Mon. Not. R. Astron. Soc. **359,** 1131–1136 (2005) doi:10.1111/j.1365-2966.2005.08972.x

The initial train radius of sporadic meteors

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Accepted 2005 February 27. Received 2005 February 22; in original form 2004 December 18

ABSTRACT

The height distributions, velocity distributions and flux measurements of underdense echoes determined from meteor radar observations are significantly affected by the attenuation associated with the initial radius of meteor trains. Dual-frequency radar observations of a very large set of sporadic radar meteors at 29 and 38 MHz yield estimates of the initial train radius and its dependence on height and meteoroid speed as determined by the time-delay method. We provide empirical formulae that can be used to correct meteoroid fluxes for the effect of initial train radius at other radio frequencies.

Key words: meteors, meteoroids.

1 INTRODUCTION

The observation of meteors using radar has many desirable characteristics: continuous operation both by night and by day and in all kinds of weather, a high echo rate and the ability to measure meteoroid trajectories and speeds. The observations are, however, subject to a number of biases and this paper addresses the problem of the attenuation of the echo amplitude that results from the destructive interference due to the initial finite radius of the ionized meteor train.

The degree of attenuation depends not only on the ratio of the radius of the train to the radio wavelength but also on the form of the radial distribution of the electron density within the train. From the earliest days since the importance of the initial train radius was first appreciated (Greenhow & Hall 1960), it has been almost always assumed that the electron density, ρ, in the train has a Gaussian distribution with radius, r, i.e.

$$\rho \sim \mathrm{e}^{-(r/r_0)^2}. \quad (1)$$

The basis for this assumption is that ambipolar diffusion will cause an initial line distribution of ionization to assume a radial Gaussian distribution. Jones (1995) pointed out that ambipolar diffusion is not important in this stage of the formation of the train and has argued convincingly that $\rho(r)$ is determined by the details of the process by which the meteoroid atoms become ionized after being shed by the ablating meteoroid. It is also possible that the magnetic field of the Earth may influence the ambipolar diffusion of the train. Unfortunately, there is no generally accepted theory of this effect and we have opted to ignore it. Hopefully, theoretical advances in the near future will allow the effect of the magnetic field to be taken into account.

The initial train radius can be estimated by comparing the initial amplitudes of meteor echoes observed by two radars operating at different frequencies. It is also important to know how the initial train radius varies not only with height but also with the speed of the meteoroid. Previous studies have tried to determine the speed dependence from measurements of the rise-time of the meteor echo – a method that is known to have poor accuracy but which is often all that is available. As a result there is a wide spread in the estimates of initial radius and its variation with height and speed that has prevented reliable meteoroid fluxes from being deduced from observed meteor echo rates.

One of the design goals when the Canadian Meteor Orbit Radar (CMOR) system was first conceived was to try to settle the initial train radius problem by having three identical radars operating at 17.45, 29.85 and 38.15 MHz with two remote stations that would allow the determination of trajectories and meteoroid speeds.

Fragmentation of meteoroids is also an important factor but at this stage there is no clear way of including this effect in our analysis. In a previous paper (Campbell-Brown & Jones 2003) we presented the results of an ambitious study in which we tried to include the effects of fragmentation constrained by the CMOR dual-frequency meteor radars and low-light-level TV observations. While the results were very encouraging, the solutions were not unique and indeed the problem entails so many variables that a complete solution is probably not yet within our grasp. In the current paper we describe a study of sporadic meteor echoes and proceed with the traditional assumption of a Gaussian radial electron density distribution. This allows us to make meaningful comparisons with previous work and to estimate the fraction of potential meteor echoes that are observed as a function of speed and radio frequency.

2 OBSERVATIONS

The observations were made with CMOR (Jones et al. 2005) located in Tavistock, Ontario, Canada (43.264° N, 80.772° W). For

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this series of observations the data from the 17.45-MHz radar were not used because of severe interference problems. Since CMOR allows the determination of speeds using delay times rather than the Fresnel oscillations in the echo amplitude, the results of this project should apply to both fragmenting and non-fragmenting meteoroids alike. We estimate the speeds at the specular reflection point to be accurate to approximately 5 per cent. All the antennas were vertically directed Yagi arrays mounted such that the system was most sensitive to the east and west. The pulse repetition frequency was 536 Hz and the transmitter pulse length was 75 μs. The transmitter powers were monitored continuously throughout the experiment. The limiting sensitivity of the system is close to +9 mag.

The observations were made over the period 2002 June–October and the data set comprises a total of 10^4 simultaneous echoes from meteors with a mean magnitude close to +6.5 and that ranged in height from 80 to 100 km with speeds in the range 15–74 km s^{-1}. The mean height was close to 88.9 km and the mean speed was 33.12 km s^{-1}. Since the initial radius attenuation applies only to underdense meteors we needed to distinguish between underdense and overdense echoes. It is well known (see, for example, McKinley 1961) that the decay time of an underdense echo can be used to estimate the height of the specular reflection point and we selected only those echoes that yielded decay-time heights that were within 10 km of that determined independently from the range and elevation angle of the echo direction.

Since it is unlikely that the echo signal would be sampled at the instant that it reached its maximum amplitude, the sampling rate was set such that each returned echo pulse was sampled at least four times. An accurate estimate of the maximum amplitude of the echo was then obtained by fitting the observed data points to the known pulse shape. The mean signal-to-noise ratio was close to 20 dB. Even in the absence of any attenuation due to the initial radius effect, the reflection mechanism (RM) causes the echo amplitude to vary as $\lambda^{3/2}$ (McKinley 1961). We must therefore multiply the ratio of echo amplitudes by a factor of $(29/38)^{3/2}$ to obtain the ratio of attenuations, $R_{29/38}$, due to the initial radius effect.

3 REMOVAL OF BIASES

The measured amplitude ratios are subject to several sources of bias: Faraday rotation, the finite velocity effect and the pulse repetition factor; we will deal with each of these in turn.

Elford & Taylor (1997) have drawn attention to the importance of Faraday rotation for very high-frequency (VHF) radar meteor observations. The polarization vector of the radio wave rotates as it passes through the lower ionosphere, with the degree of rotation depending on the frequency of the radio wave. Since the antennas are linearly polarized the received power varies with the total angle through which the polarization vector has rotated. This angle is given by

$$\Omega = 2.36 \times 10^4 \,\frac{\boldsymbol{p} \cdot \boldsymbol{B}}{f^2} \int N_\mathrm{e}\,\mathrm{d}l, \qquad (2)$$

where N_e is the electron density, $\boldsymbol{B}$ is the magnetic field of the Earth, $\boldsymbol{p}$ is a unit vector along the ray path and Ω is the angle of rotation (Ceplecha et al. 1998) and the integration is taken along the ray path. We corrected for the effect of Faraday rotation using the model ionosphere IRI-2001 (Bilitza 2001).

The attenuation of the echo due to ambipolar diffusion in the interval the meteoroid takes to cross the first Fresnel zone, known as the finite-velocity effect, is given by (Peregudov 1958)

$$\alpha = \frac{[1 - \exp(-\Delta)]}{\Delta}, \qquad (3)$$

where

$$\Delta = \frac{2k^2 D\,(2R_0\lambda)^{1/2}}{V}. \qquad (4)$$

k is the wavenumber, R_0 is the range of the echo, D is the ambipolar diffusion coefficient at the echoing point, λ is the wavelength of the radio waves and V is the speed of the meteoroid.

The pulse repetition factor corrects for the attenuation of the echo in the interval between transmitter pulses. For the CMOR system the pulse repetition frequency, f_p, is 536 Hz so that attenuation, η, is given by

$$\eta = \mathrm{e}^{-16\pi^2 D/f_\mathrm{p}\lambda^2}. \qquad (5)$$

To apply equations (4) and (5) we need an expression for the ambipolar diffusion coefficient as a function of height and we have used that given by Jones & Jones (1989):

$$\log(D) = 0.06h - 4.74 \qquad (6)$$

with D in units of m^2 s^{-1} and h in km. The electron density in the D-region of the ionosphere varies greatly over the course of 1 d and is very small doing the night-time hours. Fig. 1 shows the magnitudes of these observational biases averaged over 24 h for our data set.

Finally, we must correct for errors in the independent variables, height and log(speed). It is well known (see, for example Jones 1970; Hocking, Thayaparan & Frank 2001) that measurement errors in the independent variables cause the apparent dependence in a linear least-squares fit to be somewhat weaker than is actually the case. In our case there are significant uncertainties in the height and speed measurements. Since each radar yields an independent measure of the height of the meteor, we estimate the mean height to be uncertain to ∼ 0.85 km and the speeds at the specular point to approximately 5 per cent. It is easy to show that if x is the independent variable, then the factor by which the coefficients are reduced is $[1 + (\Delta x/\sigma_x)^2]^{-1}$, where Δx is the uncertainty in the measurement of x and σ_x is the root-mean-square (rms) scatter of the values of x. If we assume that the variation of initial radius with height and speed is well represented by the empirical expression over the range 80–100 km:

$$\log(r_0) = a_1 + b_1(h - 90) + c_1 \log(V/40) \qquad (7)$$

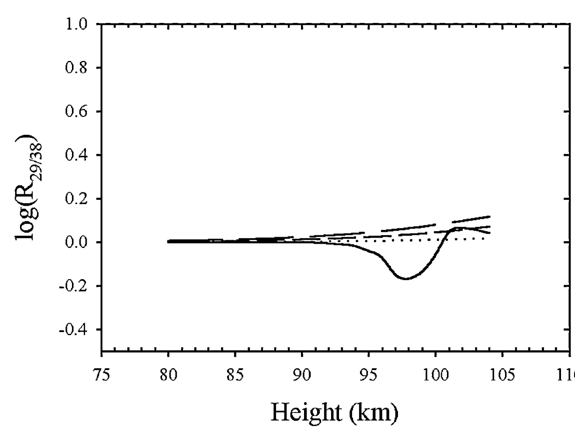

Figure 1. Effect of the observational biases on the ratios of the echo amplitudes. Solid line, average attenuation (over 24 h) due to Faraday rotation; long-dashed line, finite velocity effect at 60 km s^{-1}; short-dashed line, finite velocity effect at 30 km s^{-1}; dotted line, pulse repetition factor.

then for our data set $\sigma_h = 3.39$ km and $\sigma_{\log(V)} = 0.146$, resulting in the apparent values of b_1 and c_1 being too small by factors of 1.06 and 1.02, respectively.

4 ANALYSIS

We now wish to extract the initial train radius and its variation with height from these corrected observations.

It is easily shown (McKinley 1961), that if the radial electron density function follows equation (1), the destructive interference between the contributions from the different elements of the cross-section of the train causes the amplitude of the echo to be attenuated by a factor, α_r, given by

$$\alpha_r = \mathrm{e}^{-4\pi^2 r_0^2/\lambda^2}. \tag{8}$$

From the amplitude ratio, AR, at the two wavelengths λ_1 and λ_2 we readily find r_0 to be given by

$$r_0 = \sqrt{\frac{\ln(AR)\lambda_1^2\lambda_2^2}{4\pi^2\left(\lambda_1^2 - \lambda_2^2\right)}} \tag{9}$$

which, for our system, reduces to

$$r_0 = 2.973\sqrt{\log(AR)} \tag{10}$$

and the coefficients in expression (7) are given by

$$a_1 = -0.0802 \pm 0.0027$$
$$b_1 = 0.0238 \pm 0.0006$$
$$c_1 = -0.2000 \pm 0.0132. \tag{11}$$

We can also express r_0 in terms of the mean free path, L, and using the MSISE-90 model atmosphere (Hedin 1991) we find:

$$r_0 = a_2 L^{b_2} V^{c_2},$$

where

$$a_2 = 0.0447 \pm 0.0045$$
$$b_2 = 0.2826 \pm 0.0070$$
$$c_2 = -0.2000 \pm 0.0132. \tag{12}$$

Figs 2(a) and (b) show how the measured values of the quantity log(amplitude) and the least-square fits vary with height and speed, respectively.

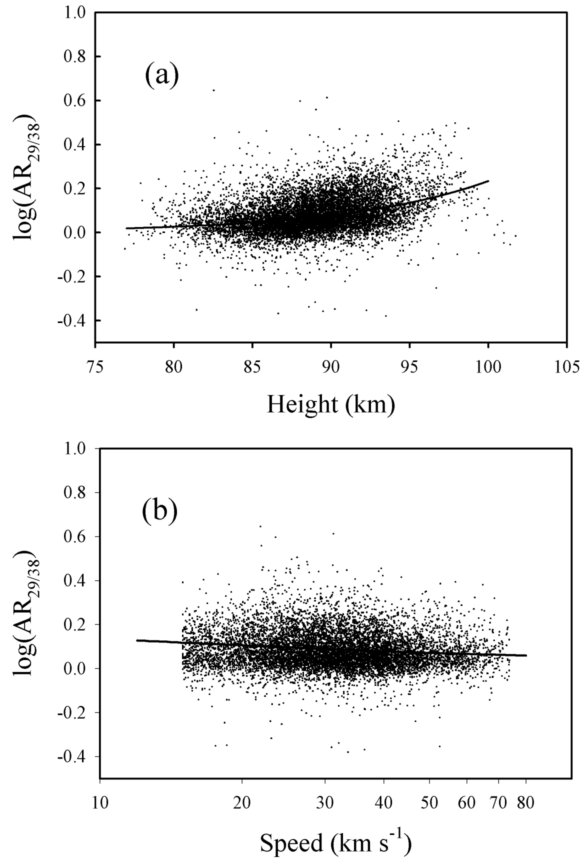

Figure 2. Comparison of observed amplitude ratios with least-squares fits: (a) height dependence (fit for $v = 30$ km s^{-1}); (b) speed dependence (fit for $h = 95$ km).

5 COMPARISON WITH PREVIOUS DETERMINATIONS OF INITIAL TRAIN RADIUS

Greenhow & Hall (1960), Baggaley (1970), Kashcheyev & Lebedinets (1963) and Bayrachenko (1963) have all made similar determinations of the initial train radius. There have been a number of studies of the initial radius of meteors brighter than those observed in the present work but we do not consider them here. Greenhow & Hall (1960) used approximately 145 and Baggaley (1970) used several hundred simultaneously observed echoes. All used echo decay times to estimate the heights so that the uncertainty in the height determinations of individual meteors was probably of the order of 4–5 km compared with 0.85 km for the present study. Baggaley (1970) tried to incorporate the effect of the magnetic field of the Earth on the diffusion of the trains but at that time the theory for this effect was in its infancy and in spite of considerable effort, a complete theory for this effect remains elusive. Baggaley (1970) felt that the effect of the reduction in the ambipolar diffusion of the train due to the magnetic field could be included by assuming the effective scaleheight used in the decay-time-to-height expression to be approximately 25 per cent greater than the pressure scaleheight. The data sets of both Kashcheyev & Lebedinets (1963) and Bayrachenko (1963) comprised less than 40 meteors with little height information.

Both Greenhow & Hall (1960) and Baggaley (1970) used echo rise times to determine meteor speeds for which the measurement error is probably of the order of 10–15 per cent compared with approximately 5 per cent for the present study. Baggaley (1980) based his estimates of the mean speed of his meteors on tables of speed distributions of meteors for times throughout the day that McKinley (1951) had obtained using combined pulse and continuous-wave (CW) radars. Kashcheyev & Lebedinets (1963) used the Fresnel oscillations of the echo amplitudes which, although much more accurate than the rise-time method, can only be used with non-fragmenting meteors. Fig. 3 shows how the results of these previous studies compare with the findings of the present work.

The excellent agreement between the present work and the results of Greenhow and Hall is somewhat fortuitous since they assumed a scaleheight of 7.0 km in their height determinations, whereas current model atmospheres give scaleheights of the order of 5.5 km at heights close to 90 km. Greenhow & Hall (1960) applied no corrections to their observations for observational biases. On the other hand, Baggaley (1970) applied a correction for the finite velocity effect but ignored the pulse repetition factor and minimized the effects of Faraday rotation by using only night-time echoes.

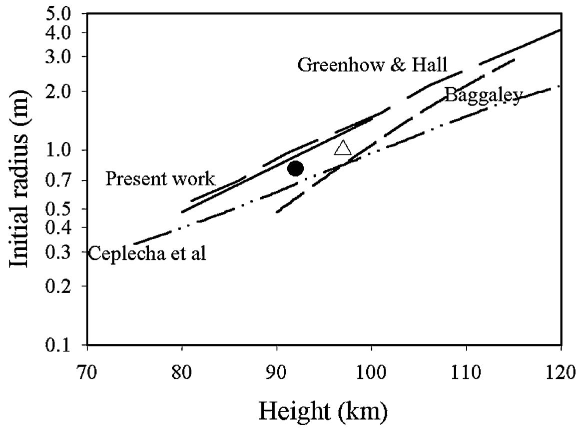

Figure 3. A comparison of determinations variation of the initial radius with height for a speed of 40 km s^{-1} for several studies. Solid line, present work; long-dashed line, Greenhow & Hall (1960); short-dashed line, Baggaley (1970); dash-dotted line, Ceplecha et al. (1998); •, Kashcheyev & Lebedinets (1963); △, Bayrachenko (1963).

The pulse repetition factor is more important at low pulse repetition frequencies such as 150 Hz used by Baggaley (1970) and we would expect echoes at 28 MHz from meteors at a height of 100 km to be only a factor of approximately 0.8 of their unattenuated amplitude which would tend to increase the apparent dependence of initial radius with height. Greenhow & Hall (1960) found the initial radius to be almost independent of meteoroid speed while Baggaley (1970) found $r_i \sim V^{0.57}$. In a later paper, Baggaley (1980) used similar observations from the Sheffield radar together with meteoroid speed distributions measured by McKinley (1951) to deduce a speed dependence for the initial radius of $r_i \sim V$. The results of the present study are in marked contrast to this previous work and show a weak dependence in the opposite sense: $r_i \sim V^{-0.20}$.

6 COMPARISON WITH THEORETICAL PREDICTIONS

Most theoretical predictions have neglected the effects of fragmentation and have assumed a single-body meteoroid with the initial radius being primarily the result of the spread of the ionization as the meteoric atoms are decelerated by collisions with the air molecules. Bronshten (1981) gives an excellent summary of the work performed in this area. The theoretical models fall into two camps: the hard-sphere model of Manning (1958) which is easily treated using classical mechanics and a deformable sphere model based on quantum mechanical principles first introduced by Massey & Sida (1955). Manning's treatment yields an initial radius of approximately three neutral mean free paths. Because the path of the meteoric atoms transverse to the train axis is a random walk with steps of constant mean value, Manning's model predicts that the electron density varies with radius in a Gaussian fashion as described by equation (1) and an initial radius that is independent of meteoroid speed as is found by Greenhow and Hall's (1960) observations. On the other hand, their initial radius is almost an order of magnitude greater than Manning's theoretical prediction.

Because an exact quantum-mechanical theory of molecule–molecule collisions is not yet possible, the deformable-sphere model has to rest on a number of assumptions and approximations. The first is that the momentum transfer cross-sections of neutral–neutral and ion–neutral collisions are similar. The second is that the momentum transfer collision cross-section varies almost inversely with the meteoroid speed so that in the initial stages, when the meteoric atom is being decelerated to thermal speeds, the momentum transfer cross-section of the collisions is very small and the associated mean free path is very large. Thus, in this model, as the meteoric atoms are decelerated, the steps in the random walk decrease, with the result that the electron density profile is no longer Gaussian. Jones (1995) has modelled this process and finds that the initial radius should vary as $V^{0.84}$, which is in fair agreement with Baggaley's (1970) results but in marked contrast to the findings of the present study.

In an effort to include fragmentation, Hawkes & Jones (1975) suggested that the ionized train is a collection of trainlets that are formed as the fragments of the original meteor are dispersed radially as a result of its rotation. This model goes some way to explaining the unexpected weak dependence of the initial radius with height since the degree of radial dispersal of the fragments will decrease with height if the meteoroid has disintegrated well before the fragments begin to ablate, while the radius of the trainlets will increase with height. The composite initial radius will therefore depend more weakly on height than for either mechanism alone. A quantitative comparison between theory and experiment will have to wait until better models of meteoroid fragmentation have been developed.

7 CORRECTION OF METEOROID FLUXES

We now address the problem of correcting meteoroid fluxes. The attenuation decreases the echo rate so that the meteoroid flux appears to have decreased. The degree to which the echo rate is reduced depends on the amplitude distribution of the echoes, and since it is generally agreed that for underdense echoes the echo amplitude is proportional to the meteoroid mass, the amplitude and mass distributions are described by similar power laws:

$$N(A) \sim A^{1-s}, \tag{13}$$

where s is a parameter that varies from shower to shower and is usually in the range 1.4–2.5 and $N(A)$ is the rate of echoes with amplitudes exceeding A. Because the echoes originate from a range of heights, they are subject to a spread of attenuations and the fraction, $F(V, \lambda, s)$, of potential echoes of a meteor shower with mass distribution index s that are detected is given by

$$F(V, \lambda, s) = \frac{\int_0^\infty \alpha_r(h, V, \lambda)^{s-1} n(h)\,\mathrm{d}h}{\int_0^\infty n(h)\,\mathrm{d}h}, \tag{14}$$

where $n(h)$ is the true height distribution of the echoes which we took to be identical to that found using the data listed in the catalogue of low-light-level TV (LLLTV) meteor observations of Sarma & Jones (1985) which covered approximately the same magnitude range (close to + 7 mag). $n(h)$ is given by

$$n(h) = \mathrm{e}^{-(h-h_{\max})^2/57.6}, \tag{15}$$

where

$$h_{\max}(V) = 46.73 + 30.98\log(V). \tag{16}$$

In practice the integrations are taken over the height range 50–150 km. Fig. 4 shows how the predicted fraction of echoes, F, varies with meteoroid speed for several sets of data. We have included the curve based on the expression suggested by Ceplecha et al. (1998) of

$$r_i = 0.9610^{0.0186(h-100)}(v/40)^{0.6} \tag{17}$$

as a summary of all the experimental determination up to that time. The present results are conveniently expressed by the empirical formula

$$F(v, \lambda, s) = \mathrm{e}^{[f(\lambda)-g(\lambda)s]v},$$

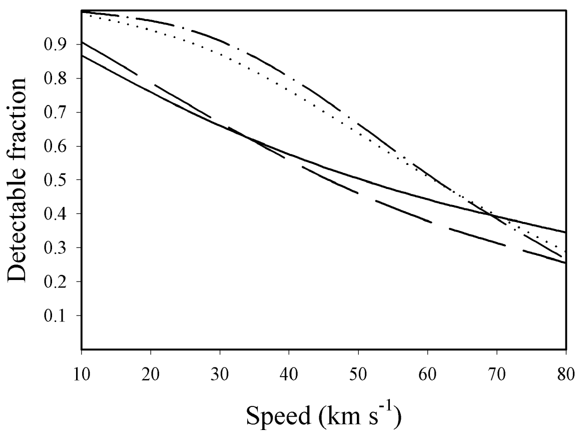

Figure 4. The comparison of the predicted fraction of potential echoes observed at 29 MHz by CMOR taking $s = 2.0$: solid line, present work; dashed line, Greenhow & Hall (1960); dash-dotted line, Baggaley (1970); dotted line, Ceplecha et al. (1998).

where

$$f(\lambda) = \mathrm{e}^{-(3.788+0.094\,\lambda)} \tag{18}$$

and

$$g(\lambda) = \mathrm{e}^{-(3.162+0.129\,\lambda)}.$$

Expression (18) allows F to be evaluated for speeds of between 10 and 80 km s^{-1}, radio wavelengths between 6 and 17 m, and s between 1.4 and 2.8 with a mean error of less than 3 per cent. Fig. 4 shows that even though the various expressions for the initial radius are very different, the predicted detectable fractions of potential echoes agree to better than 30 per cent over the range $10 < V < 70$ km s^{-1}.

8 DISCUSSION

The present study is more ambitious than any previously undertaken not only in the number of simultaneous echoes measured but because the heights have been measured directly and the method of speed measurement is more accurate than the rise-time method, applying equally well to both fragmenting and non-fragmenting meteoroids. We were surprised to find a speed dependence of initial radius significantly different from that found by previous studies even after corrections had been made for all likely sources of systematic bias. On the other hand, few of these corrections had been applied in most of the previous studies.

Greenhow and Hall's (1960) determination of the speed dependence of the initial radius is based on the ratio of the numbers of echoes observed in the height interval 95–100 km. Using equation (14) with the integration in the numerator being taken from 95 to 100 km, $\lambda = 17$ and 8.3 m and $s = 2.0$, we find how the present work compares with previous determinations as shown in Fig. 5. It is evident that the present initial radius model agrees well with Greenhow and Hall's (1960) observations, though this may be fortuitous, while Baggaley's (1970, 1980) model does not.

LLLTV observations show from the great variation in light curves that meteoroids in this size range fragment as they ablate in the atmosphere of the Earth. The meteor trains are therefore likely to have a composite structure of trainlets that are separated both radially and longitudinally as a result of the fragmentation process so that the resulting train is clearly more complex than for a single-body meteoroid. Provided that the longitudinal dispersion is much less than a Fresnel zone (~1 km) it will have little effect since the resulting phase differences in the contributions to the echo from the various fragments will be small. The large scatter in the ratio of the amplitudes of the echoes at the two frequencies shown in Fig. 2 confirms that the scale of the radial dispersion of the fragments is comparable to $\lambda/2\pi$. Before we can make further progress we need to determine the mean radial distribution of the electron density within the train. Whether the meteoroid fragments much before it ablates or the fragmentation proceeds concurrently with the ablation is not known. Nor do we know whether the dispersion is the result of gas drag as the 'glue' evaporates or if rotation plays a significant role.

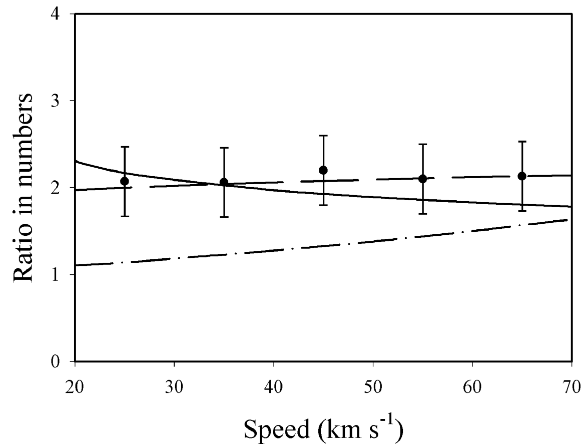

Figure 5. Ratio of the number of echoes observed at wavelengths of 17 and 8.3 m in the height range 95–100 km as a function of speed. Points: Greenhow and Hall's (1960) experimental data; solid line, prediction (see the text) based on the present work; dashed line, prediction based on Greenhow and Hall's (1960) fit; dash-dotted line, prediction based on Baggaley's (1970) fit.

It is likely that there is a distribution of fragment sizes with the larger particles being the last to ablate completely. We therefore expect that close to the end point of the train, the ablation will be essentially that of the largest fragment so that the initial radius should have little or no contribution from fragmentation. Fig. 6 shows the distribution of height/speed points of the observed echoes together with the end-point region. It is evident that the initial radii

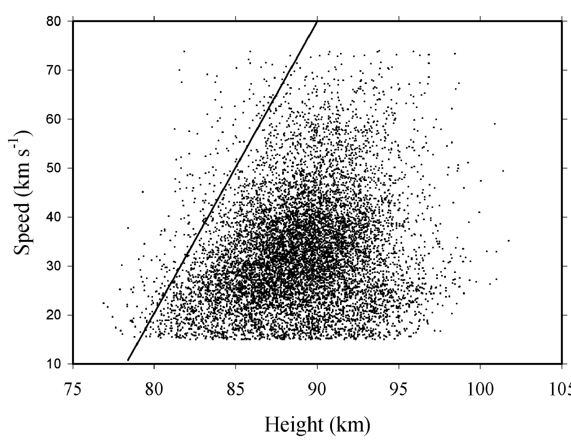

Figure 6. Distribution of the height/speed points of the present observations. We expect the largest fragments to be the last to survive before the meteoroid ablates completely so that close to the end of the train we should have only a single body without any broadening of the train due to fragmentation. The solid line (equation 18) is representative of this end-point region.

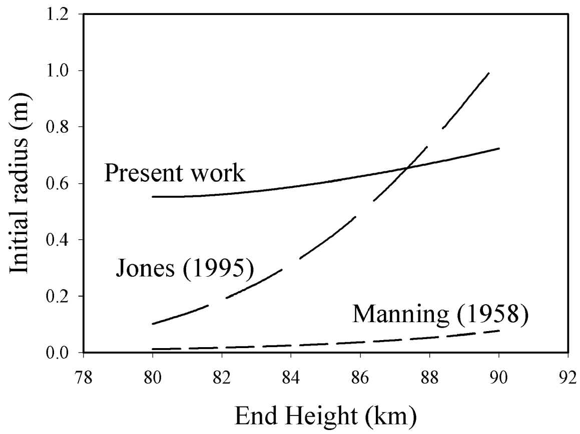

Figure 7. Initial radius along the line given by equation (18) in the end-point region as a function of height. Note that the theoretical 'effective initial radius' given by Jones (1995) exceeds the measured initial radius at heights above 88 km.

of meteors at a fixed height would decrease with increasing speed and thus provide an explanation for the speed dependence of the initial radius found in the present study. A representative line in the end-point region is described by the equation

$$h_{\mathrm{end}} = 80 + 0.167(V - 20) \tag{19}$$

and in Fig. 7 we compare the results of the present observations with the theoretical predictions of Manning (1958) and Jones (1995). The initial radii for the Jones model are 'effective initial radii', i.e. the radii that would be calculated if a radial Gaussian electron density profile were assumed. It is evident that the Jones (1995) model predicts initial radii that are greater than observed at heights above 88 km and it unfortunate that we do not have more observations of the end-point region in this region to confirm this trend.

The initial train radius problem is not yet completely solved since the present work still assumes a Gaussian radial electron density distribution. We plan to address this problem using data from all three CMOR radars as soon as all the technical difficulties have been dealt with.

ACKNOWLEDGMENTS

The authors gratefully acknowledge funding from the Space Environment and Effects Program of NASA and many useful discussions with Dr P. Brown, Dr A. R. Webster and Dr B. A. McIntosh.

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