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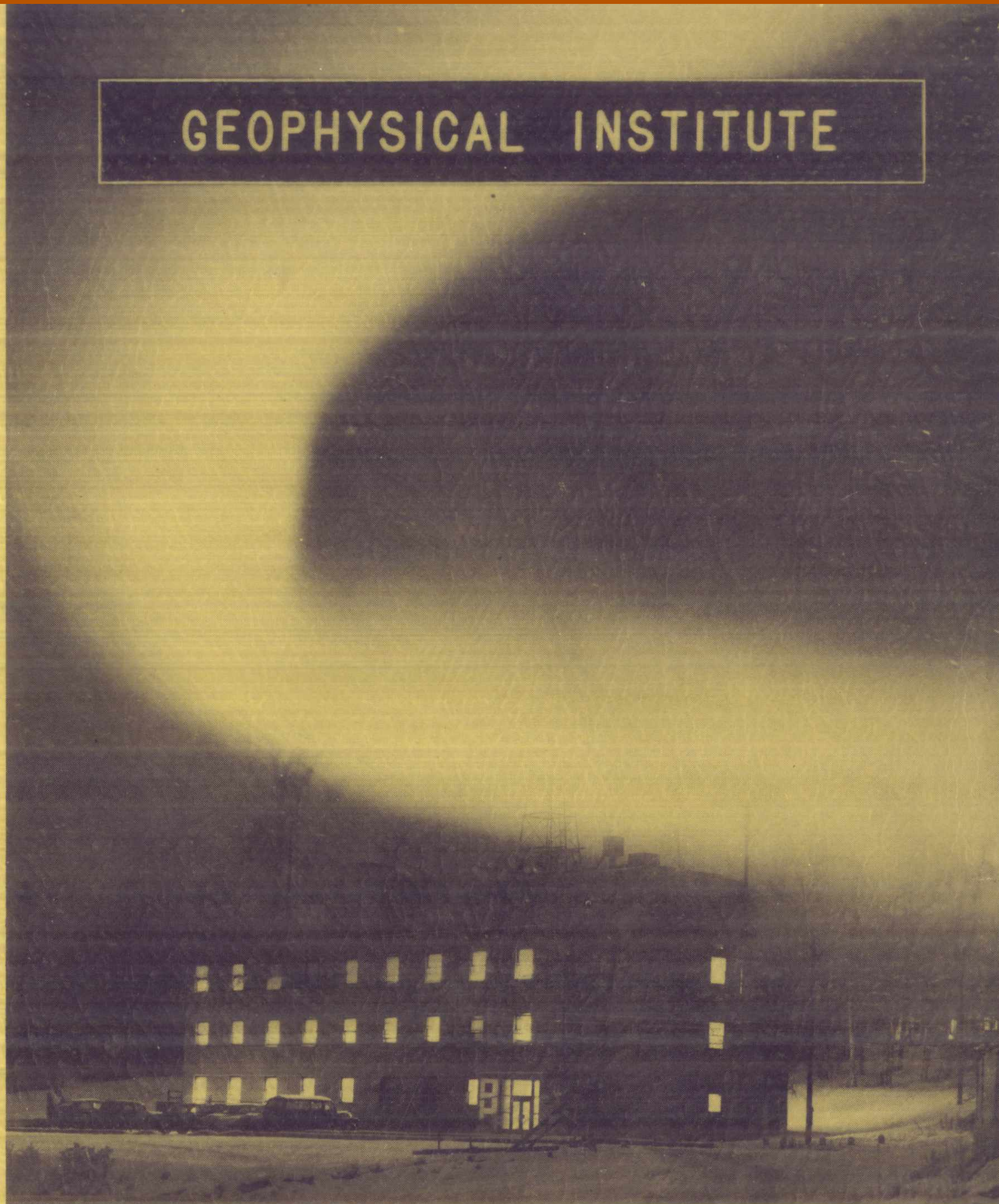

UNIVERSITY
OF ALASKA

COLLEGE
ALASKA

EXPERIMENT LUXEMBOURG

Scientific Report No. 3
Contract No. AF 19(604)-3880

by
G. C. Rumi

February 1960

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GEOPHYSICAL INSTITUTE

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GEOPHYSICS RESEARCH DIRECTORATE
AIR FORCE CAMBRIDGE RESEARCH CENTER
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ABSORPTION OF RADIO WAVES AND METEORIC IONIZATION

The present study is concerned with the contribution of meteoric ionization to the formation of the upper layer in the D region, and to the absorption of radio waves. The absorption of meteoric origin is detectable when the lower layer in the D region is relatively weak. Evidence of absorption due to sporadic meteors is deduced from experimental data reported in the literature. Evidence of absorption due to meteoric showers is found by analyzing f_{min} plot data.

Particular attention has been devoted to the Perseid meteor shower of 1958. During this shower, meteor rates were observed by means of a 100 Mc/s radar. The f_{min} has been found to increase and decrease according to the fluctuations of the meteor rates.

It is inferred that meteors contribute efficiently to the formation of the upper layer in the D region.

Meteoric Ionization

The original theory of meteoric ionization is due to Herlofson (1948). He deduced an expression for the number of meteor atoms evaporated per second as a function of meteor velocity, density and radius, atomic weight and latent heat of evaporation of the meteor, atmospheric pressure, atmospheric scale height, gravitational acceleration and zenith angle of the meteor radiant. Inference of the electron line density produced by the meteor from the number of meteor atoms evaporated per second at a given velocity requires that the probability for ejection of a free electron from a single evaporated atom be known.

Herlofson's analysis of meteoric ionization is useful for the understanding of the different processes which take place in the atmosphere as a meteor passes through it; unfortunately many parameters appearing in the analytical expressions are inadequately known.

Nevertheless, some attempts have been made to compute the intensity of the meteoric ionization. In particular, we quote the work of Dubin (1955) whose main concern was the E region. This author computed the number of electrons produced per centimeter of path by meteors during 24 hour intervals as a function of visual magnitude at 85,100, and 115 km heights. The calculations were based on an estimate of the total influx of meteoric matter due to Watson (1941) duly corrected and a probability of ionization ten and hundred times larger than the one suggested by Herlofson (1948). This larger value for the ionization probability was deduced by Greenhow and Hawkins in 1952, who applied the theory of Kaiser and Closs to the observation of long duration "overdense" meteors. In recent years some objections have been raised against Kaiser and Closs' theory (see Booker and Cohen - 1956). Nevertheless, Greenhow and Hawkins' value is in agreement with the values recently given by Öpik (1958). From the rate of ionization computed along these lines Dubin evaluates the electron density around 100 km height that could be attributed to meteors.

We are interested in the contribution meteors give to the D region electron density rather than to the E region. Furthermore, our approach will mainly be experimental. Absorption measurements should reveal whether ionization is produced by meteors in the region between 80 and 100 kilometers or not. Absorption data, being directly correlated to the total content of electrons present in the absorbing region, represent a useful source of information for our analysis. This type of absorption data can readily be obtained from f_{min} plots. The reader is referred to an earlier paper (Rumi, 1959) for an account of the proposed D_1 and D_2 layers. We recall here that two layers are thought to be present in the D region of the ionosphere and that it is possible to discriminate between them because of differences in their behavior. The upper one located between 80 and 100 kilometer height is the layer that should be affected by meteoric ionization.

In the following, we examine first the experimental material and discuss subsequently whether our results appear reasonable from the theoretical point of view.

Absorption and Sporadic Meteors

First we will be concerned with the absorption that is produced by sporadic meteors. The following simple considerations lead to the conclusion that the local times most suitable for such a detection are 0600 and 1800 hours.

Indeed at 0600 the formation of the lower layer in the D region - which is controlled by the sunlight - is not so advanced as to obliterate the detection of the absorption due to the upper layer. At the same time we should expect a peak of meteoric ionization, since a) the hourly distribution of sporadic meteors has a maximum at 0600, and b) the meteor rate of ionization has a maximum at about 0600. At 1800 the D_1 layer is dying off. At the same time we should expect a minimum of meteoric ionization since a) the hourly distribution of sporadic meteors has a minimum at 1800, and b) the meteor rate of ionization has a minimum at 1800. If the lifetime of meteoric ionization is relatively short, a sort of maximum and minimum respectively at 0600 and 1800 should appear in absorption records.

During the night, under normal conditions, the D_1 layer is absent, but the discrimination between D region and F region absorption is extremely critical.

Simple considerations of spherical astronomy show that meteoric ionization should be the same at 0600 in the winter and in the summer; a similar statement is valid for 1800. It is possible that the de-ionizing factors are different in those two seasons; therefore, different amounts of absorption might be expected in spite of the same amount of ionization. Hence, one might obtain some information about changes in the de-ionizing processes.

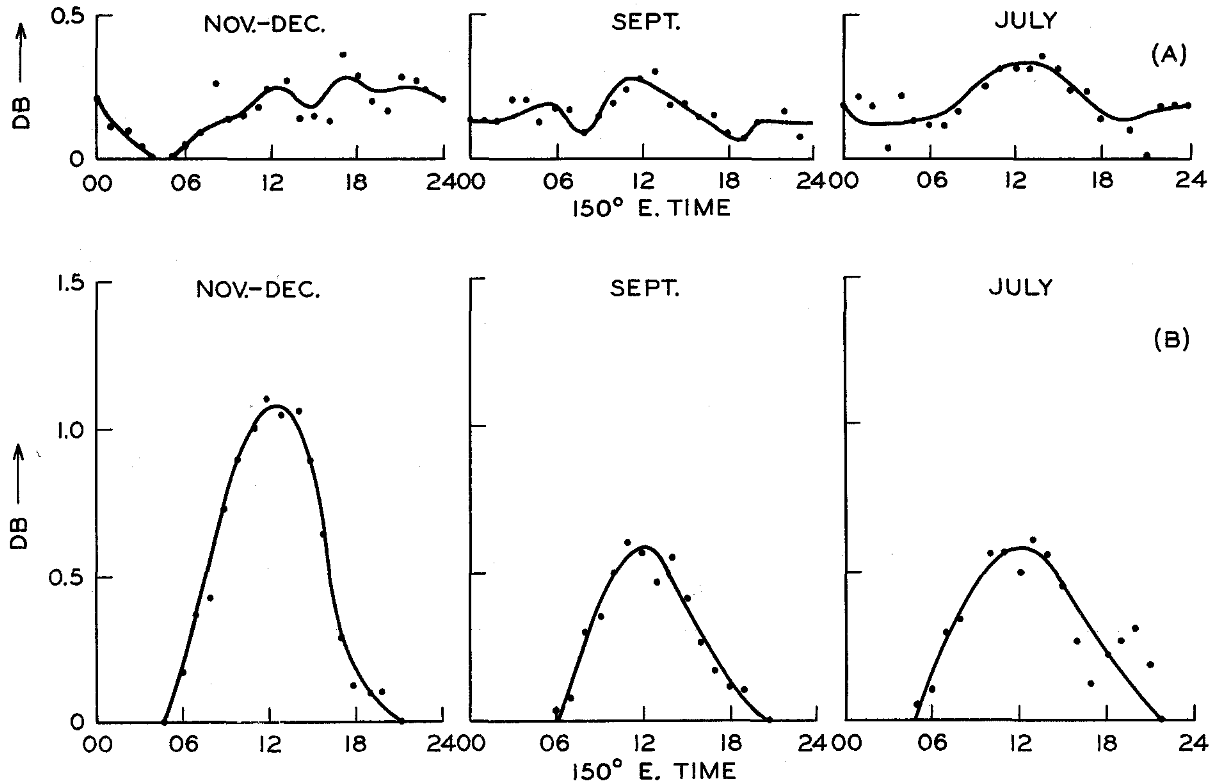
With the preceding criteria in mind we can inspect two sets of data. The first set consists of measurements of ionospheric absorption that were derived from observation of 18.3 Mc/s cosmic radio noise. These measurements were illustrated and commented on in a paper by Mitra and Shain (1953).

The second set was presented and commented on by Kamiyama

(1951) in a statistical study on the f_{min} for the E region of the ionosphere.

Figure 1 (from Mitra and Shain-1953) reproduces the monthly mean diurnal variation of the two components of total absorption: (a) is related to the F region and (b) is related to the D region. In (b) it is noticeable that the absorption begins early in the morning, before 0600, even in the winter and that the beginning does not shift with the seasons. Again in (b) it is noticeable that the smooth decay of the absorption presents an erosion centered around 1800. A long tail of absorption was recorded in July after 1800. It should be pointed out that there is some evidence that the hump recorded after 1800 in July is probably due to a true anomaly and not to some fallacy of the measurement, since a similar result has also been reported in the northern hemisphere. Abbott (1957) published a note in which observations of cosmic noise on 17.6 Mc/s, extending over a long period, are described. Cosmic noise signals registered one hour before and one hour and three hours after sunset presented a difference in intensity of 0.6 db, the after-sunset signal being weaker. Such an effect is described as having its maximum in the winter. The difference in after-sunset absorption between summer and winter should imply a difference in the efficiency of the de-ionizing processes; these should be interpreted as less active in the winter than in the summer, in the darkness than in the sunlight.

Consideration of Mitra and Shain's data makes it apparent that ionospheric absorption is affected at 0600 and 1800 local time by something independent of sunlight control; and we advance the

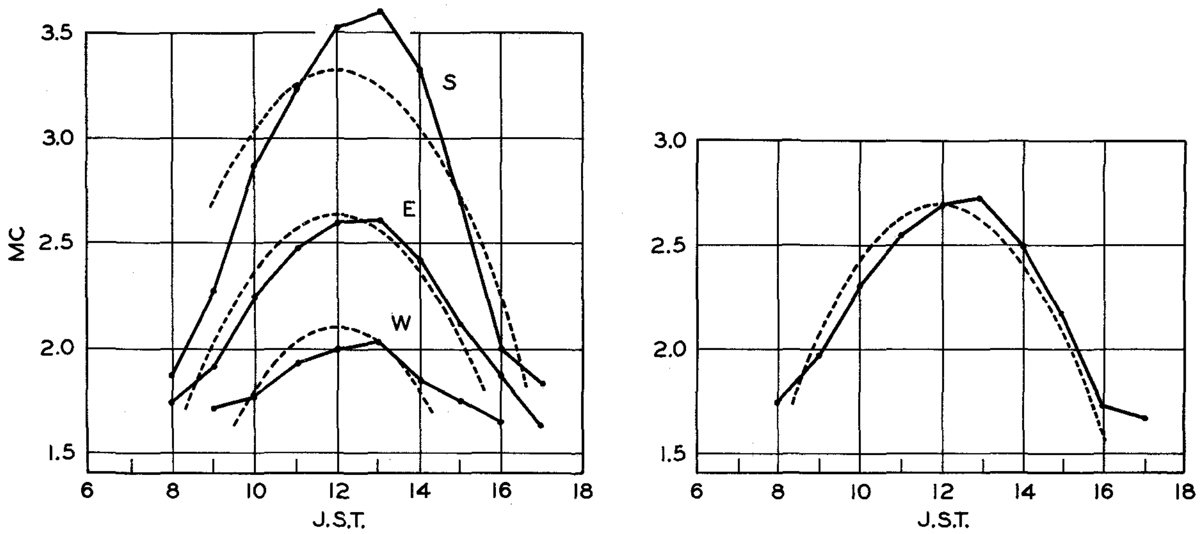


Monthly mean diurnal variation of the two components of total absorption (a) F_2 (b) other than F_2 (shown to be largely D).

Figure 1.

hypothesis that sporadic meteors are responsible for this fact.

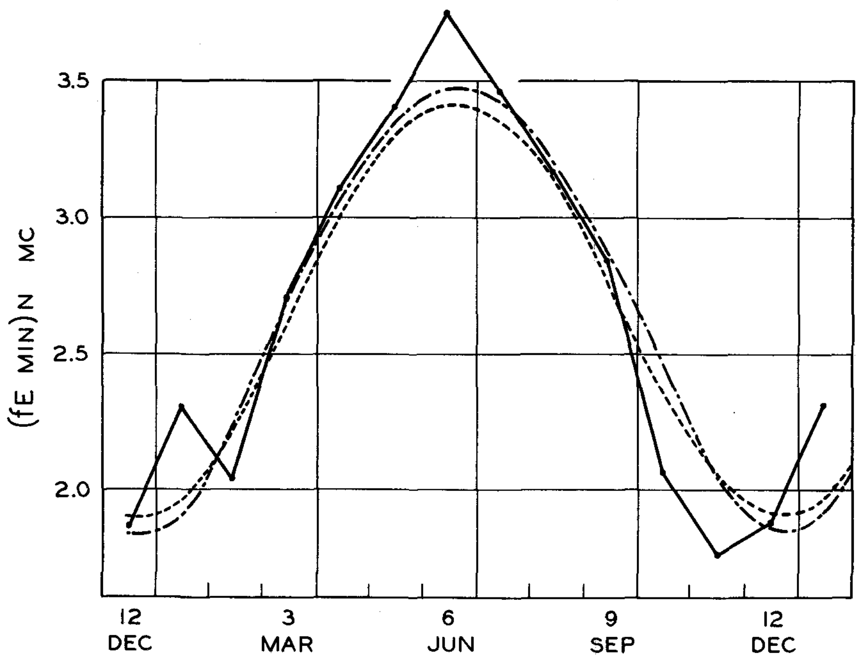
Examination of the second set of data leads to a similar conclusion. Figure 2 (from Kamiyama-1951) reproduces the diurnal variation of f_{min} for each season and Figure 3 illustrates the seasonal variation of f_{min} at noon. In Figure 2 the continuous lines give the behavior of f_{min} with the hours of the day, the dashed lines give an indication of the f_{min} that should be expected as a result of sunlight ionization. It is clear that f_{min} and thus the absorption tend to be significant even before and after the beginning and the ending of the sunlight ionization in the D region; furthermore the transition between sunlit and dark hours is marked by significant changes in the slope. Unfortunately no information is available for the hours around 0600 and 1800. It would have been interesting to check from the f_{min} point of view the difference in the summer and winter data for the after-sunset absorption. Figure 3 may be of some help in this direction. In Figure 3 the continuous line gives the seasonal variation of f_{min} at noon; the dotted line represents a theoretically derived distribution of the same f_{min}. An anomalous peak affects the winter data. Here again we have an indication that the de-ionization process is less active during the winter months. This may be the answer to the more general problem of the "winter anomaly": we recall that various authors referred to a "winter anomaly" when they found that absorption is then larger than expected; the tendency - see Appleton and Piggott (1954) - for high absorption to occur under condition of magnetic calm has been one of the



The diurnal variation of $f_{min\ E}$ for each season

The diurnal variation of $f_{min\ E}$ on the average throughout a year

Figure 2.



Seasonal variation $(f_{min\ E})_n$

Figure 3.

noteworthy aspects of the "winter anomaly".

After considering the second set of data we can state that absorption non related to sunlight is detectable early in the morning and late in the afternoon; furthermore, from f_{min} data it is possible to confirm the impression that de-ionization plays an important role in controlling the absorption and that it is more intense in the summer than in the winter.

Absorption and Meteor Showers

If sporadic meteors produce ionization in the D region at such a rate that absorption of radio waves is affected, the same should be true for meteoric showers. We inquire whether a definite increase in the ionospheric absorption is detectable during the time of major meteor showers. One has to consider the following criteria when looking for such an effect.

First: zenithal showers must produce the largest effect. The analysis of Herlofson indicates that for high values of cos χ, the radiant's zenith angle, the evaporation rate is high.

Second: showers whose upper culmination occurs during the dark hours are preferred, since there is then no sunlight control over the D region. This facilitates the detection of meteoric absorption. To an Alaskan observer winter months should be of particular interest for this reason. Another advantage of the winter season is that the de-ionizing processes are probably weaker during the winter than in the summer (see preceding section).

Third: swift showers are expected to produce more intense absorption from the point of view of the number of free electrons generated.

Under these conditions attention was concentrated upon three major showers: Quadrantids, Perseids, and Geminids. Table I gives the characteristics of these showers as listed in Norton's Star Atlas (1950).

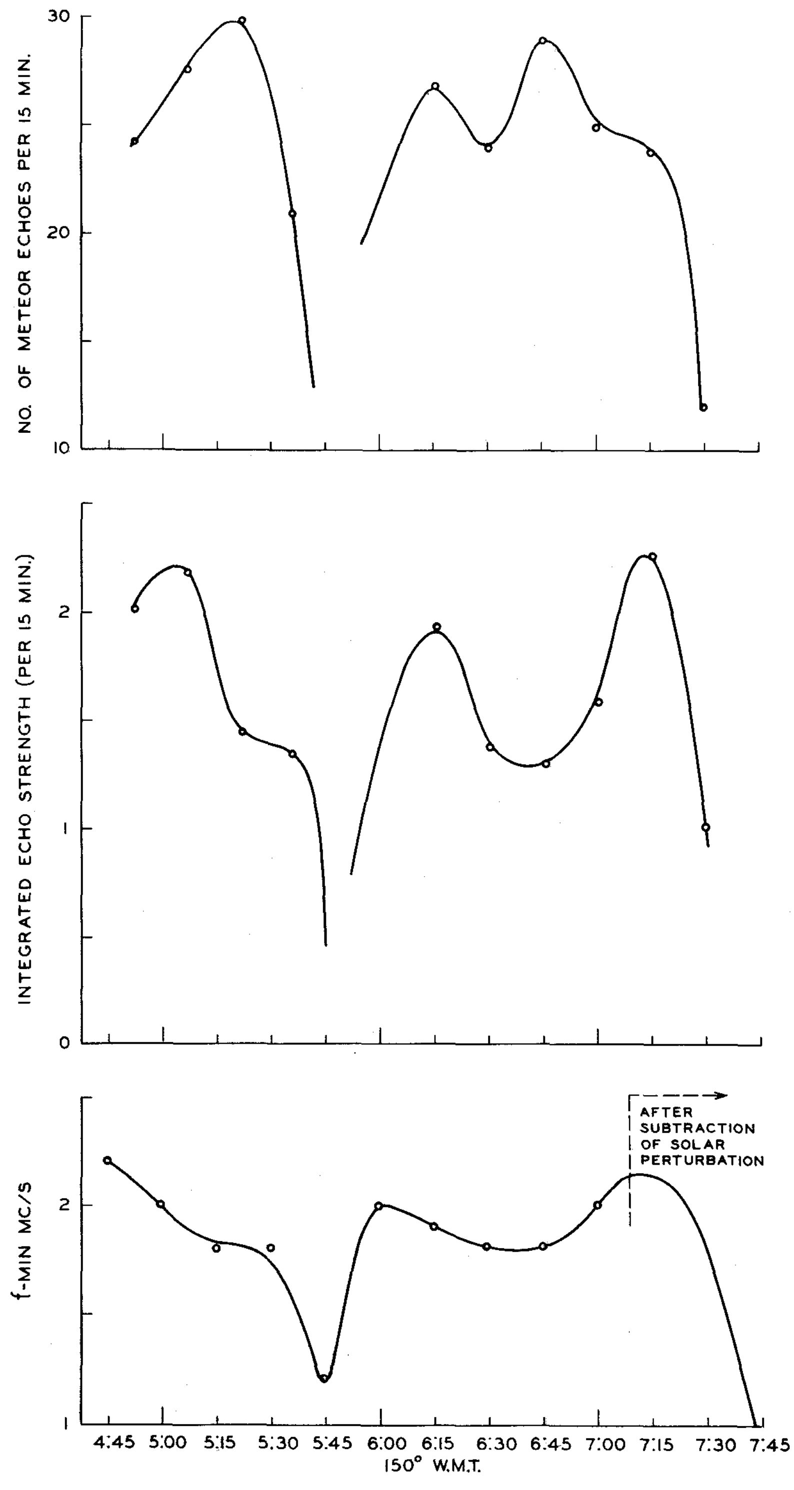
TABLE I

Date	Shower	Cul.	Radiant R.A.=h. m.	Dec.	Speed, & c.
Jan. 2-3	Quadrantids	9^a	230°=15 20	53°N	medium
Aug. 10-12	Perseids	6^a	45°= 3 0	57°N	v. swift
Dec. 10-12	Geminids	2^a	112°= 7 28	33°N	med'm,white, rich

The column headed 'Cul.' gives the Radiant's approximate hour of culmination on the central date, 'a' denoting a.m.

For the Quadrantids, f_{min} plots obtained at College in 1957, 1958 and 1959 were examined. Unfortunately some of the shower days were affected by ionospheric disturbances. Examination of the quiet days produced only one item of evidence which could be interpreted as an increase of ionization due to the shower. A sharp increase of f_{min} was recorded on 3 January 1957 around the time of upper culmination of the Quadrantids, a behavior which represents a definite deviation from the regular trend of a quiet day.

For the Perseids, data obtained with a 100 Mc/s radar in operation from 11 August to 14 August 1958 were compared with the corresponding f_{min} plots. The maximum of the activity recorded by the radar took place on 11 August. For this day a meteor count was made at 15 minute intervals. It was found that the number of



NO. OF METEOR ECHOES PER 15 MIN.
30
20
10
INTEGRATED ECHO STRENGTH (PER 15 MIN.)
2
1
0
f-MIN MC/S
AFTER SUBTRACTION OF SOLAR PERTURBATION
4:45 5:00 5:15 5:30 5:45 6:00 6:15 6:30 6:45 7:00 7:15 7:30 7:45
150° W.M.T.

Figure 4.

meteors per 15 minutes had dropped down from 30 to about zero around 0545. The decrease in the meteor count seems to occur simultaneously with the decrease of the absorption as measured from f_{min} plots. (See Figure 4).

A comparison has been attempted not only with the meteor count, but also with the integrated meteor echo strength. Summation over 15 minute intervals of the intensity of the individual echoes gives results which are in agreement with the preceding ones. The behavior of this integrated echo strength is presented in Figure 4. It should be noted that the minimum around 0600 coincides with the upper culmination of the shower.

For the Geminids an analysis similar to the one for the Quadrantids was performed. It has not been possible to find a definite and marked change in f_{min} coinciding with the shower, sufficient to support the idea of an ionization produced by the Geminid shower itself.

From the preceding analysis one is led to conclude that in general meteor showers are less efficient than sporadic meteors in producing ionization.

Ionizing Efficiency of Meteors.

The results of our preceding investigation are now reconsidered from a quantitative point of view. We will deduce from the amount of absorption attributed to meteors the electron density produced by meteors. From this the rate of ionization due to meteors can be derived. Since the amount of meteoric material reaching the earth's atmosphere and the ionizing efficiency of the meteors is known, we can check the derived rate of ionization.

Let us start with the data published by Mitra and Shain (1953). In a private communication Dr. Shain points out that the standard deviation of the hourly values plotted in Figure 1 is about 0.15 db, but that the regularity of the diurnal variation suggests a smaller uncertainty in the smooth curves. The diurnal trend is well defined by the three curves in Figure 1 (b). The rising slope in each plot is given by about 5 points. Then one can assume a standard deviation of roughly 0.05 db.

Let us consider the July (winter) early morning absorption recorded in Figure 1 (b). It seems that 0.1 db is a reasonable value for meteoric absorption around 0600.

Absorption in db is proportional to the product of electron content and collision frequency. Above 100 km the collision frequency is so small that absorption is practically negligible (the F layer absorption is mainly due to high electron densities). From the information available about the velocity of sporadic meteors we can establish 80 km as a lower limit for meteor ionization. According to the expression for absorption given by Chapman and Little (1957) it follows that

L = meteoric absorption in db at 0600 =

$$\int_{80\ \mathrm{km}}^{100\ \mathrm{km}} \frac{1.17 \times 10^{-6}}{(f + f_L)^2} \times \frac{N\nu ds}{1 + \dfrac{\nu^2}{4\pi^2(f+f_L)^2}} = 0.1$$

where ds = height interval
N = electron density
ν = electron collision frequency
f = 18.6 Mc/s

f_L= 1.5 Mc/s

and the MKS units are used.

Approximately, assuming N and ν constant over the range of integration,

$$L \sim \frac{1.17 \times 10^{-6}}{(f + f_L)^2} \times \frac{N\nu}{1 + \frac{\nu^2}{4\pi^2(f+f_L)^2}} \times 20 \times 10^3 = 0.1$$

A reasonable value for ν is 10^6; hence

$$N \sim \frac{0.2}{1.17} \times 10^{14} \times 10^{-4} \sim 10^9 \frac{\text{electrons}}{m^3} = 10^3 \frac{\text{electrons}}{cm^3}$$

We arrive at the same order of magnitude if we consider Kamiyama's (1951) data. The right diagram in Figure 2, according to Kamiyama, can be interpreted as a plot of CN = $(f_{minE})^{2/3}$ versus time, with C a constant. Kamiyama states that $\alpha/ C = 0.99$/hour where α is the recombination coefficient. At 75 km height $\alpha = 5 \times 10^{-7}$ cm^3sec^{-1} (Mitra and Jones - 1954); then $C = 2 \times 10^{-3}$. C being known the right diagram in Figure 2 can be interpreted as a plot of the ionization in the D region versus time. We attribute to meteors the difference between the actual ionization that was recorded at 0800 and the ionization that - according to the dotted line - should have been produced by the sunlight at the same time. We find CN = 0.1, that is $N = 1/2 \times 10^2$ electrons/cm^3. Kamiyama has based his computations on the hypothesis of a D_1 Chapman-like layer, centered in the neighborhood of 75 kilometers. A possible D_2 layer of meteoric origin should be located higher than the D_1 layer - in the neighborhood of 90 kilometers height - where the electron collision frequency is about one tenth of the collision frequency around 75 kilometers. Thus it does not seem unreasonable to increase by an order of magnitude the value for N deduced above. Further it seems reasonable to conclude that, according to both sets of data, meteors are likely to produce an ionization density of 10^3 electrons/cm^3 in the D region during the early morning.

From this value of the ionization that is produced by meteors we want to determine the rate of ionization. In this connection it is important to know which process removes the free electrons from the ionized layer at meteoric height. As indicated by Booker and Cohen (1956) two mechanisms must be considered: recombination and attachment. The first one is predominant with short duration meteors; the second one prevails when long duration meteors are considered. Dubin (1955) stated that short duration meteors are predominant at the E layer level. The same author points out that long duration meteors should be predominant at the D region level. Thus attachment will be taken as the more important mechanism which removes our ionization. This refers to conditions at 0600 local time.

The equation for simultaneous recombination and attachment is (Loeb - 1955)

$$\frac{\partial N}{\partial t} = -\alpha N^2 - N/t_2$$

where α = coefficient of recombination

t_2 = characteristic time for attachment

In our case we will write

$$\frac{\partial N}{\partial t} = -N/t_2$$

Figures for t_2 were given by Nicolet (1955). In our calculations t_2 will be taken equal to 50 seconds. Therefore our rate of production of electrons due to meteors becomes of the order of 20 electrons per cc. per second.

This rate of ionization is a function of the number and mass of meteors entering the earth's atmosphere and the probability of ionization of meteor atoms, β.

Meteors with mass smaller than 10^{-4} grams or, in other words, radius less than 1.67×10^{-2} cm do not contribute appreciably to the ionization in the D region. Indeed, following Dubin's approach, the rate of evaporation at a velocity of 40 km/sec at 90 km height, n_{90} in electrons per sec, is given by

$$n_{90} = 0.8 \times 10^{23}\, r_\infty^2 (1 - 1/60 r_\infty)^2$$

where r_∞ is the initial radius of the meteor in cm.

On the other hand meteors with mass larger than 10^{-3} grams are out-numbered by meteors with mass between 10^{-3} and 10^{-4} grams, the Van de Hulst meteors (1947). In this connection it is appropriate to quote the following statement by Whipple (1955): "Van de Hulst pointed out the fact that his distribution of particle sizes leads to some 10^4 times the rate of terrestrial meteoritic accretion predicted by Watson. The prediction by Van de Hulst has powerful confirmation in the observations of deep-sea sediments by H. Patterson and D. Rotsche (1950). Other less conclusive confirmation is also available from rocket soundings (Whipple 1952b) and the collection of micrometeorites (Hoffleit 1952).

In fact, Watson's low prediction (corrected for an error) of about 5 tons per day for the entire earth is based on an extrapolation below the particle sizes observed as meteors. The perturbational and collisional losses sustained by larger particles before they can complete their Poynting-Robertson spirals accounts for a discontinuity in the distribution function of particle sizes between radii of $10^{-1.5}$ and $10^{-2.5}$ cm, almost exactly as predicted by Van de Hulst. Öpik's explanation of this phenomenon as a consequence of the Jupiter barrier alone appears inadequate, at least for cometary contributions including retrograde orbits."

Therefore, we shall consider only meteors with mass between 10^{-3} and 10^{-4} grams, equivalent to radii between 4×10^{-2} and 2×10^{-2} cm. The relevant data are listed in Table II below:

TABLE II

Visual Magnitude	No. of Meteors in 24 hours	Mass g	Radius cm	No. of Atoms ev. sec^{-1}. h=90 km; v=40km/s
6	$1.1x10^{12}$	$1x10^{-3}$	$4.12x10^{-2}$	$4.82x10^{19}$
7	$2.8x10^{12}$	$4x10^{-4}$	$3.03x10^{-2}$	$1.50x10^{19}$
8	$7.1x10^{12}$	$1.6x10^{-4}$	$2.24x10^{-2}$	$2.60x10^{18}$

Note: the density used for the computation of the radius is 3.5. Van de Hulst used a density of 5.

At this point we need a figure for the probability of ionization in order to derive the rate of ionization from the rate of atomic evaporation calculated above and reported in Table II.

The information available is contradictory and confusing. Herlofson in 1948, working backward from Öpik's value for the radiation efficiency, derived the probability of ionization, $\beta = 0.01$. Subsequently this figure has been used by many workers in the field of meteoric physics. Greenhow and Hawkins in 1952, by applying the Kaiser and Closs theory to long duration meteors data, deduced a probability of ionization between 1 and 0.1. Öpik in 1958 deduced on theoretical grounds a probability of ionization of the same order of magnitude. Öpik attributes the low value of β given by Herlofson as due to some error in the derivation of the probability of ionization from the radiation efficiency. Furthermore, he quotes the results of Greenhow and Hawkins in support of his theoretical derivation. On this last point Öpik (1958) does not seem consistent since he points out that "Although for faint meteors turbulent (eddy) diffusion is unimportant, the initial penetration of the meteor atoms and ions during the process of deceleration to thermal velocities is of decisive importance and its neglect has rendered some of the results illusory". Greenhow and Hawkins' deduction is based upon the Kaiser and Closs theory for long duration meteors which completely neglects the effects of turbulence.

We are left with the impression that the only reliable information about the ionization probability β at the present time is the theoretical development of Öpik. All the experimental results in the scientific literature are unsatisfactory on account of their neglect of turbulent diffusion. We shall use the figure $\beta = 0.2$ in our calculation.

Then according to Herlofson (1948)

$$n_e = \frac{n \times \beta}{v}$$

where n_e = No. of el/cm

n = No. of atoms evaporated/sec

v = Meteor velocity in cm/sec

We take v correspondent to 40 kilometers per second. The preceding equation allows us to go from the rate of atomic evaporation to the rate of production of electrons. Values are tabulated in Table III below:

TABLE III

Visual Magnitude	No. of Meteors in 24 hours	No. of Atoms ev. sec^{-1}	No. of Electrons cm^{-1}	Total No. of Electrons cm^{-1}
6	$1.1x10^{12}$	$4.82x10^{19}$	$2.41x10^{12}$	$2.65x10^{24}$
7	$2.8x10^{12}$	$1.50x10^{19}$	$7.50x10^{11}$	$2.10x10^{24}$
8	$7.1x10^{12}$	$2.60x10^{18}$	$1.30x10^{11}$	$0.92x10^{24}$

Dividing $5.67x10^{24}$, which is the total number of electrons generated in a shell of 1 cm over the surface of the earth at 90 km height during a day, by $4.4x10^{23}$ we obtain the ionization rate of 12.9 electrons per cm^3 per sec. Our computations refer to 0600 in the morning when the rate of incoming matter is about 2 times the average value. That means that instead of 12.9 electrons per cc per second we should expect about 20 electrons per cc per second, in good agreement with the value derived from the two sets of experimental data examined. This agreement supports the qualitative analysis of the absorption data and the hypothesis of the ionization of meteoric origin.

Having completed our investigation as far as sporadic meteors are concerned, it seems appropriate to say a few words about meteoric showers. The few occasional good correlations between absorption and showers are not sufficient to permit any definite conclusion on the subject. At first glance this lack of correlation might be disturbing. Why indeed should meteoric showers be less efficient than sporadic meteors? Two studies on this subject due respectively to Levin (1955) and to Weiss (1957) indicate that such should be the case.

Levin worked on visual meteor observations and Weiss on radio echo observations. Levin deduced that the density of meteor bodies with a mass greater than $M \sim 5 \times 10^{-3}$ grams and velocity of 40 km per sec, corresponding to zenithal magnitude 4.3, is ten times greater for sporadic meteors than for the "central" part of the swarm of Perseids and other main showers. Weiss arrives at a similar conclusion from radio data that cover a larger range of zenithal magnitudes. Thus our results in connection with meteor showers are fully understandable and reasonable.

Conclusions

The present study points out some correlation between the absorption of radio waves and ionization due to sporadic meteors. Theoretical considerations also support the hypothesis that sporadic meteors are capable of producing ionization strong enough to be detected by absorption measurements. The result should be taken into account when possible correlations between meteors and different aspects of radio wave propagation are investigated.

Meteoric showers are not as efficient as sporadic meteors in producing absorption: this result has to be expected as a consequence of the difference between the mass density of showers and the mass density of sporadic meteors, the latter being larger. Nevertheless, some occasional good correspondence between the two quantities, absorption and meteoric shower ionization, might be obtained. In such a case the possibility of studying the behavior of a shower through the analysis of f_{min} has to be considered. f_{min} data could possibly furnish valuable information over an extensive cross section of the shower itself.

A further result is contained in the preceding analysis. It has to do with the Van de Hulst (1947) cut-off. This author has deduced that the density distribution of meteoric bodies of increasing size, has a cut-off in correspondence of meteors with radius of about 0.04 cm. The existence of the Van de Hulst cut-off is remarkably consistent with the absorption measurement we have examined. Indeed the absence of such a step down in the number of meteors of mass larger than 10^{-3} grams, would result in a conspicuous increase of the meteoric absorption. The fact that the amount of meteoric absorption is limited to the values discussed in the preceding section may be interpreted as a further confirmation of the Van de Hulst estimate.

Acknowledgements

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