

25. Ablation in Meteors

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PHOTOGRAPHIC AND RADAR OBSERVATIONS of meteors reveal essential discrepancies from the simplest physical theory of meteors. The simplest theory (Whipple, 1943; Herlofson, 1948; Kascheev et al., 1967) proceeds from the following suppositions: (1) the meteoroid is a dense non-fragmenting body; (2) the sole ablation mechanism is evaporation; and (3) the whole energy transferred to a body by colliding air molecules is spent on evaporation. In addition, the simplest theory of radiowave reflection from meteor trails that does not take into account diffusive and thermodiffusive expansion of a meteor trail and change of the electron line density along the trail is used for the interpretation of the results of radar observations.

The discrepancy of the observational data versus the simplest theory of meteors is usually ascribed to fragmentation of meteoroids, only one fragmentation mechanism being considered: that of a friable body of low density under the action of aerodynamical pressure. Nevertheless, at present, any detailed theory of ablation of very friable bodies free from intrinsic contradictions is absent. It is believed that the reference to friability and fragmentation automatically explains all peculiarities of meteors.

In a number of our works (Lebedinets, 1963, 1966; Lebedinets and Portnyagin, 1966a, 1967; Lebedinets et al., 1969; Lebedinets and Shushkova, 1968), a more precise theory of the ablation of dense meteoroids, as well as the theory of radar-meteor reflection and radar-meteor detectability, was devised (Lebedinets, 1963, 1966; Lebedinets and Sosnova, 1968, 1969). Comparison of the more precise theory with the observational data

permits some conclusions on the mechanism of meteoroid ablation.

RADAR-METEOR FRAGMENTATION SYMPTOMS

Verniani and Hawkins (1965) and Verniani (1966) have published the parameters of 320 radar meteors $+7^m$ to $+9^m$. Analyzing these data, Verniani (1969) concludes:

The degree of fragmentation of meteors with a mass of 10^{-4} grams appears to be even more severe than that of the average faint photographic meteors having a mass of the order of 1 gram. As a matter of fact, the discrepancy between the theory and observations is greater for radio meteors: the average length in the studied sample is very short, only 40 percent of its theoretical value.

Since the accuracy of radar measurements of individual meteor parameters is relatively small, the average values are more interesting. Table 1 lists mean parameters obtained for 320 meteors.

The density of each meteoroid was calculated according to deceleration. The shape factor was assumed to be $A=1.5$ (corresponding to a randomly oriented cube) and the drag coefficient $\Gamma=1.1$ (as "The radio meteors of the present sample are so small that, without any doubt, they have experienced free molecular flow; therefore, we shall use $\Gamma=1.1$ " (Verniani and Hawkins, 1965)). Assuming $A=1.5$ and density $\delta=0.8$ g/cm³, Verniani and Hawkins suppose that the body does not melt entirely in the process of ablation.

Let us compare mean parameters of radar meteors (table 1) with the simplest theory.

TABLE 1.—Mean Parameters of 320 Radar Meteors

No-atmosphere velocity	v_0	= 34.45 km/s
Photographic magnitude	M_{pm}	= +8.05
Zenith angle	$\cos z$	= 0.798
Beginning height	h_b	= 95.0 km
End height	h_e	= 86.9 km
Maximum ionization height	h_m	= 90.8 km
Initial mass	m_0	= 1.4×10^{-4} g
Maximum electron line density	$\log \alpha_m$	= 8.54 (cm^{-1})
Ablation coefficient	$\log \sigma$	= -11.75 (cm^2/s^2)
Meteoroid density (median value)	δ	= 0.8 g/ cm^3

According to Herlofson (1948), the atmospheric densities ρ_m at the height of maximum ionization h_m and ρ_e at the height of the trail end h_e are

$$\rho_m = \frac{2Qm_0^{1/3}\delta^{2/3} \cos z}{\Lambda A H v_0^2} \quad \rho_e = 3\rho_m \quad (1)$$

where Q is the evaporation energy of 1 g of meteor substance, Λ is the heat-transfer coefficient, m_0 is the initial mass, H is the atmospheric scale height, and v_0 is the initial velocity.

Under the conditions of free molecular flow, $\Lambda \approx 1$. According to Lebedinets and Portnyagin (1967) and Öpik (1958a), $Q = 8 \times 10^{10}$ ergs/g for stone and iron meteoroids. Substituting values of m_0 , δ , z , A , and v_0 from table 1 into equation (1) and using the Tables of the Standard Atmosphere (1964), we find $h_m = 99.4$ and $h_e = 93.3$ km. The theoretical values of h_m and h_e are correspondingly 7.6 and 6.5 km greater than the observational ones. Practically the whole observed trail is situated lower than the theoretical height of the trail end. If a meteoroid breaks up, its evaporation height increases independently from the mechanism of fragmentation, and the discrepancy between observed and theoretical heights becomes even more.

Thus, the very small mean density of radar meteors, 0.8 g/ cm^3 , assumed by Verniani (1966, 1969) is incompatible with the observed heights of radar meteors for any ablation mechanism. This result stands to reason, for stone and iron meteoroids of any density and structure with $m_0 = 1.4 \times 10^{-4}$ g and $v_0 = 34.45$ km/s moving under the

conditions of free molecular flow cannot reach the height of 80 km without melting (or evaporating) completely. After complete melting, such a small body gathers in a spherical droplet (if it does not break up in the process of heating) that is stable under the action of the forces of surface tension and aerodynamical pressure (Lebedinets and Portnyagin, 1967). Assuming a mean chemical composition the same as the most widely distributed type of stone meteorites, i.e., chondrites (Lebedinets, 1966; Vinogradov, 1965), we obtain the droplet density $\delta = 3.5$ g/ cm^3 . For a sphere, $A = 1.21$. At such a δ and A from equation (1), we find $h_m = 93$ and $h_e = 87$ km. The theoretical height of the trail end practically coincides with the observational one, and the height of maximum ionization is larger by 2.2 km than the observational height. It will be shown below that this small discrepancy is explained by the selectivity of radar observations.

Comparing the observational meteor height with the theoretical one, Verniani (1966) utilizes, instead of the simple formula, equation (1), a more complex one obtained from the combination of the equations of evaporation and deceleration, in which he includes the ablation parameter σ . For a nonfragmenting body, we have

$$\sigma = \frac{\Lambda}{2\Gamma Q} \quad (2)$$

At $\Lambda = 1$, $\Gamma = 1.1$, and $Q = 8 \times 10^{10}$ ergs/g, we obtain $\sigma = 5.6 \times 10^{-12}$ s $^2/\text{cm}^2$.

Values of σ can be calculated according to the observational data if the deceleration and electron line density at a given point of the trail, as well as the whole ionization curve, are measured. Verniani and Hawkins' radar observations did not allow measurement of the meteor deceleration; they gave only 3 to 4 values of velocity v at different moments t . Verniani and Hawkins approximated the dependence $v(t)$ by a straight line, and according to the inclination of this line, a mean deceleration related to the mean meteor height was determined. Thus, the mean value of $\sigma = 1.8 \times 10^{-12}$ shown in table 1 was obtained.

The value of $\sigma = 1.8 \times 10^{-12}$ obtained by Verniani and Hawkins turns out to be three times as small as the value of $\sigma = 5.6 \times 10^{-12}$ obtained from equation (1) at $\Lambda = 1$, $\Gamma = 1.1$, and $Q = 8 \times 10^{10}$ ergs/g.

For very small meteoroids that are heated through and that are moving under the condition of free molecular flow, the values of Λ and Γ cannot differ essentially from 1. Thus, the single parameter that may be changed in equation (1) is the energy of ablation Q . At $\sigma = 1.8 \times 10^{-12}$, $\Lambda = 1$, and $\Gamma = 1.1$ from equation (1), we have $Q = 2.5 \times 10^{11}$ ergs/g. There is no widely distributed substance with such a high evaporation energy in nature. If there is another ablation mechanism, such as blowing-off of the melted layer, separation of dust particles from a very friable body, and so on, then the ablation energy can only be lower than at evaporation.

Thus, the value of $\sigma = 1.8 \times 10^{-12}$ erg/g obtained by Verniani and Hawkins for nonfragmenting radar meteors cannot be correct at those heights where they were observed. In the case when measured deceleration is related not to the whole body but to a swarm of very small fragments, Verniani and Hawkins' procedure leads to an underestimate of the meteoroid density by $N^{1/3}$. However, the essential fragmentation assumption is incompatible with the observed radar-meteor heights. Therefore, we can conclude that the mean deceleration obtained by Verniani and Hawkins is overestimated.

The main cause of such an overestimate apparently is the influence of radar-observation selectivity. As shown in a number of works (Lebedinets, 1963, 1966; Öpik, 1958b; Greenhow, 1963), the upper parts of faint meteor trails are not registered in radar observations, owing to the influence of the initial radius of meteor trails on the amplitude of the radar echo. This effect grows with increasing radar power and decreasing wavelength, and consequently it is especially large for the equipment of the Harvard Radio Meteor Project (Hawkins, 1963). Since deceleration grows exponentially with time, we will overestimate the mean meteor deceleration when throwing away the initial part of the meteor. There are a number of causes of overstating the mean meteor deceleration of Verniani and Hawkins. The precision of radar-meteor velocity measurements is comparatively low (appreciably lower than assumed by Verniani, 1966), and negative deceleration (acceleration) is obtained for 39 meteors as a result. The authors did not

take these meteors into account. Besides accidental errors in velocity, there are two systematic ones due to the diffusion effect and the rapid change of the effective electron line density along the trails of faint meteors (Kascheev et al., 1967; Lebedinets and Sosnova, 1969). The first error leads to underestimation of mean velocity, and the second, to overestimation of mean meteor deceleration.

THE PHYSICAL THEORY OF FAINT METEORS

The physical theory of radar meteors includes three main sections: (1) the ablation theory, (2) the theory of ionization and meteor-trail formation, and (3) the theory of radiowave reflection from meteor trails and detectability of radar meteors. The first systematic statement of all main aspects of the physical theory of radar meteors was made by the author in 1963 (Lebedinets), and a more detailed one, in 1966 (Lebedinets). However, numerical calculations in those articles were preliminary to a certain degree, as only approximate solutions of the problem of radiowave reflection from meteor trails and evaporation of small meteoroids were used. These calculations can now be made more precisely.

The Ablation of Small Meteoroids

The overwhelming majority of radar meteors registered by highly sensitive equipment are produced by small meteoroids with masses less than 10^{-3} g. Such small particles have completely melted at the beginning of intensive evaporation, regardless of their initial structure and density. If the particle does not break up in the process of heating, then it gathers after melting in a droplet that is steady under the forces of surface tension and aerodynamical pressure (Lebedinets and Portnyagin, 1967). Hence, in the process of evaporation (only during this time can a meteor be observed), small meteoroids can be considered as spherical bodies with the density of stone or iron.

With provisions for the expenditure of energy on thermal radiation from the surface of a body, heating, evaporation, and deceleration of small nonfragmenting meteoroids are described by the

series of equations (Lebedinets and Shushkova, 1968):

$$\frac{\Lambda}{8} \rho v^3 = \sigma T^4 + C_1 Q T^{-1/2} \times \exp(-C_2 T) + \frac{C \delta^{2/3} m^{1/3} \rho v \cos z}{4AH} \frac{dT}{d\rho} \quad (3)$$

$$\frac{dm}{d\rho} = - \frac{4AHm^{2/3}}{\rho v \delta^{2/3} \cos z} C_1 T^{-1/2} \exp(-C_2 T) \quad (4)$$

and

$$\frac{dv}{d\rho} = - \frac{\Gamma AHv}{m^{1/3} \delta^{2/3} \cos z} \quad (5)$$

Here, ρ is the atmospheric density, σ is the Stefan-Boltzmann constant, C is the heat capacity, and C_1 and C_2 are constants that characterize the dependence of the meteoroid evaporation rate on the temperature T (Lebedinets and Portnyagin, 1967).

The system of equations (3) to (5) was integrated by Lebedinets and Shushkova (1968), and the ionization curves of meteors produced by meteoroids with different m_0 and v_0 were obtained.

Ionization and the Initial Radius of the Trail

Kascheev et al. (1967) and Lebedinets (1966) determined the values of the ionization probability of meteors, β , proceeding from the available data on the diffusion and the ionizing effective cross sections at collisions of different pairs of atoms and molecules. In the interval $20 \leq v \leq 70$ km/s, the following dependence was obtained:

$$\beta = 4 \times 10^{-25} v^{3.5} \quad (6)$$

where v is in centimeters per second. The average atomic weight is accepted to be $\mu = 23$. At $v < 20$ km/s, β must diminish rapidly with a decrease in v . The dependence $\beta(v)$ accepted by us is shown in figure 1.

An analogous calculation of β was carried out by Sida (1969), who obtained a stronger dependence for $\beta(v)$ and smaller values of β at mean meteor velocities (dotted curve in fig. 1). For example, he finds $\beta(40 \text{ km/s}) = 0.03$, but from equation (6), $\beta = 0.05$. Values of β determined by Sida are slightly underestimated, as he did not take into account that the effective cross sections of ioniza-

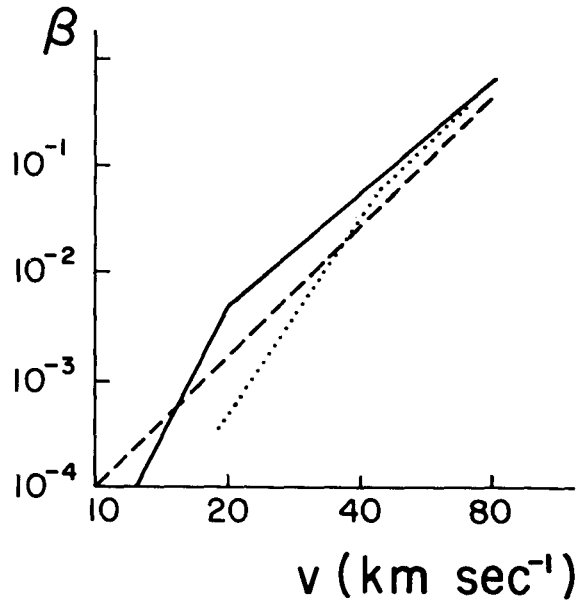


FIGURE 1.—The dependence of the probability of ionization on velocity $\beta(v)$. Solid line—dependence computed in this paper. Dashed line—dependence used by Verniani and Hawkins (1965). Dotted line—dependence computed by Sida (1969).

tion Q for Na, K, Ca, Fe, Si, and Mg are underestimated in Bydin and Buchteev's works (Lebedinets and Portnyagin, 1966b); in their model, the atoms deviating from the initial direction of motion by more than $1^\circ 20'$ were not recorded. Moreover, the dependence obtained by Bydin and Buchteev for a sufficiently wide velocity interval is weaker than that accepted by Sida, $Q_i \sim (v - v_i)^2$, where v_i is the minimum velocity corresponding to the ionization threshold. For Ca, Fe, Si, and Mg, the measurements of Q_i were carried out at velocities greater than or equal to 60, 80, 120, and 125 km/s, respectively. Extrapolating values of Q_i toward small velocities following such a strong dependence Q_i on v , Sida underestimated Q_i at small and mean meteor velocities. At higher meteor velocities, 50 to 70 km/s, the values of β by Sida practically agree with ours.

Verniani and Hawkins (1965) adopt the following dependence of β on v in the whole meteor velocity interval:

$$\beta = 10^{-28} v^4 \quad (7)$$

(dashed line in fig. 1). It seems rather unlikely that the same dependence of $\beta(v)$ applies over the

whole interval of meteor velocities, if only because ionization of oxygen (which makes up 50 percent of meteoritic matter) becomes impossible at $v < 16$ km/s.

Initial expansion of the ionized meteor trail was considered in detail by Lebedinets (1963, 1966) and Lebedinets and Portnyagin (1966b). We assumed that the initial radius of the ionized trail $r_0 \sim v\rho^{-1}$ and that at the height of 96 km and at $v = 40$ km/s, $r_0 = 1$ m.

The Detectability of Radar Meteors

It was shown by Lebedinets (1963) and Davies and Gill (1960) that detectability of radar meteors can be represented as a product of the geometrical factor P_1^{-1} , which characterizes the relative detectability of meteors with different radiant coordinates, and the physical factor P_2^{-1} , which characterizes the relative detectability of meteors with different velocities. The calculation of P_1 is comparatively simple; it is enough to know the antenna directional pattern.

The calculation of the physical factor is more complicated. The sensitivity of a meteor radar is usually characterized by the minimum value α_{ef}^{min} of the effective electron line density α_{ef} of meteor trails that can be recorded. The value of α_{ef} is that of the electron line density α obtained according to the power of the radio echo P_r , with the help of the formula of Lovell and Clegg (1948):

$$P_r = \frac{P_t G_t G_r \lambda^3 \alpha_{ef}^2}{32\pi^2 R^3} \left(\frac{e^2}{m_e c^2} \right)^2 \quad (8)$$

Here, P_t is the transmitter power, G_t and G_r are the directivities of the transmitting and the receiving antennas, λ is the wavelength, R is the range, e and m_e are the electron charge and mass, and c is the velocity of light.

The precise formula for the power of the radar echo is

$$P_r = \frac{P_t G_t G_r \lambda^3}{128\pi^4 R^3} \left| \int_{-\infty}^{x_0} g(x) \exp\left(-i \frac{\pi}{2} x^2\right) dx \right|^2 \quad (9)$$

$$x_0 = \frac{2vt}{\sqrt{R\lambda}}$$

where t is the time counted from the moment of the meteor passing across the point of specular

reflection from the trail, and $g(x)$ is the reflection coefficient at the given point in the moment t .

From equations (8) and (9), we note that

$$\alpha_{ef} = \frac{m_e c^2}{2\pi e^2} \left| \int_{-\infty}^{x_0^m} g(x) \exp\left(-i \frac{\pi}{2} x^2\right) dx \right| \quad (10)$$

where x_0^m is the value of x_0 at which α_{ef} is largest.

With provision for a random position of the specular reflection point on the trail, the probability of detection of the trail produced by the meteoroid with given m_0 , v_0 , and z is proportional to the length of the trail section $\ell(m_0, v_0, z, \lambda, \alpha_{ef}^{min})$ at which $\alpha_{ef} > \alpha_{ef}^{min}$. Then, for the relative detectability of meteors with different velocities, we can write

$$\frac{1}{P_2} = \int_0^\infty \ell(m_0, v_0, z, \lambda, \alpha_{ef}^{min}) n(m_0) dm_0 \quad (11)$$

where $n(m_0)$ is the meteor mass distribution, usually presented as a power function

$$n(m_0) \sim m_0^{-S} \quad (12)$$

where we have assumed that $S=2$.

In equation (10), $g(x)$ is a complex function of α , λ , and r_0 . The calculation of $g(x)$ for various values of α , λ , and r_0 was carried out by digital computer on the basis of the precise solution of the problem of radiowave reflection from meteor trails obtained previously by Lebedinets and Sosnova (1968, 1969).

Figure 2(a) shows the curves of P_2^{-1} as a function of v_0 for the radar at $\lambda=7.5$ m with different sensitivities α_{ef}^{min} : (1) 3.16×10^8 /cm, (2) 10^9 /cm, (3) 3.16×10^9 /cm, (4) 10^{10} /cm, (5) 5×10^{10} /cm, (6) 10^{11} /cm, and (7) 2×10^{11} /cm. We assumed that $\cos z = 2/3$ and adopted $P_2 = 1$ for all curves at $v_0 = 40$ km/s. Analogous data for the radar at $\lambda = 12$ m are shown in figure 2(b).

Radar-Meteor Deceleration

One of the most complicated problems of radar-meteor investigations is the transition from a measured meteor velocity to a no-atmosphere one. Radar observations do not allow the determination of the location of the reflection point on the trail, so we must use the same mean correction for deceleration $\Delta v(v_0)$ for all meteors with a given velocity.

For a meteor with given m_0 , v_0 , and z , the mean

correction for deceleration to the observations with the given radar is

$$\overline{\Delta v}(v_0, m_0, z, \lambda, \alpha_{ef}^{min}) = \frac{\int_{h_a}^{h_b} [v_0 - v(h, m_0, v_0, z)] dh}{\ell(m_0, v_0, z, \lambda, \alpha_{ef}^{min}) \cos z} \tag{13}$$

where $v(h, m_0, v_0, z)$ is the meteor velocity at the altitude h ; integration is over that part of the trail where $\alpha_{ef} \geq \alpha_{ef}^{min}$. The mean correction for deceleration for all meteors of a given velocity is

$$\overline{\Delta v}(v_0, \lambda, \alpha_{ef}^{min}) = \frac{\int_0^\infty \int_0^{\pi/2} \overline{\Delta v}(m_0, v_0, z, \lambda, \alpha_{ef}^{min}) \ell(m_0, v_0, z, \lambda, \alpha_{ef}^{min}) n(m_0) f(z) dm_0 dz}{\int_0^\infty \int_0^{\pi/2} \ell(m_0, v_0, z, \lambda, \alpha_{ef}^{min}) n(m_0) f(z) dm_0 dz} \tag{14}$$

where $f(z)$ is the meteor distribution in z .

The function $v(h, v_0, m_0, z)$ was found by numerical integration of equations (3) to (5). There is some uncertainty in the choice of Γ . We can write $\Gamma = 1 + k(v_a/2Q)v$ (where v_a is the thermal velocity of evaporating molecules) for small meteoroids moving under the conditions of free molecular flow including the reactive impulse of evaporating molecules. Assuming that at $T \approx 2000^\circ \text{K}$, $v_a = 1.5 \times 10^5 \text{ cm/s}$ and $Q = 6 \times 10^{10} \text{ ergs/g}$, we obtain

$$\Gamma = 1 + 1.25 \times 10^{-6} kv \tag{15}$$

k is equal to $\frac{4}{9}$ in the case of a large, nonrotating spherical meteoroid that evaporates from the frontal surface only; k is equal to 0 in the case of an infinitely small or an infinitely rapidly rotating body when the evaporation rates from both the frontal and the rear surface are the same. In the case of real bodies of finite size rotating with the finite rate velocity of evaporation from the frontal surface somewhat larger than that from the rear, the value of k is not equal to 0.

Numerical integration of equations (3) to (5) was carried out for a number of values of k from 0 to $\frac{4}{9}$; the value of k that leads to the best agreement between no-atmosphere velocities of radar meteors of streams and Super-Schmidt

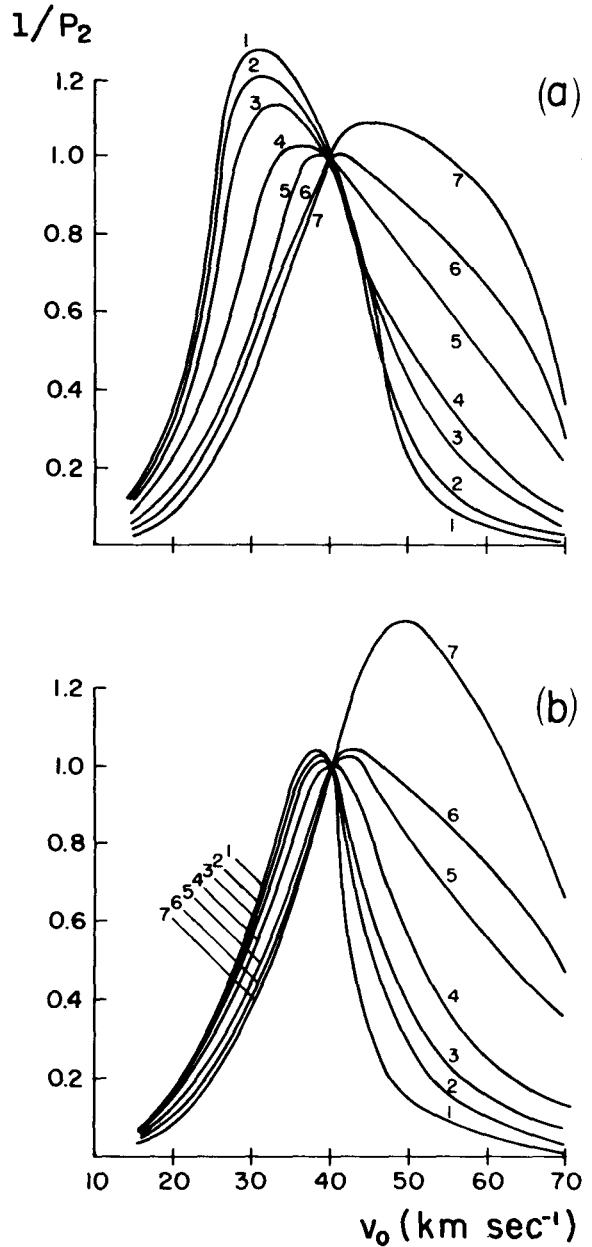


FIGURE 2.—Relative detectability of radar meteors with different velocities by radar. At (a) $\lambda = 7.5 \text{ m}$ and (b) $\lambda = 12 \text{ m}$ with different sensitivities α_{ef}^{min} : (1) $3.16 \times 10^8 \text{ /cm}$, (2) 10^9 /cm , (3) $3.16 \times 10^9 \text{ /cm}$, (4) 10^{10} /cm , (5) $5 \times 10^{10} \text{ /cm}$, (6) 10^{11} /cm , and (7) $2 \times 10^{11} \text{ /cm}$.

meteors was chosen from comparison with radar-meteor observational data. We found $k = 0.094$ for observations at $\lambda = 12 \text{ m}$ with $\alpha_{ef}^{min} = 3 \times 10^{10} \text{ /cm}$ (Korpusov, 1970; Korpusov and Lebedinets, 1970). For four active meteor streams, table 2 gives N , the number of the recorded radar meteors

TABLE 2.—Mean Velocities (in the Atmosphere and No Atmosphere) for Four Meteor Streams*

Stream	N	\bar{v} (km/s)	\bar{v}_0 (km/s)	\bar{v}_{01} (km/s)	\bar{v}_{02} (km/s)
Geminids	344	35.4	36.4	36.2	36.2
Quadrantids	163	41.6	42.6	42.9	42.6
Orionids	86	66.6	67.6	67.5	67.6
Southern Taurids	43	28.7	29.8	29.6	30.3

* The first three columns of data are taken from Korpusov and Lebedinets (1970); the fourth column is taken from Jacchia and Whipple (1961); and the last, from Hawkins and Southworth (1961).

of the stream; \bar{v} , the mean measured velocity; \bar{v}_0 , the mean no-atmosphere velocity obtained at $k=0.094$; and \bar{v}_{01} and \bar{v}_{02} , the mean no-atmosphere velocities of Super-Schmidt meteors of the stream according to Jacchia and Whipple (1961) and Hawkins and Southworth (1961), respectively.

It is seen from table 2 that mean no-atmosphere meteor-stream velocities obtained from radar observations are in agreement with photographic observational data no worse than is the agreement of the data of the most precise photographic observations among themselves. Thus, radar observations at $\lambda=12$ m (Korpusov and Lebedinets, 1970) do not reveal any deceleration that would surpass the theoretical deceleration at the meteoroid density $\delta=3.5$ g/cm³. The dependence of the mean correction for deceleration Δv on α_{ef}^{min} for the radar at $\lambda=7.5$ m at values of v_0 of 15, 20, 30, 40, 50, and 70 km/s is shown in figure 3(a) in curves (1) through (6), respectively. It is assumed that $k=0.094$ and $\cos z=2/3$. The same data for $\lambda=12$ m are presented in figure 3(b).

Radar-Meteor Heights

Ionization curves $\alpha(h, m_0, v_0, z)$ of meteors with different m_0, v_0 , and z were obtained by Lebedinets and Shushkova (1968). Curves of the effective electron line density $\alpha_{ef}(h, m_0, v_0, z, \lambda)$ for $\lambda=7.5$ and 12 m were found by them with the help of equation (10). Using these curves, we can find the theoretical height distributions of radar meteors with given v_0 and z for the observations at given λ and α_{ef}^{min} , with allowance for a random

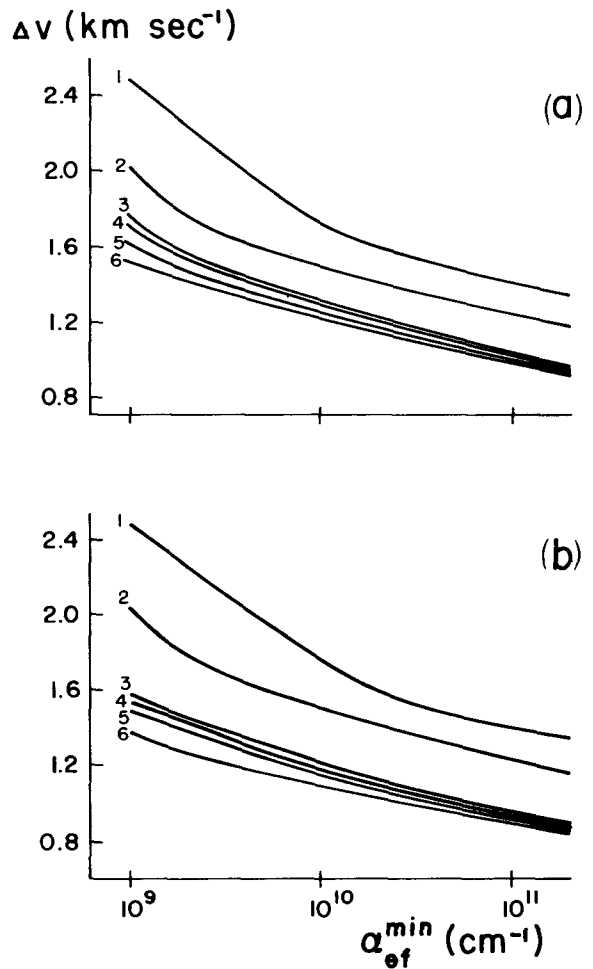


FIGURE 3.—Mean corrections for deceleration as a function of radar sensitivity α_{ef}^{min} . For (a) $\lambda=7.5$ m and (b) $\lambda=12$ m for different velocities: (1) 15 km/s, (2) 20 km/s, (3) 30 km/s, (4) 40 km/s, (5) 50 km/s, and (6) 70 km/s.

position of the reflection point on the trail:

$$N_0(h, v_0, \lambda, \alpha_{ef}^{min}) = \int_{m_{01}}^{m_{02}} n(m_0) dm_0 \quad (16)$$

Here, m_{01} and m_{02} are two roots of the equation

$$\alpha_{ef}(h, m_0, v_0, z, \lambda) = \alpha_{ef}^{min} \quad (17)$$

which is solved by a numerical method.

Comparison of the theoretical distribution of radar-meteor heights with observed ones requires that account be taken of the low precision of radar-meteor height measurements. Besides that, both the variety of meteoroid physical properties and the meteor-radiant zenith distance influence the dispersion of the observed radar-meteor heights. If we assume that all factors leading to the height dispersion follow a Gaussian distribution with the dispersion σ_h , it is necessary to transform equation (16) by the law

$$N(h, v_0, \lambda, \alpha_{ef}^{min}) = \frac{\sqrt{2}}{\sqrt{\pi\sigma_h}} \int_0^\infty N_0(h_0) \times \exp\left[-\frac{(h-h_0)^2}{2\sigma_h^2}\right] dh_0 \quad (18)$$

COMPARISON WITH OBSERVATIONS

It is seen from figure 2 that radar observations have great selectivity with respect to meteor velocities: Slow meteors are poorly observed, owing to the strong dependence of ionization probability on velocity; and fast meteors, owing to the effect of the initial trail radius on the radar echo amplitude. In this connection, it is interesting to consider the results of meteor-velocity measurements from the Harvard Radio Meteor Project (Hawkins, 1963) with a radar system of very high sensitivity, $\alpha_{ef}^{min} = 3 \times 10^9/cm$, at the short wavelength $\lambda = 7.3$ m. The histogram of the observed velocity distribution of 320 radar meteors (Verniani and Hawkins, 1965) is shown in figure 4(a), and that of 2500 Super-Schmidt meteors (McCrosky and Posen, 1961), in figure 4(b).

Radar meteors with low and high velocities are almost absent: For example, about 20 percent of the photographic meteors and less than 1 percent of the radar meteors have a velocity $v_0 > 55$ km/s. Hawkins et al. (1964) take into account the effect of the dependence of β on v alone for the

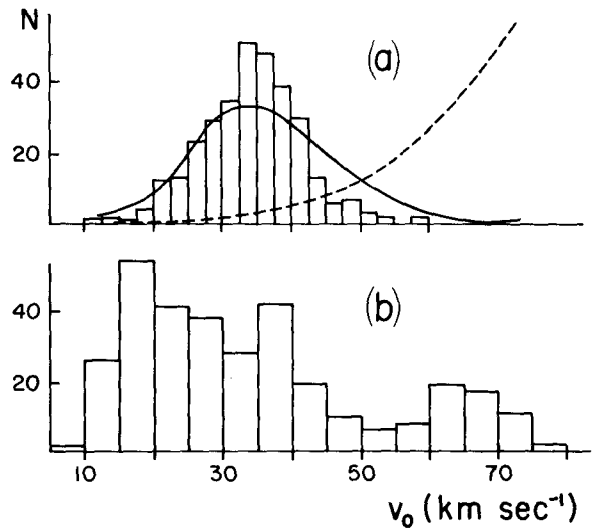


FIGURE 4.—(a) Histogram of the velocity distribution of 320 radio meteors (Verniani and Hawkins, 1965). The continuous line is the relative detectability of meteors with different velocities (curve 3 in fig. 2); the dashed line $N \sim v_0^4$. Both lines are normalized to the total number of meteors, 320. (b) Velocity distribution of 2500 Super-Schmidt meteors (McCrosky and Posen, 1961).

calculation of the physical factor, assuming $\beta \sim v^4$ (dashed line in fig. 4, normalized on the total number of meteors, 320). For the photographic method, the detectability is proportional to v^n , where n varies from 2 to 3, based on evaluations by different authors (Öpik, 1958a; Jacchia, 1949; Whipple, 1954). Thus, an increase in the relative number of radar meteors at high velocities compared with photographic meteors would be expected without allowance for the influence of r_0 ; the picture is inverse in reality. The solid curve in figure 1, which defines the relative detectability of radar meteors with different velocities according to our calculations, is plotted in figure 4(a) as a continuous line (the curve is normalized to 320 meteors); the curve satisfactorily describes the observed radar-meteor distribution. Thus, the observed radar-meteor distribution characterizes radar selectivity much better than it does the real distribution of meteoroid velocities; this is due to both the influence of the dependence of β on v (at low v_0) and the influence of r_0 (at high v_0). It is seen from the theoretical calculations (fig. 3) and from the above comparison of velocities of radar-meteor streams obtained in Obninsk with

photographic observational data (table 2) that mean velocity corrections of radar meteors for the transition from a measured velocity to a no-atmosphere one are comparatively small. This contradicts the results of velocity measurements of the Harvard Radio Meteor Project (Hawkins et al., 1964; Southworth, 1962), which found that the mean measured velocities of radar-meteor streams are about 2 to 3 km/s less than those found from photographic observational data. For example, for the Geminids, the mean velocity is 33.7 km/s, which is about 2.5 km/s less than that obtained from photographic observations (see table 2). This discrepancy cannot be explained by radar-meteor deceleration; it is a consequence of the imperfection of the method of velocity measurements. The positions of the first three maxima of the diffraction picture, including the first, are usually used for velocity measurements (Hawkins et al., 1964). It was theoretically and experimentally shown (Kascheev et al., 1967; Lebedinets, 1966) that use of the first maximum of the diffraction pattern of the radar echo leads to an understatement of the velocity by some kilometers per second for velocity measurements in the case of underdense trails. The same result was obtained for observations at $\lambda = 12$ m in Obninsk (Korpusov, 1970; Korpusov and Lebedinets, 1970). For example, for the Orionids, the mean measured velocity of radar echoes from underdense trails with the first maximum included is 65.3 km/s, and with it excluded is 66.5 km/s. This effect must be much stronger in the Harvard measurements, where the radar had higher power and a shorter wavelength. This conclusion is in good agreement with Evans' (1966) velocity determinations made by measuring the radial velocity of head echoes: For the Geminids, the mean velocity was found to be 35.98 km/s, and for the Quadrantids, 42.25 km/s; from a comparison with the data in table 2, we see that the correction for deceleration turns out to be small (approximately 0.5 km/s).

It is necessary to point out another source of error in the radar-meteor velocity determinations. Curves of $\alpha_{ef}(h)$ for faint meteors have very steep slopes at both ends, which leads to some overstatement of the radar-meteor velocity near the point of appearance and to an understatement near the point of disappearance; consequently,

the deceleration is overstated (if the first maximum of the diffraction pattern of the radar echo is used in velocity measurements).

Measured height distributions of 320 radar meteors (Verniani and Hawkins, 1965) for velocity intervals of 15 to 25, 25 to 35, and 35 to 45 km/s are shown in figure 5(a). Theoretical height distributions for velocities of 20, 30, and 40 km/s at values of σ_h of 5 and 7 km are shown in figures 5(b) and 5(c). It is seen that the theoretical distributions of radar-meteor heights are in good agreement with observed ones.

CONCLUSIONS

(1) A comparison of theoretical calculations with the results of radar-meteor observations shows that the theory of radio meteors devised by Lebedinets (1963, 1966), Lebedinets and Portnyagin (1966a, 1967), Lebedinets et al. (1969), Lebedinets and Shushkova (1968), and Lebedinets and Sosnova (1968, 1969) satisfactorily represents observational data.

(2) The results of radar-meteor observations are incompatible with the idea of low density for small meteoroids in the ablation process.

(3) Fragmentation plays no essential role in the ablation of radar meteors.

(4) The main mechanism of radar-meteor ablation is evaporation. During intensive evaporation, small meteoroids have a density close to that of usual stone meteorites.

(5) Considerable shortness of observed trails of radar meteors compared with predictions of the simplest theory of meteors is explained by two reasons: (a) The simplest theory of meteors is imperfect (a more precise theory gives shorter trails); (b) the upper parts of meteor trails are not observed in radar observations, owing to the effect of the initial trail radius on the amplitude of the radar echo.

(6) Available data from radar-meteor observations do not permit a solution of the problem of the structure and density of small meteoroids before they begin their intensive evaporation (i.e., before complete melting).

(7) Large decelerations of radar meteors obtained in a number of works are apparently the consequence of an imperfection in the method of velocity measurements.

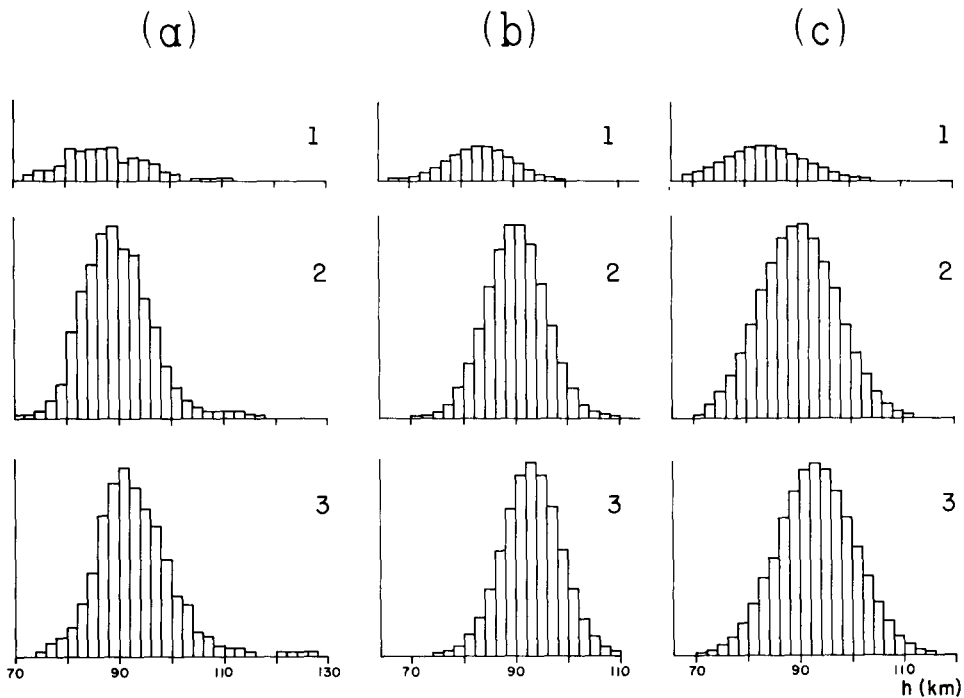


FIGURE 5.—(a) Observed height distribution of radio meteors (Verniani and Hawkins, 1965) for three velocity intervals: (1) 15 to 25 km/s, (2) 25 to 35 km/s, and (3) 35 to 45 km/s. (b, c) Theoretical height distribution for the same velocity intervals as in figure 5(a). At dispersion of height (b) $\sigma_h = 5$ km and (c) $\sigma_h = 7$ km.

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