

THE DRACONID METEORIODS

MARTIN BEECH

Department of Astronomy, University of Western Ontario, London, Ontario N6A 3K7, Canada

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ABSTRACT

The available observational data for the beginning and end heights of Draconid (Giacobinid) meteors are compared with the dustball meteor ablation theory of Hawkes and Jones, with which a good general agreement is found. Assuming that the fragile nature of the Draconid meteoroids indicates that the energy required to fragment unit mass of meteoroid material X is less than $\sim 10^5 \text{ J kg}^{-1}$, the previously found minimum value, then the Draconid meteoroids have a bulk density greater than $\sim 200 \text{ kg m}^{-3}$. The relation between comet P/Giacobini-Zinner and the Draconid meteoroids is briefly considered.

INTRODUCTION

The Giacobinid or Draconid meteor stream has been responsible for the most spectacular meteor displays of this century. Normally active between the 6th and 10th of October, with a maximum between the 8th and 9th, the shower has shown great activity, particularly during its 1933 and 1946 returns, when zenith hourly rates of up to 5000 meteors were recorded for several hours either side of stream maximum (Lovell 1954).

Since the first quantitative data became available it was clear that the Draconids were exceptional on the basis of nearly every parameter (Millman 1965), here illustrated in Table I. Particularly important, however, was the realization that in the case of the Draconid meteoroids, the standard picture of solid-body meteor theory may fail completely (Opik 1958). It is currently believed that meteoroids can be best described in terms of a "dustball" model and viewed as porous, fragile structures composed of a low melting point "glue" that holds together an assembly of small, high-melting-point stone or iron dust grains of typical mass $\lesssim 10^{-6} \text{ g}$.

The dustball meteoroid model as constructed by Hawkes and Jones (1975) makes several predictions concerning the variation of meteoroid end height with maximum meteoroid magnitude. These predictions have been tested in the case of three meteor streams; the Perseids, the Southern Taurids, and the Geminids, by Hapgood *et al.* (1982) and Beech (1984), with good agreement being found between theory and observations. We perform here a similar analysis for the Draconid meteors on the basis of data taken from Jacchia, Kopal, and Millman (1950), who report on photographic observations taken during the spectacular 1946 Draconid return.

OBSERVATIONS

The specific predictions of the Hawkes-Jones model can be summarized as (1) all meteoroids with the same initial velocity and composition will begin visual ablation at the same height H_b . (2) the end heights H_e of meteors will be constant and independent of mass for faint meteors, while the brighter, more massive meteoroids will descend increasingly lower into the atmosphere with increasing initial mass. Hapgood *et al.* (1982) showed how a critical mass m_c can be defined so that a meteoroid of mass m_c will just complete fragmentation at height H_b . If $m < m_c$, then the meteoroid will fragment but not begin visual ablation until it has reached the height H_b . For $m > m_c$, grains can still be re-

leased after the onset of visual ablation so that H_e will decrease with increasing initial mass. If the mass m_c can be estimated from the observational data, Hapgood *et al.* (1982) show that the energy required to fragment unit mass of meteoroid material X can be evaluated via the relation

$$X = C \cdot \frac{\rho(H_b) H_* v_\infty^2}{8 r_0 d \cos(z)}, \quad (1)$$

where C has a value between 1 and 3 according to the thermal conductivity of the meteoroid material, $\rho(H_b)$ is the atmospheric density at height H_b , H_* is the scale height, r_0 is the initial radius of the meteoroid, d is the meteoroid density, v_∞ is the geocentric velocity of the meteoroid, and z is the zenith angle. The data from Table I, with atmospheric parameters from Allen (1973) allows (1) to be rewritten as

$$X = \frac{C}{(r_0/\text{cm})} \cdot \frac{1}{(d/10)} 5.3 \times 10^6 (\text{J kg}^{-1}). \quad (2)$$

In Fig. 1 we show the beginning and end heights versus apparent photographic magnitude at maximum light m_p . We have considered meteoroids in the magnitude range $-5 \leq m_p \leq 0.5$ and the data for 160 meteoroids has been averaged over ten intervals of width 0.5 mag (see Table II).

The scatter is large, but would seem to indicate an approximately constant beginning height of $97.6 \pm 11.8 \text{ (km)}$. For $-2.5 \leq m_p \leq 0.0$, the end heights also appear to be approximately constant, $\sim 91 \text{ km}$, with H_e decreasing in height for $m_p < -2.5$. In terms of the Hapgood *et al.* (1982) scenario this suggests a critical mass meteoroid will have a photographic magnitude $m_p \approx -2.5$.

In order to determine m_c we have to find now a photographic magnitude-mass relationship. The mass of a meteoroid can be calculated from its observed light curve if the amount of light I_p emitted in the photographic domain is assumed to be proportional to the kinetic energy of the atoms in the meteor coma (Jacchia *et al.* 1967). In this way

TABLE I. A comparison between the Draconid and "typical" meteor parameters. Data from Jacchia *et al.* (1950), Jacchia *et al.* (1967), and Millman (1975).

	H_b (km)	v_∞ (km s ⁻¹)	ρ (kg m ⁻³)	$\cos z$	χ
Average meteor shower	102.9	39.3	280	0.69	0.27
Draconids	97.6	23.1	10-300	0.61	1.89

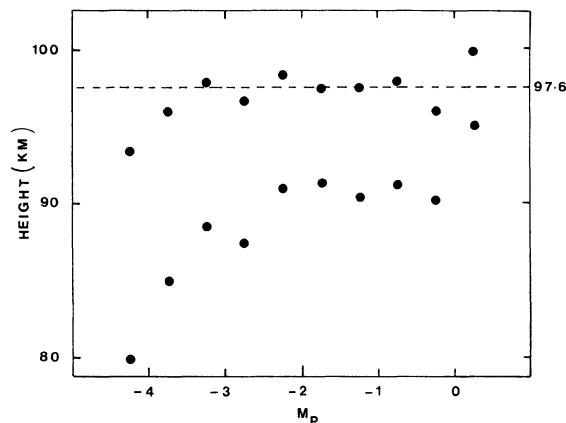


FIG. 1. Plot of the 0.5 mag, bin averaged beginning and end heights for Draconid meteors. The typical spread about each point is ± 10 km s^{-1} . Despite this large individual spread, the resultant picture appears to follow that predicted by the Hawkes and Jones (1975) dustball model.

$$m = m_R + \frac{2}{\tau_p} \int_{-\infty}^{+\infty} \frac{I_p}{v^3} dt, \quad (3)$$

where τ_p is the photographic luminosity efficiency, given by Verniani (1969) as 1.0×10^{-19} (cgs units). Assuming a constant velocity v and zero residual mass m_R , equation (3) can be rewritten as

$$m(\text{kg}) = 1.6 \times 10^{-3} \int_{-\infty}^{+\infty} I_p dt. \quad (4)$$

A straightforward least-square comparison between m_p and $\int I_p dt$ as given by Jacchia *et al.* (1950) would suggest

$$\int I_p dt = -2.35(m_p) + 0.72, \quad (5)$$

with a correlation coefficient of -0.70 . While the relationship shows considerable scatter, it would suggest that a critical-mass meteoroid with $m_p \approx -2.5$ has a mass $m_c(\text{kg}) \approx 1.1 \times 10^{-2}$.

DISCUSSION OF OBSERVATIONS

As indicated by Table I, the density of the Draconid meteoroids is not well determined. Sekanina (1985) has argued that values as high as ~ 300 kg m^{-3} may be appropriate for the meteoroid density. A spherical, critical mass Draconid meteoroid of such a density gives in (2), $X = C \cdot 8.6 \times 10^4$ J kg^{-1} .

TABLE II. The beginning and end heights of Draconid meteors in half-magnitude bins for $-5.0 \leq m_p < 0.5$.

Bin size (mag)	Number of meteoroids	$\bar{H}_b$ (km)	$\sigma(H_b)$	$\bar{H}_e$ (km)	$\sigma(H_e)$
$0 < m_p < 0.5$	13	99.9	12.0	94.9	12.1
$-0.5 < m_p < 0.0$	10	96.2	12.8	90.4	12.2
$-1.0 < m_p < -0.5$	26	98.1	12.4	91.4	12.4
$-1.5 < m_p < -1.0$	22	97.7	10.7	90.3	10.8
$-2.0 < m_p < -1.5$	23	97.6	11.3	91.3	11.2
$-2.5 < m_p < -2.0$	22	98.5	11.0	90.7	11.2
$-3.0 < m_p < -2.5$	14	96.7	12.6	87.5	12.0
$-3.5 < m_p < -3.0$	17	97.9	11.5	88.6	11.0
$-4.0 < m_p < -3.5$	7	95.9	12.7	84.8	10.9
$-5.0 < m_p < -4.0$	6	93.3	11.0	80.0	12.8

Jacchia, Kopal, and Millman (1950) recorded the observation that the Draconids have abnormally short trajectories and begin visual ablation at heights greater than those expected for meteoroids of geocentric velocity 23.1 km s^{-1} . From this they conclude that the Draconid meteoroids are more fragile than "ordinary meteors." Previous determinations of the value of X (Beech 1984) would suggest that for the Draconids $X/C \leq 10^5$ J kg^{-1} , a condition that would require the meteoroids to have a bulk density ≥ 200 kg m^{-3} . ReVelle (1983) has suggested that Draconid-like fireballs observed by the Prairie Network have a bulk density of some 340 kg m^{-3} . Adopting this value as an upper limit for the Draconid meteoroid density, the available data on known X values for shower meteoroids are compared in Table III.

For the Draconids the value of C is probably not a major source of uncertainty. The fragile nature of the Draconids might imply that they heat isothermally (appropriate to $C = 3$) and fragment completely on reaching the boiling point of the binding glue. The observations of Jacchia, Kopal, and Millman (1950) indicate a considerable variation in the beginning heights of Draconid meteors (± 12 km). This phenomenon alone can introduce considerable uncertainty into our results via $\rho(H_b)$ in (1). The reason for this large variation is at present unclear. Millman (1972) reported on the analysis of ten 1946 Draconid meteor spectrograms. He found that there was no evidence of chemical anomaly and that the meteoroids have compositional characteristics consistent with those of carbonaceous or olivine-bronzite chondrite material. Harvey (1973) found similar results from two meteor spectra obtained during the extremely weak 1972 return. It would seem that compositional anomaly does not readily account for the variation in beginning heights.

COMET P/GIACOBINI-ZINNER

It was suggested by M. Davidson in 1915 (see Davidson 1920) that the debris of comet 1900 (III) discovered by M. Giacobini in December 1900 could give rise to a meteor shower. It is now clear that this comet, later classified as P/Giacobini-Zinner, is responsible for the Giacobinid, or October Draconid, meteor shower. Jacchia *et al.* (1950) suggest that the extreme nature of the Draconid meteoroids is due to the fact that the shower is of recent origin, a result suggested by the apparent "bunching" of meteoritic material in the vicinity of the parent comet. Davies and Lovell (1955), however, note that the apparent lack of recorded activity during some years may be a result of the meteoroids' tight binding to the parent comet's orbit, with the Earth-cometary orbit encounter being greater than the stream width. In this way the meteoroids may be distributed uniformly around the stream's orbit. Since P/Giacobini-Zinner is part of the Jupiter comet family, it has undergone and will undergo large perturbations. Such perturbations will undoubtedly affect the meteoroid stream formation. If P/Gia-

TABLE III. A comparison between the known values of critical mass and energy required to fragment unit mass of meteoroid material for the Draconid, Perseid, Southern Taurid, and Geminid meteor streams.

Shower	Critical mass (kg)	X (J kg^{-1})	Reference
Draconids	1.10×10^{-2}	$\sim 8 \cdot C \cdot 10^4$	This paper
Perseids	0.20×10^{-3}	$4 \cdot C \cdot 10^5$	Beech (1984)
	0.20×10^{-3}	$3 \cdot C \cdot 10^5$	Hapgood <i>et al.</i> (1982)
S. Taurids	0.22×10^{-3}	$3 \cdot C \cdot 10^5$	Beech (1984)
Geminids	0.40×10^{-3}	$1 \cdot C \cdot 10^5$	Beech (1984)

cobini-Zinner is a young comet and the Draconid stream is of recent origin, then it is possible that the meteoroids are composed of more fragile, "softer" cometary material. Yeomans (1972) has considered the motion and orbital evolution of comet P/Giacobini-Zinner and suggests that the erratic increase in the nongravitational effect observed in its orbit may be due to a transition in the changing of surface nuclear ice from soft exterior ice to more dense interior material. This in turn enhances the time lag of heat transfer and the resultant "jet effect." Sekanina (1985) has developed an oblate-spheroid model for the nucleus of P/Giacobini-Zinner and describes the nongravitational perturbations in terms of nuclear precession and variable outgassing. Evdokimov (1972) has considered the origin of the Draconid showers of 1926, 1933, and 1946. As part of this analysis he suggests that the parent comet may eject some 5% of its mass per revolution, which implies that the comet will become dormant after some 350–700 yr. Katasev and Kulikova (1972) have modeled the formation of meteor streams, and suggest that the Draconid shower is not greater than ~100 years old. A similar age estimate was found by Plavec (1955).

The meteoroid loop formation time can be estimated in a straightforward manner. If a particle is ejected from a cometary nucleus with a velocity v_e , its heliocentric velocity v is given by

$$v^2 = v_c^2 + 2\vec{v}_c \cdot \vec{v}_e + v_e^2, \quad (6)$$

where v_c is the velocity of the comet. v will have a maximum and minimum according to whether $\vec{v}_c$ and $\vec{v}_e$ are parallel or antiparallel. If we use the icy-conglomerate model of Whipple (1951), the particle ejection velocity is

$$v_e = 793.76 \left(\frac{1}{0.278 r^{2.25}} - 0.016 \right)^{1/2} \text{ cm s}^{-1}, \quad (7)$$

where $r(\text{AU})$ is the heliocentric distance. We have taken here a cometary radius of 1.21 km (Whipple 1978), assumed a meteoroid mass of 1 g, which corresponds to $m_p = 0$, and taken a meteoroid density of 300 kg m^{-3} . A more detailed description of the meteoroid velocities may be attainable via the approach of Probst (1968), in which Whipple's model is improved upon through a rigorous hydrodynamic analysis of the cometary dust-gas interaction. The orbits of the ejected particles will have semimajor axes and periods given by

$$a = \frac{-\mu}{v^2 - 2\mu/r} \quad (8)$$

and

TABLE IV. The time required for Draconid meteoroids to form a closed loop around the orbit of P/Giacobini-Zinner as a function of the true anomaly of the ejection point. See the text for details.

True anomaly $\varpi(^{\circ})$	Heliocentric distance $r(\text{AU})$	Loop formation time $P_L(\text{yr})$	Number of cometary orbits
0	0.996	523	85
45	1.134	653	107
90	1.709	1337	218
135	3.465	5287	862
180	6.033	27354	4460

$$p = 2\pi \left(\frac{a^3}{\mu} \right)^{1/2}, \quad (9)$$

where $\mu = GM_0(1 - \beta)$ with β being a factor for radiation pressure, $\beta = 5.8 \times 10^{-5}/r \cdot d$ (cgs units), where r is the radius of the meteoroid and d is its density. According to whether $\vec{v}_e$ is parallel or antiparallel to $\vec{v}_c$, we can find periods $P_{\max}$ and $P_{\min}$, from which the loop formation time P_L can be estimated by

$$P_L \simeq P_{\max}^2 / (P_{\max} - P_{\min}). \quad (10)$$

Using the 1946 elements of P/Giacobini-Zinner as given by Lovell (1954), we find the results presented in Table IV. Even though the majority of meteoroid particles will be ejected in the vicinity of perihelion, it would seem that the stream is not old enough for the meteoroids to have spread around the orbit.

CONCLUSION

We have considered the origin and possible structure of the Giacobinid or Draconid meteoroids. It seems clear that they are extremely fragile, crumbly objects with a possible bulk density $\gtrsim 200 \text{ kg m}^{-3}$. The available observational data indicate a good general agreement with the predictions of the dustball meteor ablation model as constructed by Hawkes and Jones (1975).

By considering the distribution of Draconid meteoroids around their orbit it appears that the stream is very young and incomplete. The planetary perturbations on the stream are at present not well understood and future stream activity will be difficult to predict (Harvey 1973).

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