METEOR HEIGHT DISTRIBUTIONS AND THE FRAGMENTATION HYPOTHESIS

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Summary

This paper is concerned with a comparative study of the incidence of fragmentation amongst bright and faint meteors, as disclosed by photographic measurements of heights and light curves of brighter meteors (visual magnitudes $<+4$), and by measured radio-echo height distributions of faint meteors (visual magnitudes $\sim+6$). The discussion is based on photometric and height data for sporadic and shower meteors obtained by Harvard and Canadian observers, and on radio-echo height distributions measured at Jodrell Bank. Mean photographic light curves are shorter than predicted by evaporation theory, and there is a large residual scatter in the heights of maximum brightness after reduction to standard meteor velocity and brightness. Trail length is independent of reduced height, and also of velocity if this exceeds 25 km/sec; for slower meteors trail lengths shorten rapidly. The radio-echo height distribution as a function of trail length is calculated for a simple model which incorporates these features of the ablation process for brighter meteors. Comparison with radio height measurements indicates that meteors below the photographic threshold show a closer approach to the predictions of the evaporation theory than meteors bright enough to record photographically.

I. Introduction

The photographic recording of meteor trails has demonstrated that the process of trail formation amongst visual meteors is not correctly described by the evaporation theory (Herlofsen 1948), which treats the interaction of a solid particle with the atmosphere. Thus, Hawkins and Southworth (1958), in a discussion of basic data for sporadic meteors, conclude that the observed lengths of meteor trails are considerably shorter than predicted by the evaporation theory and appear to depart from the theory in a random fashion. They refer to a suggestion by Jacchia (1955) that this discrepancy can be accounted for by the phenomenon of fragmentation of the meteoroid. Jacchia, Kopal, and Millman (1950) had already advanced this explanation to account for their observation of exceptionally short trajectories and abnormally great heights of the 1946 Draconid (Giacobinid) meteors.

These are direct measurements, and the inapplicability of the evaporation theory is inescapable. It is more difficult to ascertain the extent to which the evaporation theory fails to describe the ionization curves of the fainter meteors accessible to radio equipments, because a radio equipment responds to only a short segment of the individual meteor trail. This question, however, is of some importance, not only in its own right but also because radio measurements of the heights of echoing points, of the echo rate, and of echo durations have been

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applied by Browne *et al.* (1956), and other workers, to the determination of the distribution of the masses of meteors whose brightnesses extend down to visual magnitude $M_v \sim +7$, and Evans (1954, 1955) has derived values of the atmospheric pressure and scale height from the height distributions. In all these applications the assumption has been made that the ablation of a meteoroid is correctly described by the evaporation theory. Unless the nature of the ablation process changes significantly over a range of meteor brightness of only two or three magnitudes, this assumption would appear to be unwarranted.

An indirect approach to the measurement of ionization curves of radio meteors has been made by Greenhow and Neufeld (1957). These workers compared echo amplitudes at two rather ill-defined points on an individual meteor trail, and from a statistical analysis of a large number of echo amplitude ratios they concluded that the mean ionization curve of these fainter meteors $(+6 < M_v < +8)$ is shorter than predicted by evaporation theory.

Apart from second-order effects introduced chiefly by the finite aperture of the aerial system and the celestial spread in radiant points of sporadic meteors, the width (r.m.s. deviation) of the sporadic radio-echo height distribution depends on four main factors. These are (*a*) the mass distribution of the meteoroids; (*b*) the atmospheric scale height and its variation with height; (*c*) the mean ionization curve of the meteor trails; (*d*) the dependence of the height of maximum ionization on the mass of the meteoroid. The mass distribution for sporadic meteors is known (Kaiser 1954*b*). If one assumes the evaporation theory, (*c*) and (*d*) are prescribed and hence the width of the radio-echo height distribution can be computed as a function of the atmospheric scale height Kaiser (1954*a*, 1954*b*; Weiss 1959). It was by comparing with his actual height measurements theoretical height distributions computed under this set of assumptions that Evans (1954, 1955) was able to study the properties of the atmosphere. The atmospheric scale height, however, is sufficiently well known to justify an alternative treatment of the height measurements, which is rendered more appropriate by the doubts which have arisen over the validity of the evaporation theory. In the absence of a physical theory of fragmentation the mean ionization curve (as regards both length and profile) and the dependence of the height of the trail on meteoroid mass may be regarded as free parameters. A comparison of the measured width of the radio-echo height distribution with the width computed with the above-mentioned trail characteristics (*c*) and (*d*) as free parameters should then lead to an estimate of the extent of the fragmentation amongst the sample of meteors measured.

The necessity for retention of two free parameters, and the possibility of random departures of individual meteors from the mean behaviour, are complications which effectively preclude the direct application of this procedure to the radio meteors. The random variations are important simply because a radio equipment responds only to a short segment of the meteor trail. A measurement of the height of a single echoing point tells us nothing about the height of the point of maximum brightness of the trail, the shape of the ionization curve, or the maximum brightness of the trail. This compels us to analyse the radio height data on a statistical basis, with the possibility of erroneous conclusions unless the causes of random variations and errors are scrutinized. Random departures of individual meteors from the mean height of maximum ionization may well be decisive ; random fluctuations in the shape of the ionization curve are of much less consequence.

For these reasons, it would obviously be desirable to have prior knowledge of the behaviour of these characteristics amongst the brighter photographic meteors, where the incidence of fragmentation is beyond dispute. Neither the Harvard nor the Canadian workers carried the analysis of their photographic data to this point ; they went little further than establishing that, for their samples of meteors, the trails were shorter than predicted by the evaporation theory, occurred at abnormally great heights, and were subject to random fluctuations. As already mentioned, Evans's approach to the radio-echo data was to assume the validity of the evaporation theory and then to proceed to the evaluation of the atmospheric parameters ; his numerical values were qualified by the remark that if fragmentation were widespread it seemed surprising that scale height results which were at all reasonable should be obtained.

The present paper is a comparative study of the incidence of fragmentation amongst bright and faint meteors, based on a more detailed analysis and rediscussion of the observational material obtained by Jacchia, Kopal, and Millman (1950), Evans (1954, 1955), and Hawkins and Southworth (1958). The photographic data are first analysed in detail, as regards light curves, trail lengths and heights, with particular emphasis on scatter about the mean behaviour. This is followed by the theoretical derivation of the height distribution which would be observed, by radio techniques, for a model group of meteors which exhibited these characteristics, including the scatter. This model height distribution is then compared with the actual observations of radio-echo height distributions of faint meteors. This comparison suggests that fragmentation is less marked amongst the fainter meteors.

II. Phenomenological Description of the Ablation Process for Photographic Meteors

In this section we derive a tentative phenomenological description of the observed lengths, light curves, and heights of photographed meteor trails. The analysis is based on photometric and height data for 286 sporadic and 74 shower meteors, with brightnesses extending down to a little below $M_v = +4$, as tabulated by Hawkins and Southworth (1958) ; and for 150 Draconid shower meteors, with brightnesses down to $M_v \sim +1$, measured by Jacchia, Kopal, and Millman (1950). These samples are taken to be representative of the brighter meteors.

It should be emphasized at this juncture that this description may not be suitable as the basis for a theory of fragmentation of meteoroids. Rather, the analysis is intended to enumerate those characteristics of photographed meteor trails which are relevant to the calculation of the corresponding radio-echo height distribution. These characteristics are not necessarily those which one would choose to examine preliminary to a discussion of the physical causes and consequences of fragmentation of the meteoroid.

(a) *Mean Light and Ionization Curves*

The data given are insufficient to define light curves for individual meteors, but by reducing all meteors to the same arbitrary height at maximum brightness a mean light curve may be determined. Photographic magnitude M_p is converted into intensity I by the simple relation

$$M_p = \text{constant} - 2\cdot5 \log I. \qquad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

Mean light intensity curves so obtained are sketched in Figure 1; the profiles are normalized so that plate limit corresponds to $I/I_{\text{max.}}=1$. The light curve for the sporadic meteors is designated BB, and that for the Draconid shower meteors, CC. For the sporadic meteors the level of maximum brightness above plate limit has been tabulated by Hawkins and Southworth. This quantity was not given for the Draconids, but since the observations extended over only 5 hr, plate threshold has been assumed constant and some $\frac{1}{2}$ magnitude below the faintest measured meteor.

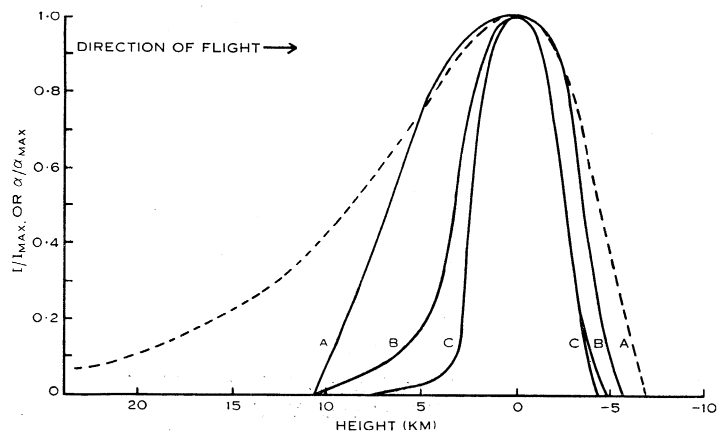

Fig. 1.—Ionization and light curves for sporadic and shower meteors. Curve AA, ionization curve proposed by Greenhow and Neufeld for faint sporadic meteors; BB, mean light curve for photographed sporadic meteors; CC, mean light curve for Draconid meteors; dashed curve, light and ionization curves predicted by evaporation theory with atmospheric scale height 6·4 km. In each case the height scale has been adjusted to height of maximum brightness as zero.

The mean ionization curve proposed by Greenhow and Neufeld (1957) for faint sporadic meteors ($+6<M_v<+8$) is also reproduced in Figure 1 (curve AA). It will be seen that the ionization curve is somewhat longer than the light curve for the photographic sporadic meteors, which are about three magnitudes brighter, but that both profiles are a good deal shorter than the prediction of the evaporation theory, namely,

$$I/I_{\text{max.}} = \alpha/\alpha_{\text{max.}} = (9/4)(\rho/\rho_{\text{max.}})(1-\tfrac{1}{3}\rho/\rho_{\text{max.}})^2 \qquad \ldots\ldots \quad (2)$$

(Herlofsen 1948). ρ is the atmospheric density and α the electron (ion) line density. The subscript " max." refers to the point of maximum electron density (and light intensity) on the trail.

The small sample of shower meteors tabulated by Hawkins and Southworth also have light curves which are shorter than predicted by (**2**). There also seem to be systematic differences between the light curves of meteors belonging to different showers. In particular, the Taurid meteors show the closest approach to the evaporation theory and the Quadrantids the largest deviations from it. However, the samples are far too small for these to be other than hints of important differences in the characteristics of meteoroids belonging to different showers.

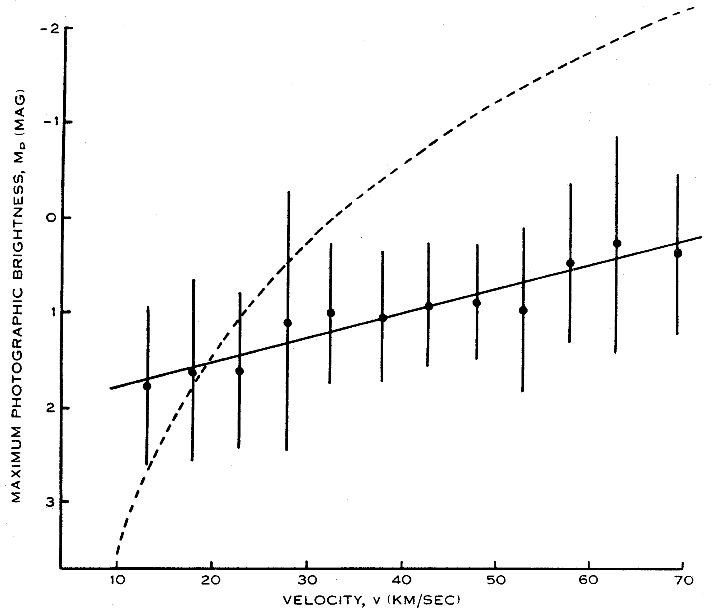

Fig. 2.—The relation between meteor velocity and photographic absolute magnitude at maximum brightness, for sporadic meteors. Vertical lines give the r.m.s. deviations of the mean brightnesses for velocity groups. The full line is the regression line for the weighted means, and the dashed curve the relation (**11**) predicted by the evaporation theory, to an arbitrary zero.

(*b*) *Heights of Maximum Brightness*

On the assumption that corrections to the observed heights of maximum brightness, $h_{\text{max.}}$, for velocity and for brightness are independent, these heights have been reduced to standard velocity and standard brightness.

For sporadics the standards are: velocity, 40 km/sec; absolute brightness $0\cdot0$ mag. The following empirical relations were determined during the course of the reduction to reduced height $h'_{\text{max.}}$ in kilometres,

$$h_{\text{max.}}=47\cdot4+12\cdot76\ln v, \qquad (3)$$

$$M_p=2\cdot04-0\cdot025v, \qquad (4)$$

$$h_{\text{max.}\,v}=93\cdot6+1\cdot22M_{Pv}. \qquad (5)$$

Here v is in km/sec, a prime indicates an observed quantity reduced to standard velocity and brightness, and the subscript v denotes reduction to standard velocity only. M_p is the absolute photographic magnitude at maximum intensity.

Relation (**3**) is given by Hawkins and Southworth. The data leading to (**4**) are summarized in Figure 2, in which individual points are the mean brightnesses for narrow velocity ranges and the regression line is determined from the weighted means. The regression coefficient in (**5**) was derived in a similar manner from the data presented in Figure 3 ; the individual points are now mean heights for narrow ranges of M_{Pv}.

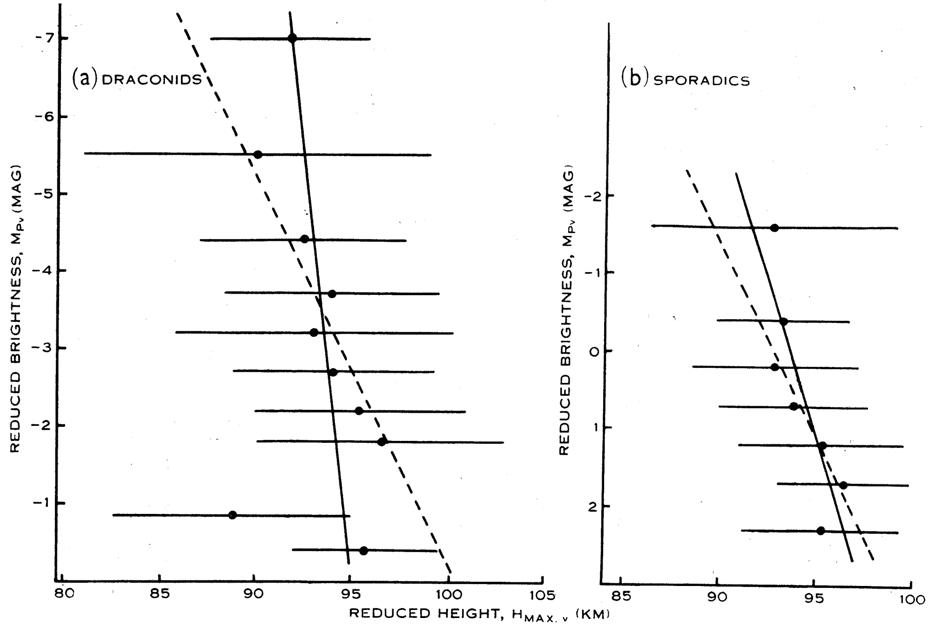

Fig. 3.—The relation between height and maximum brightness. For sporadic meteors both parameters have been reduced to the standard velocity of 40 km/sec ; for the Draconids reduction to standard velocity is unnecessary. Horizontal lines are r.m.s. deviations of the means. Full lines are regression lines for the weighted means, and the dashed lines are the relation (**12**) predicted by the evaporation theory, to an arbitrary zero.

For the Draconids (Fig. 3),

$$h_{\max.\,v} = 95 \cdot 0 + 0 \cdot 48 M_{Pv}. \qquad (6)$$

The above notation is retained although, in this case, no velocity corrections are necessary. As before, the standard brightness is $0 \cdot 0$ mag, with the proviso that the different type of plate used here may give rise to a small difference between standard brightnesses for sporadics and for the Draconids.

It is well to stress here that the empirical relations (**3**)–(**6**) apply only to the samples of photographic meteors analysed in this paper, but they are expected to be typical. After reduction to standard velocity and brightness there remains a considerable scatter in the heights of maximum brightness, whose distribution is illustrated in Figure 4. There is no dependence of this residual scatter on velocity or maximum brightness. Although such a spread is to be expected as a consequence of fragmentation, three possible causes of a spurious scatter immediately come to mind. They are : (*a*) imperfect reduction to the standard, arising from uncertainty in the regression lines in Figures 2 and 3; (*b*) the adoption of M_P as a basis for reduction to a standard meteoroid. Physically it would be more acceptable to reduce all heights to a standard mass. The distribution of trail lengths found in Section II (*c*) implies that there is no one-to-one correspondence between M_P and meteoroid mass; (*c*) a systematic change in the form of the light curve with trail length. (*a*) is proved to be negligible by the fact that the scatter in $h'_{\mathrm{max.}}$ for the Draconids is unchanged if the theoretical relation (**12**), instead of the empirical relation (**6**), is used in the reductions. (*b*) is probably responsible for the largest errors in reduction. These errors would be minimized if the integrated absolute magnitude were to be used instead of M_P. However, the Draconid data (Fig. 7) suggest that the reduction in the scatter in $h'_{\mathrm{max.}}$, which would ensue if this substitution in basic data were

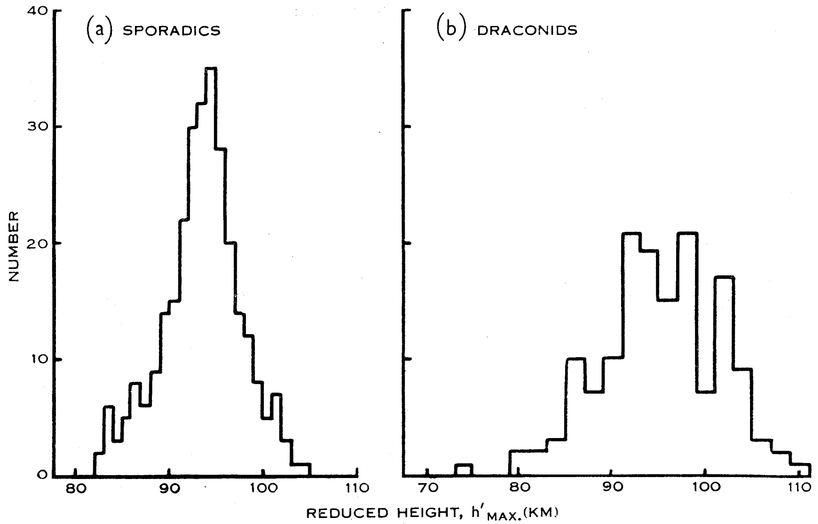

Fig. 4.—The distribution of the heights of maximum brightness, after reduction to standard velocity and standard brightness ($M_P=0$). For sporadics the standard velocity is 40 km/sec; for the Draconids reduction to standard velocity is unnecessary.

possible, cannot be very large. The spread in M_P for given integrated absolute magnitude only slightly exceeds 1 mag, which is to be compared with a total range in M_P of 8 mag. If the spread in M_P for sporadic meteors is no larger than for the Draconids, most of the residual scatter in $h'_{\mathrm{max.}}$ is undoubtedly real, and as such is characteristic of the ablation process. Figure 7 of Jacchia, Kopal, and Millman (1950), in which beginning, maximum, and end heights for individual Draconid meteors are plotted, leaves one in no doubt as to the reality of the scatter in this case.

The mean reduced height for the Draconids, 95·0 km, is close to the 93·6 km found for sporadics. The Draconid geocentric velocity (23 km/sec) is lower than the sporadic standard velocity (40 km/sec). We find using (**3**) that Draconid trails are formed, on the average, 9 km higher than sporadics of comparable brightness.

(c) *Lengths of Trails*

Observed distributions of trail lengths, defined as beginning height—end height,* are plotted in Figure 5. The abscissa is the ratio of observed length to the length expected, from the mean photographic light curves BB and CC of Figure 1, for the appropriate brightness above plate limit. This quantity will be termed the relative length of the trail. The light curve has been assumed to be independent of velocity, although this is known not to hold for the brightest meteors. Distributions for sporadics and for the Draconids are very similar, if the low velocity tail of the former is disregarded. Scatter diagrams reveal that relative trail length and reduced height $h'_{\text{max.}}$ are only weakly correlated. There is a slight tendency for relatively shorter trails to form at greater heights, but for

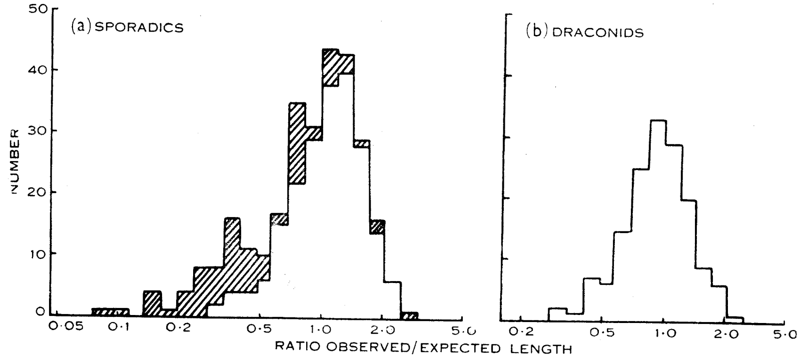

Fig. 5.—The distribution of the observed relative lengths of meteor trails. The observed relative length is the ratio of the observed length to the length expected, from the mean light curves BB or CC of Figure 1, for the appropriate brightness above plate limit. Sporadic meteors with velocities $\leqslant 20$ km/sec are indicated by cross-hatching.

practical purposes it is sufficient to regard these two properties of the trail as independent. For velocities exceeding 25 km/sec the distribution of relative trail length is independent of velocity, but as the velocity decreases below 25 km/sec the trails shorten rapidly (see Fig. 6). This may imply that extreme departures from the evaporation theory are a consequence of a long time of flight of the meteoroid, and that, on the dustball hypothesis, severe fragmentation occurs only after an appreciable time-lag, perhaps associated with thermal effects.

For the Draconids there is no correlation between relative trail length and the ratio $(h_b - h_{\text{max.}})/(h_{\text{max.}} - h_e)$ (b=beginning, e=end of trail), which suggests that there is no systematic relation between relative trail length and the form of the light curve. For sporadics, on the other hand, there is a tendency for relatively short trails to have the comparatively short, steep rise to maximum brightness which is to be expected in cases of extreme fragmentation. This

* Assuming that the light curve profile is independent of the zenith angle χ of the radiant, the true length of the trail is found by multiplication by sec χ.

discrepancy between the two groups of meteors may be real or it could be due to the small number of segments in the Draconid trails, which in many cases makes the position of maximum brightness rather uncertain.

(*d*) *Integrated Absolute Brightness of Draconid Meteors*

In addition to apparent photographic magnitude at maximum brightness (which is readily converted to absolute magnitude M_P), Jacchia, Kopal, and Millman have tabulated for the Draconids the integrated absolute magnitude, $M_i = -2 \cdot 5 \log \int I \mathrm{d}t$, to an arbitrary zero. Figure 7 is a plot of M_P versus M_i, in which trails longer and shorter than the mean length have been distinguished. Since we are dealing with a homogeneous velocity group of meteors, the influence

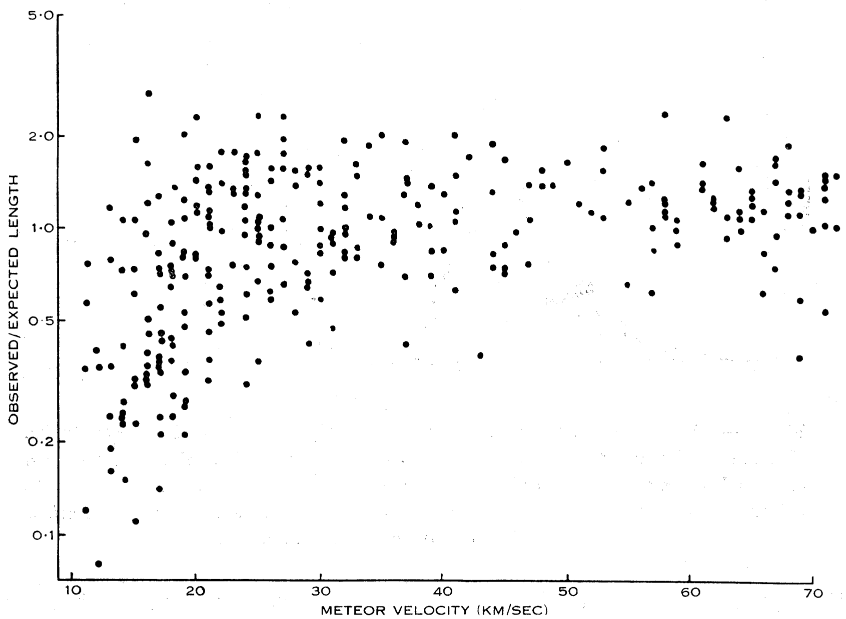

Fig. 6.—Scatter diagram of the relative trail length *v.* meteor velocity, for sporadic meteors.

of velocity on brightness does not come into consideration. If the integrated absolute magnitude M_i is taken as a measure of meteoroid mass, this diagram implies that, for given mass and velocity, a short trail is accompanied by a larger maximum brightness (smaller M_P) than a long trail.

This relation can be given a definite numerical form. Neglecting deceleration, the above definition of M_i implies that for given M_i, $\int I \mathrm{d}h$ = constant. If the shape of the light curve varies with the relative trail length l in such a way that the difference in height between any two points of equal light intensity is proportional to l, it follows that $lI_{\text{max.}}$ = constant for given M_i. This restriction on the shape of the light curve is artificial, but we may still expect that in general $lI_{\text{max.}} \simeq$ constant for given M_i. We see from Figure 5 (*b*) that for the great majority of trails $0 \cdot 4 \leqslant l \leqslant 2 \cdot 0$, i.e. l varies by a factor of 5. Now a ratio of 5 in $I_{\text{max.}}$ corresponds to a difference of $1 \cdot 75$ mag in M_P. This agrees closely with the spread actually found in M_P (Fig. 7). We conclude that almost the entire spread in M_P for given M_i is to be attributed to variations in the trail length, and that, for given mass and velocity, $\int I dh$ is independent of I_{max}.

The spread in M_P amongst the two classes of meteor, those with $l>1$ and those with $l<1$, is rather larger than expected, especially amongst the brightest meteors. This scatter could well be due to irregularities (flares) in the individual light curves, and to minor variations in the shape of the light curves for given l and M_i. It is not, however, the controlling feature in the spread of M_P for given M_i.

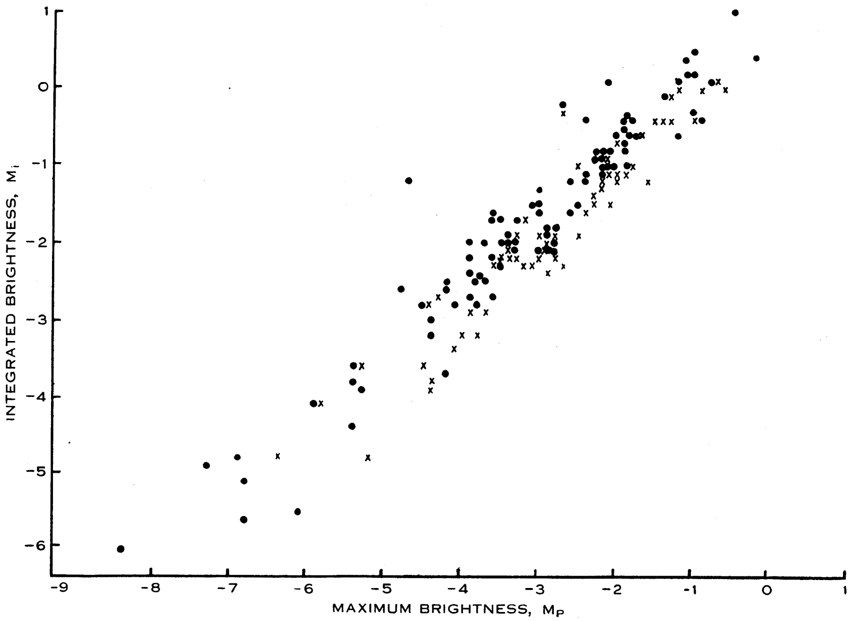

Fig. 7.—The relation between the absolute magnitude at maximum brightness, M_P, and the integrated absolute magnitude, M_i (to an arbitrary zero), Draconid meteors. ×, Trail lengths longer than the mean value for given M_P; ●, trail lengths shorter than the mean.

(e) *Remarks on the Analysis*

In their original discussions of the photographic data, both Jacchia, Kopal, and Millman, and Hawkins and Southworth stressed two aspects of the light curves, namely, the shortness of the trails and the random fluctuations which occur. The present analysis supplements the earlier conclusions and indicates the extent of the departures by individual meteors from the mean behaviour. Perhaps the most interesting new feature is the large scatter in the reduced height at maximum brightness; this is so large that it assumes considerable importance in the computation of the radio-echo height distributions for fragmenting meteoroids.

The main features of the ablation process, described above, apply equally well to sporadic meteors and to the Draconids, despite the different physical structure of the meteoroids involved. The major limitation arises from the lack of light curves of individual meteors, with the result that it has been possible to obtain only a rough qualitative estimate of the dependence of the form of the light curve on trail length. Nevertheless, it is reasonable to conclude that this description should not be modified in any essential detail by more refined observational data.

III. Comparison with Evaporation Theory

The empirical relations (**3**)–(**6**) are now compared with the predictions of the evaporation theory. If the deceleration of the meteoroid is neglected, the equations describing the relevant results of the theory for an isothermal atmosphere (see e.g. Hawkins and Southworth for a summary) are

$$\rho_{\text{max.}} \propto m^{\frac{1}{3}} v^{-2}, \qquad (7)$$

$$I_{\text{max.}} \propto m^{\frac{2}{3}} \rho_{\text{max.}} v^{5} \tau. \qquad (8)$$

$\rho_{\text{max.}}$ is the atmospheric density and $I_{\text{max.}}$ the luminous intensity at maximum brightness, m and v are the initial mass and velocity of the meteoroid, and τ is the luminous efficiency of an evaporated meteor atom. In an isothermal atmosphere of scale height H,

$$\rho_{\text{max.}} = \rho_0 \exp\{(h_{\text{max.}} - h_0)/H\},$$

and (**7**) becomes, for constant mass,

$$h_{\text{max.}} = \text{constant}^{*} + 2H \ln v. \qquad (9)$$

Hawkins and Southworth, who adopted the value of $H = 6 \cdot 38$ km established by the Rocket Panel (1952), found that (**9**) gave good agreement with their observational data.

Writing in (**8**) $\tau = \tau_0 v^{\eta}$ where $\eta \sim -0 \cdot 3$ (Weiss 1957) and using Opik's relation between visual magnitude M_v and intensity I,

$$M_v = 24 \cdot 6 - 2 \cdot 5 \log I, \qquad (10)$$

we obtain, again for constant mass,

$$M_v = \text{constant}^{*} - 6 \cdot 75 \log v. \qquad (11)$$

This is to be compared with (**4**), with M_v replaced by M_P, subject to the uncertainties associated with colour index. According to Jacchia (1957) colour index increases from $-1 \cdot 8$ mag for $M_P < -3$ to $-1 \cdot 0$ mag for $M_P = +2$, but the change in colour index is largely if not entirely physiological in origin. In any case, the discrepancy between (**4**) and (**11**) is so wide (see Fig. 2) that there is little doubt that the evaporation theory fails completely to describe the observed relation between meteor brightness and velocity.

* These constants can be evaluated from the evaporation theory if the parameters of the atmosphere and the meteoroid are specified. Their absolute values do not concern us here. With the exception of (**12**), these constant terms are a function of the mass. Since meteor mass and velocity are independent, the relations (**9** and (**11**) will still apply to the mean values of $h_{\text{max.}}$ and M_v, provided the constant is replaced by an appropriate average over all detectable meteor masses.

Eliminating the meteoroid mass from (7) and (8) gives, for constant velocity,

$$\ln I_{\text{max.}} = \text{constant*} - 3h_{\text{max.}}/H,$$

which in the notation of (5) and (6) becomes

$$h_{\text{max.}\,v} = \text{constant*} + 1\cdot96\ M_{Pv}. \quad \ldots\ldots\ldots\ldots \quad (12)$$

The observed gradients are less than required by (12), but comparison of this relation with Figure 3 shows that, for both sporadic and Draconid meteors, the central more populous points are not inconsistent with (12).

The basic equations (7) and (8) are unchanged if an atmosphere in which the scale height increases linearly with height is substituted for the assumed isothermal atmosphere (Weiss 1959). The former is a good approximation to the actual atmosphere in the meteor region. Hence the only modification required to obtain, for the actual atmosphere, the relations corresponding to (9), (11), and (12) is to replace H in (9) and (12) by the local scale height. Although significant, these alterations are not so large as to invalidate the conclusions drawn from the comparisons already made between the observations and the predictions of the evaporation theory in an isothermal atmosphere.

IV. Radio Height Measurements and the Fragmentation of Faint Meteors

We now proceed to evaluate the width of the radio-echo height distribution which would be measured for the sample of brighter sporadic meteors analysed in Section II, and to compare it with actual radio measurements of the heights of echoing points of fainter meteors. The observational data used in this comparison are the radio measurements, segregated into velocity groups, made at Jodrell Bank by Evans (1954, 1955) on sporadic meteors with $M_v \sim +6$. Evans has applied corrections for an expected error of ± 1 km in the individual height measurements, and also for the finite range of velocities included in each group.

The sample of meteors examined by Evans is very different from the samples of photographic meteors which have hitherto been considered. They are a good deal fainter and are restricted to those meteors for which both velocity and height of the echoing point could be measured. Assuming the theory of evaporation in an isothermal atmosphere, Evans deduced values of the scale height increasing from 6·2 km at a height of 85 km to 7·8 km at a height of 107 km, and atmospheric densities which agreed well with the density profile from rocket and photographic measurements of meteors obtained in New Mexico.

Since in the actual atmosphere the scale height increases with height across the meteor region, the scale heights deduced by Evans are too large. This comes about because the scale height determined for each velocity group of meteors is really an average taken over the whole spread of the heights of the echoing points of the meteors within the group. The scale height gradient, which is not considered in the isothermal theory, is thus a cause of a small additional spread in the height distributions.

* See previous footnote.

The theory of the radio-echo height distribution in a non-isothermal atmosphere, in which the evaporation theory and a linear variation of scale height with height in the atmosphere have been assumed, has been given by the author (Weiss 1959). With the aid of this theory, a reinterpretation of Evans's measurements leads to the scale height

$$H=6\cdot 1+0\cdot 06(h-95\cdot 0)\text{ km} \qquad \ldots\ldots\ldots\ldots \quad (\mathbf{13})$$

for the range of heights h from 85 to 105 km. This agrees well with the ARDC 1956 Model Atmosphere, which in the height range 90–105 km is represented approximately by the linear relation

$$H=6\cdot 4+0\cdot 09(h-95\cdot 0)\text{ km}. \qquad \ldots\ldots\ldots\ldots \quad (\mathbf{14})$$

The agreement is probably better than this, since in deriving (**13**) no allowance has been made for loss of echoes due to diffusion of the meteor trail. Diffusion will limit the number of echoes measurable in the higher height ranges, thereby reducing the measured r.m.s. deviations and mean heights for the higher velocity groups. Both mean height and height gradient in (**13**) are therefore lower limits.

Table 1

R.M.S. DEVIATIONS OF THE RADIO-ECHO HEIGHT DISTRIBUTIONS

R.M.S. Deviation	Dependence of $\rho_{max.}$ on Meteoroid Mass	γ				
		0·0*	0·2	1·0	2·0	∞†
Elementary, δx_1 ..	$m^{\frac{1}{3}}$	1·01	0·72	0·54	0·48	0·33
	m^0	1·17	0·65	0·31	0·19	0·00
Complete, δx ..	$m^{\frac{1}{3}}$	1·10	1·07	0·96	0·92	0·86
	m^0	—	0·93	0·78	0·74	0·71

* Evaporation theory.

† Trails of zero length.

Were it not for the scatter in the reduced height $h'_{max.}$ for the photographic meteors, there would be no reason to doubt that the samples of fainter meteors examined by Evans obey the evaporation theory. This scatter is, however, so large (r.m.s. deviation $\pm 4\cdot 2$ km) that if it is present amongst the samples measured by Evans it cannot fail to make a significant contribution to the observed r.m.s. deviations. The conclusion that the ablation of the fainter radio meteors is correctly described by the evaporation theory therefore cannot be accepted without further scrutiny.

Details of the calculation of the r.m.s. deviation of the radio-echo height distribution as a function of the length of the ionized trail will be found in Appendix I. The definition of trail length already given in Section II, namely, beginning height—end height, is retained. A parameter γ is introduced, in terms of which the length of the trail between the two heights where the line density $\alpha=0$ is $H \ln(1+3/\gamma)$. The complete r.m.s. deviations δx, with which the observations are compared directly, are listed in the last two lines of Table 1, for several values of γ. δx as tabulated includes the scatter in the reduced height $h'_{\max.}$.

For a trail with $\gamma=1\cdot0$, which corresponds to the mean photographic light curve BB of Figure 1, and an assumed scale height of $6\cdot4$ km, we see from Table 1 that the calculated r.m.s. deviation of the radio height distribution, δx, is $6\cdot1$ km. This is some 15 per cent. lower than the $7\cdot2$ km found by Evans (1955). This is for the case where $\rho_{\max.}\propto m^{\frac{1}{3}}$; if height is independent of mass, the deficiency of the calculated below the measured r.m.s. deviation is increased to 30 per cent. Since the photographic data suggest that the real dependence of height on mass falls between these two extremes, we may expect that the calculated r.m.s. deviation of the radio-echo height distribution corresponding to meteors brighter than $M_v\sim+4$ will fall some 20 per cent. below that actually measured for meteors with $M_v\sim+6$.

There are, however, two deficiencies in the representation of the actual photographic light curves by simplified models which will tend to reduce this discrepancy. Firstly, the value of $\gamma=1\cdot0$ was arrived at by equalizing the integrals $\int(\alpha/\alpha_{\max.})dh$ corresponding to the mean light curve BB of Figure 1 and to the adopted model (**18**). The differences in shape of the two ionization curves are not insignificant, and this may result in a slight understatement of the calculated r.m.s. deviation. Secondly, the radio height measurements do not include meteors with speeds less than 20 km/sec. It is seen from Figure 6 that about half of these very slow meteors have abnormally short trails, and consequently the adopted mean value of $\gamma=1\cdot0$ may be a little high. Against these two factors must be offset any contribution to the residual scatter in the reduced height $h'_{\max.}$ for photographic meteors which arises from irregularities and random variations in the shapes of the light curves; and also any loss of echoes by diffusion.

One other factor requires consideration. The values of δx_1 given in Table 1 were computed for an isothermal atmosphere. In fact, as we have seen, the meteor region is one in which the scale height increases quite rapidly with height. If the real gradient is approximated by the linear function (**14**), we find (Weiss 1959) that for $\gamma=0$ (evaporation theory) δx_1 should be increased from $1\cdot01$ to $1\cdot07$, i.e. by 6 per cent. For $\gamma>0$, δx_1 will require increases of approximately this same magnitude, but the increases in δx will be much less, 1 or 2 per cent. at most, because of the large correction terms in (**21**), all of which are insensitive to the scale height gradient.

Although the precise numerical evaluation of some of these corrections is difficult, not one of them is large. Collectively they seem quite inadequate to influence the first impression that the width of the radio-echo height distribution computed for sporadic meteors brighter than $M_v\sim+4$ falls considerably below that measured for fainter meteors, $M_v\sim+6$. Measured radio-echo r.m.s. deviations can be brought into agreement with predictions based on the photographic model only by assuming that the errors in the measurement of heights of individual echoing points have been grossly underestimated, by a factor of at least 4. Since this seems improbable, we may conclude that the ablation process which is typical of bright (photographic) meteors is not applicable to fainter (radio) meteors.

V. Discussion

The conclusion that the consequences of fragmentation are less marked amongst the fainter meteors is supported by other radio evidence. It is unfortunate, however, that the only radio data which might confirm the photographic evidence for fragmentation amongst bright meteors are limited and inconclusive.

On the reasonable assumption that a grouping of meteors by line densities at the reflection points is also, on the average, a grouping by absolute brightness, the variation of the height distribution with meteor brightness has been ascertained for a sample of meteors measured at Adelaide by radio techniques. In September 1953 heights and line densities were measured for 482 meteors. These have been divided into three groups, with line densities at the reflection points of $2–9\times10^{11}$, $1\cdot0–1\cdot9\times10^{12}$, and $\geqslant2\times10^{12}$ electrons/cm. Mean heights for the three groups are respectively $90\cdot6$, $91\cdot7$, and $92\cdot6$ km; r.m.s. deviations from the means are $5\cdot9$, $6\cdot8$, and $6\cdot9$ km. The increase of mean height with increasing brightness is not inconsistent with the hypothesis of an increasing severity of fragmentation, but the increase in the r.m.s. deviation is unexpected.

Evans (1955) has pointed out that estimates, by radio techniques, of the deceleration for meteoroids in the same range of brightness as those to which his height distributions apply seem to be little, if any, greater than the theoretically expected values for a solid particle.

Finally, the ionization curve of Greenhow and Neufeld (Fig. 1), although shorter than predicted by the evaporation theory, is almost twice as long as the mean light curves deduced from the samples of photographic meteors under discussion.

A difference in physical structure between fainter and brighter (and therefore more massive) meteoroids is an obvious explanation of the closer approach to the predictions of the evaporation theory shown by the former. If this is so, small meteoroids must be regarded essentially as solid particles. But this is not the only possible interpretation, and indeed it is less attractive than the alternative which is now considered.

If it is postulated that the physical structure of large and small meteoroids is identical and that they differ only in the number of particles of which they are aggregates, the difference between the ablation processes for the two classes of meteoroids may be apparent rather than real. The crumbling of a small meteoroid, composed of relatively few fragments, will be completed at a much earlier point on the flight path through the atmosphere than the fragmentation of a large meteoroid. The time-lag in the onset of fragmentation, which we have noticed as a characteristic of very slow meteors, supports this view.

The fragments into which the meteoroid is divided are individually expected to obey the evaporation theory. As is shown in Appendix I, this still implies a shortening of the ionization curve, which is the more marked the higher the density of the atmosphere at the point on the flight path where the evaporation of the fragment commences. Consequently, a small meteoroid, which fragments early in its flight, will produce a light and ionization curve conforming closely to the evaporation theory for a solid particle; the large departures from this theory shown by a massive meteoroid follow from the longer time which is required for fragmentation to be completed.

This alternative explanation requires that the individual particles composing the meteoroid be sufficiently minute.

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Appendix I

The Radio-Echo Height Distribution as a Function of Trail Length

In this appendix we derive the characteristics of the radio-echo height distribution as a function of the length of the ionized trail. Since light and ionization curves are proportional, it would be desirable to carry through these calculations using a functional representation of the mean light curves of Figure 1. This has been attempted, but the resulting mathematics is intractable. Instead, anticipating that the height distribution will be much more sensitive to the length than the shape of the ionization curve, the height distributions have been calculated for a simple model of a fragmenting meteoroid. Since our object is to compute the width of the radio-echo height distribution corresponding to the picture of a fragmenting meteoroid derived in Section II, the scatter in the reduced height $h'_{\text{max.}}$ has been incorporated into our model.

It can be shown that a particle of mass m_0 inserted at speed into an isothermal atmosphere, at a level where the density is ρ_0, produces by evaporation a trail whose maximum electron line density is

$$\alpha_{\text{max.}}=\frac{4}{9}(\beta/\mu H)m_0(1+\gamma/3)^3\cos\chi. \quad \text{..........} \quad (15)$$

This maximum occurs at the level $\rho_{\text{max.}}$ specified by

$$\rho_{\text{max.}}=\rho_1+\rho_0/3=\rho_1(1+\gamma/3). \quad \text{..............} \quad (16)$$

Here we have written $\gamma=\rho_0/\rho_1$. ρ_1 is the density at the height of maximum ionization for the same particle entering the Earth's atmosphere from outside ($\rho=0$). It is given by

$$\rho_1=\frac{8}{3}\left(\frac{3}{4\pi}\right)^{\frac{1}{3}}\frac{\rho_m^{\frac{2}{3}}l\cos\chi}{Hv^2\Lambda}m^{\frac{1}{3}} \quad \ldots\ldots\ldots\ldots\ldots \quad (\mathbf{17})$$

for a spherical particle; if the particle is not spherical, a shape factor of order unity must be included in (**17**). The meaning of the symbols employed is as follows:

ρ_m = density of meteor particle,
v = meteor velocity,
μ = mass of individual meteor atom,
χ = zenith angle of meteor radiant,
H = scale height of isothermal atmosphere,
β = ionizing efficiency of an evaporated meteor atom,
l = latent heat of evaporation of the meteoroid,
Λ = heat transfer coefficient.

The usual assumptions, that the deceleration of the particle is negligible, and that $v^2\gg 12l$, have been made. These are valid for all but the slowest meteors.

The ionization curve generated by this particle is

$$\left.\begin{aligned}\alpha&=0, && \rho<\gamma\rho_1\\ &=(\beta/\mu H)\cos\chi\, m_0\frac{\rho}{\rho_1}\left(1+\frac{\gamma}{3}-\frac{\rho}{3\rho_1}\right)^2, && \gamma\rho_1\leqslant\rho\leqslant(3+\gamma)\rho_1.\end{aligned}\right\} \quad \ldots \quad (\mathbf{18})$$

Provided that the particle mass m_0 is replaced by the meteoroid mass m, expressions (**15**)–(**18**) will describe the simple case of a meteoroid for which ablation is negligible until the meteoroid fragments, at the level specified by ρ_0, into a number of particles, all of mass m_0, which individually obey the evaporation theory.

The length of the meteor trail, defined as the difference in height between the two points where $\alpha=0$, is $H\ln(1+3/\gamma)$, independent of the zenith angle χ. The total number of ions generated by the meteoroid is independent of the length of trail, as may be verified by evaluating the integral

$$\int_{-H\ln(3+\gamma)}^{-H\ln\gamma}\alpha\,\mathrm{d}h=\frac{\beta m}{\mu}.$$

The ionization curve (**18**) exhibits a progressive shift of the position of maximum ionization towards the end of the trail as the trail shortens. These last two properties are characteristic of the observed photographic light curves.

Consider now the case of a homogeneous velocity group of meteors proceeding from a point radiant. Using the ionization curve (**18**) and following through the analysis of Kaiser (1954*a*), we find for the elementary height distribution υ^*, measured within a narrow angular sector of the echo plane,

$$\upsilon^*=\left(\frac{3}{2z^{-\frac{1}{2}}+z}\right)^{3(s-1)}-\left(\frac{3\gamma}{(3+\gamma)z}\right)^{3(s-1)}, \quad \ldots\ldots\ldots \quad (\mathbf{19})$$

with

$$z=\rho/\rho_1\geqslant(2\gamma/3)^{\frac{2}{3}}.$$

s is the mass distribution parameter, assuming a differential law $n_m dm \propto m^{-s} dm$ for the distribution of meteoroid masses. The first term of (**19**) is identical with the elementary height distribution according to the evaporation theory. The second term is introduced by the finite length of the trail, since for any given height there is now a maximum detectable mass as well as a minimum detectable mass.

Alternatively, we may consider the case in which the ionization curve is described by (**18**), but with $\rho_{\max.}$=constant replacing $\rho_{\max.} \propto m^{\frac{1}{3}}$. The elementary height distribution then becomes

$$\upsilon^* = \left\{ z^{1/2}\left(1+\frac{\gamma}{3}\right) - \frac{z^{3/2}}{3} \right\}^{2(s-1)}, \quad \gamma \leqslant z \leqslant 3+\gamma. \qquad \ldots\ldots \quad (\mathbf{20})$$

Let us now introduce the new height variable

$$x_1 = -\ln z = (h-h_1)/H,$$

h_1 being the height corresponding to the density ρ_1. R.M.S. deviations δx_1 of the height distributions (**19**) and (**20**) have been computed for $s=2\cdot0$, which is the accepted value for fainter sporadic meteors (Kaiser 1954*b*). This value of s is probably a lower limit, since Hawkins and Upton (1958) found $s=2\cdot34$ for the sample of photographic meteors analysed in Section II. These values of δx_1 are listed in Table 1 for several values of γ. $\gamma=0\cdot2$ and $\gamma=2\cdot0$ correspond roughly to the longest and shortest trails measured photographically for meteors with velocities greater than 20 km/sec. This cut-off in velocity has been imposed to conform to the lowest velocity group studied by Evans.

Before these r.m.s. deviations can be compared with the observations, corrections are necessary for (*a*) the spread in heights introduced by the finite aperture of the aerial, (*b*) the distribution of radiants over the celestial sphere, and (*c*) the scatter in the reduced heights (Fig. 4), which is approximately Gaussian. The complete r.m.s. deviation δx is found from

$$(\delta x)^2 = (\delta x_1)^2 + C_A + C_\varphi + C_\chi + R^2. \qquad \ldots\ldots\ldots\ldots \quad (\mathbf{21})$$

C_A and C_φ are the corrections for aerial polar diagram in azimuth and in elevation. They are given respectively by expressions (**16**) and (**20**) of Kaiser (1954*b*). In the present case they have been computed for a double Gaussian aerial beam; with $s=2\cdot0$, $C_A=C_\varphi=0\cdot06$. For the height distribution (**20**), of course, the aerial aperture can contribute no additional spread, and these corrections vanish. C_χ is the correction from a point radiant to the uniform distribution of radiants which is simulated by observation over an extended period. It is given by expression (**9**) of Kaiser (1954*b*); again with $s=2\cdot0$, $C_\chi=0\cdot08$. The r.m.s. deviation of the residual scatter in reduced height (Fig. 4 (*a*)) is 4·2 km, and with $H=6\cdot4$ km, $R=0\cdot66$.

Complete r.m.s. deviations δx are also listed in Table 1. These are the values with which the observations are to be compared. The corrections for aerial polar diagram and for the radiant distribution are sufficiently small that uncertainty in these geometrical factors is of little account.