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OBSERVATION OF METEORS BY MST RADAR

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ABSTRACT

The observation of meteor trails by a vertical MST radar beam has the advantage of good height resolution and an approximate knowledge of the zenith angle since the trails are horizontal or near-horizontal. An extension of the ablation theory of meteors has been developed for near horizontal trails which takes into account the curvature of the earth.

Observations of the Geminid meteor shower by MST radar reveal the "diffusion heights" to be in fair agreement with the true height, but with some discrepancies that can amount to 4km. The true heights are almost entirely confined to the range 87-91km, although the upper limit is attributed to the coherent integration time of the existing MST radar processing.

INTRODUCTION

The vast majority of meteors give appreciable back scatter radar echoes only from a region near the "reflection point" on the perpendicular from the train to the receiver (see McKinley 1961). This implies trains observed with the verical beam of an MST radar to be horizontal; thus relatively few meteors will be observed, the majority having burned up before reaching the reflection point. On the other hand, the height resolution is very good and the zenith angle is fairly accurately known, so that the circumstances of observation are worth further investigation. We should mention that the use of an MST radar as a meteor radar has been discussed before (see Avery *et al*, 1983) but we shall be concerned here with the physics of the meteors themselves rather than as tracers for the measurement of atmospheric winds.

The first point that needs to be emphasised is that when considering the ablation of a meteor observed with a vertical or near vertical beam, it is essential to take account of the curvature of the Earth. From fairly general assumptions, principally that the rate of ablation is directly proportional to the energy of impact with the molecules of the atmosphere, one obtains an expression in which the rate of change with time is converted into a rate of change with height under the assumption that the Earth may be taken to be flat so that the height changes as $v\cos\chi$, where χ is the zenith angle (Herlofson 1948). This leads to an expression in which the rate of ablation is proportional to $\cos\chi$, so that it is predicted to be zero for horizontal meteors. In the following we shall examine the requisite modifications to the usual theory when the effect of the Earth's curvature is included.

We have used the MST radar at Aberytswyth, Dyfed, Wales to observe the Geminid meteor shower of December 1990, recording heights and the rate of decay of the echo, and in the following we shall present these preliminary results. We shall interpret the results as far as we can by means of the modified ablation theory. With regard to echo decay we should also note that the heights of underdense meteors are commonly estimated on the basis of diffusion theory. This theory predicts that the exponential decay time of the radar echo will be inversely proportional to the diffusion coefficient D and thus directly proportional to the air density. However, because of the difficulty of estimating the meteor height by other means, confirmation of this procedure has been largely statistical and not completely satisfactory. The MST radar provides us with accurate heights for individual meteors, and since the zenith angle is known, we can use the true heights to compare with the estimates of the diffusion theory.

ATMOSPHERIC HEATING OF NEAR-HORIZONTAL METEORS

It appears that most meteoroids are fragile in structure (so that one speaks of the object as "friable" or as a "dustball") although the Geminids do appear to be more solid than the constituents of most streams (see Bronshten 1983). It is reasonable to suppose that the "grains", the basic or ultimate particles, can be treated as solid bodies to which the "classical" ablation theory applies.

Because at the point of observation with the MST radar the meteor is moving horizontally, or near horizontally, we must modify the usual ablation theory (Herlofson 1948, Jones and Kaiser 1966) to take account of the curvature of the Earth. Because of limitations of space we omit the detailed derivation and merely quote the relevant final results, valid for particles of sufficient size that radiation and retardation effects may be neglected.

We introduce T_a the temperature at which the material ablates, ρ the atmospheric density, ρ_m the density of the meteoric material, v the velocity of the meteoroid, L the latent heat of the meteoric material, r the particle radius, r_∞ the original radius at infinity, R the radius of the Earth and χ the zenith angle of the meteor trail. Coefficients η and γ are also introduced, for mathematical convenience, with $\eta = v^2/(8\rho_m L)$ and $\gamma = CT_a/L$, C being the specific heat. A locally isothermal atmosphere is assumed, so that we may write $\rho \propto \exp(-h/H)$ where h is the height and H the scale height.

Provided ablation begins, the radius of the particle at the point of observation is found to be

$$r = r_\infty [\, 1 + \gamma/3 - \eta\rho I\,(0,\chi)/r_\infty \,] \quad (1)$$

where

$$I(\chi) = \sqrt{(\pi RH/2)}\exp[\, R\cos^2\chi/(2H)\,]\ \mathrm{erfc}\,[\,(R\cos\chi)/\sqrt{(2RH)}\,] \quad (2)$$

We might note that using the asymptotic expansion for erfc(x) we may show that

$$I(\chi) \to H/(\cos\chi) \quad (\cos^2\chi >> 2H/R) \quad (3)$$

in which case eqn (3.6) reduces to the result of previous theory (Jones and Kaiser 1966), However,

$$I(\chi) \to \sqrt{(\pi RH/2)} \quad (\cos^2\chi << 2H/R) \quad (4)$$

and this is the appropriate result when using the vertical beam of the MST radar.

Universal form of the ablation curve

The line density of ionisation can be expected to be given by an expression of the form

$$\alpha = C\ r^2\ dr/dt \quad (5)$$

where C is a constant. From (1) we now obtain an expression for the ionisation in the "universal" form

$$\alpha = 9\alpha_m [\, 1 - \rho/(3\rho_m)\,]\ \rho/(4\rho_m) \quad (6)$$

in terms of the density ρ_m at the height of observation for which the line density is a maximum α_m, these quantities being given by

$$\rho_m = (1 + \gamma/3)r_\infty \quad (7)$$

and

$$\alpha_m = 4(1 + \gamma/3)^3 r^3_\infty/(27I\eta) \quad (8)$$

When the limit (3) applies (6) and (7) give the usual result for the variation of ionisation with height.

Meteors are often characterised by α_z, the maximum line density the meteoroid would produce if incident vertically (see Kaiser 1954). From the above it will be seen that

$$\alpha_z = \alpha_m \times\ I(\chi)/H \quad (9)$$

For horizontal meteors ($\chi = 0$) we find $\alpha_m \approx \alpha_z/40$

Limits to observational size

It is evident that equation (1) can be valid only provided

$$r_\infty < 3\eta\rho_o/\gamma\ \times\ I(0) \quad (10)$$

(otherwise the equation predicts that r will increase) and the detailed theory in fact shows that if this inequality is not satisfied the particle will not ablate at all, thus giving an upper limit to observable size. On the other hand, the particle will have burnt out before the observation point if the right-hand side is negative, which yields a lower limit to size for a particle to be observable, viz,

$$r_\infty > \eta\rho/(\, 1 + \gamma/3)\ \times\ I(0) \quad (11)$$

We take as typical values $\rho_m = 4\times10^3 kg{,}m^{-3}$, $L = 6\times10^6 Jkg^{-1}$ (stone). For horizontal meteors observed at 90km, these conditions then give $5 < r_\infty < 50$, where the radius is measured in millimetres.

EXPERIMENTAL RESULTS

We observed the Geminids on the night of 13 December 1990 using the newly commissioned MST radar at Aberystwyth. Since the meteor trains must be perpendicular to the beam to be observed, they must be horizontal to be detected by the vertical beam - that is, the radiant must be rising or setting. We identified the meteors as members of the Geminid meteor shower by virtue of the fact that in the time that observations were made echoes were in fact detected only within ten minutes of the rising or setting of the radiant.

As already remarked, the heights of underdense meteors are commonly estimated on the basis of diffusion theory. This theory predicts that the exponential decay time of the radar echo will be inversely proportional to the diffusion coefficient D and thus directly proportional to the air density. In the figure we show the results we obtained for underdense meteors, plotting the actual height as registered by the radar with the diffusion height obtained from Verniani's empirical formula

$$0.086h_D = \log_{10}D + 7.23 \qquad (12)$$

where D is the diffusion coefficient given by $D = \lambda^2(16\pi^2\tau)$, λ being the wavelength and τ the time taken for the echo amplitude to decay to l/e of its original value. It will be seen that our results are restricted in height range, a fact to be commented on shortly, but where they exist they are in good agreement with Verniani's, though there is considerable scatter about the mean. The new element here is that the radar height estimates are accurate to ±0.1km so that we can identify the scatter as principally due to variation in diffusion height.

A striking aspect of the figure is the restricted height, as already remarked. The absence of echoes above 93km, can be attributed to the fact that at present the radar presents data only at intervals of 1/12th second so that the echo from any underdense meteor at greater altitude would decay before being recognised as such. However, the almost complete absence of echoes below 87km indicated a sharp cutoff in the size distribution.

CONCLUSIONS

The principal aim of the present investigation has been to evaluate the potential of MST radars in the investigation of meteors and this has involved the extension of the usual ablation theory to meteors with horizontal or near-horizontal trails.

Ablation theory

We have found that the usual analytic expression of the "classical" ablation theory may be generalised to take into account the curvature of the Earth, this being essential in considering near-horizontal meteor trains. The theory allows us to estimate upper and lower limits as to the initial size of the meteoroid particles: if a particle is too small it will have burnt out before reaching the zenith at Aberytswyth, whereas if it is too large it will have not become hot enough to ablate. Taking the values suggested by Jones and Kaiser (stony meteoroids) this gives the sizes of observable particles to be between 0.5 and 5cm, at 90km.

Preliminary experimental results

We observed the Geminid meteor shower on the evening of 13 December 1990 using the newly commissioned radar at Aberystwyth, with results for underdense meteors as displayed in fig.1.

Diffusion heights

Because the MST radar has a very accurate height resolution we wished to investigate the expression, based on diffusion theory, commonly used to estimate the heights of underdense meteors, and the "diffusion heights", using the formula of Verniani (1973), are shown in the figure. It will be seen that while there is reasonable statistical agreement between the true and diffusion heights there is considerable scatter. We hesitate to ascribe this to variations in the diffusion process at the moment as comparatively few data points were obtained per meteor, the radar returning information only every 1/12th of a second.

Height and size distribution

It will be seen that the meteors are clustered between 87 and 92km. We attribute the upper limit as due to the fact that the radar returns data every twelfth of a second so that an underdense meteor will decay too quickly to record more than one data point. The almost entire absence of echoes below 87km, would however appear to be the result of a fairly sharp cutoff in the size distribution. Eqn(2.14) above, with the values for stony meteoroids as quoted, gives the minimum size for observation at 87km, to be about a centimetre. An interesting possibility is that the cutoff results from the fracture of larger particles by thermal shock and we intend to investigate the generalisation of the work of McCrosky and Ceplecha (1970) to horizontal trails.

Further experimental work

It is clear that the further use of MST radars in the observation of meteors trains will be very fruitful. It will be important, however, to modify the data collection so that it is essentially on a pulse to pulse basis, rather than at the 1/12th second used for atmospheric work. A straightforward way of doing this would be to install a separate receiver and data processing unit of the same design as currently used in meteor radars and it is the intention to do this at Aberystwyth.

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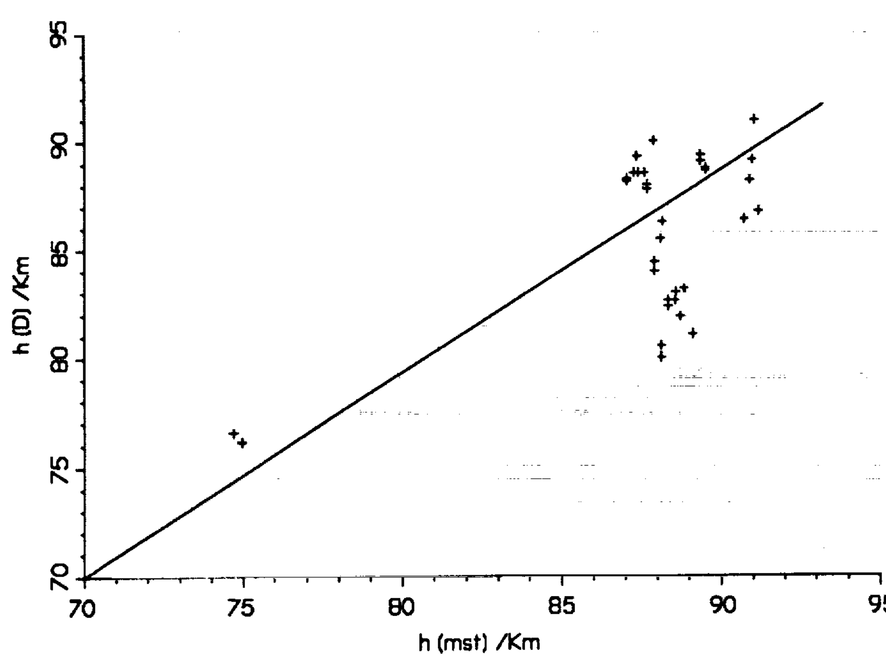

Fig. 1. Diffusion height, h(D), against true height, h(MST) for Geminids