 50-60 km/sec (with a strong favouring of small values, on account of zenith distance), and the advantage of a safe, sharp margin at 72 km/sec was lost, too. How could more clarity be expected from such an obscured case?

From all the evidence, including that furnished by opponents of the idea of hyperbolic meteors, the writer feels that the reality of the interstellar component among meteors has a very high probability, not far from practical certainty. Precise photographic observations may soon decide this issue beyond doubt.

Armagh Observatory,
September 4, 1950.

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