COMPARATIVE STUDY OF MODELS OF METEOROID DISRUPTION INTO A CLOUD OF FRAGMENTS

Irina Brykina[1], Michael Bragin[2,3]

[1]Lomonosov Moscow State University, Institute of Mechanics, Russia, shantii@mail.ru
[2]Keldysh Institute of Applied Mathematics of RAS, Russia
[3]Moscow Institute of Physics and Technology, Russia

Abstract

Models of meteoroid disruption into a cloud of fragments are considered:

- Two-parameter model, which takes into account changes in the cloud shape and density.
- Simple models used in the literature without accounting these effects.

These models are used to simulate the energy deposition of the Chelyabinsk superbolide by numerical calculating the meteor physics equations.

Influence of the heat transfer coefficient on the energy deposition and lateral expansion of the fragmented meteoroid, and on applicability of fragment cloud models is studied.

For simple fragmentation models, optimal coefficient in the equation for the midsection radius is proposed as a function of the heat transfer coefficient.

Introduction & Background

When meteoroid breaks up into a large number of fragments, at the first stage they move with a common shock wave, before dispersing enough distance to move independently. To simulate meteoroid disruption at this stage, models of a cloud of fragments moving as a single body were proposed and used [1–9, and others]. By pressure forces the cloud is compressed in a flight direction, and expands in a lateral. Models differ in equation for the rate of lateral expansion. Comparison of models [3, 4] was made in [9].

Here we consider different fragment cloud models: two-parameter model [8], and simple models, for example [1, 4, 5], with the purpose to compare the ability of models to reproduce the observational energy deposition of the Chelyabinsk bolide, to study the influence of the heat transfer coefficient on applicability of models and to find the optimal simple model depending on the heat transfer coefficient. Fragmentation models are used together with the ablation model proposed by authors.

Models of a cloud of fragments

Equations for midsection radius R_S

Two-parameter model

$$\frac{dR_S}{dt} = \left(\frac{\gamma^3}{k}\right)^{1/2} \left(\frac{\rho}{\delta_e}\right)^{1/2} V$$

$$k = \frac{4\pi\delta_e}{3}\frac{R_s^3}{M\gamma^3}, \quad \gamma = 1 + \frac{\rho^{1/2} - \rho_f^{1/2}}{\rho_m^{1/2} - \rho_f^{1/2}}(\gamma_m - 1)$$

k is flattening parameter,
γ is parameter of density decrease due to increase of spacing between fragments: density $\delta = \delta_e/\gamma^3$ ($\gamma \le 3$)
δ_e is initial meteoroid density

Simple models

$$\frac{dR_S}{dt} = c\left(\frac{\rho}{\delta_e}\right)^{1/2} V, \quad c = \text{const}$$

$c = 1$ in model [1, 5]
$c = (7/2)^{1/2}$ in model [4]

R_s equation have analytical solution which shows: R_S is determined only by initial parameters, ablation does not affect R_s

t – time, ρ – atmospheric density, V, M – meteoroid velocity and mass

Basic differences between models

	Two-parameter model	Simple models
Accounting change of meteoroid shape		no
Accounting decrease of meteoroid density		no
Fragmentation and ablation are coupled		no

Models application to the Chelyabinsk event

We use various fragment cloud models to simulate interaction of the Chelyabinsk meteoroid with the atmosphere, solving the ablation and motion equations together with equations (1) or (2), by Runge-Kutta method.

Initial parameters [11]: V_e = 19 km/s, θ =18°, δ_e = 3.3 g/sm³.

Entry mass is determined to match observed energy deposition peak [12], Q = 6 km²/s².

Drag coefficient of a spheroid is $C_D = 1.78 - 0.85/k$.

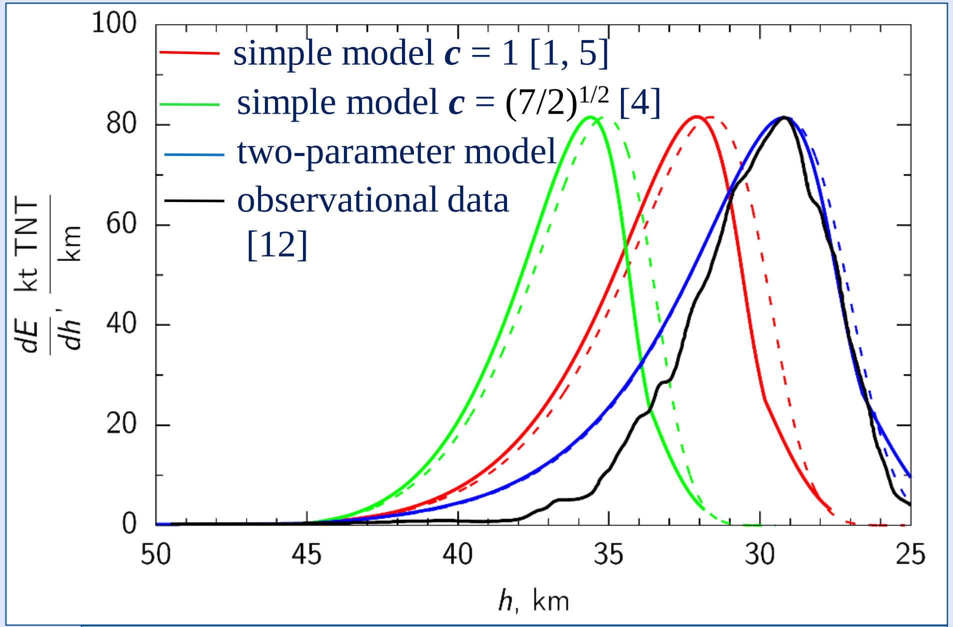
Radiative heat transfer coefficient of spheroid is $C_H = \psi\varphi\beta C_{H0}$.

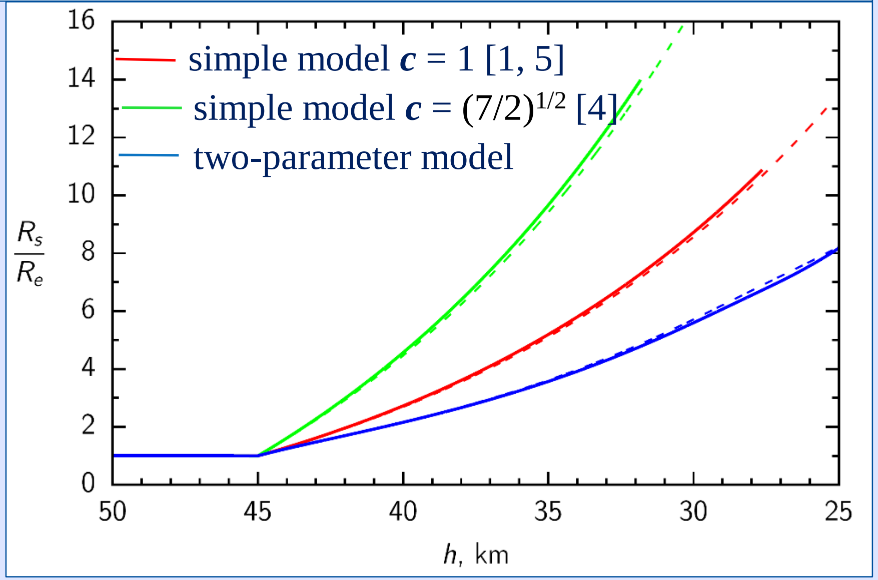
Functions φ (V, k), $\beta(k)$ are given in [8], heat transfer coefficient at a stagnation point of sphere C_{H0} (V, R, ρ) is given in [10].

Uncertainty factor **ψ** is introduced to account for effects of precursor, absorption by a vapor layer, and other factors.

ψ is varied to study effect C_H uncertainty on meteoroid mass loss, energy deposition, midsection radius and entry mass estimate. Constant C_H is also used.

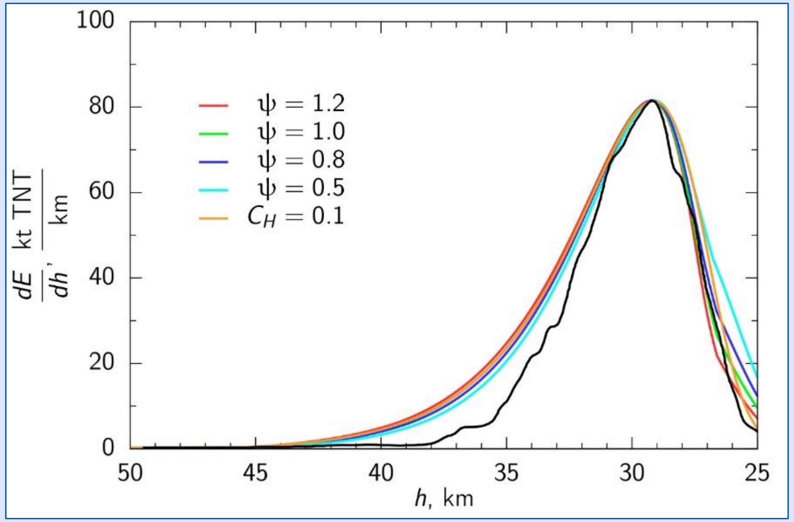
Energy deposition and midsection radius at ψ = 1 (solid lines) and C_H = 0.1 (dashed)

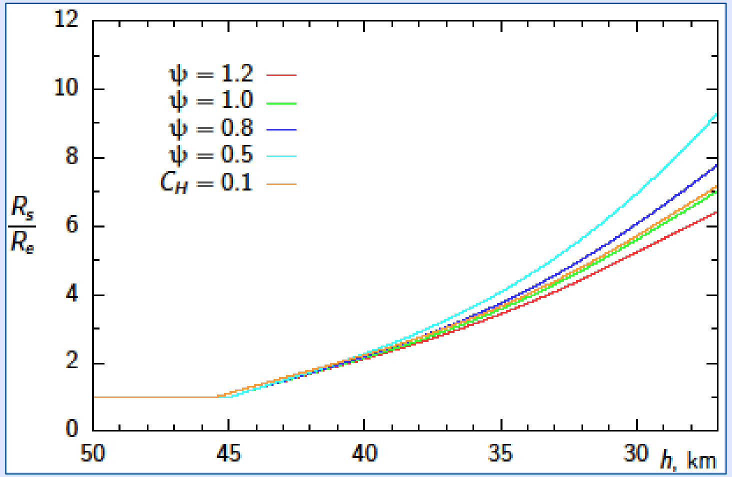




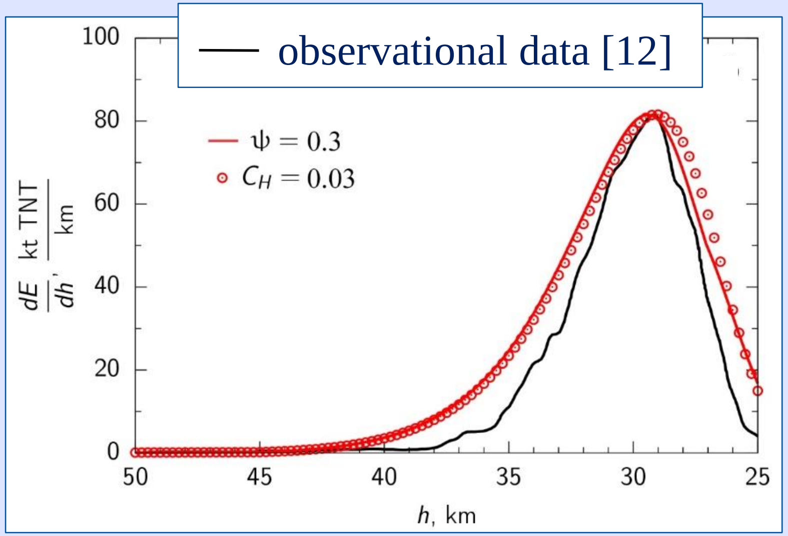
Influence of heat transfer coefficient on energy deposition and midsection radius modeling for various fragmentation models

Two-parameter model

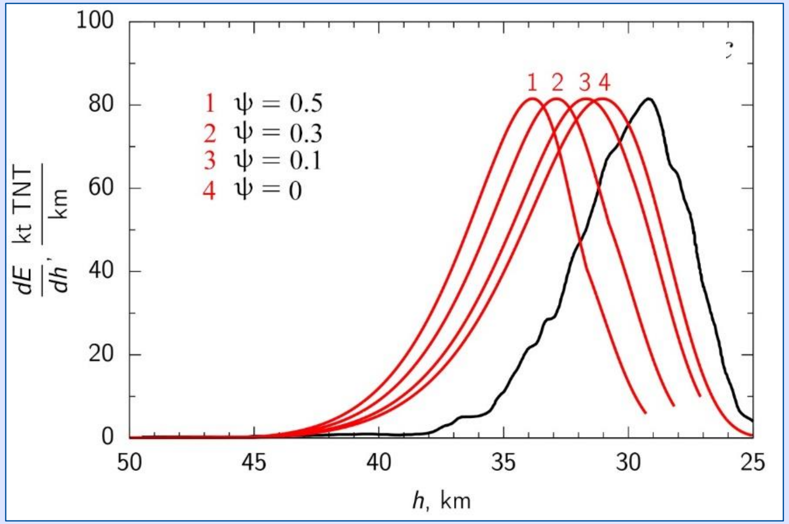




Simple model *c* = 1 [1, 5]



Simple model *c* = $(7/2)^{1/2}$ [4]



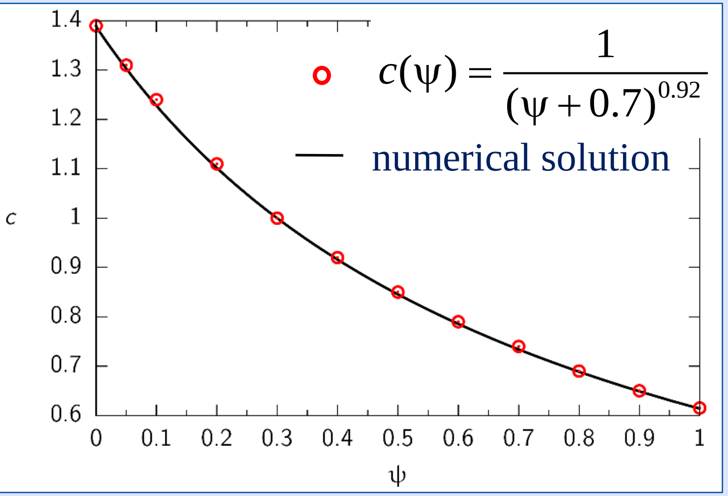
For simple models, changing heat transfer coefficient does not affect the midsection radius and significantly affect the height of peak brightness of the bolide.

For model [1, 5] with *c* = 1, satisfactory agreement with the observational energy deposition curve is achieved at ψ = 0.3.

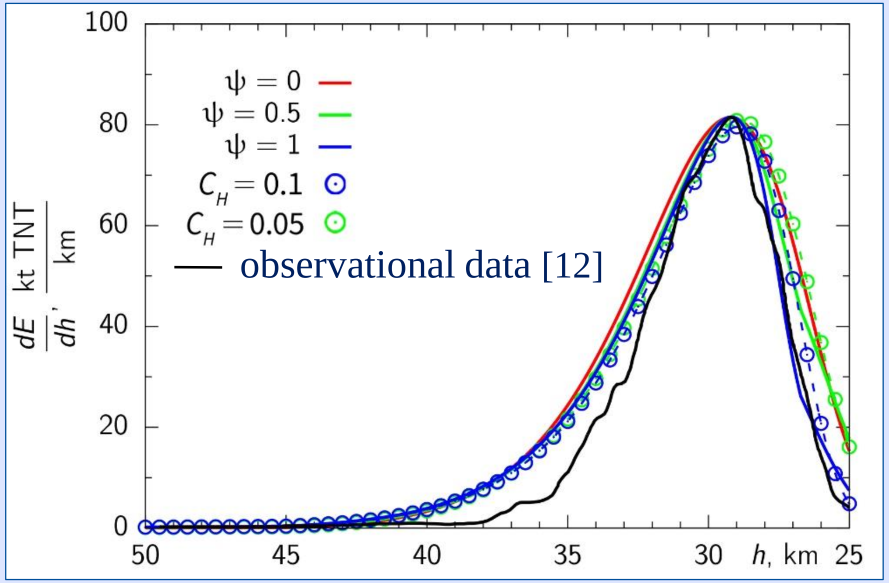
For model [4] with *c* = $(7/2)^{1/2}$, it is not possible to obtain satisfactory agreement with observational data when varying parameter ψ

Optimal simple model which gives the best agreement with observational energy deposition curve of the Chelyabinsk bolide with coefficient *c* depending on the heat transfer coefficient

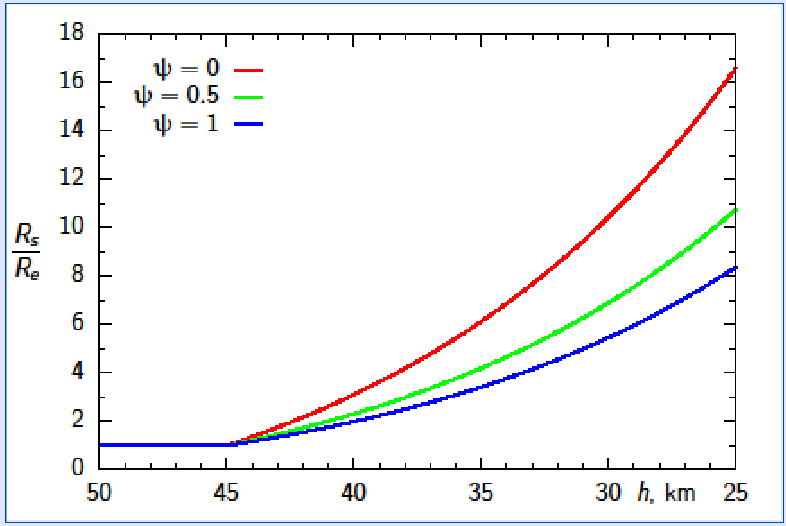
Optimal coefficient *c* in midsection radius equation as function of parameter ψ



Energy deposition modeling using optimal simple models at various heat transfer coefficients



Midsection radius in optimal simple models at various heat transfer coefficients



Discussion & Conclusions

When using two-parameter model, in contrast to simple models, changes of the density and shape of fragmented meteoroid are taken into account, and the combined problem of meteoroid fragmentation, ablation and motion is solved. In simple models the fragmentation problem is separated from the problem of ablation and motion, so ablation affects the meteoroid mass and does not affect its midsection radius.

When using simple fragment cloud models, heat transfer coefficient significantly affect the height of peak brightness of the bolide. For simple models, optimal coefficient *c* in the midsection radius equation is proposed as function of heat transfer coefficient, which gives agreement of the calculated height of peak brightness of the Chelyabinsk bolide with observational.

For model [1, 5] with $c = 1$, satisfactory agreement with the observational energy deposition curve is achieved at $\psi = 0.3$ and $C_H = 0.03$ and entry mass 1.46×10^{10} g. For model [4] with $c = (7/2)^{1/2}$, it was not possible to obtain satisfactory agreement with observational data at any heat transfer coefficient.

The best agreement with the observational energy deposition curve of the Chelyabinsk bolide is obtained: when parameter ψ in the heat transfer coefficient is equal to 1 or when setting the constant $C_H = 0.1$, and when using two-parameter fragmentation model or optimal simple model with $c = 0.615$.

These models give the entry meteoroid mass estimates 1.325×10^{10} g and 1.285×10^{10} g, which are close to each other and to estimates in [12, 13].

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