THE ATTENUATION OF LIGHT BY METEORIC DUST IN THE UPPER ATMOSPHERE

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Summary

An examination of Zacharov's results on the wavelength variation of attenuation of solar radiation following the Perseid meteor shower shows that the effects could be produced either by absorbing particles of diameter about 10^{-5} cm or less, or by transparent particles of diameter in the range 5×10^{-5} to 10^{-4} cm. The rapid disappearance of attenuation, however, can be explained only if the particles evaporate on falling and it is concluded that they are ice crystals formed on nuclei of meteoric origin at a height of about 80 km where there is a temperature minimum. From estimates of the light scattered by these ice crystals it is deduced that they would be visible as noctilucent clouds.

I. Introduction

The recent claim by Bowen (1953) of a correlation between days of heavy rainfall and meteor showers stimulates interest in the nature of meteoric dust in the high atmosphere.

Zacharov (1952) has recently analysed measurements of atmospheric transparency made over the period 1908–1920 by Abbot, Fowle, and Aldrich (1913, 1922) using the so-called "long" method. He found a reduction of transparency whose maximum value, of the order of 2 per cent., occurs some 3 days after the maximum of the Perseid meteor shower, and he considered that the recovery was not complete for some 24 days. At maximum, the continuous decrease in attenuation with increasing wavelength was taken to indicate particles of diameter not exceeding 10^{-5} cm. The time of recovery in attenuation was taken to indicate a duration of atmospheric pollution lasting no more than about 24 days; a time of fall of this order requires particles of some 10^{-3} cm diameter, from which it was deduced that agglomeration must occur, probably at a level of about 80 km.

We show here, on the assumption of spherical particles, that the attenuation of sunlight associated with the Perseid shower is due to ice crystals of average diameter about 7×10^{-5} cm, at an elevation of about 80 km. Disappearance of attenuation is due to evaporation of the particles after they fall through the region of temperature minimum. The particles should scatter sufficient light to be detectable in directions near the Sun, provided the atmosphere be sufficiently pure, and they should be visible as a noctilucent cloud around dusk; Bowen (1953) has in fact found that noctilucent clouds are always associated with meteor showers.

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II. Attenuation of Light by Small Spherical Particles

(a) *Conductors*

The scattering and attenuation of a light beam by small spherical particles was first discussed by Mie (1908). For very small absorbing particles, $2a \ll \lambda$, the scattering cross section Q_s is given by

$$Q_s = \frac{2^7\pi^5 a^6}{3\lambda^4}\left|\frac{N^2-1}{N^2+2}\right|^2 = \pi a^2\left[\left(\frac{2a}{\lambda}\right)^4 \cdot \frac{2^3\pi^4}{3}\left|\frac{N^2-1}{N^2+2}\right|^2\right], \quad \ldots \ (\mathbf{2.1})$$

where $N = k_1/k_2$ is the ratio of the propagation constants in the particle and in the surrounding medium, a is the particle radius, and λ the wavelength in air.

The cross section for attenuation, Q_t, is given by

$$Q_t = \frac{2^3\pi^2 a^3}{\lambda} \cdot \mathrm{Re}\left(-\mathrm{i}\frac{N^2-1}{N^2+2}\right) = \pi a^2\left[\left(\frac{2a}{\lambda}\right)2^2\pi\mathrm{Re}\left(-\mathrm{i}\frac{N^2-1}{N^2+2}\right)\right]. \quad \ldots \ (\mathbf{2.2})$$

Since $N^2 = (2\pi\mu/\lambda)^2(1+\mathrm{i}\varkappa)^2$ where μ is the refractive index and $\varkappa$ the absorption index, the cross sections may be computed from the optical constants of the particle. Typical values of K_s and K_t, where $Q = K(\pi a^2)$, are given in Table 1 for several metals at $0 \cdot 59\ \mu$ and for carbon.

Table 1

TYPICAL VALUES OF K_s AND K_t FOR VERY SMALL ABSORBING SPHERES ($2a \ll \lambda$)

Material	K_s	K_t
Silver	$420 \times (2a/\lambda)^4$	$0 \cdot 39 \times (2a/\lambda)$
Iron	340	4·7
Nickel	390	4·8
Carbon	92	2·6

An upper limit beyond the range of validity of the above expressions is set by the conditions $Q_s \leqslant Q_t$. For the three metals considered in Table 1 and for carbon, expressions (**2.1**) and (**2.2**) are certainly no longer valid when the diameter is greater than about $\lambda/4$.

Ruedy (1941, 1942) has calculated the attenuation and scattering by carbon spheres over a larger range of diameters, $2a \lesssim \lambda$. Values of K_t derived from his graphs are given in Table 2. For large values of diameter, K_t decreases to a value of 2. Ruedy's results showed K_s to be very small compared with K_t until $2a/\lambda \approx 0 \cdot 125$, then to rise rapidly to about $0 \cdot 3K_t$ for $2a/\lambda \approx 0 \cdot 25$ and then more slowly to about $0 \cdot 5K_t$ when $2a/\lambda \approx 0 \cdot 75$ to $1 \cdot 25$. For large diameters, $K_s = 0 \cdot 5K_t$, as readily follows, e.g. from van de Hulst's (1946) discussion.

van de Hulst has also given results for the attenuation and scattering of light by various absorbing media. For iron at $0 \cdot 42\ \mu$, K_t rises almost linearly to about $2 \cdot 8$ when $2a/\lambda = 0 \cdot 25$, then slowly to a maximum of $3 \cdot 0$ when $2a/\lambda \approx 0 \cdot 5$, from which it slowly drops to 2 for large diameters. The behaviour is rather like that of carbon. For metals the scattered light is intermediate between that for transparent media and carbon.

TABLE 2
K_t FOR CARBON AND WATER SPHERES

$\frac{2a}{\lambda}$	K_t	
	Carbon	Water
0·25	1·9	<0·15
0·5	2·6	0·33
0·75	3·0	1·0
1·0	2·5	1·8
1·5		3·4
2·0		3·9
3·0		2·2

(b) *Insulators*

For insulators, the attenuation cross section is equal to that for scattering, and for very small spheres is proportional to $(2a/\lambda)^4$. Data have been calculated by Stratton and Houghton (1931), Ruedy (1943*a*), and la Mer (1943), and are summarized for water in Table 2. On the whole, the results for different refractive indices are rather similar, the cross sections being compressed or expanded along the $2a/\lambda$ axis. The values of $2a/\lambda$ for maximum values of K_t are given in Table 3.

TABLE 3
VARIATION WITH REFRACTIVE INDEX OF THE SPHERE DIAMETER FOR MAXIMUM K_t

Refractive Index	$2a/\lambda$ for K_t (max.)
2·25	2·5
1·33	1·9
1·44	1·5
1·50	1·3
1·55	1·2

III. The Diameter of Particles in the Upper Atmosphere as Derived from Selective Attenuation

Zacharov was able to obtain the variation of atmospheric transparency t with wavelength at the time of maximum absorption, and data from his graphs are given in Table 4.

Although the changes Δt in transparency are small, the uniform variation with wavelength suggests that the effect is real. Zacharov inferred from the selectivity that the particle diameters did not exceed 10^{-5} cm. It is possible, however, to interpret these results otherwise, as we shall show.

If the particles be conducting, then for diameters less than about $\lambda/4$ the attenuation may be derived from (**2.2**). It is usually agreed that this results in the attenuation varying approximately as λ^{-1}, although the term involving the propagation constant does depend on wavelength. For the longer wavelengths, the values of $\Delta t/t$ in Table 4 vary approximately in this manner. The trend of the curve suggests a maximum at a wavelength somewhat shorter than $0 \cdot 35\ \mu$. By comparison with the value of $2a/\lambda$ for maximum K_t with carbon (see Table 2), we infer that for $\lambda = 0 \cdot 35\ \mu$, $2a/\lambda \lesssim 0 \cdot 5$, i.e. the diameters of the particles, if conducting, are of the order of $1 \cdot 7 \times 10^{-5}$ cm or less.

TABLE 4

OBSERVED ATTENUATION AS A FUNCTION OF WAVELENGTH (ZACHAROV 1952)

Wavelength (μ)	Transmittance t	Δt	$\frac{\Delta t}{t}$
0·35	0·60	0·0245	0·041
0·4	0·72	0·025	0·035
0·45	0·80	0·031	0·039
0·5	0·85	0·0225	0·026
0·6	(0·89)*	0·020	(0·022)
0·7	0·93	0·014	0·015
0·8	(0·95)	0·012	(0·012)
1·0	(0·96)	0·0095	(0·0095)
1·2	(0·97)	0·0075	(0·0075)
1·6	(0·98)	0·0025	(0·0025)

* Values in parentheses are estimates.

On the other hand, suppose the particles are transparent ; then a fair fit of the values of K_t to $\Delta t/t$ can be achieved by taking the maximum of the K_t curve to be at about $0 \cdot 35\ \mu$, as can be seen by comparing the cross sections for water, Table 2, with $\Delta t/t$, Table 4. If the refractive index is $1 \cdot 33$ (water droplets) the particle diameter is about 7×10^{-5}. van de Hulst (1949) has given reasons to suppose that the refractive index of particles in interstellar space may be about $1 \cdot 25$, while the index of most minerals is appreciably higher. In view of the uncertainties, including those of the experimental data, it would seem that diameters in the range 5×10^{-5} to 10^{-4} cm are likely.

It is clear that selective attenuation can be explained by either absorbing or transparent particles, but the diameters required differ in order of magnitude.

IV. The Time Variation of Attenuation

In order to explain the disappearance of attenuation, Zacharov suggested that the particles agglomerate and fall to the ground over a period of 24 days. This time, however, is somewhat uncertain. Zacharov plotted against time the 3-day averages of the transmission, the central 3-day group in each year being centred on the maximum of the Perseid shower. For each wavelength, the mean curve, derived from 10 years' observations, shows fluctuations about the mean ; and, from inspection, these do not seem asymmetrical more than 24 days after the time of maximum attenuation. But the attenuation 3 days after the maximum of the shower shows the only increase which is statistically significant, being of the order of three times the standard deviation, and the time for recovery is thus uncertain.

The attenuation coefficient of n particles of diameter $2a$ in a column of unit cross section is

$$k = K_t \pi n a^2. \quad \ldots\ldots\ldots\ldots \quad (4.1)$$

If dust particles grow in size without coalescing, then the attenuation varies as $K_t a^2$, and increases continuously for all types of material. This clearly cannot be the process of disappearance of attenuation.

Since the total volume V of all particles is $4\pi n a^3/3$, then

$$\frac{k}{V} = \frac{3K_t}{4a}. \quad \ldots\ldots\ldots\ldots \quad (4.2)$$

If particles coalesce, so that a increases while V remains constant, their attenuation varies as K_t/a. For both absorbing and transparent particles of initial diameters as found in the preceding section, K_t/a decreases with a, and the attenuation varies roughly as a^{-1}, so that in each case coalescence would reduce the attenuation.

Zacharov has plotted times for particles of the density of water to fall through various heights in the atmosphere. To fall to the ground in 24 days the particles would require diameters of the order of 10^{-3} cm.; for shorter times of fall the diameters would need to be even greater. However, the attenuation produced by transparent particles after coalescence to a diameter of 10^{-3} cm would be reduced by a factor of about 0·05–0·1 ; for absorbing particles the factor would be even smaller, about 0·02. This argument would suggest that the disappearance of attenuation is due to coalescence rather than to the fall of the particles. We shall now consider whether or not coalescence is physically possible.

V. Processes Affecting Particle Diameter

For particles not affected by condensation or evaporation there is only one conceivable mechanism of particle growth, coalescence by collision. Kunkel (1948) has estimated the collision rate between a particle of radius a_1, charge q_1, and particles of radius a_2, charge q_2, and concentration N falling freely in air of viscosity η. If

$$|C_1| > |V_0| (a_1 + a_2)^2, \quad \ldots\ldots\ldots\ldots \quad (5.1)$$

where

$$C_1 = \frac{q_1 q_2 (a_1 + a_2)}{6\pi\eta a_1 a_2},$$

$$V_0 = \frac{2g\rho(a_1^2 - a_2^2)}{9\eta},$$

g being the acceleration due to gravity and ρ the density of a particle, then Kunkel's discussion shows that the mean time τ between collisions is

$$\tau = -\frac{1}{4\pi N C_1}. \quad \ldots\ldots\ldots\ldots \quad (5.2)$$

During day-time, particles in the upper atmosphere will be positively charged due to photoelectric ionization, and collisions will be improbable. At night-time, recombination will result in particles whose average charge is zero, although the average absolute magnitude of the charge per particle will differ from zero, being such that

$$\frac{1}{2}\frac{q^2}{a}\approx kT. \qquad \text{(5.3)}$$

If $T=250$ °K., $a=3\cdot5\times10^{-5}$ cm, then $q\approx1\cdot6\times10^{-9}$ e.s.u.

The value of N is obtained by noting that at the time of maximum attenuation $a\approx3\cdot5\times10^{-5}$ cm, $K_t\approx2$ for transparent particles, so from (**4.1**),

$$n\approx3\times10^{6}\ \text{cm}^{-2}.$$

If these are assumed to be in a layer 10 km thick, then $N\approx3$ cm^{-3}, which is much greater than Bowen's estimate of 10^{-6} cm^{-3} for the concentration of meteoric dust particles in the upper atmosphere. Then with $\eta\approx1\cdot7\times10^{-4}$ g cm sec^2, $a_1\approx a_2\approx3\cdot5\times10^{-5}$ cm, $a_1^2-a_2^2\leqslant10^{-9}$ cm^2, $q_1\approx-q_2\approx2\times10^{-9}$ e.s.u., and $\rho=1$ g cm^{-3}, it follows that (**5.1**) applies, and $\tau\approx10^9$ sec, which is so long that such collisions may be completely neglected. Agglomeration cannot occur, and the attenuation cannot have been due to meteoric dust alone.

It seems very likely, however, that the particles consist of nuclei of meteoric origin, on which water vapour has condensed to form water droplets or ice crystals. Since this requires relative humidities of the order of 100 per cent., the regions in which condensation can occur are limited. Although we have scanty knowledge of the variation of water vapour content of the atmosphere with altitude, the approximate temperature and pressure distributions are known (Havens, Koll, and la Gow 1952). Above 40 km, the only region where the total pressure exceeds the saturated water vapour pressure is in the neighbourhood of 80 km, where the temperature has a minimum value of about 190 °K, and this is the only region where condensation can occur. Furthermore, at such low temperatures any condensation must be as ice crystals. Zacharov has estimated the velocity of fall of spherical particles of unit density and diameter 7×10^{-5} cm to be of the order of 10 cm sec^{-1} at the 80 km level ; the lifetime of the ice crystal, which is the time to fall through the low temperature region, about 10 km thick, is thus of the order of a day.

VI. Brightness of Particles

(*a*) These particles must cause an increase in the brightness of the sky near the Sun. The distribution of light scattered in the forward direction may be obtained approximately on the assumption that it results from diffraction by opaque disks, in which case it readily follows that the change b in sky luminance at an angle θ to the Sun, produced by a layer having n particles in a column of unit section along the line of sight, is

$$b=\frac{nB\Omega a^2}{\theta^2}\,J_1\left(\frac{2\pi a\theta}{\lambda}\right), \qquad \text{(6.1)}$$

B and Ω being the mean luminance of and the solid angle subtended by the Sun. But

$$J_1(x)=\frac{x}{2}-\frac{x^3}{16}+\frac{x^5}{384}-\ldots,$$

so

$$\frac{1}{\theta}J_1\left(\frac{2\pi a\theta}{\lambda}\right)=\frac{\pi a}{\lambda}-\frac{1}{2}\left(\frac{\pi a}{\lambda}\right)^3\theta^2+\ldots$$

and varies but slowly with θ while θ is small, falling to $1/\sqrt{2}$ of its maximum value when $\theta\simeq 0\cdot 5\lambda/2a$, i.e. $0\cdot 25$ if $\lambda/a=1$. Provided θ is small in this sense,

$$\frac{b}{B}=\frac{\pi^2 na^4\Omega}{\lambda^2}=\frac{\pi ka^2\Omega}{K_t\lambda^2}. \quad\ldots\ldots\ldots\ldots\ldots\ldots (6.2)$$

With $k=0\cdot 025$, $K_t\approx 2$ and $2a/\lambda=1\cdot 25$, then

$$\frac{b}{B}\approx 10^{-6}.$$

This is measurable, and of the order of magnitude of the luminance of a very pure sky near the Sun, but, in view of the variable nature of the light scattered in the low atmosphere, considerable care would be needed to detect variations of this amount. There is, in fact, only very limited published data on the brightness of the sky near the Sun, the most extensive tables available being being of the Fraunhofer Institut (1951–53) which give brightness of the sky a few minutes from the Sun's limb at wavelength $0\cdot 5303\,\mu$. At such small angles of scattering the brightness and its fluctuations are so high as to hide increases of the above order of magnitude without many more observations, and these should be made preferably not too close to the Sun's limb.

(*b*) The amount of light scattered at large angles from an ice crystal depends on the shape and size of the particle, and on the angle of scattering. A short extrapolation from a graph given by Ruedy (1943*b*) indicates that at right angles to an incident beam of illumination e the intensity of a spherical particle, refractive index $1\cdot 33$ and $2a/\lambda=1\cdot 25$, is about $8\times 10^{-2}ea^2$. A column of such particles, n per unit section along the line of sight, will have a luminance of $8\times 10^{-2}nea^2$; if $n=3\times 10^6$ cm^{-2}, $a=3\cdot 5\times 10^{-5}$ cm and $e\approx 10^4$ lumen ft^{-2} (as in sunlight), then the luminance is about 3 cd ft^{-2} or 9 ft lamberts. It is unlikely that such a change in sky brightness could be measured during daylight, or be seen visually even if it possessed a structure. At dusk, however, when the background sky luminance becomes very small the cloud of ice crystals should be readily seen. Bowen's (1953) findings that noctilucent clouds have been reported only at times of meteor showers thus lead to the conclusion that Zacharov's absorption is probably due to noctilucent clouds. There would seem to be no measurements of the luminance of such clouds, but it must be of the above order of magnitude.

VII. Conclusions and Discussions

The above results may be summarized briefly as follows. From the variation in absorption with wavelength, it is deduced that attenuation of sunlight within a few days of the Perseid meteor shower is due either to absorbing particles of diameter of 10^{-5} cm or less, or to transparent particles of diameter 5×10^{-5} to 10^{-4} cm. The rapid disappearance of absorption can be due only to decrease in size of the particles and it is concluded that they are ice crystals or water droplets condensed on nuclei of meteoric origin. The only region where the relative humidity can be high enough for this is around 80 km, where because of the low temperature (190 °K) the particles must be ice. It is then deduced that the mean diameter is 7×10^{-5} cm, with about 3×10^{6} particles/cm^2 along the line of sight, and of the order of 3 particles/cm^3.

Particles of the above size and concentration would be visible as a noctilucent cloud around dusk, though not bright enough to be seen in daytime. In the neighbourhood of the Sun, however, there should be an increase in sky brightness of the order of 10^{-6} of that of the Sun, which should be detectable provided suitable precautions are taken against scattering by particles in the low atmosphere.

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