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TESTING OF THE NEW METEOROID FRAGMENTATION MODEL APPLIED TO THE CHELYABINSK EVENT

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Introduction

Main processes which essentially influence on the interaction of meteoroid with the atmosphere are disruption and ablation

Approaches to modelling of meteoroid disruption:

1. Fragments move separately with their own shock waves:
models of one-stage and progressive fragmentation - discrete and continuous

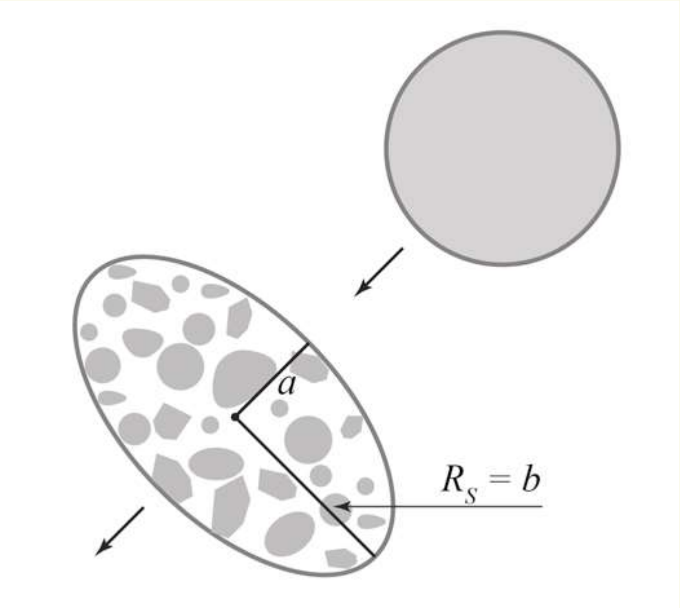
2. Breakup of the meteoroid into a cloud of small fragments which move with a common shock wave as a single body deformed by the aerodynamic loading:
it is expanding in a lateral direction and reducing in thickness in a flight direction

Grigoryan S.S. Cosmic Research. 1979. V. 17, 724–740
Melosh H.J. Proc. Lunar Planet. Sci. 1981. V. 12A, 29–35
Zahnle K.J. J. Geophys. Res. 1992. V. 97. No E6. 10,243–10,255
Hills J.G., Goda M.P. Astron. J. 1993. V. 105. No. 3. 1114–1144
…
Register P.J., Mathias D.L., Wheeler L.F. Icarus. 2017. V. 284, 157–166

3. Combinations of the first and second approaches

FRAGMENTATION MODEL

Breakup starts at the altitude h_f:



We assume two processes:

Flattening - the sphere is transformed into the spheroid with ratio of axes $b/a = k$ $(k \geq 1)$

Decrease of density due to increase of spacing between fragments: $\delta = \delta_e / \gamma^3$

δ is a density of disrupted meteoroid, δ_e is its initial density

parameter of flattening $\boldsymbol{k}$ and parameter of density decrease $\boldsymbol{\gamma}$

Before breakup start $k = 1$, $\gamma = 1$

Model of this work:

$$\frac{dR_S}{dt} = \frac{1}{k^{1/2}}\left(\frac{\gamma^3\rho}{\delta_e}\right)^{1/2} V, \quad k = \frac{4\pi\delta_e}{3}\frac{R_s^3}{M\gamma^3}$$

R_S – midsection radius
V – meteoroid velocity
M – meteoroid mass
ρ – atmospheric density

$$\gamma = 1 + \frac{\gamma_m - 1}{\rho_m^{1/2} - \rho_f^{1/2}}\left(\rho^{1/2} - \rho_f^{1/2}\right)$$

Models used in the literature:

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

$c = 1$ – *Grigoryan S.S.* Cosmic Research. 1979
$c = 1.8$ – *Hills J.G., Goda M.P.* Astron. J. 1993

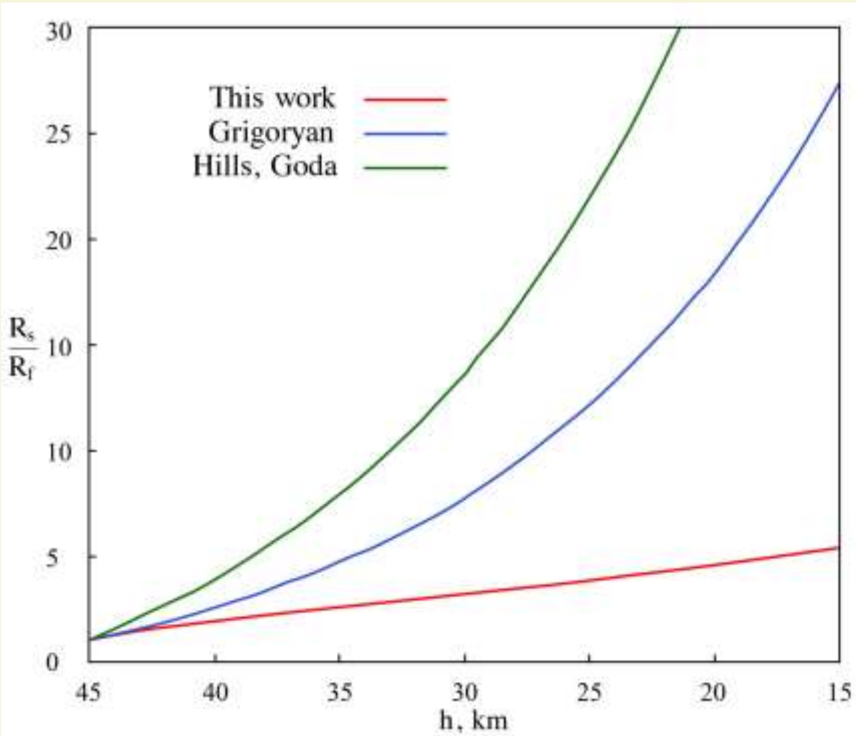
$$R_S = R_f\left(1 + \frac{2ch^*}{\sin\theta\,\delta_e^{1/2}R_f}\left(\rho^{1/2} - \rho_f^{1/2}\right)\right)$$

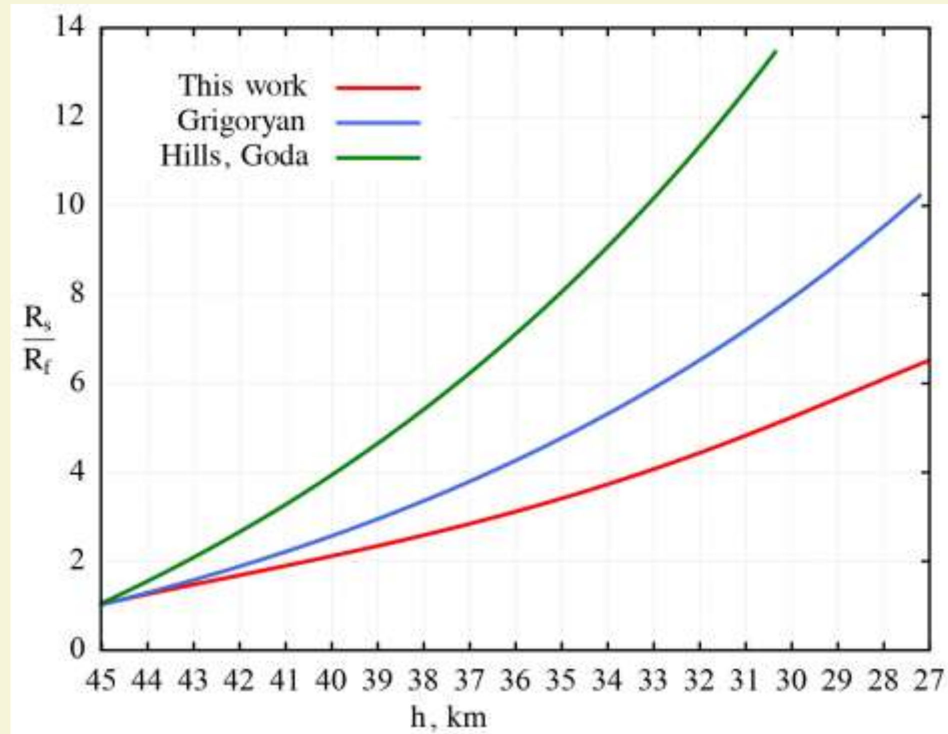
R_S is determined only by initial parameters:
θ – entry angle, R_f – meteoroid radius at h_f *and* δ_e

Main differences between models

1. Taking account of change of the meteoroid shape — no
2. Taking account of decrease of the meteoroid density — no
3. Fragmentation depends on ablation process — no

Change of the meteoroid midsection radius along the trajectory





without ablation

with ablation

$h_f = 45$ km, $R_f = 10$ м, $\theta = 18°$, $M_e \sim 1.3 \cdot 10^{10}$ g

SOLUTION OF METEOR PHYSICS EQUATIONS

$$M\frac{dV}{dt} = -\frac{\pi}{2}R_s^2 C_D \rho V^2, \quad Q\frac{dM}{dt} = -\frac{\pi}{2}R_s^2 C_H \rho V^3$$

$$\frac{dh}{dt} = -V\sin\theta, \quad \rho = \rho_0 \exp\left(-\frac{h}{h^*}\right)$$

THE DRAG COEFFICIENT C_D OF A SPHEROID

$$C_D = \frac{2k^2}{k^2-1}\left(1-\frac{\ln k^2}{k^2-1}\right), \quad \lim_{k\to 1} = 1, \quad \lim_{k\to\infty} = 2 \qquad C_D = 2-\frac{1}{k}$$

within accuracy of 5 %

RADIATIVE HEAT TRANSFER COEFFICIENT C_H FOR A SPHEROID

The approximate expression in depedence on V, R, k, ρ - combination of formulas of

Suttles J.T., Sullivan E.M., Margolis S.B. NASA TN D-7622. 1974
Brandis A.M., Johnston C.O. AIAA 2014-2374. 2014

with corrections in accordance with

Biberman L.M., Bronin S.Ya., Lagar'kov A.N. Fluid Dyn. 1972
Biberman L.M., Bronin S.Ya., Brykin M.V., Mnatsakanyan A.Kh. Fluid Dyn. 1978
Biberman L.M., Bronin S.Ya., Brykin M.V. Teplofiz. Vysok. Temp. 1979
Apshtein E.Z., Vartanjan N.V., Sakharov V.I. Fluid Dyn. 1986

THE CHELYABINSK SUPERBOLIDE OF FEBRUARY 15, 2013

Observational data and their analysis and processing are presented in the papers

•*Emel'yanenko V.V., Chugai N.N., Shelyakov M.A., et al.* Sol. Syst. Res. 2013. V. 47(4), 240–254

•*Borovicka J., Spurny P., Brown P.* et al. Nature. 2013. V. 503, 235–237.

•*Brown P.G., Assink J.D., Astiz L.*, et. al. Nature. 2013. V. 503, 238–241.

•*Popova O.P., Jenniskens P., Emel'yanenko V.* et. al. Science. 2013. V. 342, 1069–1073

It was determined

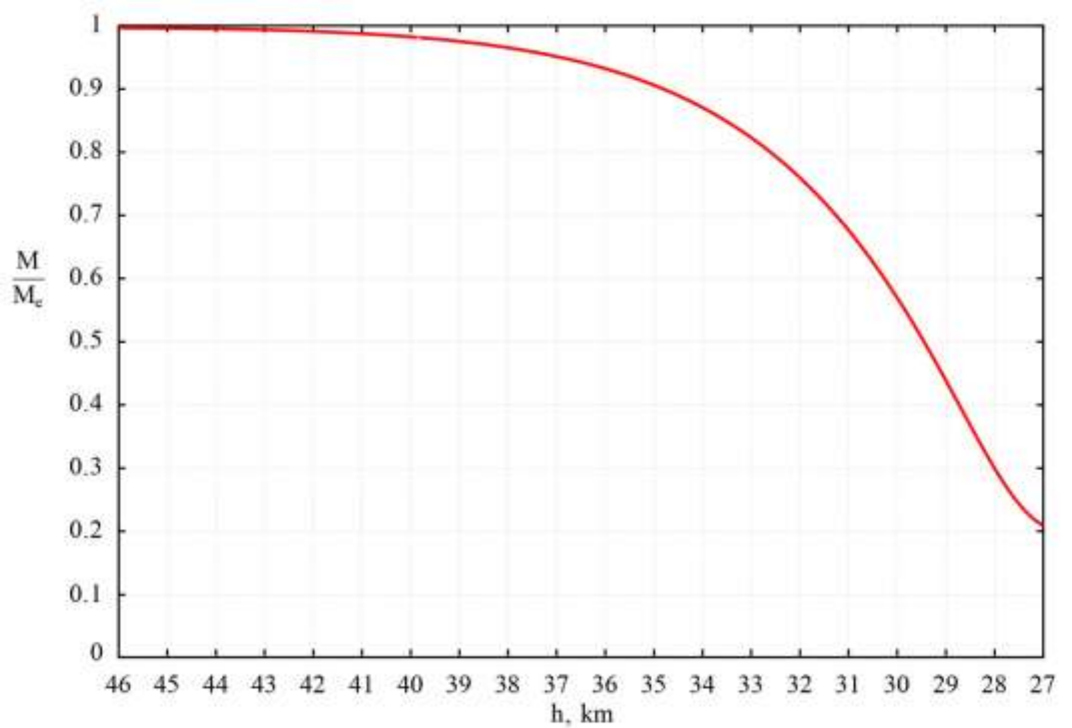
The entry angle with respect to the horizon $\theta \sim 18°$

$V \sim 19$ km/s at 95–40 km; 18.9 km/s at 30 km; 18 km/s at 25 km; 14.2 km/s at 20 km

Altitude of the maximum brightness ~ 29.5 km

Meteorites classified as LL5 ordinary chondrites

MASS LOSS OF THE CHELYABINSK METEOROID ALONG THE TRAJECTORY



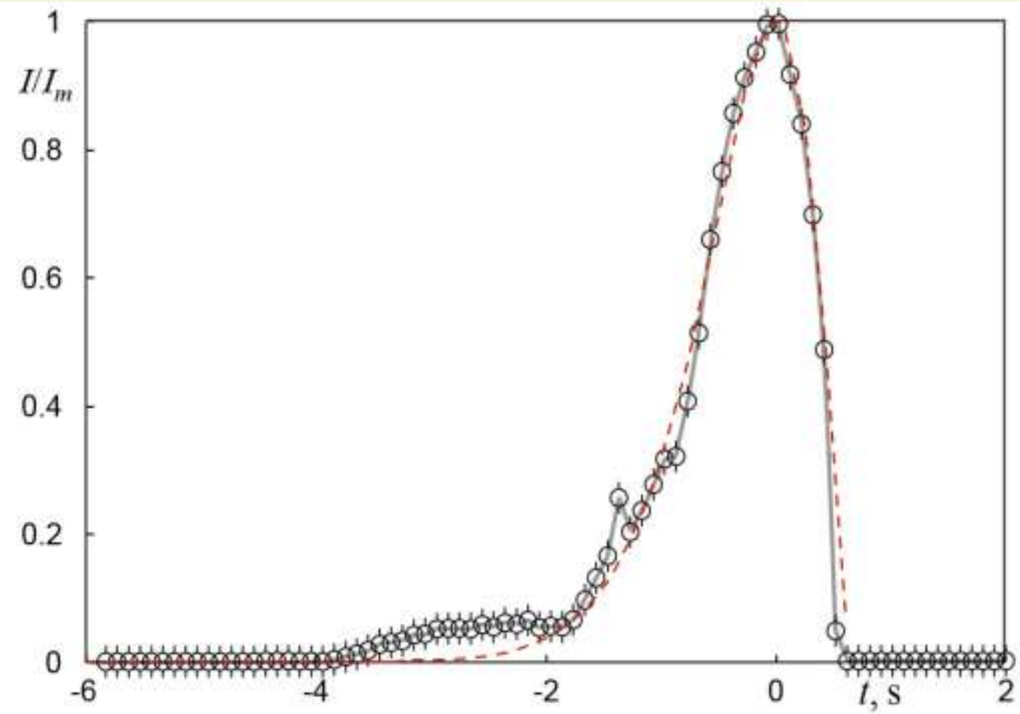
bulk strength σ = 0.7 MPa, altitude of breakup start $h_f \sim 45$ km

entry density $\delta_e \sim 3.3$ g/sm^3, entry mass $M_e \sim 1.28 \cdot 10^{10}$ g

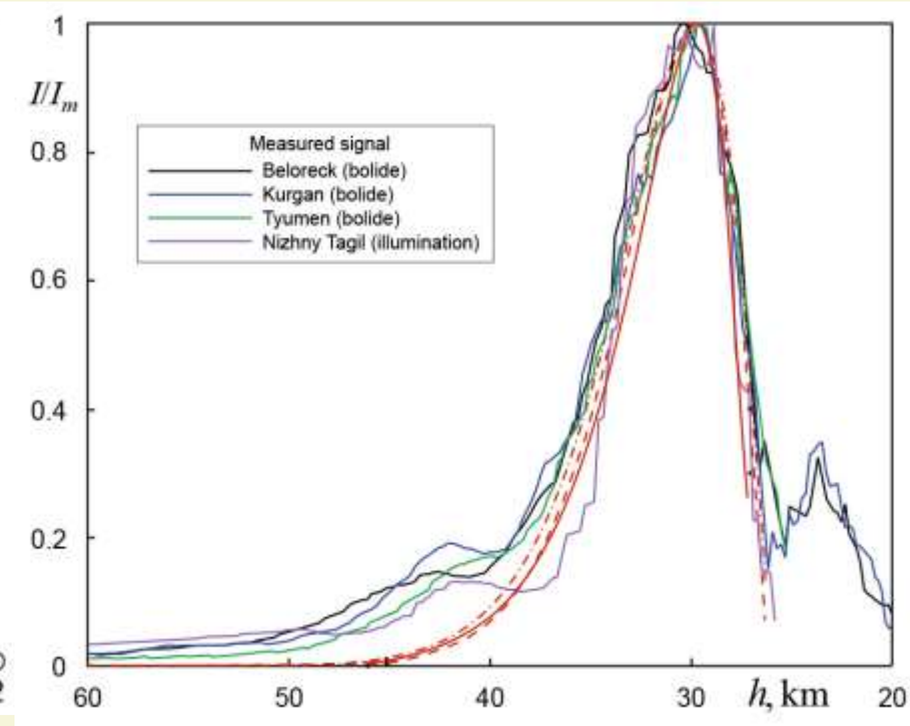
Comparison of the light curve, normalized to the maximum brightness (red lines) with observational data

Popova, O.P., Jenniskens, P. and Glazachev D.O. Dynamic processes in geospheres, Collection of research papers of IDG RAS, Iss. 5, 2014, 59–78.

Borovicka J., Spurny P., Brown P. et al. Nature. 2013. V. 503. P. 235–237



time from the peak of brightness

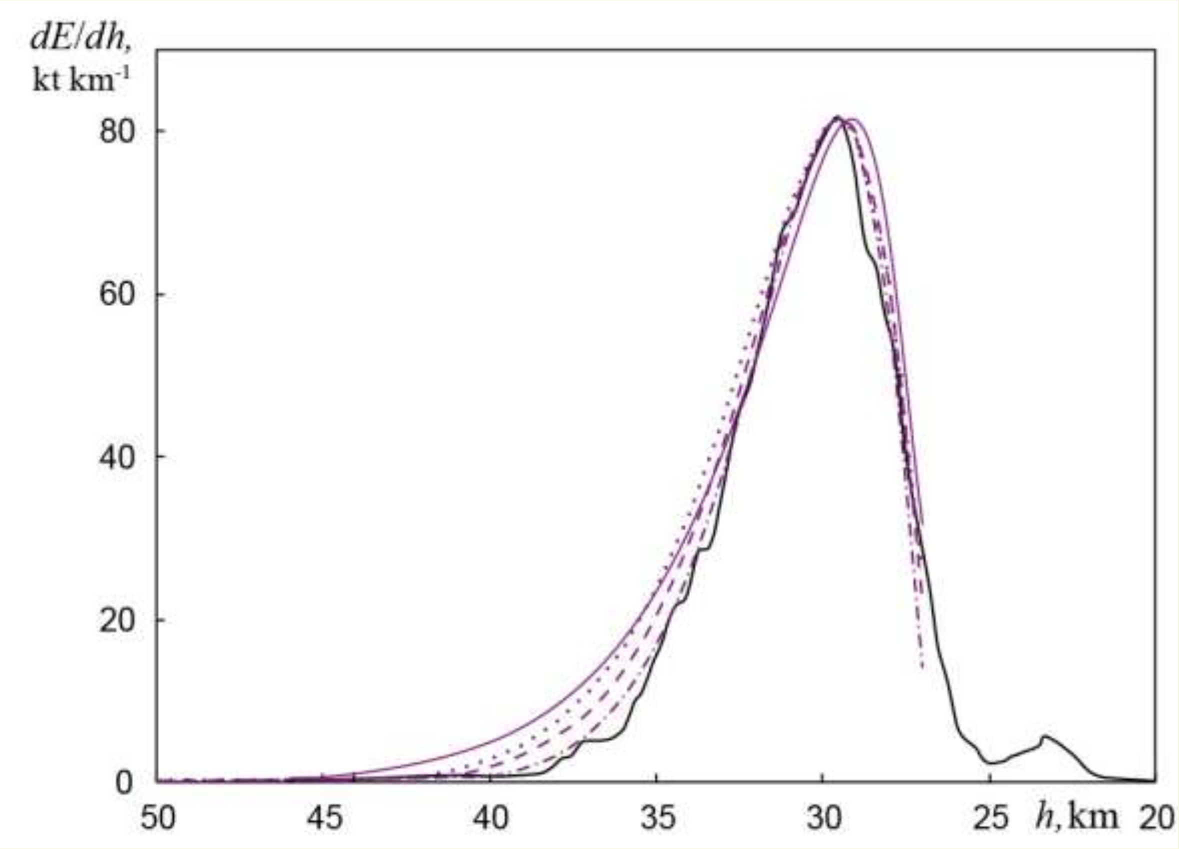


altitude

σ = 0.7 MPa dashed and solid lines – analytical and numerical solutions
σ = 0.5 MPa dash-and-dot line – analytical solution

Comparison of the energy deposition per unit height with observational data

____ *Brown P.G., Assink J.D., Astiz L.,* et. al. Nature. 2013. V. 503, 238–241



σ = 0.7 MPa solid line – numerical solution

σ = 1, 1.2, 1.5 MPa – dots, dashed, dash-and-dot lines – analytical solution

SUMMARY

- The developed fragmentation model takes into account decrease of density of disintegrated meteoroid and dependence of the rate of lateral expanding on the degree of flattening. That leads to considerably smaller values of midsection radius as compared with other “pancake” models.
- The mass loss, energy deposition and relative light curve of the Chelyabinsk meteoroid have been modeled down to an altitude of 27 km.
- The modelling results satisfactorily agree with observational data.