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OPTICAL PREDICTIONS FOR HIGH GEOCENTRIC VELOCITY METEORS

L. A. ROGERS, K. A. HILL and R. L. HAWKES
Physics Department, Mount Allison University, Sackville, NB, Canada E4L 1E6
(E-mail: rhawkes@mta.ca)

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Abstract. In this study we numerically modelled the atmospheric ablation and luminosity of cometary structure meteoroids with geocentric velocities from 71 to 200 km/s. We considered meteoroid masses ranging from 10^{-13} to 10^{-6} kg. Expected heights of ablation and maximum luminosity absolute magnitudes are determined. Height and trail length values are used to calculate the angle traversed in a single video frame. It is found that for pre-atmospheric meteoroid masses of greater than 10^{-8} kg, high geocentric velocity meteors should be detectable with current electro-optical technology if properly optimised.

Keywords: Ablation, high velocity, interstellar meteoroid, meteor, optical detection

1. Introduction

There exist several mechanisms such as stellar radiation pressure and dynamical N-body processes for injection of high speed meteoroids into interstellar space (Hawkes and Woodworth, 1997; Murray et al., 2004). A recent study by Quirt and Hawkes (2005) suggests that in some cases small meteoroids may be ejected from pre-main sequence stellar systems by radiation pressure with velocities on the order of several hundreds of km/s. While destruction and velocity alteration processes in interstellar space (see e.g. Jones et al., 1997; Murray et al., 2004) may mean that very few of these meteoroids would survive to Earth with their velocities intact, the possibility of a small population of high geocentric velocity meteoroids remains. Although there is some evidence for the detection of high geocentric velocity meteors by radar (Taylor et al., 1996), meteors having geocentric velocities in excess of 80 km/s have not been conclusively observed by electro-optical methods. In this paper, the ablation heights and luminosities of high geocentric velocity meteors in the Earth's atmosphere are predicted.

Current address: L. A. Rogers, Department of Physics, University of Ottawa, Ottawa, Canada

2. Computational Model

A single body, isothermal, cometary structure meteoroid in the free molecular flow regime experiencing thermal meteoroid ablation was assumed. Meteoroid masses ranging from 10^{-13} to 10^{-6} kg in increments of 10, and initial meteoroid velocities of 71, 80, 90, 100, 125, 150, and 200 km/s were considered. A fourth order Runge-Kutta method with a semi-adaptive step size was employed to numerically solve the system of coupled differential equations describing meteoroid flight through the atmosphere. For more information on the equations of thermal meteoroid ablation and the physical as well as thermal meteoroid parameters assumed, please see Appendix A. Averaged data from various months from the NASA MSISE 90 model (Hedin, 1987, 1991) were employed to develop a profile of the atmospheric mass density with altitude (details of the numerical fit are outlined in Rogers et al., 2005).

The luminous efficiency factor, which relates meteor light intensity to incident kinetic energy, is one of the least conclusively established values in meteor physics, particularly at high velocities. In this work the dependence of luminous efficiency on velocity is based on relationships developed by Jones and Halliday (2001). They used atomic collision theory for predicting the dependence of luminous efficiency factor on velocity (through an intermediate quantity, the excitation coefficient). While their results are only strictly applicable to velocities below 46 km/s, they found that an extrapolation to 60 km/s yielded excellent agreement with observations. Based on this agreement, they extrapolated their values of excitation coefficient to 100 km/s. We applied a further linear extrapolation of their excitation coefficient from 100 to 200 km/s. This means that we have less confidence in the values obtained for velocities above 100 km/s (the height and trail length data are not dependent on the luminous efficiency value). A detailed account of the equations of the assumed luminous efficiency factor can be found in Hill et al. (2005). The values of the luminous efficiency factor employed here are presented in Table I. The corresponding values given by the linear increase of luminous efficiency with velocity as suggested by Whipple (1938) and Verniani (1965) are provided for comparison.

TABLE I
Luminous efficiency used in this work, and as proposed by Verniani

velocity (km/s)	71	80	90	100	125	150	175	200
τ_I (this work)	0.0076	0.0064	0.0054	0.0046	0.0033	0.0025	0.0020	0.0017
τ_I (Verniani)	0.0037	0.0042	0.0047	0.0053	0.0066	0.0079	0.0092	0.0105

3. Results

The dependence of maximum light intensity (expressed in absolute meteor magnitude) on velocity is given in Figure 1. Only a very slight increase in peak light intensity with velocity occurs, despite the increase of the kinetic energy of the ablated meteoric particles proportional to the square of velocity. This is due to the decay of the extrapolated luminous efficiency at high velocities.

The heights where the meteors reached their peak brightness (displayed in Figure 2) are largely independent of the luminous efficiency factor. As anticipated, the ablation heights decrease with increasing mass. They are also shown to increase with velocity, for example a 10^{-8} kg meteoroid with an initial velocity of 100 km/s reaches its maximum brightness at an altitude of 116 km while a similar meteoroid having an initial velocity of 200 km/s reaches its peak at 135 km.

4. Observational Implications

In Table II the times for which each of the modelled meteors was brighter than $+8^M$ are presented. A light intensity of $+8^M$ was chosen as a representative limit of detection for sensitive electro-optical equipment. If a meteor had such a high angular velocity that it could only be detected in a single frame an accurate determination of its velocity would be impossible and even detection could be substantially compromised. It can be seen from Table II that high geocentric velocity meteors having pre-atmospheric masses of at

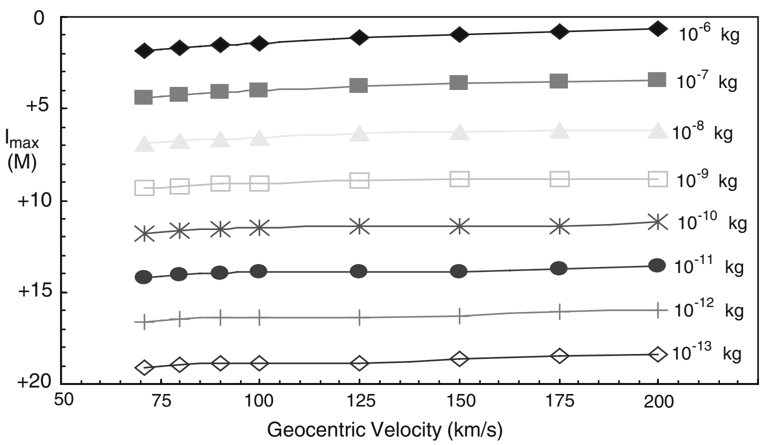

Figure 1. Plot of the peak luminous intensity (expressed as absolute meteor magnitude) versus the geocentric velocity (in km/s).

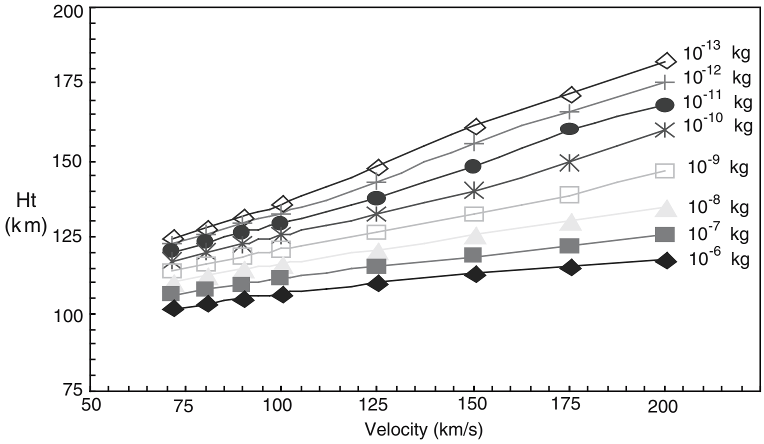

Figure 2. Plot of height of maximum intensity (in km) versus the geocentric velocity (in km/s).

TABLE II

Times (s) for which meteors are brighter than $+8^M$

velocity (km/s):	71	80	90	100	125	150	175	200
10^{-6} kg	0.379	0.354	0.333	0.317	0.294	0.286	0.285	0.286
10^{-7} kg	0.390	0.371	0.356	0.347	0.339	0.345	0.352	0.350
10^{-8} kg	0.242	0.241	0.241	0.238	0.241	0.252	0.281	0.294

Meteoroid masses not included in the table had maximum light intensities fainter than $+8^M$.

least 10^{-8} kg last long enough to be present in a number of video frames, so this is not an observing limitation.

High geocentric velocity meteors are characterized by very long trail lengths (see Hill et al., 2005). It is, therefore, possible that although a meteor lasted for several video frames, its high angular velocity might result in less than one full video frame within the field of view (preventing a velocity calculation). The angular displacement traversed in one standard video frame ($\frac{1}{30}$ s) by the modelled meteors detected at their points of peak light intensity in the centre of the field of view of a ground-based observing system pointed directly at zenith is displayed in Figure 3. Even the fastest heaviest meteoroid modelled travels just 2.3° in one video frame. Since most fields of view in use in meteor detection (Hawkes, 2002) are significantly in excess of this, high geocentric velocity meteors should be detected in multiple video frames electro-optically.

The greater angular velocities of high geocentric velocity meteors also have the effect of reducing the apparent meteor magnitudes. The faster meteor will cross proportionally more pixels across the CCD in one integration period and have a corresponding reduction in apparent magnitude. Hawkes

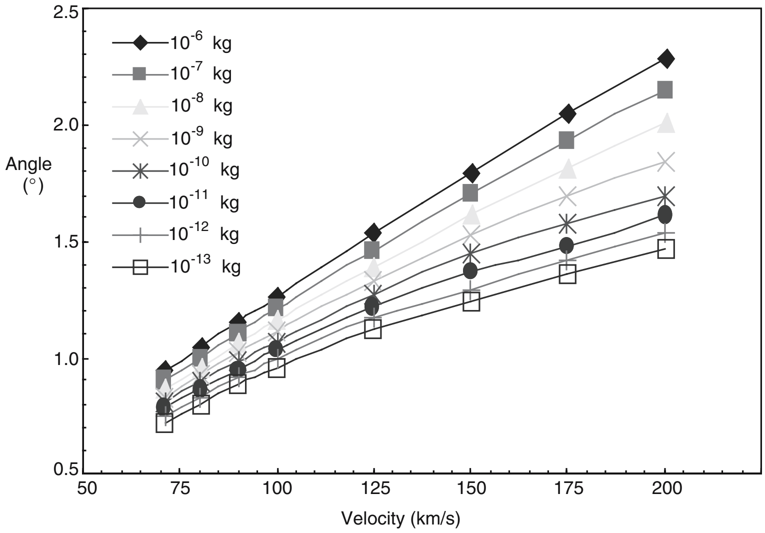

Figure 3. Plot of angle traversed by meteor during one video frame ($\frac{1}{30}$ s), versus the geocentric velocity (in km/s).

(2002) shows that to first order the meteor limited magnitude, m_m, is related to the apparent stellar magnitude of an observing system, m_s, by the following relationship, where d is the number of pixels of effective resolution traversed by the meteor in a single frame integration time.

$$m_m = m_s - 2.5 \log d \tag{1}$$

For example, it can be seen in Figure 3 that for a 10^{-8} kg meteoroid having a zenith angle of 45° detected at its point of peak light intensity, doubling the initial velocity from 100 to 200 km/s results in a 72% increase of the angular velocity of the meteor from 1.16° to 2.00° in one frame ($\frac{1}{30}$ s).

Meteors with very high geocentric velocities also suffer a decrease in detection probability due to observing system geometry. Due to their high ablation heights very high velocity meteors will be biased against in conventional multi-station meteor observations (Woodworth and Hawkes, 1996). This effect is most significant for small fields of view pointed in directions well offset from the vertical.

5. Discussion

We will first consider potential limitations of the model used. This paper has only dealt with cometary structure meteoroids. A later paper (Hill et al., 2005) will consider other structures. An isothermal meteoroid was assumed which should be valid for the small meteoroid masses employed. Although meteor ablation heights are independent of the luminous efficiency factor, the meteor absolute magnitudes presented here depend strongly on the luminous efficiency assumed. While it has been shown that physical sputtering is a significant ablation mechanism (Hill et al., 2005; Rogers et al., 2005), the model employed considered thermal meteoroid ablation only. Because the importance of sputtering has been shown to diminish at high velocities (Rogers et al., 2005), and because the results presented in this work are dependent on the later portions of the meteor light curve where thermal ablation dominates, sputtering is not expected to play a large role.

The model results suggest that, although they are not as bright as would be anticipated by a linear dependence of the luminous efficiency factor on velocity, very fast meteors having initial (pre-atmospheric) masses of at least 10^{-8} kg would be bright enough to be detectable by typical sensitive electro-optical meteor equipment (see Hawkes (2002) for a review). There are several biases though, which have been described in the Observational Implications section.

The results from our model can assist in optimising a search strategy for high velocity meteoroids. A multi-station observing system configured to an appropriate optimum intersection altitude on the order of 120 km is required. Because very few high velocity particles having masses larger than 10^{-7} kg would be ejected from pre-main sequence stars by radiation pressure (Quirt and Hawkes, 2005), one would need a system capable of detecting very small faint meteors. A moderately large aperture system would be advisable. Unfortunately, this usually implies a relatively narrow field of view which would increase the observational bias. This may be overcome by using several systems at each station directed at slightly different but overlapping fields to create a large net field of view.

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6. Appendix A

6.1. Thermal ablation equations and parameters

The differential equations describing the motion through the atmosphere of an isothermal, homogeneous, single body meteoroid experiencing thermal ablation in the free molecular flow regime are presented below. The thermal and physical meteoroid parameters found within the equations are defined in Table A1, and the values employed in the model are provided. More information on thermal ablation theory may be found in Öpik (1958), McKinley (1961), Hawkes and Jones (1975), Ceplecha et al. (1998) and Fisher et al. (2000).

The rate of change of the meteoroids height above the surface of the Earth, h, is related to the meteoroids velocity, v, by simple trigonometry.

$$\frac{\mathrm{d}h}{\mathrm{d}t} = -v\cos z \tag{A.1}$$

The deceleration of the meteoroid can be obtained through conservation of linear momentum, where m is the meteoroid mass and ρ_{a} represents the atmospheric mass density.

$$\frac{\mathrm{d}v}{\mathrm{d}t} = -\frac{\Gamma A}{m^{1/3}\rho_{\mathrm{m}}^{2/3}}\rho_{\mathrm{a}}v^2 \tag{A.2}$$

The rate of change of temperature, T, of an isothermal meteoroid may be derived from conservation of energy.

$$\frac{\mathrm{d}T}{\mathrm{d}t} = \frac{A}{cm^{1/3}\rho_{\mathrm{m}}^{2/3}}\left(\frac{1}{2}\Lambda\rho_{\mathrm{a}}v^3 - 4\sigma\epsilon(T^4 - T_{\mathrm{a}}^4) + \frac{L}{A}\left(\frac{\rho_{\mathrm{m}}}{m}\right)^{2/3}\frac{\mathrm{d}m}{\mathrm{d}t}\right) \tag{A.3}$$

We used the vapour pressure relationships given by the Clausius-Clapeyron equation to model the rate of meteoroid mass loss following

TABLE A1
Physical and thermal meteoroid parameters

Symbol	Definition	Numerical Value
z	zenith angle	45°
ρ_m	meteoroid mass density	1000 kg m^{-3}
Γ	drag coefficient	1.0
A	shape factor	1.21
Λ	heat transfer coefficient	1.0
ϵ	emissivity	0.9
T_{a}	atmospheric temperature	280°
c	specific heat of meteoroid	1200 J K^{-1} kg^{-1}
L	latent heat of fusion plus vaporisation	6.0 × 10^6 J kg^{-1}
μ	mean molecular mass of ablated material	20 amu
C_{A}, C_{B}	Clausius Clapeyron parameters	10.6, 13,500 K

Bronshten (1983) and Adolfsson et al., (1996).

$$\frac{dm}{dt} = -4A\left(\frac{m}{\rho_m}\right)^{2/3} 10^{C_A - \frac{C_B}{T}} \left(\frac{\mu}{2\pi kT}\right)^{1/2} \quad \text{(A.4)}$$

The light intensity of the meteor, I, may be related to the rate of mass loss though the luminous efficiency factor, τ_I.

$$I = -\frac{\tau_I}{2}\frac{dm}{dt}v^2 \quad \text{(A.5)}$$

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