THE INCIDENCE OF METEOR PARTICLES UPON THE EARTH

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Summary

Radio echo rates for both shower and sporadic meteors, measured at Adelaide with the 27 Mc/s C.W. equipment, are applied to the calculation of the incident flux of meteors above limiting brightnesses in the range $M_R < +7 \cdot 5$. On the hypothesis of a strongly velocity-dependent ionizing probability, reached after a critical evaluation of the observational material, the meteor flux above prescribed limiting meteor particle masses, and the space densities of meteor particles, are also calculated. These fluxes and densities agree reasonably well with independent evaluations from visual meteor rates. The amount of meteoric matter falling on the whole Earth per day within particle mass limits 10^{-1} to 10^{-4} g, for sporadic meteors and some showers, is also estimated.

I. Introduction

This paper is the third of a series dealing with meteor observations at Adelaide with the 27 Mc/s C.W. equipment. Paper I (Weiss 1957*a*) discusses the sporadic background. Paper II (Weiss 1957*b*) is concerned with shower meteors and presents an overall picture of the meteor activity. The present paper, based on the data of the preceding two, deals with the influx of meteor particles over the whole surface of the Earth, and with their density in space.

Meteors are counted by radio equipments in terms of the line density or the equivalent radio brightness—an equipment will detect in a given direction all meteors which satisfy the geometrical conditions for specular reflection and whose line densities exceed the threshold appropriate to the equipment. Similarly, visual observers record all meteors above the visual threshold brightness which fall within a prescribed field of view. These brightness counts are not necessarily simply related to the total influx of meteors above a prescribed radio brightness (because of the influence of aerial aperture and polar diagram, and trail aspect) or a prescribed visual brightness (visual aperture and subjective factors), nor to the total influx of meteors above a prescribed limiting mass.

Several estimates have been made (Kaiser 1955, p. 119; Levin 1955; Hawkins 1956*b*; Davies 1957) of the number of meteor particles, above a given limiting brightness, radio or visual, falling on the whole Earth. Meteor brightness is directly measurable, and the above estimates of the numbers of incident particles and the flux found from the Adelaide counts are reasonably concordant. The extension of these results to the determination of the influx of meteors above a prescribed limiting mass, or of the density of meteor particles in space, can

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only be made if the ionizing probability and the luminous efficiency, i.e. the efficiencies of production of free electrons and radiation, are known. This further analysis has been made for the visual counts by Levin, who concluded that the maximum particle densities in shower orbits are considerably lower than the density of sporadic meteors. Although the question of the dependence of ionizing probability upon meteor velocity is not fully resolved, there is a growing body of evidence which suggests that this parameter is strongly dependent on meteor velocity. Interpretation of the Adelaide radio counts on this basis leads to the conclusion already reached by Levin from the visual data: above the limiting mass corresponding to the visual threshold brightness for a meteor with a velocity of 60 km sec^{-1}, the sporadic meteor density is higher than that in the most dense portions of all the major day-time and night-time meteor streams.

This agreement is, in itself, rather convincing evidence for the correctness of the forms of velocity dependence, weak for luminous efficiency and strong for ionizing probability, which emerge from the discussion of the relevant observational material in Section V.

II. The Brightness and Mass Distributions

The maximum value of the line density of electrons in the meteor trail is

$$\alpha_{\text{max.}} = (4/9\mu H) m \beta(v) \cos \chi, \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where χ is the zenith angle of the radiant, μ the atomic weight of the (average) meteor atom, H the atmospheric scale height, and $\beta(v)$ the ionizing probability, i.e. the probability that a single evaporated meteor atom will produce a free electron. The analogous parameter in visual detection is the luminous intensity I. According to Levin (1955) the brightness estimated by a visual observer may characterize some average luminous intensity $\bar{I} \propto (I_{\text{max.}})^x$, $\frac{1}{2} < x < 1$. However, Browne *et al.* (1956) find $x \sim 1$ and it is sufficient to put $x = 1$. Then the maximum value of the luminous intensity is

$$I_{\text{max.}} = \text{const. } m v^3 \tau(v), \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where $\tau(v)$ is the luminous efficiency, i.e. the fraction of the total energy dissipated which is emitted as visible radiation. The velocity-dependence of the parameters β and τ is examined in Section V. In the meantime, attention may be drawn to the factor v^3 which already appears in (2).

The visual and radio brightnesses are now, as usual, taken to be

$$M_V = \text{const.} - 2 \cdot 5 \log_{10} I_{\text{max.}}$$
$$M_R = \text{const.} - 2 \cdot 5 \log_{10} \alpha_{\text{max.}}$$

The frequency distribution of both radio and visual magnitudes will be assumed to have the form

$$\nu_M \propto a^M, \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where $\nu_M dM$ is the incident flux of meteors with magnitudes between M and $M+dM$. The corresponding flux of meteors with masses between m and $m+dm$ is then assumed to be

$$\nu_m dm \propto m^{-s} dm, \qquad (4)$$

where $s=1+2\cdot 5 \log_{10}a=1+\chi$, if $\chi=2\cdot 5 \log_{10}a$.

Detailed investigations of the structures of several showers by Browne *et al.* indicate that the distributions (3) and (4) do not hold exactly over extended ranges of brightness and mass. They do, however, form a useful first approximation, and in the present paper mass distributions are, with one exception, discussed with s=constant over the range of interest. Values of s adopted for showers are listed in Table 1. For sporadic meteors $s=2\cdot 0$.

III. Shower Meteor Flux above a Prescribed Radio Brightness

From equations (1) and (4), assuming β to be independent of the mass m, the incident flux of meteors, across unit area of a plane normal to the meteor paths, with zenithal line densities greater than $\alpha_z=\alpha_\theta/\cos\chi$, is

$$\Theta(\alpha_z)=\{C/(s-1)\}\alpha_z^{1-s}. \qquad (5)$$

The zenithal line density is the maximum number of electrons per unit length which the meteor would produce if it travelled vertically downwards. α_θ is the minimum detectable line density in the direction θ, which is the direction of the reflection point of the meteor trail in the echo plane, following the geometry and notation of Kaiser (1955, p. 119). From (5) it follows that

$$\Theta(\alpha_\theta/\cos\chi)=\Theta(\alpha_0/\cos\chi)(\alpha_0/\alpha_\theta)^{s-1},$$

where α_0 is the minimum detectable line density on the axis of the aerial beam, which for the Adelaide equipment is directed to the zenith.

Kaiser (loc. cit.) has given expressions for the total radio echo rate in terms of the equipment geometry and parameters, and the incident flux. Shower fluxes have been computed using these expressions and the radio counts at zenith angles $\chi=70°$ given in paper II. At this zenith angle collection is confined to the major lobe; the limiting sensitivity contours are given in paper I. A horizontal collecting surface for meteors, at a height of 90 km, has been assumed; this introduces an error of less than 1 per cent. The further approximation is made that only short, decay type echoes are observed ($\alpha<2\times 10^{12}$ cm^{-1}); this is true over most of the major lobe.

With these approximations, the echo rate integrated over the whole aperture of the major lobe is

$$N_{\chi=70°}=\Theta(3\cdot 5\times 10^{11})\,.\,1500I(s), \qquad \textbf{(6a)}$$

$$I(s)=(s-1\cdot 14)^{-\frac{1}{2}}\int_{\substack{\text{major}\\ \text{lobe}}}(\alpha_0/\alpha_\theta)^{s-1}\cos^{-2}\theta\,d\theta. \qquad \textbf{(6b)}$$

The integral (**6b**) is illustrated in Figure 1. For a given flux Θ the echo rate is evidently quite sensitive to the mass distribution within the stream.

TABLE 1

SHOWER METEOR FLUXES AND STREAM DENSITIES

Shower	Observed Velocity v (km sec^{-1})	Radio s	Visual χ*	Hourly Rates			Fluxes above Limiting Brightness (km^{-2} sec^{-1})		Fluxes above Limiting Mass (km^{-2} sec^{-1})		Stream Densities (km^{-3})	
				Radio		Visual*						
				J.B.R.	A.W.		$\Theta(10^{12})$ $\times 10^8$	$\Theta(4\cdot3)$ $\times 10^8$	$\nu(10^{12})$ $\times 10^8$	$\nu(4\cdot3)$ $\times 10^8$	$D(10^{12})$ $\times 10^8$	$D(4\cdot3)$ $\times 10^8$
Perseids ..	60	1·6	1·0	47		55	58	310	58	310	1·0	5·1
Geminids ..	36	1·7	1·3	70	24	60	110	330	470	2500	13	68
Quadrantids ..	40	1·8	1·0	92		40	78	220	290	760	7·	19
Arietids ..	38	2·5	—	61	24		100		1600		41	
ζ-Perseids ..	29	2·5	—	40	16		67		5200		180	
		2·0					81		1500		51	
δ-Aquarids ..	40	2·5	1·4		23		140		1600		41	
		2·0					150		780		20	
		1·75					150		500		13	
η-Aquarids ..	64	2·0	0·9		11	36	72	200	56	170	0·9	2·6
Orionids ..	66	2·5	1·5		14	10	86	56	49	37	0·7	0·6
		2·0					95		65		1·0	

* After Levin.

Using (**6**) and the average echo rates at maximum activity given in paper II, the following fluxes are obtained :

Geminids	$\Theta(\alpha)=3\cdot6\times10^{2}\ \alpha^{-0\cdot7}$ km^{-2} sec^{-1}
June day-time showers	$=2\cdot4\times10^{12}\alpha^{-1\cdot5}$
and in general	
$s=1\cdot5$	$\Theta(\alpha)=5\cdot3\times10^{-8}(10^{-12}\alpha)^{-0\cdot5}N$ km^{-2} sec^{-1}
$2\cdot0$	$=6\cdot7\times10^{-8}(10^{-12}\alpha)^{-1\cdot0}N$
$2\cdot5$	$=6\cdot1\times10^{-8}(10^{-12}\alpha)^{-1\cdot5}N$

Zenithal line densities (the suffix z has been dropped) are measured in electrons cm^{-1}. These figures may be compared with some reductions by Kaiser of radio counts made at Jodrell Bank with a wide-aperture aerial system. Small

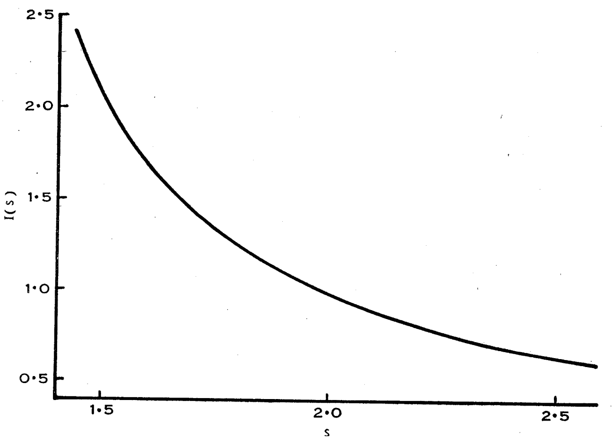

Fig. 1.—The dependence of the shower echo rate upon the mass-distribution parameter s, for the Adelaide 27 Mc/s equipment.

corrections have been made to bring some of the parameters into agreement with those adopted for the reduction of the Adelaide counts. The amended fluxes are :

Geminids	$\Theta(\alpha)=1\cdot9\times10^{2}\ \alpha^{-0\cdot7}$ km^{-2} sec^{-1}
Perseids	$=3\cdot4\times10^{4}\ \alpha^{-0\cdot6}$
June day-time showers	$=1\cdot0\times10^{12}\alpha^{-1\cdot5}$

There appears to be a systematic difference between estimates of the same flux arrived at using the two different equipments. This is undoubtedly due to interaction of the approximations made upon the respective geometries, together with uncertainty in the absolute limiting sensitivities of the two equipments.

Data relating to some of the more active showers are listed in Table 1. A division of the composite day-time activity between the Arietids and the ζ-Perseids has been made on the basis of the Jodrell Bank echo rates obtained with the 72 Mc/s radiant equipment. The values of the mass-distribution parameters s for the last four showers are not known and several possible values are used. The Quadrantid flux has been estimated by comparing radio echo rates (72 Mc/s radiant equipment at Jodrell Bank) for Perseids and Quadrantids. The Perseid flux is known from Kaiser's reductions, and the geometry for the two showers in the Jodrell Bank equipment will be almost identical, as the two radiants transit at the same elevation and the streams have very similar mass distributions. The Quadrantid flux is thus found to be

$$\Theta(\alpha)=3\cdot1\times10^{3}\alpha^{-0\cdot8}\ \mathrm{km^{-2}\ sec^{-1}}.$$

The fluxes $\Theta(10^{12})$ in Table 1 are estimates of the numbers of meteors ($\mathrm{km^{-2}\ sec^{-1}}$) whose zenithal line densities exceed 10^{12} electrons $\mathrm{cm^{-1}}$, crossing a plane normal to the meteor paths. Fluxes calculated for the same shower from counts made with different equipments may differ by factors of 2 or so. This discrepancy is satisfactorily small.

An examination of the effects of non-uniform s upon the calculated fluxes has been made for the Geminids, a typical stream for which s decreases from $2\cdot3$, for $+2>M_R>0$, to $1\cdot45$ at $M_R=7\cdot0$. It appears that $\Theta(10^{11})$ for this stream, if calculated from the constant value of $s=1\cdot7$, will be overstated by about 30 per cent., whereas $\Theta(10^{12})$ will be correct. For the Arietids, for which s appears to increase towards fainter radio brightnesses (decreasing α), the assumption of uniform s will of course result in $\Theta(10^{11})$ being understated. Because of these errors it seems wise to confine the use of the flux expressions derived in this section to line densities above 10^{11}, $M_R<+7\cdot5$.

Some visual data, as reduced by Levin (1955), are also given in Table 1. Comment on these is deferred until Section VI.

IV. Sporadic Meteor Flux above a Prescribed Radio Brightness

(a) *Isotropic Distribution of Radiants*

Following Kaiser, denote by $\Theta(\alpha_z)\mathrm{d}\omega$ the flux, across unit area of a plane normal to the meteor paths, of sporadic meteors with line densities greater than α_z, whose radiants lie within an element of the celestial sphere of solid angle $\mathrm{d}\omega$. This form for the sporadic flux, derived from (1) and (4), applies in the presence of an extended velocity distribution provided this distribution is independent of radio brightness, as it appears to be. The mean, taken over the whole Earth, of the sporadic meteor flux through a horizontal plane from above, is

$$\Theta_1(\alpha_z)=\tfrac{1}{4}\int_{4\pi}\Theta(\alpha_z)\mathrm{d}\omega,$$

and, if Θ is isotropic, $\Theta_1=\pi\Theta$.

Although sporadic radiants are known to be anisotropically distributed over the celestial sphere, it is convenient as a first step to derive from the Adelaide sporadic echo rate a sporadic flux Θ on the assumption that Θ is isotropic. Using Kaiser's expression for the total sporadic echo rate, assuming circular symmetry for the aerial polar diagram (east-west traverse) and putting $s=2\cdot 0$, the total sporadic echo rate is found to be

$$N=17800\Theta(\alpha_0)(I_M+\tfrac{2}{3}I_m),$$

$$I_M=\int\limits_{\substack{\text{major}\\ \text{lobe}}}(\alpha_0/\alpha_\varphi)\cot^2\varphi\, d\varphi=0\cdot 057,$$

$$I_m=\int\limits_{\substack{\text{minor}\\ \text{lobe}}}(\alpha_0/\alpha_\varphi)\cos^2\varphi F(\varphi)d\varphi=0\cdot 053.$$

φ is the elevation of an element of the aerial beam and

$$F(\varphi)=(R/h)(R/R_e+\sin\varphi)^{-1},$$

with R=slant range, h=mean height of reflection points=90 km, and R_e=radius of the Earth. The factor $\frac{2}{3}$ has been introduced to compensate for the departure of the minor lobe from the assumed circular symmetry. From paper I, $N\sim 10$ hr^{-1}, so that

$$\Theta(\alpha)=1\cdot 2\times 10^5\ \alpha^{-1}\ \text{km}^{-2}\ \text{sec}^{-1},$$
$$\Theta_1(\alpha)=3\cdot 8\times 10^5\alpha^{-1}. \qquad (7)$$

This sporadic flux agrees well with some values derived by Kaiser, also on the assumption of a uniform geocentric distribution of radiants. These are $1\cdot 4$, $3\cdot 6$, and $4\cdot 2\times 10^5\ \alpha^{-1}$ for Θ_1. It is considerably smaller than the flux arrived at by Hawkins (1956*b*), $1\cdot 2\times 10^6\alpha^{-1}$, from the Jodrell Bank radio surveys. Hawkins uses an indirect method, based on echo durations, for the determination of the limiting sensitivity of the Jodrell Bank equipment and applies large corrections for radiants outside the sensitive sector of the aerial. In the case of the Adelaide equipment, with spaced transmitter and receivers and deliberate leakage of ground wave into the receivers, direct calibration of the minimum recorded echo power, which lies far above noise level, has been made ; and the correction for aerial aperture is much smaller. For these reasons and because of the good agreement with Kaiser's values, the value of $\Theta_1(\alpha)=3\cdot 8\times 10^5\alpha^{-1}$ km^{-2} sec^{-1} is used elsewhere in this paper for the sporadic flux.

(*b*) *Non-isotropic Distribution of Radiants*

One useful example of a non-isotropic geocentric distribution of sporadic radiants is easily discussed. Let the radiants be uniformly distributed within a narrow strip of the celestial sphere, of constant angular width ψ and centred on a great circle (Fig. 2). Echoes from a radiant at any point R within this strip will be received from all angles θ in the echo plane. The relative echo rate as a function of the zenith angle of the radiant has already been computed in paper I, and if this relative echo rate be denoted by Z,* the total echo rate from a strip at elevation $90-\varphi$ is proportional to

$$\iint\limits_{\text{strip}} Z d\psi d\xi.$$

* Expression (6) of paper I for the function $Z(\chi)$ has been evaluated without regard to the actual height distribution of reflection points ; this may be taken into account by division by $(R/R_e+\sin\varphi)$ under the integral sign in (6) of paper I. This correction is negligibly small in the applications of this function Z made here and in paper I.

Strip echo rates obtained in this way may be normalized to the absolute values of the preceding section by performing similar calculations for sectors bounded by great circles. The echo rate from such a sector is proportional to

$$\iint_{\text{sector}} Z \cos \xi d\psi d\xi,$$

and summation over all sectors, normalized to the isotropic flux (7), should reproduce the observed echo rate.

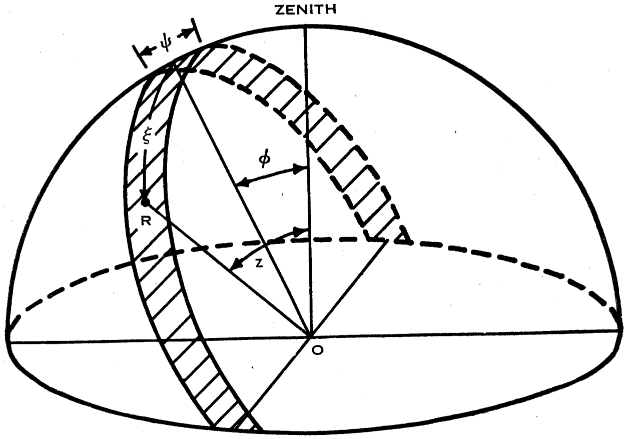

Fig. 2.—Geometry for assumed non-isotropic distribution of sporadic radiants.

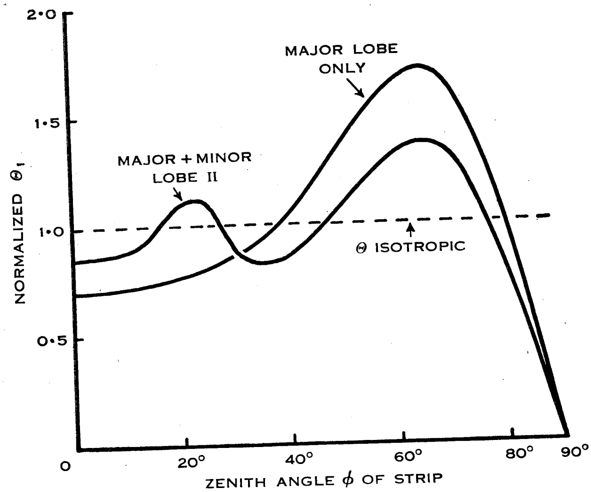

Fig. 3.—Normalized average sporadic meteor fluxes Θ_1 as a function of strip zenith angle φ.

Values of Θ_1 for two possible aerial patterns—major lobe alone, and major lobe+minor lobe II (see paper I)—normalized to Θ_1 (isotropic)$=1$, are shown in Figure 3. Further averaging of the echo rates for narrow strips within the range $10° < \varphi < 60°$ will lead to the value of Θ_1 to be expected from a concentration of sporadic radiants to the plane of the ecliptic, or to the apex of the Earth's way, when averaged over the whole year. These normalized estimates of Θ_1 are: major lobe alone, $1\cdot02$; major lobe+minor lobe II, $1\cdot05$. The resultant flux is clearly insensitive to the finer detail of the aerial pattern.

This conclusion, that the sporadic echo rate averaged over the whole year is almost independent of the source distribution and depends only on the average flux across unit horizontal surface averaged over the whole surface of the Earth, has been reached using the Adelaide equipment. It is expected to apply to any equipment with a wide-aperture aerial system directed not too far from the zenith. With this assurance, the value $\Theta_1\,(10^{12})=38\times10^{-8}\,\mathrm{km}^{-2}\,\mathrm{sec}^{-1}$ may be adopted as the best estimate from all sources. Since the rate of incidence of meteors upon the whole surface of the Earth is proportional to $\pi R_e^2\Theta$ for showers and to $4\pi R_e^2\Theta_1$ for sporadics, the incidence upon the whole Earth of meteors brighter than $M_R=5$ ($\alpha=10^{12}$) is approximately the same for shower meteors and for sporadic meteors, with sporadics perhaps slightly more numerous.

V. Luminous Efficiency and Ionizing Probability

A good deal of information bearing on the question of these parameters, respectively τ and β as defined in Section II, is scattered throughout the literature. It is intended in this section merely to summarize the conclusions reached by a critical evaluation of this material. Several relevant articles appear in the report of the symposium on meteor physics held at Jodrell Bank (Kaiser 1955); other important references are Greenhow and Hawkins (1952), Millman (1956), and Hawkins (1956*a*).

There is some measure of agreement on the dependence of τ upon velocity, but its absolute value is not well known. Photographic results suggest that for bright meteors ($M_V<0$) $\tau\propto v$, whilst for fainter meteors ($M_V>0$) τ is almost independent of v. Absolute values of τ have usually been taken in the range $0\cdot001<\tau<0\cdot01$; photographic decelerations of 11 bright Perseid meteors (mean $M_V=-3$) give, with some scatter, $\tau\sim0\cdot01$. These absolute values, and the influence of the mass of the meteor upon the velocity-dependence of τ, receive some theoretical support from Opik's treatment, and the following expressions for the luminous efficiency have been adopted:

$$\tau=8\cdot5\times10^{-5}v,\qquad M_V<0,\qquad\ldots\ldots\ldots\ldots\quad\textbf{(8a)}$$

$$=2\cdot1\times10^{-3}v^{-0\cdot3},\qquad M_V>0,\qquad\ldots\ldots\ldots\ldots\quad\textbf{(8b)}$$

if v is in $\mathrm{km\,sec^{-1}}$.

Several estimates of the ionizing probability β for Perseid meteors have been made. These fall in the range $0\cdot2<\beta<1$. With one exception, these estimates have been obtained by prior evaluation of the ratio τ/β. The exception is McKinley's bright Perseid ($M_R\sim-3\cdot5$) which leads to the highest value, $\beta\sim1$. The dependence of β upon velocity has been estimated from radio-visual correlations for Perseid and Geminid meteors, independently by Hawkins and by Evans and Hall using different material. The two estimates are reasonably concordant, and may be averaged to give

$$\tau/\beta=1\cdot6\times10^{5}v^{-4\cdot3},$$

which implies, with τ appropriate to fainter meteors (expression (**8b**)) and v in km sec^{-1},

$$\beta=1\cdot3\times10^{-8}v^4. \qquad (9)$$

For Perseid meteors ($v=60$) this gives $\beta=0\cdot17$, in satisfactory agreement with the estimates of β given above. Millman and Whipple advance other evidence, based respectively on echo durations and on the ratio of radio to photographic meteor counts, which supports the value 4 for the exponent in (**9**). It should, however, be mentioned that an indirect determination of this exponent, made by Evans and Hall and based on the theory of the height distribution of sporadic meteors, suggests that β should be, at most, weakly dependent upon velocity. This approach has been criticized by Whipple and by Hawkins (1956*a*), who consider that further study is necessary before this method can be considered reliable.

In accepting (**9**) for the form of dependence of the ionizing probability upon velocity, two reservations must be made. Firstly, according to Millman τ/β is roughly constant for Perseid meteors in the range $-5<M_V<+5$. This, with the relations (**8**), implies a dependence of β upon the meteor mass which has not been taken into account in the formulation of (**9**). As the radio data are largely confined to fainter meteors, this reservation may not be serious. Of greater consequence is the limited velocity range upon which the derivation of (**9**) depends : the power law dependence of β upon v is assumed and the value of the exponent determined from two points only, $v=60$ (Perseids) and $v=36$ (Geminids). For shower meteors, with $66\geqslant v\geqslant 29$, (**9**) should give a fair representation of β ; but a large extrapolation is involved in the application of this relation to sporadic meteors, for which $72\geqslant v\geqslant 12$.

VI. Meteor Fluxes above a Limiting Mass

Before proceeding to an examination of the consequences of a velocity-dependent ionizing probability on the derived meteor flux, it is well to reiterate that the results of Sections III and IV dealing with directly measurable brightness limits are not influenced by the reservations imposed by the uncertainty in either the absolute value or the velocity-dependence of this probability. The only requirement is that the velocity distribution, amongst sporadic meteors or amongst the particles of a given stream, should be independent of the brightness. If it is accepted that luminous efficiency and ionizing probability are different functions of velocity, direct comparisons of visual and radio fluxes above corresponding limiting visual and radio brightnesses are precluded. The physically significant comparisons are those between visual and radio estimates of the numbers of particles incident on the whole Earth, for different showers and for sporadic meteors, within definite ranges of mass, or above a prescribed limiting mass.

(*a*) *Shower Meteors*

Denote by $m(\alpha)$ the mass of a meteor, with datum velocity $v=60$ km sec^{-1}, which produces a trail whose maximum line density is α ; $m(\alpha)$ is termed the limiting mass. Then the flux of meteors, per unit area across a plane normal to the meteor paths, with masses exceeding $m(\alpha)$, is from (**5**) and (**9**),

$$\nu(\alpha)=\Theta(\alpha)(60/v)^{4(s-1)}. \qquad (\mathbf{10})$$

The velocity appropriate to equation (**10**) is the observed geocentric velocity v, in the terminology of Lovell (1954, p. 90). Fluxes $\nu(10^{12})$ so obtained are enumerated in Table 1.

For visual data, the expression analogous to (**10**) is

$$\nu(M_V) = \Theta(M_V)(60/v)^{3\chi},$$

as adopted by Levin (1955) with τ independent of v, in close agreement with (**8b**). For the data collected by Levin, $M_V = 4\cdot 3$ and rates are corrected to a radiant at the zenith; the datum velocity has been increased to 60 km sec^{-1} to facilitate comparison with the radio data. Fluxes $\nu(4\cdot 3)$ are also given in Table 1.

With the exception of the Orionids, for which the Adelaide radio rates may be overstated, the visual fluxes are consistently higher than the radio fluxes, by factors of from 3 to 5. The disagreement is rather larger than the dispersion amongst the radio fluxes for a given shower. Moreover, it is usual to consider that $\alpha = 10^{12}$ corresponds to $M_V = +5\cdot 0$; on this basis $\nu(4\cdot 3)$ should never exceed $\nu(10^{12})$ and the discrepancy is further increased. One simple way of resolving this discrepancy would be to increase the field of view proposed by Levin for the visual observations. For instance, a field 90° in diameter, at an altitude of 90 km, with an area of 25,000 km^2, is not unreasonable and would go far towards bringing the visual and radio fluxes into agreement.

The s-value for the δ-Aquarids is unknown. From a comparison of orbits and shower durations there is reason to believe that the δ-Aquarids and the day-time Arietids are two manifestations of the same meteor stream. It is interesting to note that if the value of $s = 2\cdot 5$ found for the Arietids is applied to the δ-Aquarids, the fluxes $\nu(\alpha)$ for the two showers are identical. Measurement of the s-value for the δ-Aquarids should suffice to confirm the identity of these two streams.

(*b*) *Sporadic Meteors*

Following Levin, define by $\delta(\alpha)$ the density on the celestial sphere of the true individual radiants of sporadic meteor particles with masses exceeding $m(\alpha)$, i.e. the number of particles which are travelling in unit time onto unit area normal to the flux and stationary with respect to the Sun. As before, $d\omega$ denotes an element of the geocentric celestial sphere at apparent elongation ε from the apex, and let $d\omega_0$ be the element of the heliocentric celestial sphere at true elongation ε_0. $\bar{V}$ is the heliocentric velocity of the meteor, and v the observed velocity, which may be distributed. It is assumed that $\bar{V}$ is the same for all sporadic meteors; the extension of the treatment to a distribution of velocities is readily made and involves no new principle. Then

$$\delta(\alpha) = \Theta(\alpha)(d\omega/d\omega_0)(\bar{V}/v).$$

The apparent flux of sporadic meteors above the limiting mass $m(\alpha)$ passing through unit horizontal surface from above is

$$\nu_1(\alpha) = \tfrac{1}{4}\int_{4\pi} \Theta(\alpha)(60/v)^{4(s-1)} d\omega. \quad \dots\dots\dots\dots \quad (\mathbf{11})$$

Similarly, for visual meteors

$$\nu_1(M_V)=\tfrac{1}{4}\int_{4\pi}\Theta(M_V)(60/v)^{3\chi}\mathrm{d}\omega. \qquad \ldots\ldots\ldots\ldots \quad (\mathbf{12})$$

For constant $\vec{V}$, v is now a function of the apparent elongation ε and therefore of ω, and (**11**) and (**12**) can only be applied to the measurements already discussed if the distribution of Θ, i.e. the distribution of sporadic radiants over the geocentric celestial sphere, is known.

For the radio data, two model distributions of Θ have been considered. In paper I it was shown that the Adelaide echo counts could be explained by two quite different distributions of Θ, one a concentration to the plane of the ecliptic with an observed apex/antapex ratio of 4 (model E) and the other a much less extreme distribution over the whole of the celestial sphere (model U_{42}). Fluxes $\nu_1(10^{12})$ found for these two distributions of Θ, with $\bar{V}=42$ and 35 respectively, are given in Table 2. For the visual data, the radiant distribution

Table 2

SPORADIC METEOR PARTICLE FLUX

Flux Function	Type	Flux $\times 10^8$ (km^{-2} sec^{-1})	
		$\bar{V}=42$	$\bar{V}=35$
$\Theta_1(10^{12})$*	R	37	37
$\Theta_1(4\cdot3)$*	V	86	86
$\nu_1(10^{12})$ Model U_{42}	R	160	690
$\nu_1(4\cdot3)$	V	604	1950
$\nu_1(10^{12})$ Model E	R	800	3200

* Not a function of velocity.

used by Levin, after correction to the new datum velocity $v=60$ km sec^{-1}, leads to the fluxes $\nu_1(4\cdot3)$ also given in Table 2. The visual data do not appear to have been corrected to zenithal brightness, and no information is (or can be) available visually on radiants near the helion position.

After correction for the systematic error discussed above in connexion with shower fluxes, which is justified if the correction is one for aperture, the visual model and the radio model U_{42} appear to be in reasonable agreement. But this agreement must not be overstressed. As mentioned above, agreement between the radio $\Theta(10^{12})$ and visual $\Theta(4\cdot3)$ cannot be expected because of the different functional forms of τ and β. Even after allowance for this factor a strong disagreement in the vicinity of the apex remains between the radio and the adjusted visual estimates of Θ—see Figure 4 in which $\Theta(4\cdot3)$ has been normalized so that $\nu_1(10^{12})=\nu_1(4\cdot3)$. The visual Θ, although based on incomplete data and influenced by subjective factors, should be at least as acceptable as the radio Θ, which is obtained by fitting an inadequate model to the radio counts, a model moreover which could be appreciably altered in the vicinity of the antapex without much effect on the echo rate.

All the distributions of Θ considered above imply a very large preponderance of direct orbits, with the consequence that meteors with apparent elongations $\varepsilon \leqslant 90°$ produce a high proportion of the flux Θ observed above a limiting brightness, but only a very small fraction of the flux $\nu_1(\alpha)$ above the limiting mass. This aspect, which considerably lowers the accuracy with which ν_1 can be estimated, has been adequately discussed by Levin. The position is particularly acute in case of model E; for example, with $\bar{V}=35$, 80 per cent. of the flux $\Theta(10^{12})$ proceeds from meteors with $\varepsilon \leqslant 90°$, whereas these same meteors contribute only 7 per cent. of the flux $\nu_1(10^{12})$. For this reason the fluxes $\nu_1(10^{12})$ obtained with model E, which does not fairly represent the observed radiant distribution in the vicinity of the antapex, are certainly too high.

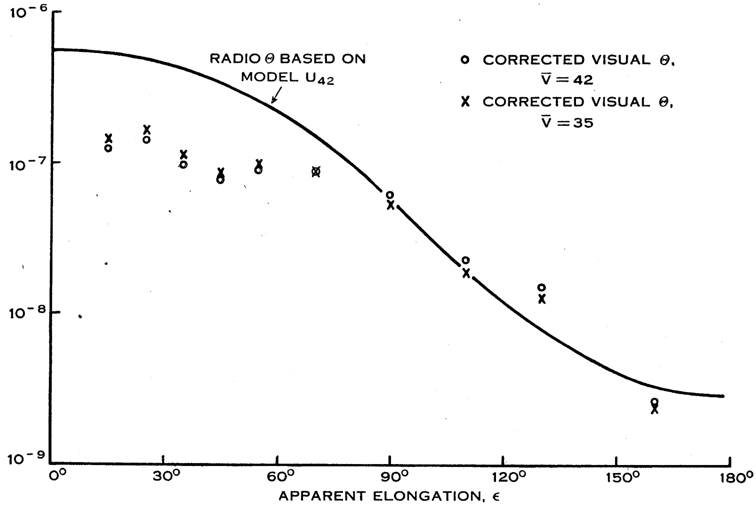

Fig. 4.—Radio and visual sporadic fluxes Θ. Visual Θ has been reduced to the same velocity-dependence as radio Θ for purposes of comparison.

Because of lack of detailed knowledge of the sporadic radiant distribution, of the distribution of velocities, and of the exact form of the dependence of luminous efficiency and ionizing probability upon the velocity, it is difficult to arrive at a reliable estimate of the flux $\nu_1(10^{12})$ for sporadic meteors. The value $\nu_1(10^{12})=10^{-5}\ \mathrm{km}^{-2}\ \mathrm{sec}^{-1}$ has been adopted.

(c) *Comparison of Shower and Sporadic Fluxes*

The total number of particles above the limiting mass $m(\alpha)$ falling on the Earth's surface per second is $\pi R_e^2 \nu$ for showers and $4\pi R_e^2 \nu_1$ for sporadics. These numbers are compared in Table 3, in which $4\pi R_e^2 \nu_1(10^{12})$ has been normalized to $100\ \mathrm{sec}^{-1}$. As an indication of the absolute values involved, $4\pi R_e^2 \nu_1(10^{12}) \sim 5100\ \mathrm{sec}^{-1}$. Most probable values of s have been selected.

Bearing in mind the uncertainty in the value of ν_1, it appears that the number of sporadic meteor particles, with masses exceeding $m(10^{12})$, incident on the whole Earth, is at least as great as, and may well considerably exceed, the corresponding numbers for the daylight showers and the δ-Aquarids at the times of maximum activity. The sporadic influx certainly far exceeds that due to the major night-time streams. On passing to a lower limiting mass, say $m(10^{11})$, the dominance of the sporadic influx relative to showers other than the day-time Arietids and possibly the δ-Aquarids, is still further enhanced.

TABLE 3
NUMBERS OF PARTICLES ABOVE LIMITING MASSES INCIDENT ON WHOLE EARTH

Type of Meteor	No. of Particles*	
	$m(10^{12})$	$m(10^{11})$
Perseids	1·5	6
Geminids	11	58
Quadrantids	7	46
Arietids	39	1200
ζ-Perseids	37	370
δ-Aquarids	41	1300
η-Aquarids	1·4	14
Orionids	1·6	52
Sporadics	100	1000

* Normalized to sporadic meteors $m(10^{12})=100$.

VII. The Space Density of Meteor Particles

The space density $D(\alpha)$ of sporadic meteors, defined as the density of sporadic meteors above the limiting mass $m(\alpha)$ moving in all directions within unit volume in heliocentric coordinates, is

$$D(\alpha)=\int [\Theta(\alpha)/v](60/v)^4 \mathrm{d}\omega.$$

The analogous density for shower meteors is simply $\nu(\alpha)/v$.

With the same reservations as applied to the estimate of $\nu_1(\alpha)$ the space density $D(10^{12})$ is found to be $200\text{–}300\times10^{-8}$ km^{-3} for sporadic meteors. This is to be compared with the densities within the major streams, listed in Table 1. The space density of sporadic meteors far exceeds the density within the major permanent streams, at least for the more massive particles with $m(\alpha)\geqslant m(10^{12})$.

VIII. The Incident Mass

From the relative numbers of meteor particles incident on the whole Earth, as listed in Table 3, and the absolute value $4\pi R_e^2\nu_1(10^{11})=5\cdot1\times10^4$ sec^{-1}, it is possible to calculate the total mass of the meteoric matter falling per day on the whole Earth.

From (1), with $\chi=0°$, $\mu=10^{-22}$ g, $H=7$ km, and β given by (9), $m(10^{11})\sim10^{-4}$ g. The mass falling on the Earth per day in different mass ranges is listed in Table 4 for sporadic meteors and two typical showers. Total masses within the mass range 10^{-1} to 10^{-4} g are respectively : sporadics, 3000 ; Arietids, 1600 ; Perseids, 70 kg day^{-1}. In this mass range, then, sporadic meteors bring in at least as much mass per day, and probably much more, than the major showers at their times of maximum activity. Outside this mass range the incident mass becomes quite sensitive to the value of the mass-distribution parameter s. Extrapolation to lower mass limits is conjectural because of suggestions (Davies 1957) that there is an unexpected increase in numbers of sporadic meteors fainter than 9th-10th magnitude, and to higher mass limits because the manner of the cut-off of those streams with $s\leqslant 2$ is unknown.

TABLE 4

MASS INCIDENT ON THE EARTH PER DAY

Mass Range (g)	Mass (kg day^{-1})		
	Perseids	Arietids	Sporadics
10^{1}–10^{0}	240	11	1000
10^{0}–10^{-1}	94	36	1000
10^{-1}–10^{-2}	46	110	1000
10^{-2}–10^{-3}	15	360	1000
10^{-3}–10^{-4}	6	1100	1000

If the strong dependence of ionizing probability on velocity is accepted, it would appear reasonably certain that the permanent showers, with the exception of the Arietids and possibly the δ-Aquarids, seed into the atmosphere an amount of matter per day, averaged over their duration, which is rather less, and may be much less, than the matter per day brought in by sporadic meteors. In the event that the ionizing probability proves to be independent of, or at most weakly dependent upon, the meteor velocity, the major showers will rank about equally with sporadic meteors.

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