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Effect of the geomagnetic field on the diffusion of meteor trains

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ABSTRACT

A solution to the problem of the diffusion of a meteor train in the geomagnetic field from an initial line density may be written in closed form in terms of effective diffusion coefficients depending on direction, enabling detailed calculations across the entire range of angle of train to field and relevant heights.

While the effective diffusion coefficient in the plane of train and field then remains close to the zero field ambipolar value right up to 90° the effective coefficient in the direction of the normal to plane of train and field drops steadily to its $\Theta = 0$ value at $\Theta = 90°$. At 95 km this corresponds to a change of almost 5km, in "diffusion height", that is, the height of an underdense meteor calculated on the basis of the exponential decay of its radar echo. We have estimated the consequent changes in the expected distribution of diffusion heights for various orientations of radar antenna and find the dependence on azimuth is very marked. The effect of the field is relatively minor for a south pointing beam but very strong if the beam is pointing north.

INTRODUCTION

The theoretical description of the diffusion of meteor trains in the Earth's magnetic field is a long standing problem of considerable interest. At first sight it would appear that the field could have an effect on all meteors ablating above 95km, or so but it was suggested by Kaiser (1968) that the effect is appreciable only if the meteor is very closely aligned with the field. Detailed numerical work was carried out by Kaiser, Pickering and Watkins (1969), and Pickering and Windle (1970), in which the meteor was modelled as an irregularity in a uniform ionised background and the distribution of ions and the electric field or potential were calculated at the points of a grid within a rectangle perpendicular to the meteor axis, so that the partial differential equations could be reduced to a finite system of linear equations. These calculations appeared to support Kaiser's contention, though later work by Pickering (1973) and Lyatskaya and Klimov (1988) suggests that the magnetic field may well have considerable influence when the train and field are not closely aligned. This is also the conclusion of Rozhansky and Tzendin (1977) in their qualitative assessment of the main features of the diffusion of irregularities. However, their work is concerned with changes in the ionisation much less than that of the ambient plasma, so that any application to meteors must be treated with caution. Furthermore, all the detailed numerical calculations mentioned above were limited in scope. The complexity of the numerical procedure and the requisite computing time limited the computations to an unrealistically small ratio of meteor ionisation to background (of the order of three or so). Moreover, the boundary conditions imposed at the perimeter, that the electric potential and the normal component of the ionic number density be zero, are artificial. In the interpretation of observations of meteors, it has been almost always assumed that one can ignore the effect of the magnetic field in practice.

In a recent examination of the problem a direct analytical generalisation of the standard solution for the zero-field case, describing the time development from an initial line density of ionisation, has been sought (Jones 1991). It was found that such a generalisation is indeed possible, enabling detailed calculations across the entire range of angles and relevant heights, these calculations being essentially exact within the framework of the model. Our results show that for heights of 95km, and above the diffusion is severely inhibited by the field if Θ, the angle between train axis and the field lines, is close to zero, and that this effect diminishes very rapidly as Θ is increased. This is in accordance with the original suggestion by Kaiser (1968) but the important new feature of the present results is that, for Θ greater than about 2°, the effective diffusion coefficient in the direction of the normal to plane of train and field, drops steadily to its $\Theta = 0°$ value at $\Theta = 90°$. The effect is very marked - even for a height as low as 95km, the magnetic field can reduce the diffusion by a factor of two below the zero field value. In contrast the diffusion coefficient in the plane of train and field remains close to the zero field ambipolar value right up to 90°. These results are in general agreement with exisiting experimental results (see Baggaley and Webb 1980), which, however, have primarily been concerned up to now with the exploration of the small Θ dependence.

The question now arises as to how this will affect the detailed nature of the results and interpretation of meteor observations and we shall illustrate this here by discussing the radio echoes from underdense meteors. The heights of underdense meteors are commonly estimated on the basis of diffusion theory. Assuming that one can neglect the influence of the magnetic field, the 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. As we shall see, this assumption must be profoundly modified, the "diffusion heights" obtained in this way being strongly dependent on the orientation of the meteor relative to the field.

AVERAGING OF DIFFUSION HEIGHTS OF SPORADIC METEORS

To obtain the average diffusion height of meteors of a given true altitude it is necessary to estimate weightings for given Θ and μ, the angle between the incoming wavevector and the normal to the plane of the train and the magnetic field. It is reasonable to assume that the incident directions of sporadic meteors are uniformly distributed over the celestial sphere (see Kaiser 1953), but the degree of ionisation will depend on the zenith angle χ. In the conventional theory of meteoric ionisation (Herlofson 1951, Jones and Kaiser 1966) the ionisation at a given height is a function of the maximum line density α_m only, and this is turn may be expressed as $\alpha_m = \alpha_z \cos\chi$, where α_z characterises the meteor independent of χ (in fact as one can see, α_z is the maximum line density the meteor would have if it were incident vertically). The proportion of meteors within the range $(\alpha_z, \alpha_z + d\alpha_z)$ may be approximated by $C\alpha_z^{-s} d\alpha_z$ where C and s are constants; from this one can see that for a given angle χ the proportion of meteors with maximum line density in the range $(\alpha_m, \alpha_m + d\alpha_m)$ is

$$C\,\alpha_m^{-2}\,(\cos\chi)^{-s-1} d\alpha_m \qquad (6.1)$$

It appears that we may set s = 2 to a good approximation (Kaiser 1954), in which case the dependence on zenith angle is simply $\cos\chi$, and we have taken this to be the case.

We have performed detailed calculations for a pencil beam at an elevation angle of 30°, this corresponding to the maximum of a half-wave dipole above perfect ground. Figure 6 shows the average diffusion height, for various true heights, as a function of beam azimuth, while in figure 5 we show the proportion of echoes, as a function of diffusion heights; in this example the azimuth of the beam is 90° and the true heights 102 and 108km. The results for 95 and 97.5km are roughly similar, though much more compressed, the respective ranges of diffusion height being 1.7 and 3.5km.

DISCUSSION

We have presented calculations of the diffusion heights of meteors taking into account the effect of the geomagnetic field by a direct generalisation of the analytic solution for the zero-field case within the quasineutrality approximation, the meteor train being treated as a cold cylindrical plasma.

As we have already remarked, in the interpretation of observations of meteors it has almost always been assumed that one can ignore the effect of the magnetic field in practice. Recent results (Jones 1991) indicate that for heights of 95km, and above the diffusion is severely inhibited by the field if Θ, the angle between train axis and the field lines, is close to zero, and that this effect diminishes very rapidly as Θ is increased up to about 2°. However, an important new aspect of the results is that as Θ is increased further D_v, the effective diffusion coefficient in the direction of the normal to plane of train and field, drops steadily to its $\Theta = 0°$ value at $\Theta = 90°$. In contrast D_u, the diffusion coefficient in the plane of train and field, remains close to the zero field ambipolar value right up to 90°. Even for a height as low as 95km, the magnetic field can reduce D_v by a factor of two below the zero field value. This corresponds to a change of almost 5km in "diffusion height", that is, the height of an underdense meteor estimated on the basis of the exponential decay of its radar echo.

To illustrate how this will affect the detailed nature of the results and interpretation of meteor observations we present here calculations of "diffusion heights", i.e., heights obtained from the decay of underdense echoes by the application of the standard diffusion theory, under reasonable assumptions as to meteor ablation and distribution.

In Figure 1 we show calculations of the proportion f of echoes, as a function of diffusion heights for a pencil beam at 30° elevation and a magnetic azimuth (azimuth relative to magnetic north) of 90°. Figure 2 shows calculations of the mean diffusion height, again for a pencil beam at 30° elevation, against magnetic azimuth. The azimuthal dependence is very marked. For a south pointing beam the mean diffusion height and true height are in good agreement but for a north pointing beam the effect of the magnetic field is to pull down the diffusion heights considerably, especially for the true heights of more than 100km. That is, the effect of the magnetic field is to elevate the "echo ceiling". This arises from two effects, (i) the finite radius of formation increases with height and (ii) the ionised trail diffuses faster than it is formed if the height is great enough. We expect the initial radius to be largely unaffected by the field but once the train is formed the field will greatly diminish the rate of decay of the radar echo from diffusion provided the orientation is favourable.

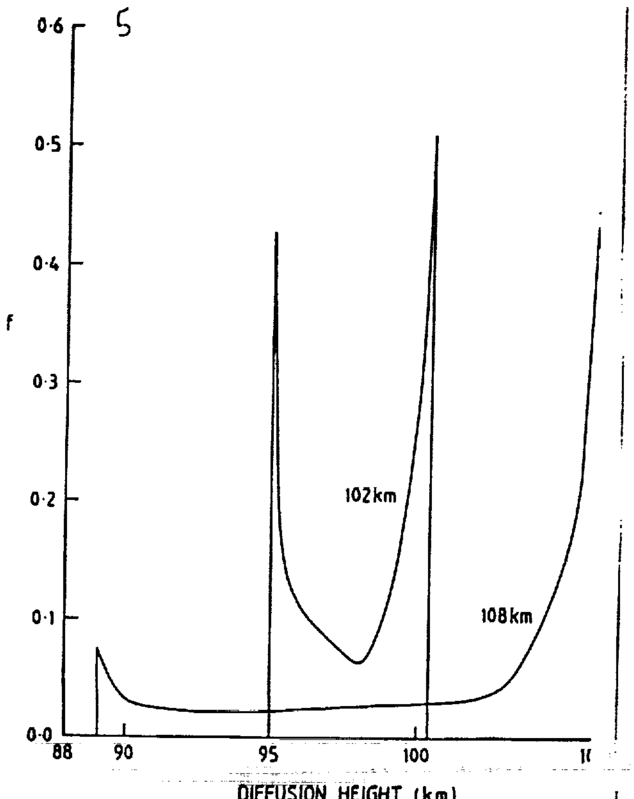

Figure 1.

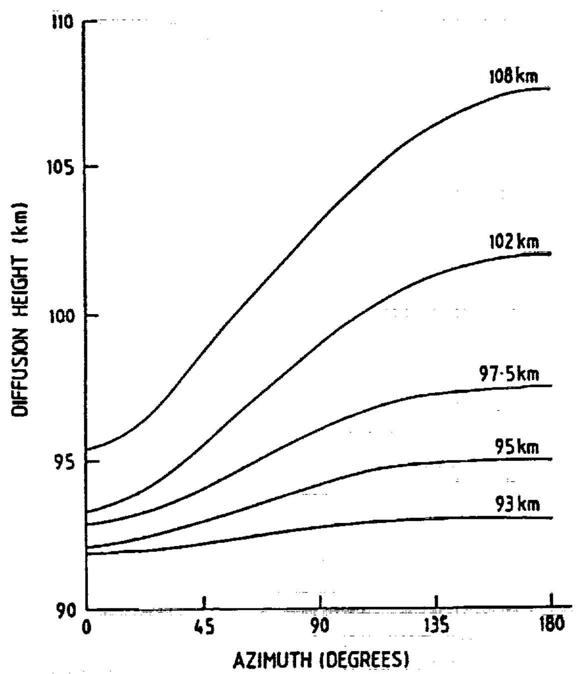

Figure 2.

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