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Meteor Geomagnetic Effects

SYDNEY CHAPMAN[1] and ATTIA A. ASHOUR[2]

1. Introduction

Kalashnikov (1949) reported the observation of small changes of the geomagnetic field, which he attributed to meteors. The record was made using a large horizontal coil as fluxmeter; thus it referred to the vertical magnetic component Z. Kalashnikov's evidence for the connection with meteors was partly statistical, but was also based on correspondences between observed meteors (Leonids, Geminids) and magnetic peaks on the fluxmeter record.

His first and later papers (1952) aroused interest in the subject. Recently Ellyett and Fraser (1963) summarized subsequent observational work in this field, carried out by Bumba (1955), Hawkins (1958), Campbell (1960, 1962), Jenkins, Phillips, and Maple (1960), and Ellyett and Gillion (1963). They state (pp. 5937–8): "Experimental work already carried out thus gives no evidence of a magnetic effect due to a single meteor, with the possible exception of the first worker, Kalashnikov. The correlation to date with showers also lacks conviction, ..."

Ellyett and Fraser (1963) further investigated the question, using a large horizontal loop near Christchurch, New Zealand, to record magnetic micropulsations, and radar to record meteors (down to a zenithal magnitude of 8.2). The sensitivity of their magnetic measures considerably exceeded that of any work previously published; their minimum detectable signal was 50 microgammas ($\mu\gamma$), or 5×10^{-10} gauss. Their amplifier had a bandwidth of 1 cps centered on 1.5 cps, so that the rise time was about 1 sec. They showed by a graph the mean daily variation of the mean hourly all-sky meteor rate for the period March 5–16, 1962; the daily mean was about 100 meteors per hour.

"Owing to the possible occurrence of man-made pulsations in the daytime" (p. 5940), they restricted their detailed studies to evenings. They claim that the variation of meteor rates for each hour, plotted through a succession of nights, is not significantly related to the corresponding micropulsation activity. They examined the relation between individual meteors and micropulsations, recording them on the same chart. They conclude that most individual meteors do not have any observable associated micropulsation activity, but the number of coincidences is greater than random. It remains possible that some of the larger meteors do produce magnetic effects. They add (p. 5945) that "if the matter is to be pursued further it will be desirable to investigate the characteristics of the individual meteor echo and the frequency coverage of the accompanying micropulsation. . . . The frequency of 1.5 cps was chosen to make the results strictly comparable with previous work, but it might well be that this is not the best frequency for the detection of such an effect."

Kalashnikov (1949) suggested two ways in which a meteor might modify the geomagnetic field: by motion of charges along the trail, and, as a second phase, by the convective motion of the ionized train, here called the *trail*. He envisaged the possibility of studying meteor phenomena by two stations, 80 or 100 km apart, each equipped with 3-component fluxmeters, to obtain the direction of the meteor magnetic field disturbance vector at each station; this might enable the meteor velocity and trajectory to be determined.

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2. General considerations

Any magnetic effect of a meteor must certainly depend on the ionization along its trail and on electric currents introduced or modified by this ionization. If the whole trail were situated in previously non-ionized air, the only way in which current could be caused to flow would be by an electromotive force induced by the convective motion of the trail. Any component of this emf along the trail would cause current to flow; but this would also quickly set up opposite polarization charges at the two ends, whose electric field would annul the component emf. The current would thus flow only very briefly. All meteors entering the atmosphere, however, first traverse the ionosphere, where they add to ionization already present and where currents are already flowing. The sudden creation of extra ionization and conductivity will modify these currents. This modification is equivalent to the superposition, upon the pre-existing currents, of an additional "meteor" current system, whose magnetic field may be observable at the ground.

The meteor current system will be proportional to the intensity of the pre-existing currents and will depend on the location and direction of the trail in relation to those currents. The magnetic effect recorded at a particular observing station will depend also on the position of the station relative to the meteor trail. The recognition of the effect will depend not only on its magnitude and type, but also on the ability to distinguish it from other changes unconnected with meteors. Thus, quiet magnetic conditions will be the most favorable for the investigation of meteor magnetic effects. As magnetic disturbance is most prevalent and intense in the higher latitudes, especially near the auroral zone, such localities are least suitable for the study.

In quiet magnetic conditions the main current system flowing in the ionosphere is the Sq system associated with the quiet-day daily magnetic variations. The direction and intensity of the Sq currents are functions of latitude, longitude, local time, and sunspot epoch; Sq also undergoes an unpredictable day-to-day variation. The current is most intense in the equatorial electrojet, which lies nearly along the magnetic equator, where the magnetic dip is zero. There its greatest intensity occurs at the hours around 11 a.m. local time. Hence a station under or nearly under the jet will be most favorable for the study of meteor effects. The meteors most likely to give observable magnetic records are daytime meteors entering the atmosphere nearly horizontally, within two or three hours of 11 a.m. local time; their mass and speed should be such as to produce very considerable ionization. According to McKinley and Millman (1949), radar-detectable ionization is usually produced only between 80 and 110 km.

These considerations do not seem to have been taken sufficiently into account in past studies of meteor magnetic effects. In the study by Ellyett and Fraser, only nighttime meteors were examined, although the radar data doubtless gave information about daytime meteors. Moreover, in past discussions little or no attention has been paid to the height of the meteors whose passage has been correlated with small magnetic pulsations. The only meteors likely to give observable magnetic effects at ordinary times are those of considerable speed and brightness that traverse the ionosphere between about 90 and 130 km height. Thus, statistical studies, if they are to be convincing, must be more selective than heretofore as to the meteor records used in comparison with the magnetic data. For satisfactory demonstration of meteor magnetic effects, it is really necessary to show an association between (a) particular meteors (preferably daytime meteors) fully observed as to time, location and direction of trail, and intensity of ionization per cm along the trail, and (b) particular magnetic changes fully recorded in all three magnetic components at one or more observatories not too far away. This is a considerable undertaking. Lovell (1954) quoted only one case where such complete radar *meteor* data had been obtained up to the time of his writing. The observations were made by McKinley and Millman (1949), who did not, however, give any information about the intensity of the ionization along the trail. (It may still be worthwhile to examine the magnetic records of the stations nearest to the plan location of the trail to see whether any identification of a magnetic effect can be made.)

The Harvard-Smithsonian Radio Meteor Project now makes regular determinations of the distribution of ionization along the trails observed at its six stations.

Photographic observations of meteors, such as were considered by Hawkins (1958) in his study of meteor magnetic effects, are less suitable than radar studies, because of the smaller intensity of the Sq currents in the nighttime ionosphere; the relative disadvantage is by a factor probably of order 5 or more. Most photographic meteors have trails that lie too low in the atmosphere to be promising for magnetic effects, because the Sq current intensity probably falls off rapidly below 100 km (*cf.* rocket observations of current heights [Singer, Maple, and Bowen, 1951; Cahill, 1959]).

Magnetic pulsation measurements by horizontal coils—giving data of the kind most considered in past discussions of this subject—are the least favorable for identification of magnetic changes with meteors. In general, the peak magnetic effect will be shown by the horizontal component at places under the trail. The peak effect on the vertical component will be smaller and will occur some distance away; it is smaller because of the induced currents caused by a rapid change in the external magnetic field. Such currents tend to increase the external change in the horizontal force by about half and to decrease the change in the vertical force (see sec. 5). Hence, coils in vertical planes are preferable to horizontal ones, though a set of three perpendicular coils is most desirable. Kalashnikov set up such a system at his Borok station near Moscow; Hawkins (1958) also used three perpendicular coils.

Identification of the magnetic effect of a fully observed meteor and its trail requires clear agreement in their time relations, not only as to the beginning of the magnetic effect, but also as to the duration of the two phenomena.

It is useful in this connection to infer as fully as possible what is the expected nature and magnitude of the magnetic effects of meteors moving in specified directions at known heights in known regions of the Sq current system. An example of such identification between magnetic effects of other kinds and their inferred cause is the association of Sqa, the augmentation of the normal Sq current system, with observed solar flares. X-rays from the flares greatly enhance the ionization of the *D* layer and thus extend downward the ionospheric layer in which dynamo-induced Sq currents flow; the duration in this case is of order 20 minutes to an hour. The phenomenon is much easier to study than are meteor magnetic effects. Because the magnetic Sqa effects are much larger, they are easily identified in the magnetic records, and the solar flare can be identified visually on the sun and also by its sudden disturbance of the ionosphere (called an SID), as shown by ionospheric recorders (Dellinger, 1937; Fleming, 1936; McNish, 1937; Veldkamp, 1960; Van Sabben, 1961).

3. Formulae for meteor magnetic effects

a. **Vertical trail.**—The first theoretical estimation of a meteor magnetic effect was carried out by Jenkins and DuVall (1963). They considered a meteor descending vertically through the Sq currents, which they took to be uniform in horizontal direction and intensity j_0, throughout a uniformly ionized ionosphere with electric conductivity K, bounded by horizontal planes at heights h and $h+d$ above the ground. They took the extra meteor ionization to be uniform through a cylinder of radius a with its axis on the meteor trajectory, such that the previously existing conductivity K within the cylinder was increased to K'. They treated the current flow as being steady in the presence of this conductivity distribution, ignoring any rise time and decay of the meteor current system. All these features of their work are suitable in a pioneer study of the problem. They estimated only the peak magnetic effect of the meteor at the ground, i.e., the disturbance at the point directly below the meteor.

The modification of the uniform current flow by the cylinder of enhanced uniform conductivity constitutes a well-known electrical problem. The mathematics is the same as that used by Chapman (1933) in discussing the magnetic effect of a solar eclipse, although in that case the changed conductivity K' is less than K, instead of being greater, as here; also, the change is more gradual, continues longer, covers a much larger area, and is perhaps less uniform. The current intensity within a cylinder of modified uniform conductivity remains uniform, but its intensity becomes $2K'j_0/(K+K')$. The modified current distribution corresponds to superposition, on the uniform flow with intensity j_0, of an additional current system (fig. 1), consisting of a uniform flow of intensity $(K'-K)j_0/(K+K')$ within the cylinder and an equal return flow outside the cylinder, along current lines that are circular arcs. Chapman gave an approximate calculation of the magnetic field of this superposed current system for different points on the ground below the cylinder. In his case a/h is large; in the meteor case, this ratio is small.

It is convenient to denote by J the total *excess* current flowing through the cylinder; thus

$$J=2ad\frac{K'-K}{K'+K}j_0. \qquad (1)$$

The magnetic change at the ground caused by the meteor is greatest at the point O where the meteor trajectory meets the ground. The change there (dH_0) is horizontal and transverse to the direction of the Sq current flow; it enhances the normal Sq magnetic vector at O. Jenkins and DuVall give a formula for dH_0, which in the notation used here is

$$dH_0=\frac{\pi J}{2a}\left(\frac{a^2}{h^2}+\ldots\right), \qquad (2)$$

neglecting higher powers of a/h. They do not indicate how they obtained this result.

In another paper (Ashour and Chapman, 1965) we give a complete determination, for any point of space, of the magnetic field of the current in a thin plane sheet, corresponding to a thin horizontal slice of the ionosphere and the meteor current system here indicated. By integration with respect to height, the field of the thick meteor current system can be obtained from our formulae. For the point O this gives the approximate formula

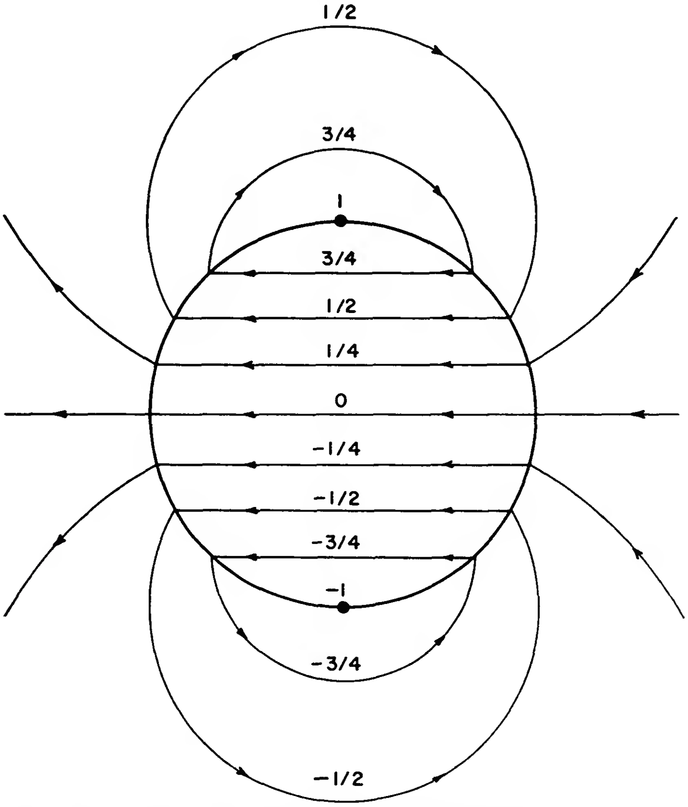

Figure 1.—Meteor current system for a vertically descending meteor. The current lines are straight lines within the cylindrical trail and arcs of coaxial circles outside. They are drawn at intervals of one-eighth of the total current flux through the cylinder.

$$dH_0=\frac{\pi J}{2a}\left\{\frac{a^2}{h(h+d)}-\frac{a^4(d^2+3dh+3h^2)}{4h^3(h+d)^3}\right\}, \quad (3)$$

thus replacing h^2 in (2) by $h(h+d)$. For the eclipse case, where a/h is large, we find the true value of dH_0 to be about 5 percent greater than the estimate made by Chapman (1933).

In considering the meteor field at a point P on the ground elsewhere than at O, it is convenient to take right-handed Cartesian coordinates x, y, z, relative to O as the origin, Oy being along the direction of the undisturbed Sq current flow; Ox, along the direction of dH_0; and Oz, vertically downward. For example, if the Sq current flow is eastward, Ox is northward. The corresponding components of the meteor magnetic field will be denoted by X, Y, Z. It is also convenient to use plane polar coordinates r, ϕ instead of x, y, measuring ϕ clockwise from Ox (looking down toward the ground); the corresponding meteor field components will be denoted by R, Φ. Our formulae for a plane horizontal sheet can be integrated with respect to the height, to obtain the (accurate) results:

$$=(2\pi J/d)\{f_1(a,h,d,r)$$
$$-(1/r)f_2(a,h,d,r)\}\cos\phi; \quad (4)$$

$$\Phi=(-2\pi J/rd)f_2(a,h,d,r)\sin\phi; \quad (5)$$

$$Z=(2\pi J/d)f_3(a,h,d,r)\cos\phi; \quad (6)$$

where the functions f are defined in terms of integrals of Bessel functions:

$$f_1=I(1,0;-1), f_2=I(1,1;-2), f_3=I(1,1;-1),$$
$$I(m,n;p)=\int_0^\infty J_m(at)J_n(rt)e^{-ht}(1-e^{-td})t^{-p}dt. \quad (7)$$

In the integrand t has the dimensions of an inverse length.

Using Luke's (1962, p. 319) formulae (26) and (27) we obtain the following approximate forms of R, Φ, Z:

$$R=(\pi aJ/2d)\{\psi_1(r,h,d)-(a^2/4)\psi_3(r,h,d)$$
$$+(3a^2r^2/8)\psi_5(r,h,d)\}\cos\phi, \quad (8)$$

$$\Phi=(\pi aJ/2d)\{\psi_1(r,h,d)$$
$$-(a^2/4)\psi_3(r,h,d)\}\sin\phi, \quad (9)$$

$$Z=(\pi arJ/2d)\psi_2(r,h,d)\cos\phi. \quad (10)$$

Here

$$\psi_n(r,h,d)=(r^2+h^2)^{-n/2}-\{r^2+(h+d)^2\}^{-n/2}. \quad (11)$$

In (8) and (9) terms involving ψ_n are neglected for $n \geq 7$, as ψ_7 is of order $a^5r^2/(r^2+h^2)^{7/2}$. Hence, to this high degree of approximation,

$$X(r)=(\pi aJ/2d)\{\psi_1(r,h,d)$$
$$-(a^2/4)\psi_3(r,h,d)\}, \quad (8a)$$

and

$$Y(r)=0. \quad (9a)$$

Thus the horizontal component of the meteor field everywhere at the ground is in or almost in the same direction as dH_0, that is, perpendicular to the Sq current flow. Its magnitude $X(r)$ varies (over the ground) only with r; that is, its isolines are circles. Figure 2 shows $X(r)/dH_0$ for points on the ground as a function of $r/h=R$, when $d/h=D=0.3$ (e.g., for such typical values as $h=100$ km and $d=30$ km). It falls to about one-half when $R=0.85$.

From (10) we find that

$$(Z\sec\phi)/dH_0$$
$$=R(1+D)(2+D)/[(R^2+1)\times$$
$$\{R^2+(1+D)^2\}]. \quad (10a)$$

Thus at the ground $(Z \sec \phi)/dH_0$ is a function of R only; it has a maximum at $R=R_m$, given by

$$R_m=(1/\sqrt{3})(1+D/2+D^2/8+7D^3/32), \quad (10b)$$

ignoring D to powers of 4 or more. The points of maximum Z on the ground along any radial direction from O lie on a circle of radius R_m; $(Z \sec \phi)/dH_0$ for points on the ground is shown in figure 2 for the particular value $D=0.3$. The peak ground values of Z/dH_0 are about ± 0.65 at $R=0.62$, in directions ($\phi=0$, $\phi=\pi$) perpendicular to the Sq current flow. If the Sq current flow is eastward, the "meteor" vertical component Z is downward (+) to the south of the trail and upward (−) to the north.

b. **Horizontal trajectory along Sq current.**—The problem of the meteor magnetic effect is especially simple for an infinitely long horizontal meteor trajectory at height h' lying along the direction (y) of the Sq current flow j_0. The conditions, axes, and notation in other respects (such as h, d, a, j_0, K, K') are

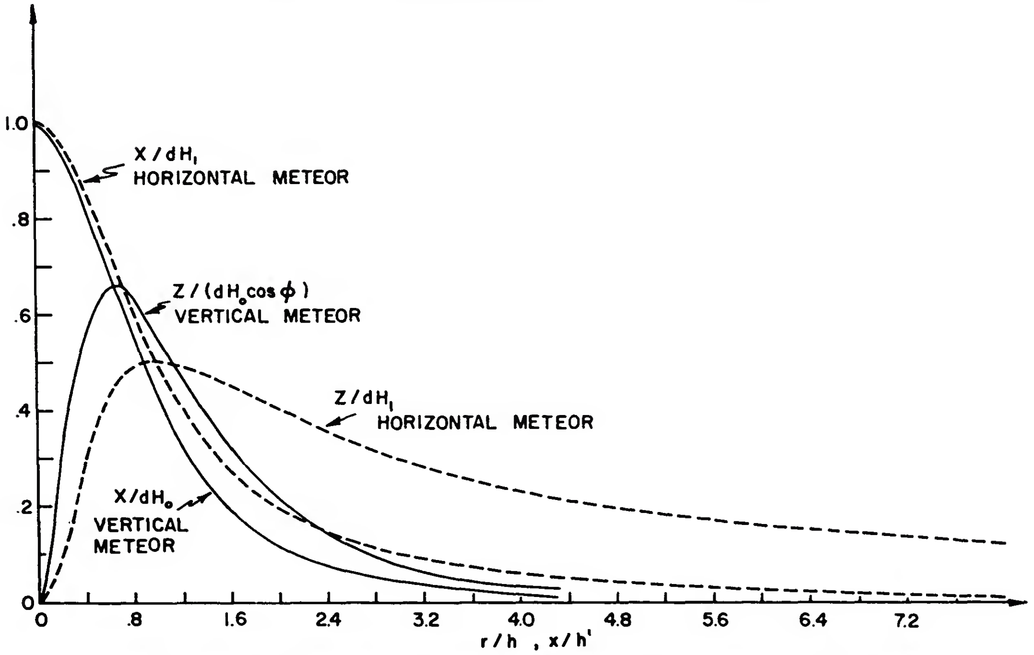

FIGURE 2.—Variation of the meteor magnetic field at the ground with distance. Solid curves show $Z/(dH \cos \phi)$ and X/dH_0 for a vertically descending meteor as functions of r/h: for $d/h=0.3$. Broken curves show Z/dH_1 and X/dH_1 for a horizontal meteor trail in the direction of the Sq current flow as functions of x/h'.

taken to be the same as before, O now being any point directly under the meteor trajectory. If the trajectory lies in the layer previously considered, in which current flows under the impulse of a uniform dynamo emf because of a uniform convection of the layer, the same emf will act along the meteor trail, and the current intensity within the cylindrical trail will be $K'j_0/K$; in this case there will be no change in the current elsewhere. Thus the effect of the meteor is simply to produce an additional horizontal current, of cylindrical cross section and mean height h', with no return current. The total additional current J_0' along the trail is given by

$$J_0'=\pi a^2 j_0(K'-K)/K; \tag{12}$$

its magnetic effect dH_1 at the ground anywhere directly beneath the meteor trajectory is given by

$$dH_1=2J_0'/h'=2\pi a^2(K'-K)j_0/Kh'. \tag{13}$$

As in the case of the vertical trajectory, the direction of dH_1 is perpendicular to the direction of the Sq current flow; it enhances the normal Sq field under the trail.

Elsewhere, the horizontal field of the meteor current at the ground is a function of the x coordinate only; the Y component is zero. The X and Z components are given by

$$X=2J_0'h'/(h'^2+x^2)=h'^2dH_1/(h'^2+x^2), \tag{14}$$

and

$$Z=-2J_0'x/(h'^2+x^2)$$
$$=-h'x\,dH_1/(h'^2+x^2)=-(x/h')X. \tag{15}$$

Thus X steadily decreases with distance from the plan position of the meteor trajectory, whereas Z rises along the x direction from zero to a peak value $\pm(1/2)dH_1$ at $x=\mp h'$ (there $Z=\pm X$). Beyond this distance Z numerically exceeds X. Figure 2 shows X/dH_1 and Z/dH_1 as functions of x/h'.

The supposed uniform Sq current intensity j_0 corresponds to the flow under the impulsion of a dynamo-produced electric field E such that $j_0=KE$. Outside the Sq layer the air may be in convective motion with a different speed;

there the induced dynamo field will differ from E. If at height h' it is E', the current J_0' along the infinitely long horizontal meteor trail will be $\pi a^2 K'E'$, which could flow in an otherwise insulating layer of the atmosphere below the Sq layer. Such an infinitely long trail in insulating air, however, falsifies nature. Owing to the curvature of the earth and the passage of the meteor through the ionosphere before reaching the supposed nonconducting layer, the intensity and duration of the current flow would depend on the end conditions of the trail.

A less crude model is a horizontal trail of finite length $2b$. In this case the meteor magnetic field at the ground would be greatest at O, the point under the center of the meteor trajectory, and X and Z would depend on both coordinates x, y. The meteor current system now includes return currents outside the trail, which reduce the magnetic effect of the current along the trail. The mathematical problem of the modification of uniform current flow caused by a uniform enhancement of previously constant conductivity K to the value K' throughout a cylinder of radius a and finite length b, with its axis along the direction of the electric field E, has not been solved even where the region of flow is unbounded; the problem is still more difficult when the region is bounded by two horizontal planes. The current intensity within the cylinder will not be uniform, although if b/a is large, its value at the center of the cylinder will not be much less than $K'E$. If as an approximation the intensity were taken to have the value $K'E$ everywhere inside the cylinder, the field at O on the ground, under the center of the cylinder, would be partly caused by this flow within the cylinder, reduced by the field of the return currents. The part resulting from the idealized uniform current within the cylinder, which may be calculated as if the current J_0' were concentrated along the axis, would be

$$bdH_1/(b^2+h'^2)^{1/2}. \tag{16}$$

If b/a is large, this will be a good approximation to the field at O caused by the current within the cylinder. It is more difficult to estimate the field of the return currents, whether the ionosphere is taken to be unbounded or of finite thickness.

The problem becomes somewhat simpler, mathematically, for an unbounded ionosphere, if the meteor trail of finite length is taken to create extra uniform ionization in a prolate *spheroid* with a long horizontal axis of length $2b$ and a short axis of length $2a$. In this case (whatever the ratio b/a) the modification of the uniform current flow is known (for example, see Smythe (1950), p. 208, problem 82). The magnetic field of the modified current system has not, however, been determined, so far as we are aware; it is probably a difficult problem. It is, however, possible to infer from Ampère's theorem the meteor magnetic field at any point in the vertical diametral plane. In that plane the field lines are circles about C, the center of the spheroid. At distance r from the axis, we have

$$2\pi r\,dH=\int 4\pi\,j\,dS=8\pi^2\int jr\,dr. \tag{17}$$

Within the cylinder (hence from $r=0$ to $r=a$) the extra "meteor" uniform current density, when b/a is very large, is very nearly $(K'-K)j_0K$; beyond $r=a$ the current is reversed, and its density, when b/a is very large, is approximately

$$-(J_0'/\pi b^2)(\coth^{-1}q-1/q),$$

where

$$q=\{1+r^2/(b^2-a^2)\}^{1/2}. \tag{18}$$

Hence from (17) we infer that at distance $r=h$ from the axis of the spheroid, the "meteor" magnetic intensity is

$$(2J_0'/h)\{1-c/b+c(h^2+c^2)^{1/2}/b^2$$
$$-(h/b)^2\sinh^{-1}(c/h)+(a/b)^2\sinh^{-1}(c/a)\}, \tag{19}$$

where

$$c^2=b^2-a^2. \tag{20}$$

This model current system associated with a spheroidal meteor trail differs, however, from the more realistic case of such a trail lying in the bounded ionosphere. Even if the trail lies at the middle level of the thick ionospheric layer, there will no longer be axial symmetry of the current distribution. So far as we know, the distribution for such a layer has not been determined, and the above method of determining dH in the diametral plane is not applicable. The return current of the meteor current system lies wholly in the ionospheric layer, but the magnetic field lines will not be confined to this layer; there will be a magnetic field at the ground. Its value at O will be less than that given by (19), but perhaps only moderately less, if a is small compared with d and h'.

The mathematical problems involved in an exact determination of the meteor magnetic field for a horizontal meteor trail of finite length, whether cylindrical or spheroidal, are so complex that it would seem simpler to determine the field experimentally in the laboratory. The uniform current flow might be created in a large rectangular vessel full of brine, with a small body of the shape of the trail suspended in it, and composed of metal or other material suitably more conducting than the brine of the concentration used. The magnetic field of the uniform flow in the absence of the inserted body could be neutralized, in the "ground" plane over which the distribution of the "meteor" magnetic field was to be explored, by an opposite current flow in a metal sheet between the vessel and the ground plane. Then the "meteor" field could be directly determined over the ground plane.

Of course a uniform horizontal trail of finite length does not truly simulate nature; it is merely a mathematical idealization of the reality. For a long trail, the curvature of the level surfaces in the ionosphere and the consequently changing inclination of the meteor trajectory along its length, whatever its direction, may need to be taken into account, as well as the variation of the ionospheric conductivity with height. Such calculations as are made here are intended only to indicate the order of magnitude of the meteor magnetic effect.

c. **Horizontal trajectory normal to Sq current.**— When the meteor trail is horizontal, infinitely long, and perpendicular to the (y) direction of the Sq current flow, the problem is mathematically two-dimensional, in that all the dependent variables are functions of y and z only, provided that the uniform ionosphere is bounded, if at all, by horizontal planes. The meteor-modified current lines, and those of the meteor current system, will lie in planes of constant x. At any point P the magnetic field of the meteor current system is given by an integral of the form

$$\iiint \frac{\mathbf{di}\times\mathbf{r}}{r^3},$$

where **di** denotes an element of the volume-distributed current. The integrand has the form

$$\frac{1}{r^3}\begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 0 & di_2 & di_3 \\ x & y & z \end{vmatrix}$$

because **di** has no x component. The **j** and **k** components of the field of the meteor current system are zero, because in the integrals involving xdi_3 and $-xdi_2$, x takes all positive and negative values. Thus the meteor magnetic field (here denoted by X') is purely in the x direction, that is, parallel to the lines of force of the Sq field.

If the ionosphere is unbounded in the vertical as well as in the horizontal direction, the current lines of the meteor current system are as shown in figure 1 (p. 184), but now they lie in the vertical planes where x is constant. The magnetic field of a thin vertical section of the meteor current system has been calculated by Ashour and Chapman (1965) and must be integrated with respect to x to obtain X'. Thus:

$$\begin{aligned} X' &= 4\pi a j_0 \frac{K'-K}{K'+K}\times \\ &\qquad \int_{-\infty}^{\infty}\int_0^{\infty} J_1(at)J_1(t\rho)e^{-tx}\,dt\,dx \cos\phi \\ &= 8\pi a j_0 \frac{K'-K}{K'+K}\int_0^{\infty} t^{-1}J_1(at)J_1(t\rho)\,dt \cos\phi, \end{aligned} \tag{22}$$

in terms of the polar coordinates ρ, ϕ in the vertical current plane relative to the center C of the current system.

Hence, according to Luke's formulae (1962, equation 24, p. 318), X' for points outside the meteor trail ($\rho>a$) is given by

$$X' = 4\pi \frac{a^2}{\rho} j_0 \frac{K'-K}{K'+K}\cos\phi. \tag{23}$$

For a point P on the ground, at x, y, $-h'$, the cylindrical coordinate ρ is $(y^2+h'^2)^{1/2}$; as ϕ denotes the angle made by OP with the vertical, $\cos\phi = h'/\rho$. Hence the meteor magnetic intensity is $(X', 0, 0)$, where

$$X' = 4\pi \frac{a^2 h'}{y^2+h'^2} \frac{K'-K}{K'+K} j_0. \tag{24}$$

Expressed in terms of dH_1, the field intensity on the ground vertically below a similar meteor trail, at the same height h', directed *along* the Sq current flow, is

$$X' = \frac{2K}{K'+K} \frac{h'^2}{h'^2+y^2} dH_1. \tag{25}$$

This result for an infinitely long meteor trail in a completely unbounded ionosphere is not accurate for the magnetic field set up by a trail of finite length in an ionosphere bounded by horizontal planes above and below. But if the length of the trail is comparable with h', equation (25) probably gives the order of magnitude of the meteor magnetic field at the point directly below the central point of the trail. Elsewhere, the field will have y and z components as well as X'. Since to work out the meteor field exactly in this case would involve much complexity, we do not attempt it here, particularly because it seems likely that an actual trail that could appreciably modify the Sq field if it were directed along the Sq current flow would have a very much smaller magnetic effect if it were perpendicular to the flow (see sec. 5*c*.)

4. Meteor ionization and meteor currents

The formulae for meteor magnetic effects involve the meteor trail radius a and the electrical conductivities K, K'. In the ionosphere the electrical conductivity is anisotropic because of the presence of the geomagnetic field and the insulating boundary below. K refers to the effective conductivity in the direction of the Sq current flow. The conductivity K' for the same direction, enhanced by the presence of the meteor trail, is $n_e' K/n_e$, where n_e, n_e' denote the normal electron density and the density enhanced by the meteor ionization. (A complication ignored in previous calculations of meteor magnetic effect is that the modified current flow is not uniform in direction, so that its distribution will depend also on the conductivity in directions other than that of Sq.)

Radar workers, in discussing meteor ionization, refer to α, the meteor "line" electron density per cm length of trail. This is given by

$$\alpha = \pi a^2 (n_e' - n_e). \tag{26}$$

Let β be the corresponding normal electron line density per cm length of trail, so that

$$\beta = \pi a^2 n_e. \tag{27}$$

Then

$$(K'-K)/K = (n_e'-n_e)/n_e = \alpha/\beta, \tag{28}$$

and

$$(K'-K)/(K'+K) = 1/(1+2\beta/\alpha). \tag{29}$$

Hence the field dH_0 for a vertical meteor trajectory, to the first approximation (see equation (3)), can be thus expressed

$$dH_0 = \pi a^2 j_0 d/h(h+d)(1+2\beta/\alpha). \tag{30}$$

Likewise, the field dH_1 immediately below an infinitely long horizontal meteor trail (see equation (13)) can be expressed as

$$dH_1 = 2\alpha j_0/n_e h', \tag{31}$$

if the trail is directed along the Sq current flow; if it is perpendicular to the current flow, the maximum meteor magnetic field immediately below the trail ($y=0$) is X', given (see equation (25)) by

$$X' = 2\beta\, dH_1/(\alpha+\beta). \tag{32}$$

The results for the meteor magnetic field, in the various cases considered here, will next be evaluated numerically.

5. Numerical discussion

a. **Vertically descending meteor.**—Jenkins and DuVall (1963), in calculating the numerical magnitude of the magnetic effect of a vertically descending meteor, from their formula (2), adopted the following values:

$$h = 100\text{ km};\ d = 30\text{ km}, \tag{JD(33)}$$

$$j_0 = 10^{-10}\text{ amp/cm}^2 = 10^{-11}\text{ emu}, \tag{JD(34)}$$

$$K'/K = 3, \tag{JD(35)}$$

$$a = 3\times10^4\text{ cm} = 300\text{ m}. \tag{JD(36)}$$

Here JD signifies that the values in (33) through (36) are those used by Jenkins and DuVall. The value of a is quoted from Öpik (1958, p. 22), who also estimates n_e' as varying from 3×10^4 to 3×10^5/cc. In the E layer n_e (at noon in low and middle latitudes) is of order 10^5/cc, so that JD(30) corresponds to Öpik's upper limit for n'_e.

The uniform horizontal magnetic field on either side of a current distribution of uniform density j_0 in a horizontally unbounded layer of thickness d is $2\pi j_0$ gauss if j_0 is expressed in emu. The values (33) and (34) give the field intensity as $6\pi(=19)\gamma$; allowing for an additional earth-current field of about half this magnitude, the field at the earth's surface would be about 30γ. This is of the right order of magnitude for Sq(H) at sunspot maximum over a considerable range of latitude (cf. Chapman and Bartels, 1940, p. 233, where the daily peak value is given as 20γ for the sunspot *minimum* year 1902). At Huancayo under the equatorial electrojet, however, Sq(H) can be seven times as great (Chapman and Bartels, 1940, p. 243, fig. 25, July 24, 1928). Thus it is possible to take

$$j_0=7\times10^{-11}\text{ emu} \qquad (37)$$

for the epoch around 11 a.m. at Huancayo for a sunspot maximum year on a quiet day of large Sq range.

Jenkins and DuVall evaluate dH_0 from (2) using the values (33) through (36) as about $100\mu\gamma$; but the result seems instead to be $42\mu\gamma$. The correction of h^2 in (2) to $h(h+d)$ further reduces this to $32\mu\gamma$.

Their values of a and n'_e correspond to

$$\alpha=5.7\times10^{14}/\text{cm}, \qquad \text{JD}(38)$$

and for the same value of a, taking $n_e=10^5$/cc,

$$\beta=2.8\times10^{14}/\text{cm}. \qquad \text{JD}(39)$$

Radar workers refer to values of α up to 10^{16}/cm; e.g., Greenhow and Lovell (1960, p. 545) quote 10^{16}/cm as an average value of α for a bright meteor at height 80 km. This corresponds to

$$K'/K=36.3\text{ (for }a=300\text{ m).} \qquad (40)$$

Supposing this value of α to apply in the E layer, in the Sq current layer, substitution in the first term of (3) from (37) and (40) gives 424 $\mu\gamma$ as the value of dH_0, valid for a place such as Huancayo, near noon, at sunspot maximum. The factor of increase between the two values of dH_0, 32 $\mu\gamma$, and 424 $\mu\gamma$, is less than twice the ratio 7 of (37) to (34). This is because the factor $(K'-K)/(K'+K)$ is increased only from 0.5 (JD) to 0.95; it can at most only be doubled, even if K'/K were infinite.

The value of a used by Jenkins and DuVall much exceeds the values mentioned in discussions of meteor trails by some writers; e.g., Greenhow and Lovell (1960, p. 562) refer to "the large initial radius of the ionized column" in connection with values of the radius comparable with the wavelengths, such as 8 and 17 meters, used in radar meteor studies. They infer initial trail radii of 1 m at 90 km height and 3 m at 115 km. Cook, Hawkins and Stienon (1962) observed the optical width of meteor trails during the Geminid shower of 1957. Their results indicate that the trail width is usually of the order of 1 m, although in individual cases the width may be as much as 6 m. Hawkins (1963) states: "It is difficult to see how the initial ionization column can be any larger in diameter than the measured optical values, i.e., of the order of 1.0 meter over the normal range of meteor heights from 90 to 105 km."

The initial radius of the trail depends on the distance of penetration of the ionizing agent associated with the passage of the meteor. Later the trail radius increases, owing to molecular and eddy diffusion, but at the same time α decreases because of attachment and recombination of the electrons. At 100 km the coefficient of diffusion is of order 10^5 cm^2/sec, indicating that in 1000 sec (or about ¼ hour) diffusion would enlarge a to about 100 m. At this height, however, and in this time, n'_e might have been greatly reduced by attachment and recombination. It is worth remembering, however, that in the daytime, when meteor magnetic effects are likely to be most easily measurable, the effect of attachment will be reduced by photodetachment.

Öpik (1958, p. 22) treats the positive ions in the meteor trail as being mainly O_2^+ and N_2^+, ionized by *photons* from high temperature gas close to the meteor; he estimates the range of penetration of the photons to be

300 m. Greenhow and Lovell (1960, p. 546) consider that the bulk of the ions are those of meteor atoms, such as Ca^+, Fe^+, Mg^+ and Si^+; they state that if the ions were molecular, the electron density would decay (in the E layer, by dissociative recombination) more rapidly than is observed. The penetration range of such meteor atoms is of order 10 to 20 times the mean free path, giving an initial radius at 100 km height of a few meters at the most. It may be that different authors are quoting values of a at different epochs in the life of the trail, or are referring to meteors at different levels and of different sizes.

If, however, the appropriate value of a should be of order 1 m instead of 300 m, the above estimates of dH_0 would have to be reduced by a factor of about 100,000. In that case the magnetic effect of a vertically descending meteor would be only a fraction of .01 $\mu\gamma$ at most, even directly under the meteor trajectory; elsewhere it would be still less in H, and less again for Z.

b. Horizontal trajectory along Sq current.—Meteors with horizontal (or nearly horizontal) trails are likely to have a larger magnetic effect, *ceteris paribus*, than those that descend vertically. A reduction of a from 300 m to 1 m does *not* affect dH_1, the magnetic change in H immediately under the midpoint of a horizontal trail along the Sq current flow, *for a given value of* α (see equation (31)). Thus, for $\alpha=10^{16}$/cm, $j_0=7\times10^{-11}$ emu, $h'=115$ km, and $n_e=10^5$/cc, (31) gives $dH_1=120,000$ $\mu\gamma$, or 0.12 γ. As we have stated above, however, the value of dH_1 given by (31), valid for an infinitely long horizontal trail in an unbounded horizontally uniform ionosphere with uniform Sq electric currents, is an overestimate of the actual dH_1 for a trail of finite length, because it takes no account of a return current in the superposed "meteor" electric current distribution.

For a prolate spheroidal trail with short and long semiaxes a,b, in an ionosphere with no upper and lower boundary, equation (19) gives dH_1, taking the return current into account. The result is practically independent of the value of a, so long as we can ignore a^2/b^2 in (19); this is certainly the case when a is 300 m or less and b is 50 km or more. The following table shows the values of dH_1 for a few values of b, taking the same values of α, j_0, and h' as before:

b(km)	50	100	200
$2b$(km): trail length	100	200	400
$dH_1(\mu\gamma)$	26,800	58,900	99,106.

Comparing these values with 120,000 $\mu\gamma$, for b infinite, it is clear that the finite length of the trail and the return current do not greatly reduce dH_1 when the ionosphere is unbounded. The effect of the vertical limitation of the actual ionosphere is difficult to calculate mathematically and may be best found by experiment, as suggested above (sec. 3*b*). The return current will spread out laterally from the trail more in the horizontal than the vertical direction. The lack of axial symmetry in the current and field distribution precludes the application of the above simple "Ampère" method of calculating dH_1. But it seems not unlikely that the change of dH_1 caused by the limitation of the ionosphere will be moderate, by only a small factor. If so, it should easily be possible to measure the magnetic effect dH_1 for a horizontal trail along the direction of the Sq current flow, if $\alpha=10^{16}$/cm at a time when j_0 is given by (37); indeed, αj_0 could be less by a factor of 100 and dH_1 should still be rather easily measurable.

There is perhaps some doubt whether a trail of line density as large as 10^{16}/cm could be formed at a height of 115 km. Greenhow (1963, p. 7) gives a diagram showing the level of the mean height of maximum electron line density α for meteors of different speeds and different values of α_{max}; for $\alpha_{max}=10^{16}$/cm the greatest height shown is 90 km. At this level j_0 may perhaps at times be not less than a hundredth of the value (37). However, during a solar flare (sec. 2) the Sq layer is extended downward, and at such a time j_0 at 90 km may approach the value (37) under the electrojet. In that case a trail for which $\alpha=10^{16}$/cm should give a magnetic effect, near 11 a.m., of some tens of thousands of $\mu\gamma$; a less intensely ionized trail should easily be detectable, e.g., one for which $\alpha=10^{15}$cm.

We should also remark that α will vary along the trail, whereas our calculations have supposed it to be constant; thus if α_{max} is 10^{16}/cm, the average value of α will be less; this would need to be taken into account in any attempt to connect a meteor trail with a measured coincident magnetic change. Such a variation of α along the trail could be taken into account in the suggested experimental determination of the effect of the return current (sec. 3*b*).

***c.* Horizontal trajectory perpendicular to Sq current.**—The maximum meteor magnetic intensity (X_1') at the ground owing to an infinitely long horizontal trail normal to the direction of the Sq current flow is shown by (32) to be $2\beta/(\alpha+\beta)$ times the value of dH_1 for a physically similar horizontal trail *along* the current flow. If n_e' exceeds n_e only by a factor of 2 or 3, as in the case considered by Jenkins and DuVall, (X_1') will be only moderately less than dH_1. But if a is of order 1 m and α of order 10^{16}/cm—in which case dH_1 appears readily observable, if the trail occurs at a suitable place and time—then β is very small compared with α, and (X_1') may well be below the level of detection.

***d.* Trail in general direction.**—The meteor current system is more complicated when the trail is neither vertical nor horizontal. Let θ denote its azimuth relative to the direction of the Sq current flow and ϵ its inclination to the horizontal; its direction cosines relative to **i**, **j**, **k** are $\sin\theta\cos\epsilon$, $\cos\theta\cos\epsilon$, $\sin\epsilon$. Suppose that the extra ionization along such an inclined trail is uniform throughout a cylinder of radius a with the meteor trajectory as axis. The horizontal sections of the cylinder are ellipses with axes inclined to **i**, **j** at the angle θ. In successive layers traversed by the meteor the ellipses are progressively displaced. If each thin horizontal layer of the ionosphere were insulated from its neighbors, the current distribution in each layer, resulting from the uniform excess conductivity within the elliptic section, is determinable mathematically from known results. But the magnetic field of such a sheet-current distribution is not known in mathematical terms. As the ionospheric layers are *not* insulated from one another, and as the electric potential varies over each, the displacement of the current pattern from layer to layer involves the existence of vertical electric fields. Hence the current flow will no longer be in horizontal planes. In this case the mathematical problem of the magnetic field of the meteor current system is complex. Experiment (sec. 3*b*) seems to offer the only presently available means of determining the meteor magnetic field. But it seems not unlikely that the peak field intensity at the ground, especially when a is small and α/β is large, is of the same order as the peak intensity dH_1 for a physically similar horizontal trail at the mean height of the Sq currents, in a uniform current flow parallel to the trail but less intense than that of the Sq currents by a factor of $\cos\theta$.

6. Meteor magnetic field as modified by induced earth currents

The varying magnetic field of the meteor current system in the atmosphere will induce currents in the sea or land below the earth's surface ($z=0$). The meteor magnetic effect observed anywhere at this surface is the sum of the direct field X, Y, Z generated in the atmosphere and the induced field X', Y', Z' generated in the earth.

The induced field is determined by the variation of the direct meteor magnetic field and its space distribution and by the distribution of electric conductivity k below the earth's surface. The calculation involves the determination of the induced current distribution and of its magnetic field at the surface. The mathematical solution is rarely simple, even for the surface of the sea, for which k may be considered known (4×10^{-11} emu) and effectively uniform. On land the problem is simplest for desert areas under which there is no ground water; there k may be taken as uniformly 10^{-15} emu, down to a considerable depth. Where there is a moist surface layer, k for the layer is much greater (e.g., 10^{-13} emu). Deeper down, k increases to such an extent that the material below about 800 km is shielded from external field changes.

The simplest type of direct meteor magnetic field is that for an infinitely long horizontal trail along the direction of the Sq current flow. In this case the field is that of an infinitely long horizontal current at height h' above the surface. The time variation of this current is considered in sec. 8. For the present purpose of estimating the order of magnitude of the induced field it is convenient to treat the variation as periodic, so that the linear current is taken to be

$$J_0' \mathbf{j} \cos pt.$$

In this case

$$X=\frac{2J_0'h' \cos pt}{h'^2+x^2},\ Z=\frac{2J_0'x \cos pt}{h'^2+x^2}. \qquad (41)$$

Price (1950, equation 10.7) has determined the induced field for such a varying line current, at a height h' above a uniform medium of conductivity k filling all space below the surface $z=0$. In our notation his result is

$$X'+iZ'=(2J_0'\alpha \cos pt)\{1/\zeta-2^{1/2}/\zeta^2+\ .\ .\ .\ \}$$
$$+(2J_0'\alpha \sin pt)\{-2^{1/2}/\zeta^2+\ .\ .\ .\ \}. \qquad (42)$$

Here

$$\alpha=2(\pi kp)^{1/2},\ \zeta=\alpha(h'+z+ix),$$
$$(1/\zeta)_{z=0}=(h'-ix)/\alpha(h'^2+x^2). \qquad (43)$$

This result is valid for large $|\zeta|$. This condition is fulfilled if the medium is sea water and the period is one second; then $\alpha=5.6\times10^{-5}$; if h' is 100 km, $|\zeta|$ at the ground is at least 560, and the terms in $1/\zeta^2$ are negligible. Hence, to this order of approximation

$$X'=X,\ Z'=-Z. \qquad (44)$$

Thus the induced field doubles the horizontal component of the direct field and annuls the vertical component. Even if the period of variation is as large as a minute, $\alpha h'$ is 75, and again $1/\zeta^2$ is negligible, and the same remarks apply. To a good degree of approximation, the induced field is that of an image line current at depth h'.

As the ocean is not infinitely deep, these results need to be examined to see at what depth the induced currents become negligible; if this is less than the depth of the ocean considered, the finite depth of the ocean will not appreciably affect the result. From Price's result (1950, equation 10.3) it is not difficult to show that for the above values of $\alpha h'$ (560 and 75), the rate of decay of the currents with depth is approximately as $\exp(-\alpha z/2^{1/2})$. This is the same rate as in the ordinary case of the "skin effect." For sea water and a period of 1 second, the currents at a depth of 1.16 km are reduced in intensity by a factor of 100. Thus for this period the induced field is of image character, as above. For a period of a minute the reduction of the current intensity is by a factor of 10 at a depth of 4.5 km, so that again the image field is a good approximation for an ocean of this or greater depth. If the depth is 4.5 km and the period is an hour or more, the ocean does not fully shield the region below from the varying external field, and the problem becomes more complicated.

On land, in places where the conductivity may be taken to be of order 10^{-15} emu down to 100 km or so, $\alpha h'$ is 2.8 for a field varying with a period of a second. In this case the field penetrates to a much greater depth before the induced currents shield the region below. The induced field at the surface is reduced in intensity, so that the direct horizontal field is less enhanced and the direct vertical field is less reduced. Price (1950, equations 10.8–10.11) gives expressions for this particular surface-induced field and numerical tables of the functions involved. Figures 3 and 4 have been calculated from his formulae and tables for the case $h'=2.8$; they show on the same scale the horizontal and vertical components, both direct and induced, and the total field in each case.

7. Time relations

The preceding sections have discussed in various cases the magnitude of the maximum magnetic

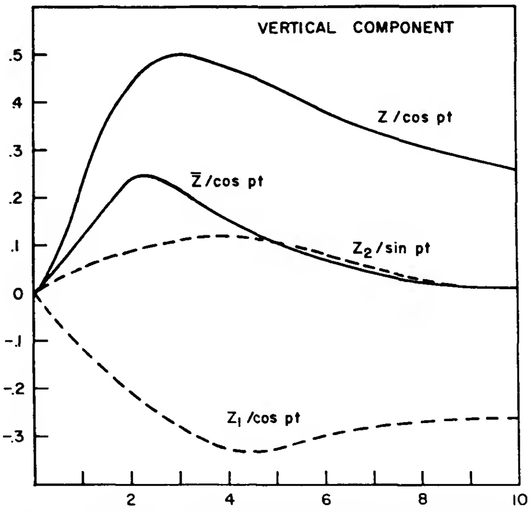

FIGURE 3.—Effect of induction in the earth, in a desert area, on the magnetic field of an infinitely long horizontal meteor trail along the direction of the Sq current flow. Vertical component: of the inducing field$=Z$; of the induced field$=Z_1+Z_2$; of the total field$=\bar{Z}+Z_2$. Components are all drawn as functions of x/h'.

effect of a meteor on the horizontal and vertical components of magnetic force at ground level and also the variation of the magnetic effect with position on the ground relative to the meteor trail. In determining the best instrumental means of detecting and identifying meteor magnetic effects, it is necessary also to consider how the effects are likely to vary with time.

Three rates of change are especially involved:

(1) the rate at which the meteor travels along its trajectory, creating or increasing the ionization there;

(2) the rate at which the ionospheric electric currents adjust themselves to the changed distribution of ionization and conductivity;

(3) the rate at which the pre-existing distribution of the electric currents is restored by the decay of the excess ionization produced by the meteor, thus terminating the duration of the meteor magnetic effect.

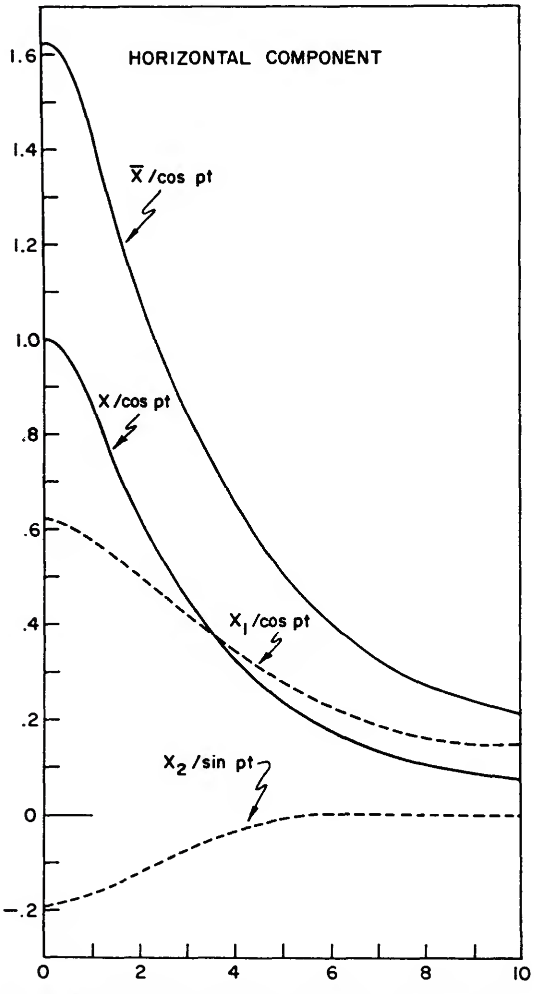

FIGURE 4.—Effect of induction in the earth, in a desert area, on the magnetic field of an infinitely long horizontal meteor trail along the direction of the Sq current flow. Horizontal component: of the inducing field$=X$; of the induced field$=X_1+X_2$; of the total field$=\bar{X}+X_2$. Components are all drawn as functions of x/h'.

a. **Development of ionized trail.**—Meteor speeds of entry into the atmosphere range from 10 to 72 km/sec (Greenhow and Lovell, 1960, p. 516). There is not much retardation in the course of the passage of the meteor along its trajectory during the period in which it is partly evaporated, emitting atoms that are themselves ionized and may also ionize atmospheric atoms and molecules. Hence a vertically descending meteor would take from 3 to 0.4 sec to develop its ionized trail in the thickness of the ionospheric layer in which the Sq currents mainly flow—taking this layer to be between 100 and 130 km height (Jenkins and DuVall, 1963). The smaller value, 0.4 sec, corresponding to a high entry speed, seems the more relevant here, as it is the more likely to give a large line density of ionization along the trail and an appreciable magnetic effect. However, vertically descending meteors are relatively ineffective magnetically.

For a horizontal meteor trail, even one of a meteor of high entry speed, the corresponding time would be greater. This is because the magnetic effect at a ground point P immediately under the trail would depend on the length $2s$ of the trail within a distance s on either side of the zenith of P on the trail. For magnetic observability of the meteor current system, s may be taken to be of the same order as the height h' of the trail, or preferably rather more. Thus $2s$ may be at least 200 km, requiring a travel time of about 3 sec or more. Hence the most easily detectable meteor magnetic effects, those of a long horizontal trail at a suitable height and along or nearly along the direction of Sq current flow, would be likely to have a rise time of order 1 second or more.

b. **Modification of electric currents.**—As the meteor creates a trail of increased ionization, the electric currents driven by pre-existing and continuing electromotive forces will adjust themselves to the new distribution of conductivity; this adjustment may be viewed as the formation of a superposed meteor current system.

The preceding estimates of the meteor magnetic effect have been made as if the meteor current system were steady and permanent. The mathematical determination of its actual mode and rate of *growth* would be very difficult, and we have not attempted it. Perhaps the order of magnitude of the growth time may be estimated as follows. In a simple circuit of resistance R and self-induction L, to which an emf is suddenly applied and thereafter kept constant, the development of the current is proportional to $1-\exp(-Rt/L)$. The growth time for the current to attain 90 percent of its steady final intensity is (L/R) ln 10, or 2.3 L/R. We apply this formula to our problem, substituting for the actual distribution of the meteor current system that of a toroidal current, with cross-sectional radius r and mean distance b from its axis. Then $L=4\pi b\{\ln(8b/r)-7/4\}$ and $R=(2\pi b/\pi r^2)\sigma$, where σ denotes the resistivity of the toroid material. As extreme cases we take the combinations $r=10$ m, $b=100$ km, $\sigma=10^{14}$ emu, and $r=300$ m, $b=30$ km, $\sigma=10^{14}/3$ emu. The corresponding values of 2.3 L/R are 1.4×10^{-7} sec and 1.9×10^{-3} sec. These times are very small compared with those considered in the previous section. This suggests that the meteor currents may be taken to appear without significant delay as the meteor develops ionization along the trail.

c. **Decay of meteor currents and magnetic field.**—The ionized trail formed by the meteor decays and diffuses; it may also be distorted by nonuniform winds or turbulence. These processes have been much discussed by the radio physicists who have made radar observations of meteor trails; this is because such observations depend essentially on the ionization along the trail. The duration of the radar echoes is determined by the distribution of the excess ionization, as well as by its total line density α; the peak magnetic effect of the meteor, however, at least in the ideal case of an infinitely long horizontal trail in the direction of the Sq current flow, is directly proportional to α (see equation 31). Thus the influence of diffusion on the radar echoes may somewhat modify the parallelism that would otherwise be expected between their variation and that of dH_1 in this ideal case. It is probable, however, that the time scale of the meteor magnetic field, after the peak value is reached, will be similar to that of the decay of the radar echoes. This time scale has a considerable range of values, up to some minutes. Apparatus designed to measure and identify meteor magnetic effects should be able to cope with such differences of time scale.

8. Conclusions

The present discussion of meteor magnetic effects leads to conclusions that may be summarized as follows:

(1) Past statistical studies of correlations between radar or other observations of meteors and small concurrent magnetic variations have not been well adapted to determine whether observable meteor magnetic effects occur.

(2) The sensitivity of the magnetic recorders used in some of the past studies would seem to be amply adequate to detect meteor magnetic effects in favorable cases, but the time scale of the magnetic recorders should allow for time scales of magnetic variation ranging from a few seconds to minutes.

(3) As proposed by Jenkins and DuVall, the meteor magnetic effects are likely to result from modifications of the Sq ionospheric currents.

(4) Because these currents are much stronger by day than by night, the meteor magnetic effects are likely to share this characteristic; hence they should be investigated by daytime radar meteor observations during quiet magnetic periods (to avoid confusion with disturbances caused by the impact of solar plasma on the geomagnetic field).

(5) The Sq currents being strongest under the equatorial electrojet at hours around 11 a.m., this location and time offer the best likelihood of observable meteor magnetic effects; the current flow then being eastward, a parallel meteor trail is likely to enhance the northward deviation of the horizontal magnetic component from its nighttime value. At other locations in the daytime, the Sq currents have other directions, and the meteor effect will involve

the magnetic declination as well as the horizontal intensity.

(6) The meteor magnetic effect will depend on the inclination of the meteor trajectory, on the angle it makes with the direction of the Sq current flow, and on the height of the trajectory; favorable circumstances include a high meteor electron line density α, e.g., 10^{15} or 10^{16}/cm, and a height near that of the level of maximum Sq current intensity—probably about 110 or 120 km. These two requirements may be conflicting; the greatest values of α may occur below the level of the peak Sq current intensity $i_{\max}$. Meteors that give the greatest value of the product $\alpha i_{\max}$ and have nearly horizontal trails lying along or nearly along the direction of $i_{\max}$ should give the most easily observable magnetic effect. Solar flares, accompanied by an SID and a magnetic Sqa (temporary augmentation of the Sq variation), extend appreciable ionization downward into the D layer and should, therefore, enhance the magnetic effect of meteors at that level.

(7) The effect on the horizontal component at the ground is greatest directly under the meteor trail and is increased by earth currents induced by the direct field of the varying meteor current system. The effect decreases to a small fraction of the maximum value at distances from the ground plan of the trail that are comparable with the height of the trail.

(8) The vertical component at the ground is less affected by the trail, and its peak value is reached at a distance from the ground plan of the trail comparable to the height of the trail; the direct meteor effect on this component is reduced by earth currents. Hence if coils are used to record the magnetic changes, those in a vertical plane containing the direction of the Sq current are best, and horizontal coils will have smaller meteor changes to record.

(9) The *growth* of the meteor magnetic effect is determined mainly by the speed of the meteor, which governs the rate of formation of the trail. The decline of the meteor magnetic effect may be expected to resemble that of the radar echoes from the trail.

(10) To establish the occurrence and magnitude of meteor magnetic effects, it is desirable to have radar measurements of *individual* strongly ionized trails that are of the right height and low inclination, and that lie nearly along the direction of the Sq current at the time and place of the observations during a time of low magnetic activity.

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Abstract

Past studies of magnetic effects ascribed to the passage of meteors through the ionosphere are reviewed, and the expected effects are estimated for different levels, inclinations, azimuths and electron line densities of the meteor trails, at different times and geographical locations. The most favorable circumstances for the identification and measurement of meteor magnetic effects are inferred. The conclusion is that they should be easily measurable during times of low magnetic disturbance, when strongly ionized trails are formed in the daytime at or near the level of maximum intensity of the Sq ionospheric currents, along or nearly along or opposite to the direction of these currents. The effects should be greatest under the equatorial electrojet, especially at times of strong solar flares.

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