

An Investigation of How a Meteor Light Curve is Modified by Meteor Shape and Atmospheric Density Perturbations

E. Stokan • M. D. Campbell-Brown

Abstract This is a preliminary investigation of how perturbations to meteoroid shape or atmospheric density affect a meteor light curve. A simple equation of motion and ablation are simultaneously solved numerically to give emitted light intensity as a function of height. It is found that changing the meteoroid shape, by changing the relationship between the cross-section area and the mass, changes the curvature and symmetry of the light curve, while making a periodic oscillation in atmospheric density gives a small periodic oscillation in the light curve.

Keywords meteor • meteoroid ablation modeling

1 Introduction

The ablation of small objects, meteoroids, in the atmosphere produces light that may be observed on the ground. As the meteoroids enter the atmosphere, particles are removed from the rapidly heating body and excited or ionized. Atmospheric particles may also be excited and ionized in smaller numbers. These excited atoms and ions emit photons in narrow bands that may be analysed for meteoroid chemical composition using a spectrometer, or examined in their time-dependence to suggest velocity, structure, or other physical properties of the meteoroid. Thus, meteors, the streaks of light that occur as meteoroids burn up in the atmosphere, reveal information about the composition and properties of meteoroids when observations are combined with ablation models. Since the meteoroids originate from parent bodies throughout the Solar System, one is able to learn about the structure and history of the Solar System without sending exploration or sample return missions.

When examining the light curve, the graph of meteor magnitude versus time, properties such as the shape and symmetry of the curve can reveal whether the meteoroid is fragmenting, or what sort of cross sectional area it is presenting to the atmosphere, as examined in Beech (2009). In some cases, light curves with varying symmetry may be observed for particles belonging to a single shower, such as the Leonid particles modeled by Campbell-Brown and Koschny in 2004. Periodic oscillations in the light curve, such as those examined by Beech and Brown (2000), or Beech, Illingworth, and Murray (2003), may indicate meteoroid rotation that is as rapid in frequency as 10^2 Hz, but is not rapid enough to make the meteor appear like an evenly-heated sphere. These oscillations occur as local maxima in the light curve, flares, which are distinct from noise.

The purpose of this brief investigation is to qualitatively comment on how a meteor light curve is influenced by two phenomena: variation in meteoroid shape and ablation, and periodic oscillations in atmospheric density. Specifically, we examine whether either of these perturbations can result in flares

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in the meteor light curve. To model meteoroid shape variation, the equation relating an object's cross-section area to mass employed by Beech (2009) is utilized. Periodic atmospheric density oscillation is modelled by introducing an oscillation to the isothermal atmosphere profile. Meteoroid motion and ablation is modeled using the standard equations. Solutions for velocity, mass, and intensity as a function of height are obtained numerically.

2 Method

The fundamental equations of motion and ablation are as follows:

$$\frac{\Lambda(\rho_{atm}SV)V^2}{2} = \frac{\Lambda\rho_{atm}SV^3}{2} = -Q \frac{dm}{dt} \quad (1)$$

$$m \frac{dV}{dt} = -\Gamma S \rho_{atm} V^2 \quad (2)$$

where Λ is the dimensionless heat transfer coefficient, Γ is the dimensionless drag coefficient, ρ_{atm} is the density of the atmosphere, S is the cross-sectional area of the object, V is the object's velocity, and m is the mass of the object.

The cross-section area is made a function of the mass of the object with power α , following Beech, 2009:

$$S = \pi \left(\frac{3m_i}{4\pi\rho_i} \right)^{2/3} \left(\frac{m}{m_i} \right)^\alpha \quad (3)$$

Here, m_i is the initial mass of the object, and ρ_i is the initial density (assumed constant throughout the trajectory). α may take any value, with larger positive values of α indicating that the cross-sectional area is a more sensitive function of the mass of the object. $\alpha = 0$ gives an object with a constant cross-section, possibly representing a cylinder that ablates along the height axis, while $\alpha = 2/3$ gives a spherical object that ablates radially, or self-similarly. Negative α gives an object that experiences a larger cross-section area as the mass depletes, which may represent an object that fragments as it ablates.

The atmospheric density profile is represented by an isothermal atmosphere with a small relative oscillation:

$$\rho(h) = \rho_0 [1 + A \cos(kh)] \exp\left(-\frac{h}{h_0}\right) \quad (4)$$

Oscillation amplitudes between 2% and 10% are employed, as well as wavelengths between 1 and 10 km. Oscillation in atmospheric density may originate from two main sources: physical phenomena such gravity waves or transient oscillations in the atmosphere (small amplitude and large vertical wavelength), or other physical phenomena observed in radiosonde data, which is usually smoothed out (amplitude of about 10%, and possible wavelength of 1 km), as noted in Hedin (1991).

The equations of motion and ablation are recast as the following:

$$\frac{dV}{dh} = \pi\Gamma \left(\frac{3m_i}{4\pi\rho_i} \right)^{2/3} \frac{m^{\alpha-1}(h) V(h)}{m_i^\alpha \cos Z} \rho(h) = \xi m^{\alpha-1}(h) V(h) \rho(h) \quad (5)$$

$$\frac{dm}{dh} = \frac{\pi\Lambda}{2Q} \left(\frac{3m_i}{4\pi\rho_i} \right)^{2/3} \left[\frac{m(h)}{m_i} \right]^\alpha \frac{V^2(h)}{\cos Z} \rho(h) = \eta m^\alpha(h) V^2(h) \rho(h) \quad (6)$$

These equations are solved numerically using simple Euler integration. This gives the velocity and mass of the object as a function of height. The light curve is then produced assuming that the luminous intensity I is proportional to the loss of kinetic energy:

$$I = \tau \frac{dE_k}{dt} = \tau \left(\frac{1}{2} \frac{dm}{dt} V^2 + mV \frac{dV}{dt} \right) = -\tau V^2 \cos Z \left(\frac{V}{2} \frac{dm}{dh} + m \frac{dV}{dh} \right) \quad (7)$$

The natural logarithm of the intensity gives a scale that approximates the magnitude for the light curve. Appendix 1 gives meteoroid properties and parameters used in the numerical simulation.

3 Results and Discussion

Varying the shape of the object by varying α produced light curves with different properties. Table 1 summarizes the properties, while Figure 1 shows the light curves and mass loss graphically.

Table 1. Summary of qualitative observations of light curves for objects ablating with different α

	Concavity, symmetry of light curve	Maximum brightness	Height of maximum brightness	Ending height
$\alpha < 0$	Upward, highly asymmetric	Highest	Highest	Same as height of maximum brightness
α small ($0 < \alpha < 1$)	Downward, highly asymmetric	Moderate	Moderate	Above $h = 0$
α large ($\alpha > 1$)	Lowest, more symmetric	Lowest	Lowest	$h = 0$

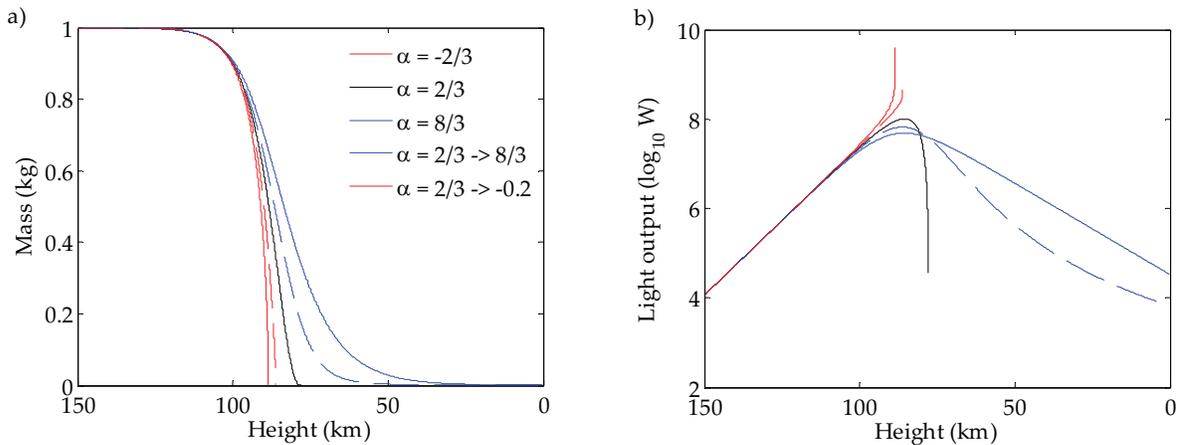


Figure 1. a) Mass and b) rough light curve for ablation with modified shape (α -parameter). The same legend applies to both figures.

For $\alpha < 0$, the light curve is concave upward, with the meteoroid burning up at the highest altitude compared to other choices for α . This represents an object that reveals more cross-section area as the mass decreases, perhaps a fragmenting, pancaking object:

$$S \propto \frac{1}{m^{|\alpha|}} \tag{8}$$

For $\alpha = 2/3$, the light curve is concave downwards and is asymmetrical with a slow rise to a peak brightness, and a rapid drop. This is the standard single-body light curve, that of a self-similar spherical object. As α increases, the object’s maximum brightness decreases and is moved to lower heights, making the light curve more symmetric. In the limit of large $\alpha > 1$, the object survives to the ground. This may represent an object that becomes more aerodynamic or resistant to ablation as the mass decreases. In any case, *no* flares, or local maxima in the light curve, are created if α has a constant value through the trajectory of the object. Even varying α from one value to another during object ablation, representing a quickly rotating object that becomes oriented, gives a light curve that initially resembles the curve of first α value, then slowly merges towards that of the second α value, with no flares being observed.

The light curve associated with the oscillatory atmospheric density profile displays oscillations about the light curve with the smooth atmospheric density, as shown in Figure 2.

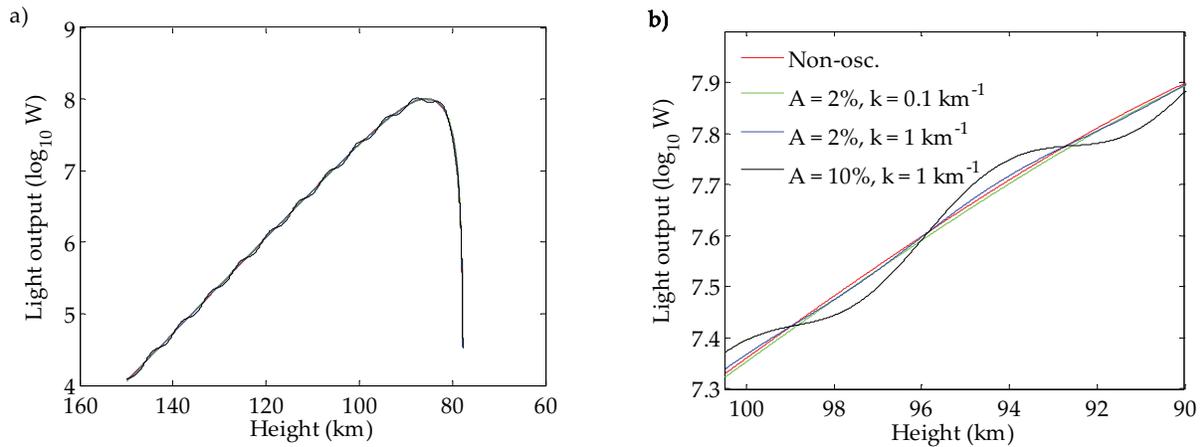


Figure 2. a) Rough light curve and b) enlarged rough light curve for ablation with oscillating atmosphere density, $\alpha = 2/3$. The same legend applies to both figures.

In this case, small flares are observed, but even the largest oscillations with the smallest wavelengths, corresponding to transient oscillations in the atmospheric density data, produce small oscillations in the light curve. Such small oscillations in a measured light curve would likely be indistinguishable from noise. This suggests that periodic flares in a light curve are not likely to be caused by oscillations in atmospheric density. Perhaps some other mechanism, such as meteoroid rotation or periodic charge separation is responsible for oscillatory flares observed in some light curves. This will be investigated in more detail in the future.

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Appendix: Values used for numerical simulation

A	1	h_0	6.5 km
Q	$6 \cdot 10^6$ J/kg	m_i	1 kg
Γ	1	ρ_i	3.5 kg/m^3
τ	0.1	Z	45°
ρ_0	1.01 kg/m^3	V_i	35 km/s