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METEOROID DENSITIES

B.A. Lindblad

Lund Observatory
S-222 24 Lund, Sweden

Introduction

The composition and density of meteoroids has been the subject of a number of investigations in recent years. Analysis of photographic meteor data have been presented by Jacchia et al (1967). Verniani (1964, 1967, 1969), Benyuch (1968, 1973, 1974), McCrosky and Ceplecha (1969) and others. The density of radio meteors have been studied by Verniani and Hawkins (1965) and Verniani (1966). In the present paper the dependence of meteoroid density on the type of the orbit is discussed.

Luminosity- and drag equations

It is generally assumed that the luminous flux of a meteor is at any instant proportional to the kinetic energy of the ablated meteor atoms. The luminosity equation may then be written

$$I = -\frac{\tau}{2} v^2 \frac{dM}{dt} \qquad (1)$$

where I is the luminous flux, τ the luminous efficiency coefficient and M and v are mass and velocity of the body. Present knowledge about the luminous efficiency coefficient has been summarized by Verniani (1965, 1967). If the photographic observations give intensity and velocity as a function of time, a photometric mass can be determined from

$$M = \frac{1}{\tau} \cdot \frac{2}{\bar{v}^2} \int_{t_E}^{t} I \, dt \qquad (2)$$

where t_E is the time at which the meteor luminosity ends (assumed zero mass), and $\bar{v}$ is a value of v at some instant between t_E and t.

The drag equation may be written in the form

$$\frac{dv}{dt} = -\frac{C_D}{2} \cdot A_o \cdot \rho_m^{-2/3} \cdot v^2 \cdot \rho_a \cdot M^{-1/3} \qquad (3)$$

where C_D is the drag coefficient, A_o the shape factor, ρ_m the meteoroid density, ρ_a the atmospheric density and M the dynamic mass of the meteoroid.

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The drag coefficient, shape factor and meteoroid density are physical properties of the meteoroid body. It is convenient to introduce a characteristic constant C defined as

$$C = \frac{C_D}{2} \cdot A_o \cdot \rho_m^{-2/3} \tag{4}$$

The drag equation may then be written

$$-\frac{M^{1/3}}{v^2} \cdot \frac{dv}{dt} = C \cdot \rho_a \tag{5}$$

For a given point on a photographic meteor trail it is in principle possible to determine v and $\frac{dv}{dt}$. For the mass M we may substitute the photometric mass from eq. (2). The atmospheric density ρ_a may be taken from the US Standard Atmosphere (1962). The characteristic constant C may then be computed for any given point on the meteor trail. Finally, if the drag coefficient and shape factor are known, the meteoroid density may be computed from eq. (4).

Mean meteoroid density

Jacchia et al (1967) have analyzed 413 precisely reduced atmospheric trajectories of meteors photographed by the Harvard Super-Schmidt cameras. For determining a mean meteoroid density 350 meteors with several measured decelerations each were selected. A weighted logarithmic average over each trail and over the 350 objects gave log C = 0.603. Jacchia et al assumed $C_D = 2.2$, $A_o = 1.5$ and thus from eq. (4) obtained for the mean bulk density of the precisely reduced photographic meteors $\bar{\rho}_m = 0.26$ g cm^{-3}. Stream meteors and sporadic meteors, studied separately, yielded the same density value. Verniani (1967, 1969) has summarized the information on meteoroid densities from the Super-Schmidt meteors. The analysis suggests that the meteoroids are of a low-density, porous structure. This is in agreement with the generally accepted model of a comet (Whipple 1951) which predicts low-density meteoroids.

Individual meteoroid densities and dimensions

Jacchia et al (1967) give for each meteoroid a quantity $\Delta \log \rho_{corr}$, which is related to the meteoroid density ρ_m by the equation

$$\log \rho_m = -1.5 \, \Delta \log \rho_{corr} + \log \bar{\rho}_m \tag{6}$$

where $\bar{\rho}_m$ is the mean meteoroid density of the sample. Using the weighting

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procedures of Jacchia et al (1967) we computed individual densities for all meteors for which reliable values of deceleration and fragmentation were available. It is obvious that individual values of ρ_m per se have little significance and that only group averages merit any degree of confidence. Mean values of log ρ_m for 11 meteor streams of short period are plotted in fig. 1 versus the mean inverse semi-major axis of the stream orbit. Datum points for the Virginids, Northern Iota Aquarids and Draconids are based on two meteors each and are of low significance. Fig. 1 shows a progressive increase in the mean density of a stream meteoroid as the size of the orbit decreases.

In a second study all short period stream and sporadic meteors were combined and grouped in intervals of 0.05 (a.u.)$^{-1}$ in inverse semi-major axis. The weighted mean log density for each group is plotted in fig. 2. Again we see a progressive change in meteoroid density with 1/a.

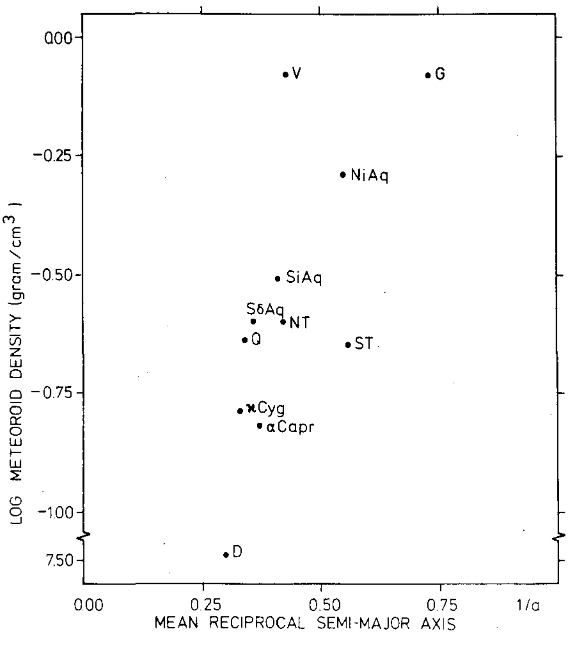

Fig. 1. Mean log meteoroid density g/cm^3) vs mean inverse semi-major axis (a.u.$^{-1}$) for 11 streams of short period.

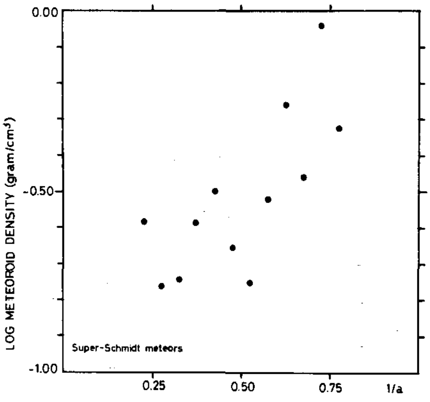

Fig. 2. Mean log meteoroid density (g/cm^3) vs inverse semi-major axis ($a.u.^{-1}$). All meteors with orbits of short period.

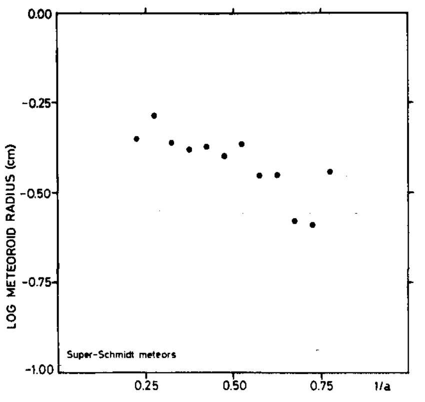

Fig. 3. Mean log meteoroid radius (cm) vs inverse semi-major axis ($a.u.^{-1}$). All meteors with orbits of short period.

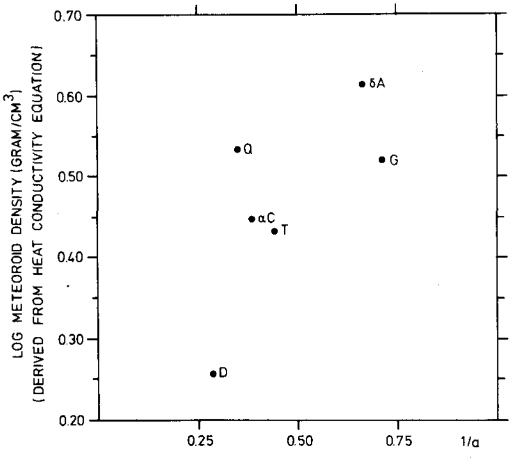

Fig. 4. Log meteoroid density (g/cm^3) as derived from the equation of heat conductivity vs inverse semi-major axis ($a.u.^{-1}$) for six short period streams.

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Mean log meteoroid mass for the selected Super-Schmidt meteors was plotted against 1/a. There was no appreciable variation in the photometric mass over the range of 1/a values studied by us. Knowing meteoroid mass and density it is in principle possible to compute an effective particle "radius" for the meteoroid. Mean particle "radius" is plotted against 1/a in fig. 3. The mean log meteoroid radius varies by a factor of about two over the range of 1/a studied by us.

Meteoroid densities determined from the equation of heat conductivity

The equation of heat conductivity may be written in the form

$$T_B = \frac{\Omega}{2} v_{\sim}^{5/2} \rho_a (\lambda \rho_m c\ b \cos z_R)^{-1/2} \tag{7}$$

where T_B is the surface temperature of the meteoroid, Ω = heat transfer coefficient, $v_{\sim}$ = no atmosphere velocity, ρ_a = air density, λ = heat conductivity of the meteoroid, ρ_m = density of the meteoroid, c = specific heat of the meteoroid, b = air density gradient and z_B = zenith distance of the radiant. The suffix B refers to the beginning point of the luminous meteor trail. The equation of heat conductivity has been discussed by Levin (1961), Ceplecha and Padavet (1961) and Benyuch (1968). The equation may be written as

$$\log \frac{2T_B}{\Omega} + \frac{1}{2} \log (\lambda \rho_m c\ b) = \log \rho_a^B + \frac{5}{2} \log v_{\sim} - \frac{1}{2} \log \cos z_R \tag{8}$$

The right hand member, which includes only direct measureable quantities, is denoted k_B. The k_B parameter has been extensively used in statistical studies by Ceplecha (1958, 1966, 1967).

The meteoroid density may be determined from eq. (8) provided the parameters T_B, k_B, Ω, λ, c and b are known. This approach to density determination has been used notably by Benyuch (1968, 1973, 1974). In fig. 4 the mean density is plotted against 1/a for 6 short period streams listed by Benyuch (1974). A primary feature of fig. 4 is a dependence of density on 1/a of a similar nature to that found in fig. 1.

The use of eq. (8) for determination of density has been commented on by Kruchinenko (1969), Kruchinenko and Tryashin (1970) and Kolomiets (1971). The "mineralogical densities" computed by Benyuch are of an order of a magnitude higher than the "bulk" densities derived from the drag and luminosity equations. The reason for this discrepancy is not fully understood.

Discussion

In order to get a sample of meteoroids with a similar evolutionary history we studied only meteoroids for which a < 5.20 a.u. These objects may be considered related to, and possibly remnants of, short period comets of the Jupiter family. The dispersion in the orbital elements of short period meteor streams has been studied by Lindblad (1972, 1974). The dispersion increases with 1/a, i.e. very short period orbits generally represent more dispersed and therefore presumably older meteor streams.

Fig. 1, 2 and 4 show that meteoroid density increases with decreasing size of the orbit. The progressive increase in density with 1/a may be ascribed to differences between the conditions under which the meteoroids were formed. Meteoroids in very short period orbits may have originated in short period comets, and the now observable members of stream may consist of inner, and more dense comet core material. The composition and mass may be the same for all short period meteoroids, but the difference in pressure to which the different layers of the parent comet have been subjected is responsible for the spread in particle density.

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