New Models for the Prediction of Leonid Meteor Properties and Signatures

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Abstract

A simplified analytic model is obtained by neglecting the very small decreases in velocity during most entries. This model shows the dependence of the maximum brightness altitude and maximum absolute magnitude on meteoroid radius, density, and heat of ablation. A numerical model is used to consider the effects of variations in the Stanton number during the entry. It is shown that the shape of meteor light curves and the meteoroid demise altitude are significantly affected by the effects of mass transfer on the Stanton number. Monte Carlo molecular simulations are used to investigate the meteoroid ablation and trail development processes. Output from this model provides insight to make improvements in the numerical model. Monte Carlo transient wake output shows considerable potential for providing new insight in the interpretation of meteor trails and the analysis of spectra.

Nomenclature

h = altitude
ΔH_a = heat of ablation
m = meteoroid mass
M = meteor magnitude
r_m = meteoroid radius
St = Stanton number, heat flux/freestream kinetic energy flux
V_E = atmospheric entry velocity
γ_E = atmospheric entry angle relative to Earth tangent
λ = atmospheric scale height
ρ^o = coefficient in exponential atmosphere
τ = luminous efficiency

Subscripts

mM = maximum magnitude
o = initial

Introduction

Leonid meteors present many challenges for understanding the meteoroid properties and the interaction of these high-velocity objects with the atmosphere. The signatures, for instance, are the result of complex processes of fluid mechanics, aerothermodynamics, and chemistry. Modeling of these processes is particularly difficult because they occur in a flow regime beyond the range of applicability of the Navier-Stokes equations and at largely unstudied collision velocities. To begin the improvement of understanding of these meteoroid- atmosphere encounters and meteoroid properties, our work develops three new interrelated models. The three models are needed in order to improve understanding of basic parameter scaling relationships, to more accurately interpret meteor transient light curves in terms of meteoroid properties, and to probe the molecular processes responsible for the observed ablation rates, trail development, and spectra.

A simplified model has been developed to provide insight concerning the scaling of meteoroid ablation response, demise, and transient light intensity in terms of meteoroid properties. This model is an asymptotic (constant velocity) approximation of the analytic solutions to the single body meteoroid problem developed by Öpik (1937), Hansen (1957), and Pecina (1983). To improve the interpretation of meteor light curves in terms of meteoroid properties, a numerical procedure has been implemented. This allows, in particular, inclusion of the significant variation in the Stanton number during the entry time. The approximation used to predict this variation is derived from physical arguments and qualitiatively agrees with calculated results obtained using the highest fidelity third model. This detailed model utilizes Monte Carlo molecular simulation to study meteoroid-atmosphere interactions. The model provides significant insight concerning the heat transfer and ablation processes and the nonequilibrium chemical and molecular relaxation processes occurring as the meteor trail develops.

Simplified Model

Approximate predictions of meteor light curves assume that the meteor ablation process and the atmospheric response process can be decoupled [Ceplecha (1998)]. Thus, the first step is the simultaneous solution of mass, momentum and energy conservation equations to obtain the meteoroid mass (radius) as a function of time or altitude. Solution of these equations in terms of analytic functions has been given by Pecina (1983) and references therein. These solutions give the rate of kinetic energy deposition into the atmosphere as a function of altitude. Because the solutions are given in terms of an exponential integral function, the scaling of maximum intensity and the corresponding altitude with meteoroid properties is somewhat obscured.

For the Leonid meteors a simpler, constant velocity, asymptotic solution is applicable with very little loss of accuracy. The simplified solution is obtained by neglecting the momentum equation and simultaneously solving the mass and energy conservation equations. As in prior work, it is assumed that the heat transfer rate is represented by the free molecular heating expression and that the ratio of the Stanton number to the heat of ablation is a constant. With these assumptions, it can be shown that the meteoroid radius and the relative magnitude of the meteor are given as functions of altitude by

$$\frac{r_m}{r_{mo}} = \left\{1 - \frac{e^{-\lambda(h - h_{mM})}}{3}\right\} \qquad M = -2.5\log_{10}\left[\left(\frac{9}{4}\right)\left\{1 - \frac{e^{-\lambda(h - h_{mM})}}{3}\right\}^2 e^{-\lambda(h - h_{mM})}\right]$$

These universal solutions are shown in Figures 1 and 2. The meteoroid radius at the maximum brightness altitude h_{mM}, is 2/3 of the initial radius. This altitude is given in terms of meteoroid properties , the Stanton number, and entry conditions by

$$\lambda h_{mM} = \ln\left[\frac{3St\rho^o V_E^2}{8\lambda \sin\gamma_E r_{mo}\rho_m \Delta H_a}\right]$$

and the maximum absolute magnitude is given by

$$M_{\max}^{abs} = -2.5\log_{10}\left[\left\{\frac{8\pi\lambda\sin\gamma_E}{27}\right\}\tau r_{mo}^3 \rho_m V_E^3\right] = -2.5\log_{10}\left[\left\{\frac{2\lambda\sin\gamma_E}{9}\right\}\tau m_{mo} V_E^3\right]$$

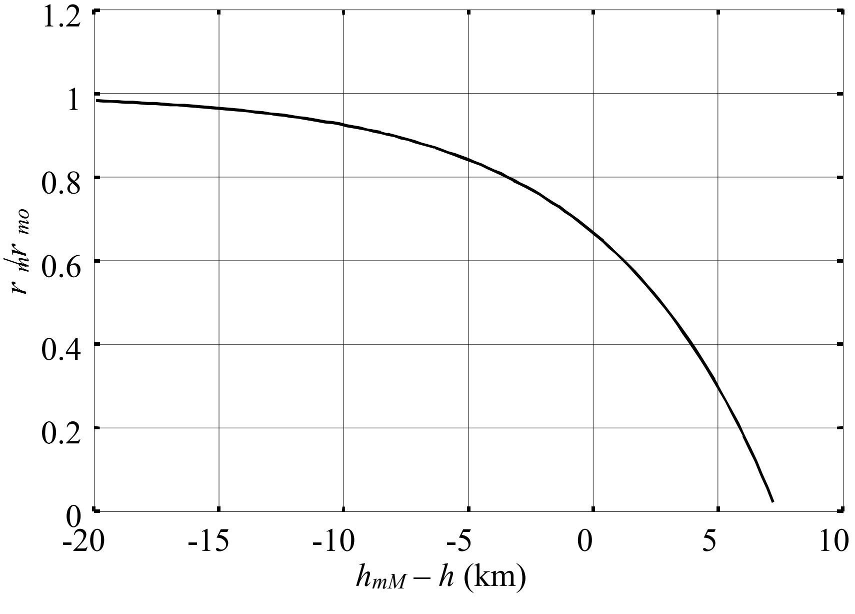

Figure 1. Meteoroid radius as a function of altitude

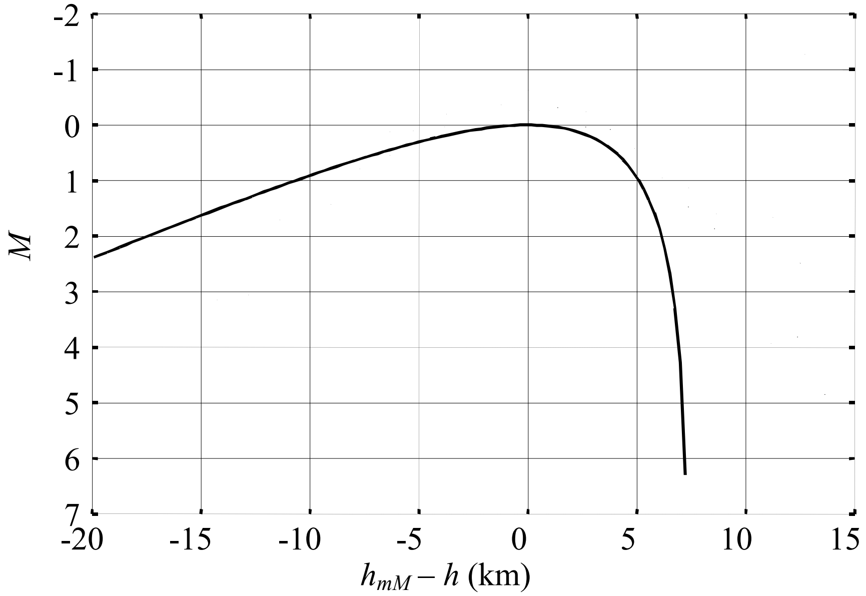

Figure 2. Meteor relative magnitude as a function of altitude

Monte Carlo Molecular Simulations

The model with the greatest amount of physical detail is discussed next because output from this model is needed to specify the variation of Stanton number with altitude in the numerical model. Direct Simulation Monte Carlo (DSMC) methods are well developed [Bird (1998)] and suited for analyses of the fluid mechanics and chemical relaxation processes of small objects moving through the atmosphere at high altitudes. Our work uses the DSMC method to probe details of the meteoroid heat transfer and ablation processes and to investigate the nonequilibrium processes occurring during the transient development of the meteor trail.

Leonid meteor sizes (< 10 cm) are such that in the absence of mass transfer, the heat transfer rates would be almost entirely in the free molecular flow regime. The extremely high kinetic energy flux of atmospheric air molecules intercepting the meteoroid surface however results in substantial mass loss rates. This ablated mass in effect induces significant molecular collision effects resulting from the interaction of the incoming atmospheric molecules with the outgoing ablated meteoroid molecules. The net result is a Stanton number considerably decreased below the value predicted by free molecular heating without the mass transfer effect. DSMC results showing the effect of mass transfer on the Stanton number are shown in Figure 3. The flux ratio expresses the reduction in the Stanton number and the blow ratio is the quotient of the mass flux leaving the meteoroid to the freestream intercepted mass flux. These results and others at different altitudes provide benchmark results from which approximations for the effect of mass transfer on Stanton number can be derived and utilized in the numerical model.

Our work, as in all of the referenced work except Boyd (2000), assumes that the ablation of the meteoroid and the interaction of the ablated meteoroid mass with the atmosphere can be decoupled. The DSMC method is used to model the transient development of the meteor trail. For time scales the order of 10^{-5} s, the mass loss rate from the meteoroid can be considered to be a constant and can be determined at altitude from the numerical model or from the DSMC results. Simulations at an altitude of 90 km have been made in which mass is deposited into the atmosphere at 70 km/s. The output from these calculations defines a nonequilibrium cylindrical blastwave, which can be interpreted as the transient development of the meteor trail. The radial distribution of number density, for a meteoroid with a radius of 1 cm and a density of 1000 kg/m^3 is shown in Figure 4 for various times. The distributions of translational, rotational, and vibrational temperature are also calculated. The longer-term objectives of these calculations are to utilize insights to make further improvements in the numerical model and to predict synthetic spectra of meteor trails and trains.

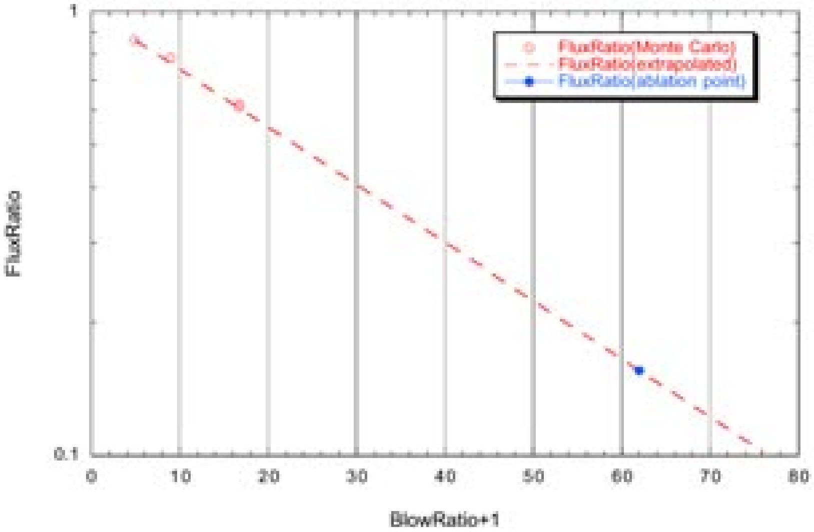

Figure 3. Effect of mass transfer on heat transfer at 120 km

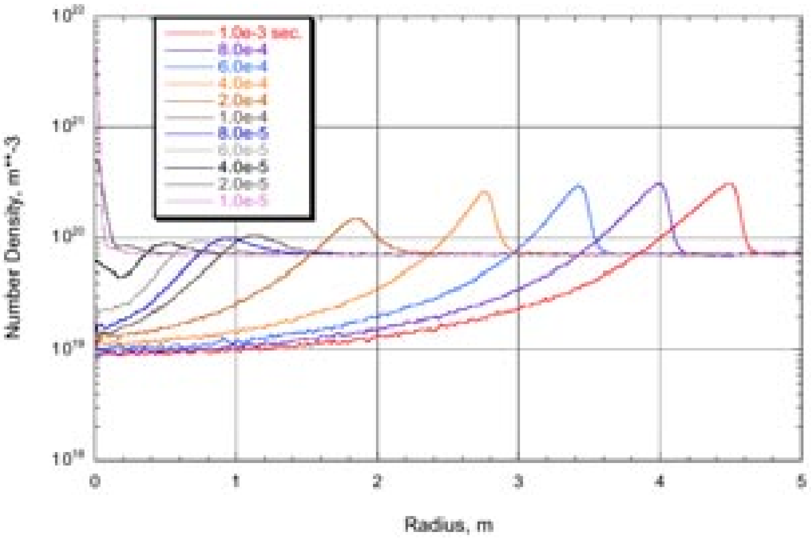

Figure 4. Wake development due to mass addition, *h* = 90 km, V_E = 70 km/s

Numerical Simulations

The simplified model can not take into account the substantial variation of the Stanton number during the entry of a Leonid meteoroid. The DSMC model can not be used to predict light curves because of the considerable computational requirements to calculate the heat transfer and ablation processes together with the atmospheric response at just one altitude. Thus a numerical model is used to predict light curves taking into account variable Stanton number as well as velocity slowdown and variable drag coefficient effects. This model calculates light curves from the predicted mass loss rate versus altitude results in the historical manner [Öpik (1937), Hansen (1957), Pecina (1983)]. Our work seeks to improve their methodology through the use of correlated output from the DSMC calculations. Preliminary numerical results, constant velocity with variable Stanton number, are shown in Figure 5. The solid curve shows results predicted by the simplified model. The other three curves illustrate the extension of the meteoroid survival to lower altitudes resulting, in part, from decreases in the Stanton number due to mass transfer. The values of meteoroid radius r_{mo}, meteoroid density ρ_m, and heat of ablation ΔH_a used for the calculations are shown in Table 1. They were chosen so that the product of these three parameters is a constant and the product $\rho_m r_{mo}^3$, and therefore the initial meteoroid mass, is also a constant. The solid curve is the simplified solution for all three cases. For this model, m_{mo} fixes the absolute magnitude and the altitude of maximum brightness is set by the value of the product $r_{mo}\rho_m\Delta H_a$.

Table 1. Parameters for results given in Figure 5

Parameter Set	r_{mo} (m)	ρ_m (kg/m^3)	ΔH_a (J/kg)	$r_{mo}\rho_m\Delta H_a$ (J/m^2)	m_{mo} (kg)
1	0.002	3.91	1.00 E8	7.83 E5	1.31 E-7
2	0.001	31.2	2.51.E7	7.83 E5	1.31 E-7
3	0.0005	250.	6.28 E6	7.83 E5	1.31 E-7

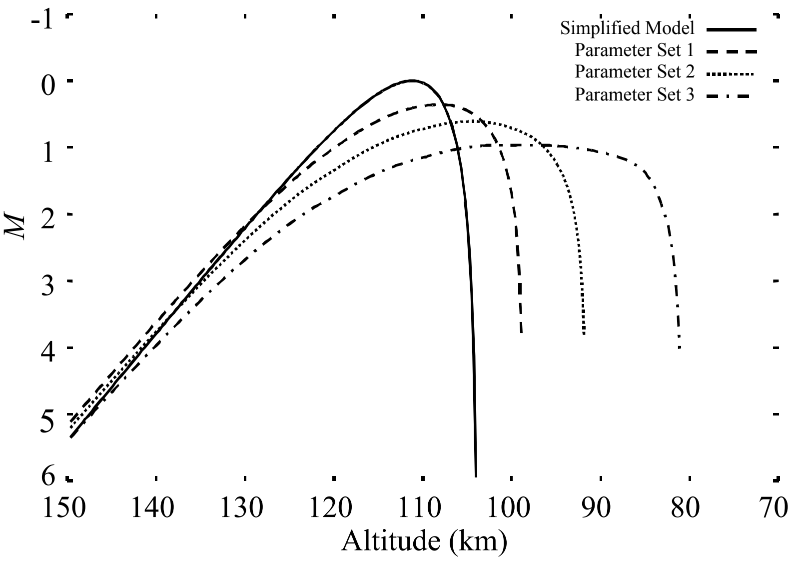

Figure 5. Meteor relative magnitude for variable Stanton number

Summary and Conclusions

Historical analyses of meteoroid entries have relied upon solutions obtained by assuming that the Stanton number is constant during the entry. Very few analyses have examined the problem at the detailed level of molecular interactions. Our work presents three new models which build upon prior work and extend analysis capabilities to consider both the effects of variations in Stanton number during the entry and the effects of meteoroid-atmospheric molecular interactions on the ablation process and the development of the meteor trail and optical signature. A simplified model shows the dependence of the altitude of maximum brightness and the maximum absolute magnitude on meteoroid radius, density, and heat of ablation. This will aid in the interpretation of light curves. A numerical model demonstrates the effects of variable Stanton number on the ablation process and light curves. It is concluded that both the shape of meteor light curves and the meteoroid demise altitude are significantly affected by mass transfer effects on the Stanton number. Monte Carlo molecular simulations have been used to model the ablation and the transient meteor trail development processes. It is shown that results from this detailed model can be used to make improvements in the numerical analysis model, thereby enhancing light curve interpretations in terms of meteoroid properties.

Acknowledgements

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