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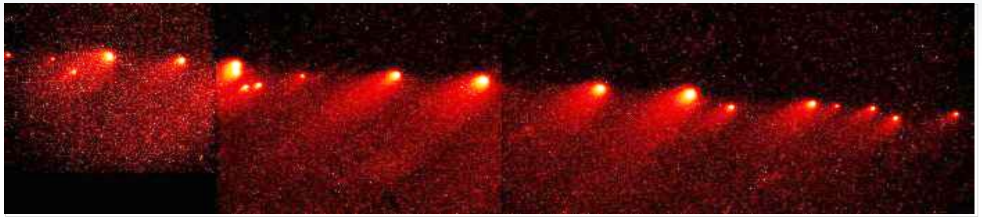
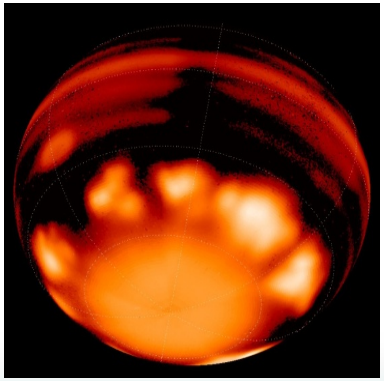


EXPLOSIVE DECELERATION AND FRAGMENTATION OF METEORITES IN THE ATMOSPHERE

Dmitriy V. Petrov, Oleg N. Shubin, Vasiliy P. Elsukov,Vadim A. Simonenko



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Забабахинские
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ЗАБАБАХИНСКИЕ
НАУЧНЫЕ
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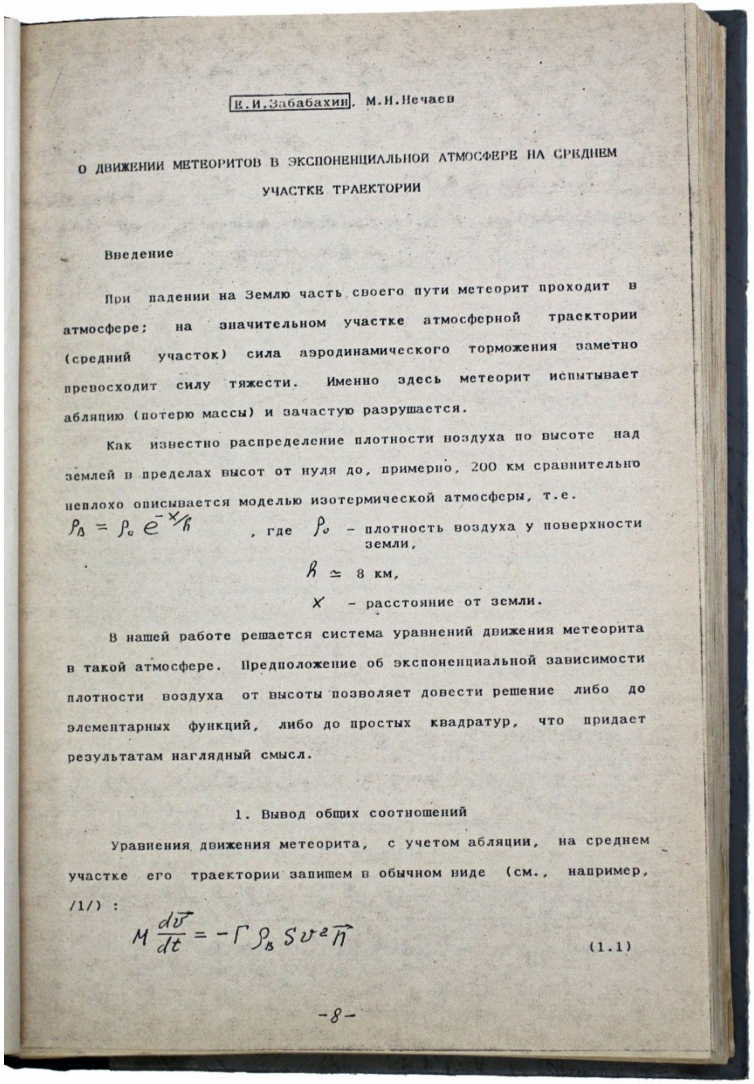


Е.И.Забабахин, М.Н.Нечаев

О ДВИЖЕНИИ МЕТЕОРИТОВ В ЭКСПОНЕНЦИАЛЬНОЙ АТМОСФЕРЕ НА СРЕДНЕМ УЧАСТКЕ ТРАЕКТОРИИ

Введение

При падении на Землю часть своего пути метеорит проходит в атмосфере; на значительном участке атмосферной траектории (средний участок) сила аэродинамического торможения заметно превосходит силу тяжести. Именно здесь метеорит испытывает абляцию (потерю массы) и зачастую разрушается.

Как известно распределение плотности воздуха по высоте над землей в пределах высот от нуля до, примерно, 200 км сравнительно неплохо описывается моделью изотермической атмосферы, т.е.

$\rho_в = \rho_0 e^{-x/h}$, где ρ_0 – плотность воздуха у поверхности земли,

$h \simeq 8$ км,

x – расстояние от земли.

В нашей работе решается система уравнений движения метеорита в такой атмосфере. Предположение об экспоненциальной зависимости плотности воздуха от высоты позволяет довести решение либо до элементарных функций, либо до простых квадратур, что придает результатам наглядный смысл.

1. Вывод общих соотношений

Уравнения движения метеорита, с учетом абляции, на среднем участке его траектории запишем в обычном виде (см., например, /1/):

$$M \frac{d\vec{v}}{dt} = -\Gamma \rho_в S v^2 \vec{n} \qquad (1.1)$$

-8-

CONTENTS

Experimental facts

- ➢ explosion of Tunguska meteorite
- ➢ registered bursts like nuclear explosion fireballs with the yield of 1 to 100 kilotons TNT

The paper describes a theoretical model simulating the explosive interaction between meteorites and the atmosphere, as well as meteorite fragmentation.

A meteorite entering the atmosphere interacts with an approaching air stream and this results in a large-scale loss of hydrodynamic stability. The meteorite disintegrates into several approximately equal fragments. Then a chain reaction of meteorite fragmentation is observed, the fragments being decelerated by the atmosphere.

This physical model can lead to two outcomes:

- **meteorites with small density and sizes less than some critical value** reach some critical height above the Earth surface. Final sizes of meteorite fragments reaching the ground would depend on the existence of some minimal fragment size and/or critical velocity of these fragments in the atmosphere;
- **When meteorite density and dimensions are large enough,** the fragmentation process has no time to develop deeply. The fragments reaching the ground will be of microscopic sizes.

STARTING POINT

$$\begin{cases} M\dfrac{d\bar{v}}{dt} = -G\rho_a S v^2 \bar{n} \\ \dfrac{dM}{dt} = -\dfrac{L}{Q}\rho_a S v^3 \end{cases}$$

Merits

1. The theory (if constants are selected properly) describes rather well the meteorite deceleration in the mid-trajectory.

Drawbacks

2. Great uncertainties in choosing system constants.
3. At certain velocities the ablation equation contradicts the law of energy conservation.
4. The theory does not predict meteorite fragmentation.
5. The theory does not predict meteorite explosion in the atmosphere: dE/dH spread over the whole atmosphere.

PHYSICAL MODEL. ZERO-ORDER APPROXIMATION

1. Interaction with an approaching air stream
2. Loss of hydrodynamic stability
3. Disintegrations (repeating)

The meteorite is a sphere.
Fragmentation is discrete and time intervals between the acts of fragmentation are independent of meteorite velocity and air density.

Meteorite disintegration time

$$t_f = \tau \cdot R_0 \frac{\sqrt[3]{n}}{\sqrt[3]{n} - 1}$$

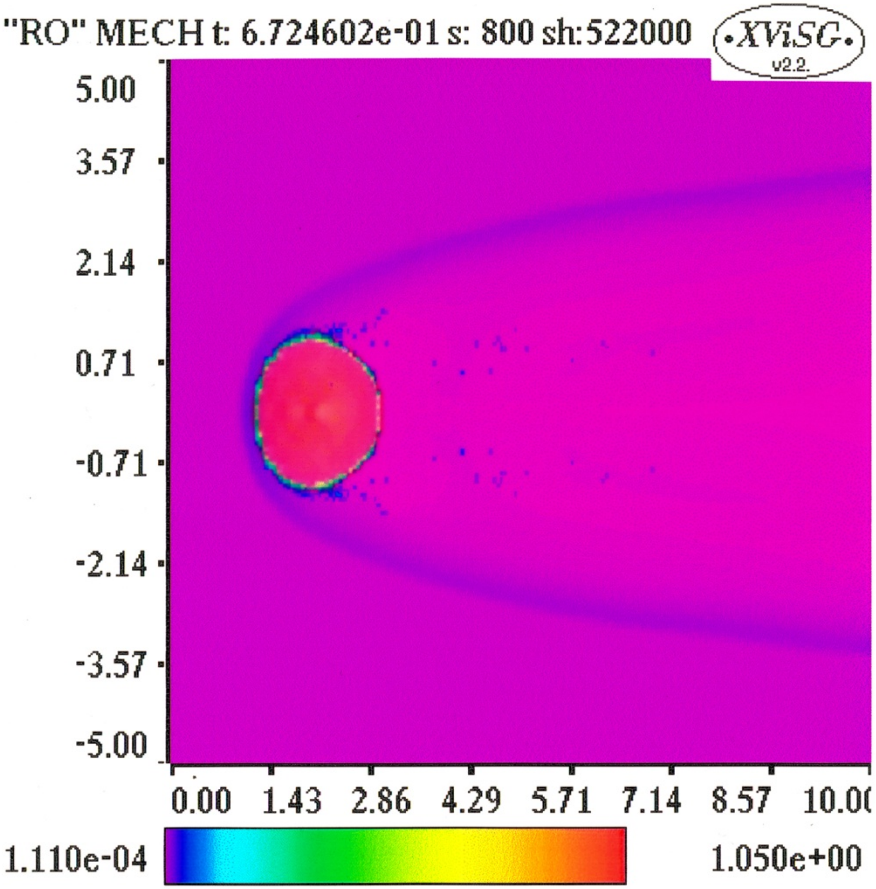
n – number of fragments resulted from disintegration

n – number of fragments
resulted from disintegration

Number and size of fragments

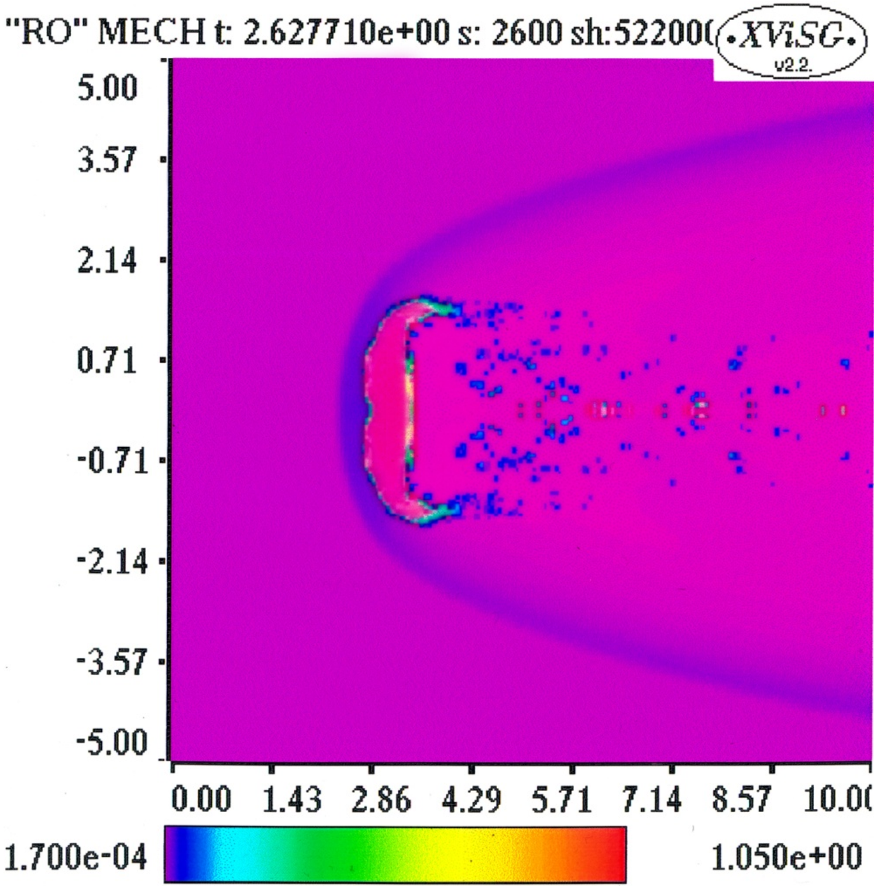
$$\begin{cases} N(t) = \dfrac{1}{\left(1 - \dfrac{t_i}{t_f}\right)^3} \\ R(t) = R_0 \left(1 - \dfrac{t_i}{t_f}\right) \end{cases}$$

NUMERICAL SIMULATION



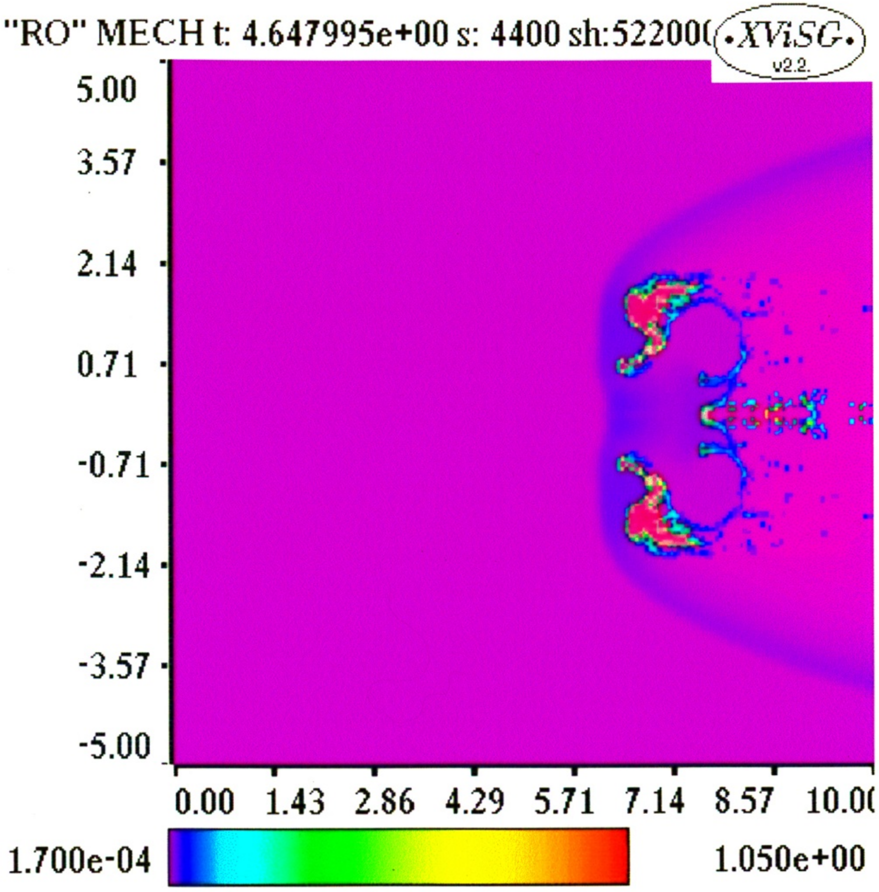
Steady-state flow

NUMERICAL SIMULATION



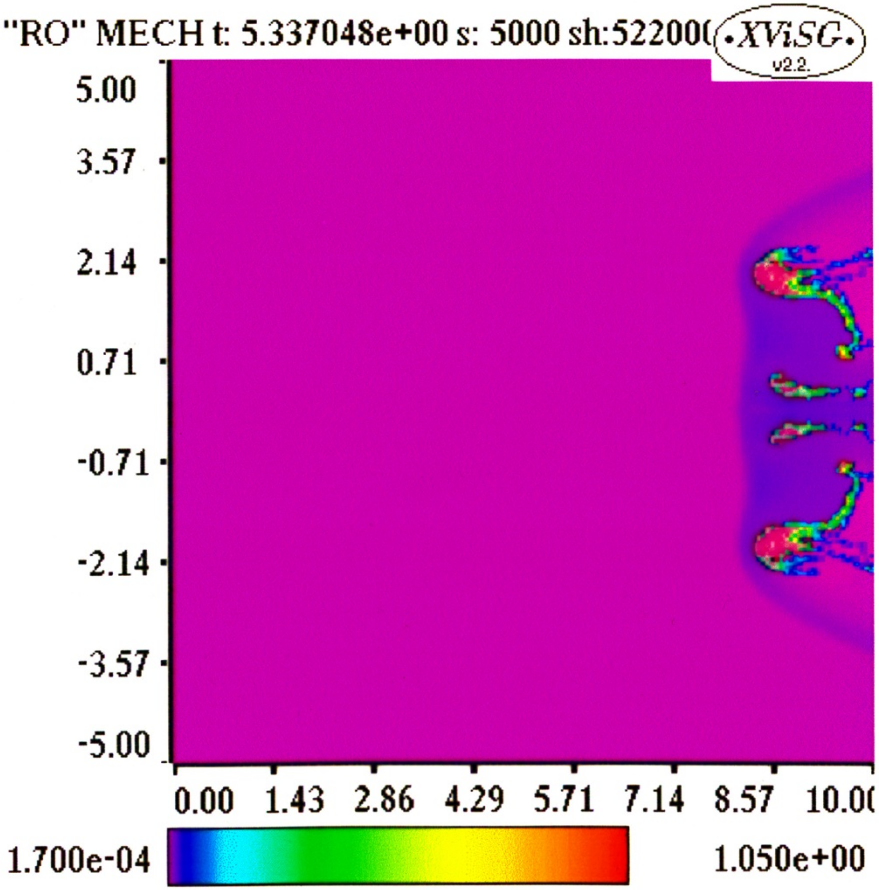
A recess on the axis of symmetry

NUMERICAL SIMULATION



Transformation of initial sphere into a torus

NUMERICAL SIMULATION

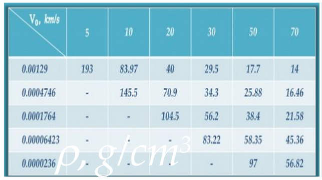


Two tori

NUMERICAL SIMULATION

$P=(\delta-1)\rho_0\cdot c_0^2(\delta-1)$ – equation of state

Break-up time τd (in μs) for a sphere of the unit radius as a function of air velocity and density

 V_0, km/s ρ, g/cm^3	5	10	20	30	50	70
0.00129	*193*	*83.97*	*40*	*29.5*	*17.7*	*14*
0.0004746	*-*	*145.5*	*70.9*	*34.3*	*25.88*	*16.46*
0.0001764	*-*	*-*	*104.5*	*56.2*	*38.4*	*21.58*
0.00006423	*-*	*-*	*-*	*83.22*	*58.35*	*45.36*
0.0000236	*-*	*-*	*-*	*-*	*97*	*56.82*

Brake-up time interpolation formula

$$\tau_d = 6{,}633\,\frac{1}{\rho^{0{,}386}\,v}$$

РФЯЦ–ВНИИТФ

ANALYTICAL ESTIMATES
EXPONENTIAL ATMOSPHERE

The ballistic form of the equation of motion between fragmentation acts

$$\frac{dv^2}{dz} = \frac{2GA}{\rho_M^{2/3} M_m^{1/3} \cos\varphi} \rho_a v^2$$

Limits of integration

$$t_m - t_{m-1} = \tau_m$$

$$\tau = \frac{1}{v} f\left(\frac{\rho_M}{\rho_a}\right) = \frac{1}{v} B \left(\frac{\rho_M}{\rho_a}\right)^{\alpha}$$

$$\int_{t_{m-1}}^{t_m} v_d \, dt = \int_{t_{m-1}}^{t_m} \frac{dt}{t(v, \rho_a)} = R_{m-1}$$

$$\tau = \frac{1}{v} f\left(\frac{\rho_M}{\rho_a}, \frac{c_0}{v}, \frac{c_a}{v}, \gamma \text{ etc.}\right)$$

Integration results

$$v_m = v_{m-1} \exp\left(-\frac{h\gamma}{2} \Delta\rho_m\right)$$

$$\gamma = \frac{2GA}{\rho_M^{2/3} M_{m-1}^{1/3} \cos\varphi}$$

$$\Delta\rho_m = \rho_{m-1} \left(\sqrt[\alpha]{1 + B \cdot \alpha \cdot \cos\varphi \frac{R_{m-1}}{h} \left(\frac{\rho_M}{\rho_{m-1}}\right)^{\alpha}} - 1 \right)$$

РФЯЦ–ВНИИТФ

ANALYTICAL ESTIMATES
EXPONENTIAL ATMOSPHERE

$\boldsymbol{\alpha = 1}$

$$\bar{v}_m = v_{m-1} exp\left[-\frac{GA}{\left[\frac{4\pi}{3}\right]^{1/3}}B\right] = v_{m-1}f$$

$$\Delta E_m = E_0 f^{2m}\left(1-\frac{1}{f^2}\right)$$

Energy loss after m acts of fragmentation

$$\Delta E(m) = -E_0\left(1-\frac{1}{f^2}\right)\sum_{n=1}^{m} f^{2n} = E_0\left(1-f^{2m}\right)$$

$\boldsymbol{\alpha \neq 1}$

=

$$B\alpha\cos\varphi\frac{R_{m-1}}{h}\left(\frac{\rho_M}{\rho_{m-1}}\right)^{\alpha} << 1$$

$$\Delta\rho_m = \rho_{m-1}B\cos\varphi\frac{R_{m-1}}{h}\left(\frac{\rho_M}{\rho_{m-1}}\right)^{\alpha}$$

At m → ∞ the meteorite is able to reach only the final altitude

$$z_f = \frac{h}{\alpha}\ln\left[\frac{1-\frac{1}{\sqrt[3]{n}}}{B\cdot\alpha\cdot\cos\varphi\left(\frac{\rho_M}{\rho_{a0}}\right)^{\alpha}\frac{R_0}{h}}\right]$$

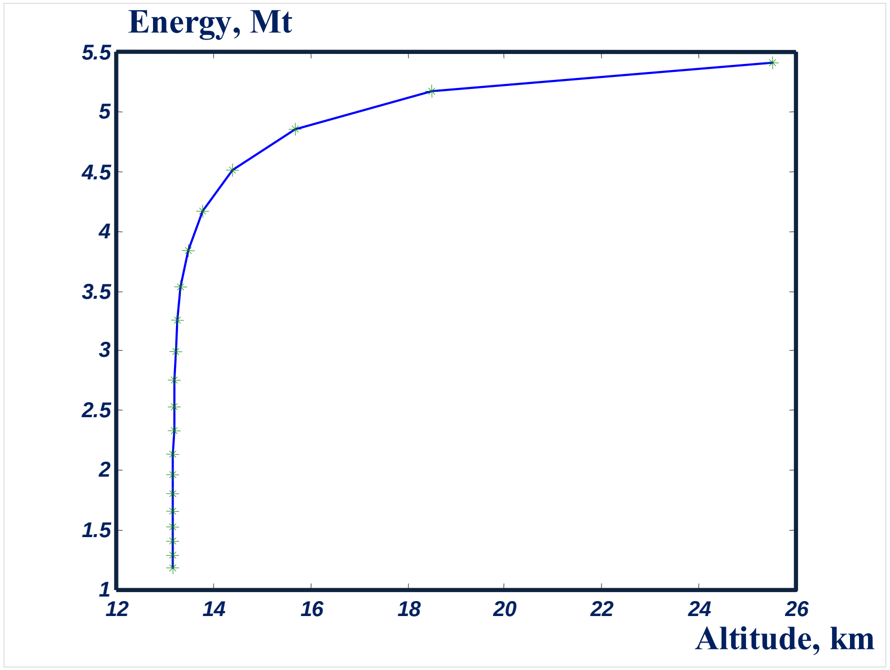
РФЯЦ–ВНИИТФ

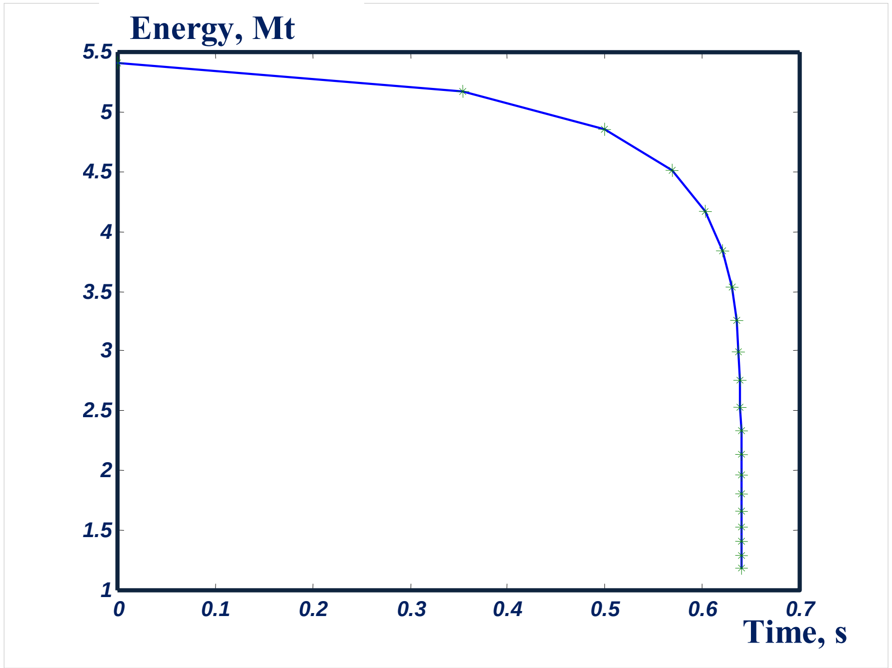
CALCULATIONS FOR THE METEORITE

Initial conditions:

At the altitude of **25.5 km** the meteorite **30 m** in radius had the initial velocity of **20 km/s,** kinetic energy of the meteorite was **5.4 Mt**

Kinetic energy of the meteorite versus altitude and time during fragmentation





ANALYTICAL ESTIMATES
ATMOSPHERE OF CONSTANT DENSITY

Due to the fact that almost all the energy is lost within a narrow range of altitudes – **50%** of energy is lost within **1 km** – it is reasonable to assume that within this range the atmosphere density is constant.

$$E(t) = \frac{E_0}{\left[1 + \beta u_0 \frac{\ln\left(1 - \frac{t}{t_f}\right)}{\ln x}\right]^2}$$

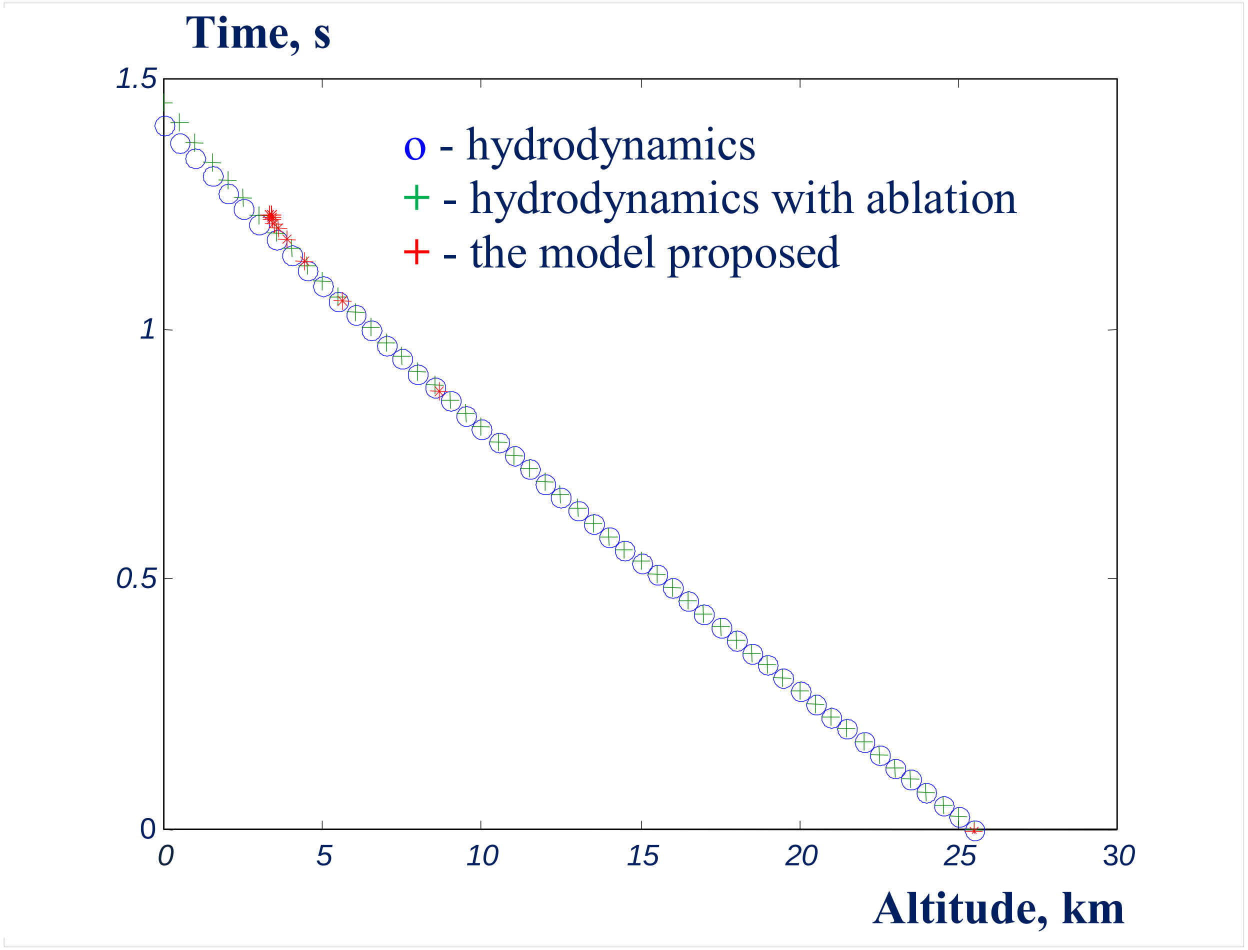
$$x = \sqrt{n}$$

$$\beta = GA\tau \frac{\rho_a}{\rho_M}\left(\frac{3}{4\pi}\right)^{1/3}$$

At $t \to t_f$ $\frac{dE}{dt} \to \infty$ – an explosive process

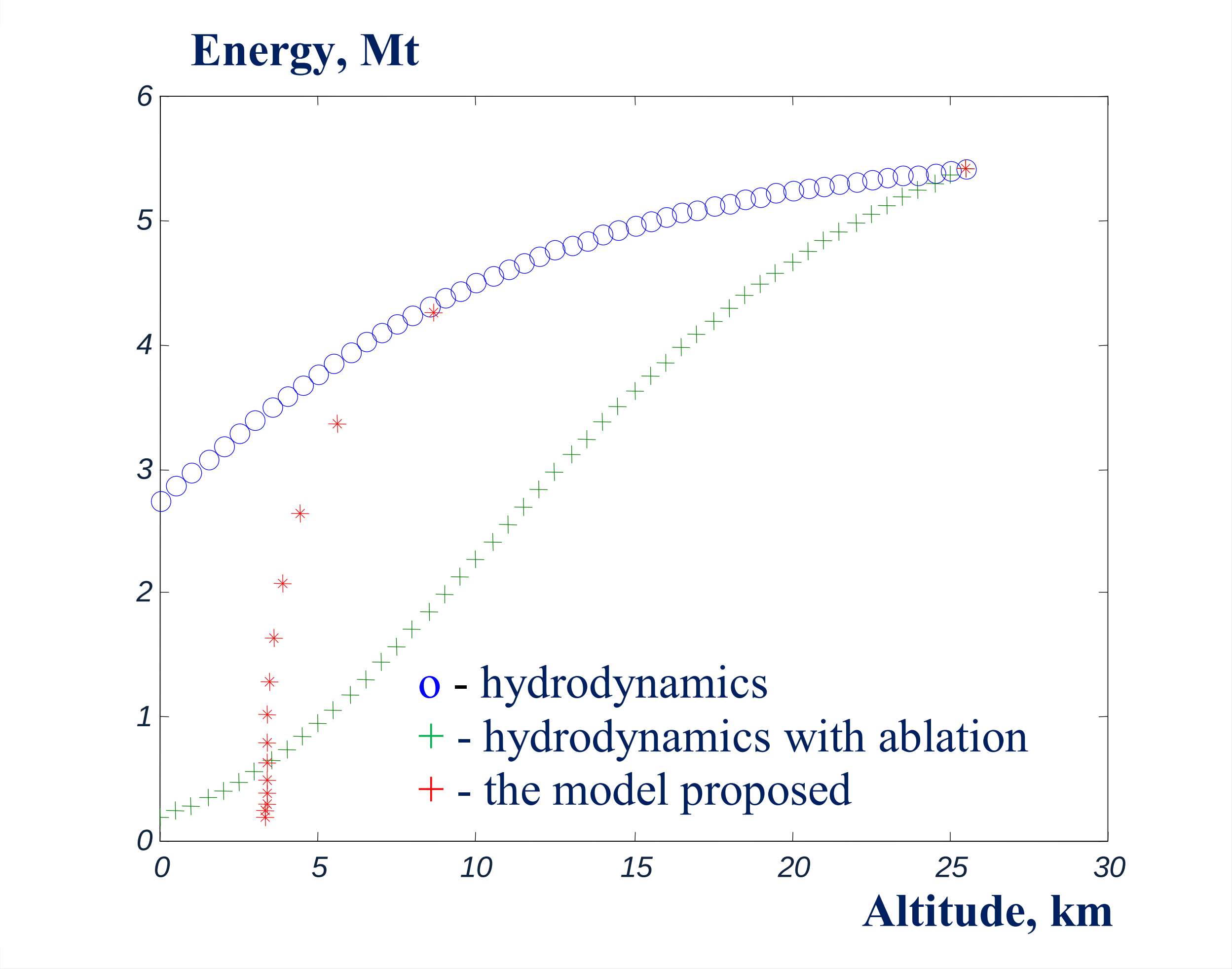
The rate of energy loss is limited. Its maximum depends on the final size of micro-fragments and/or velocity finiteness.

COMPARISON OF DIFFERENT MODELS



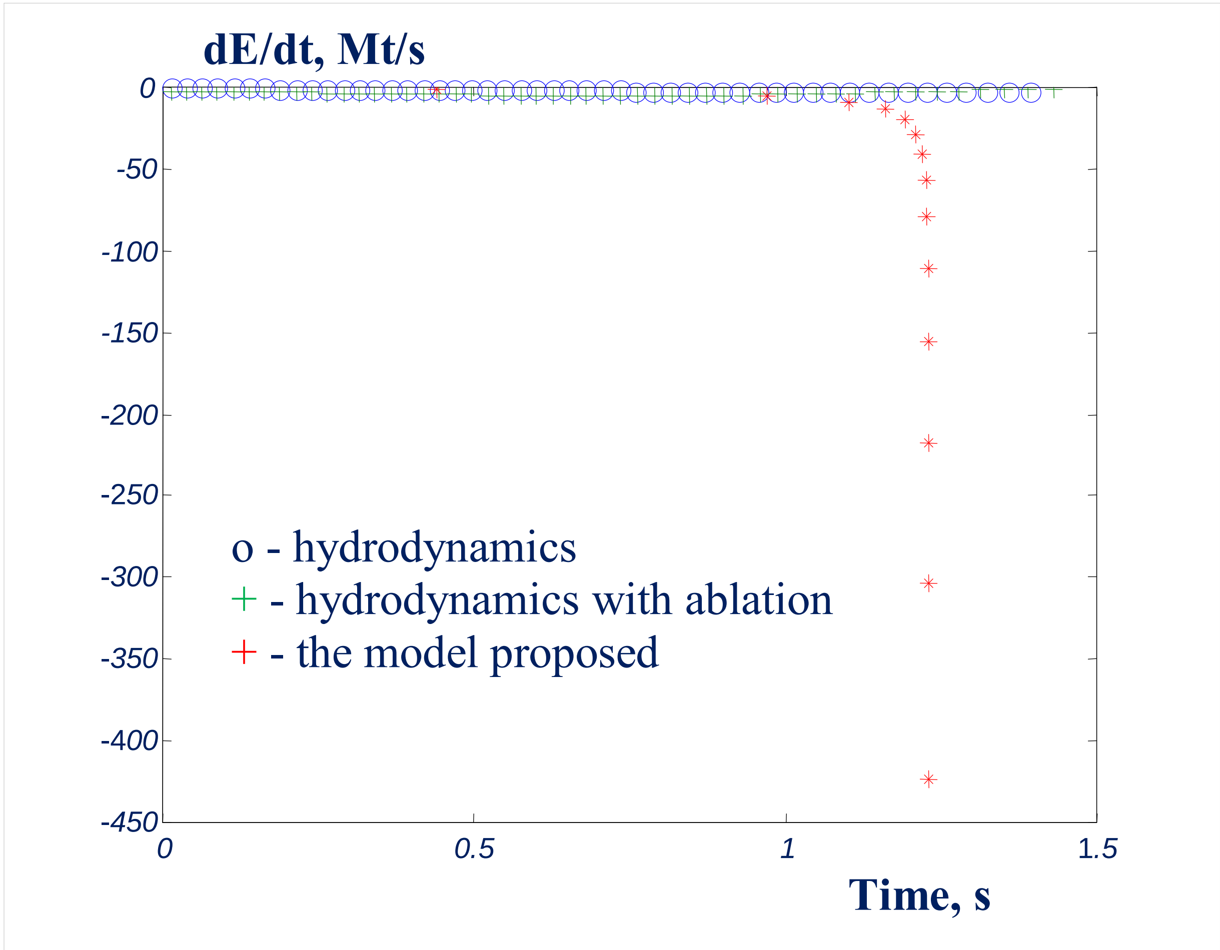
Time of the meteorite flight versus altitude above the ground

COMPARISON OF DIFFERENT MODELS



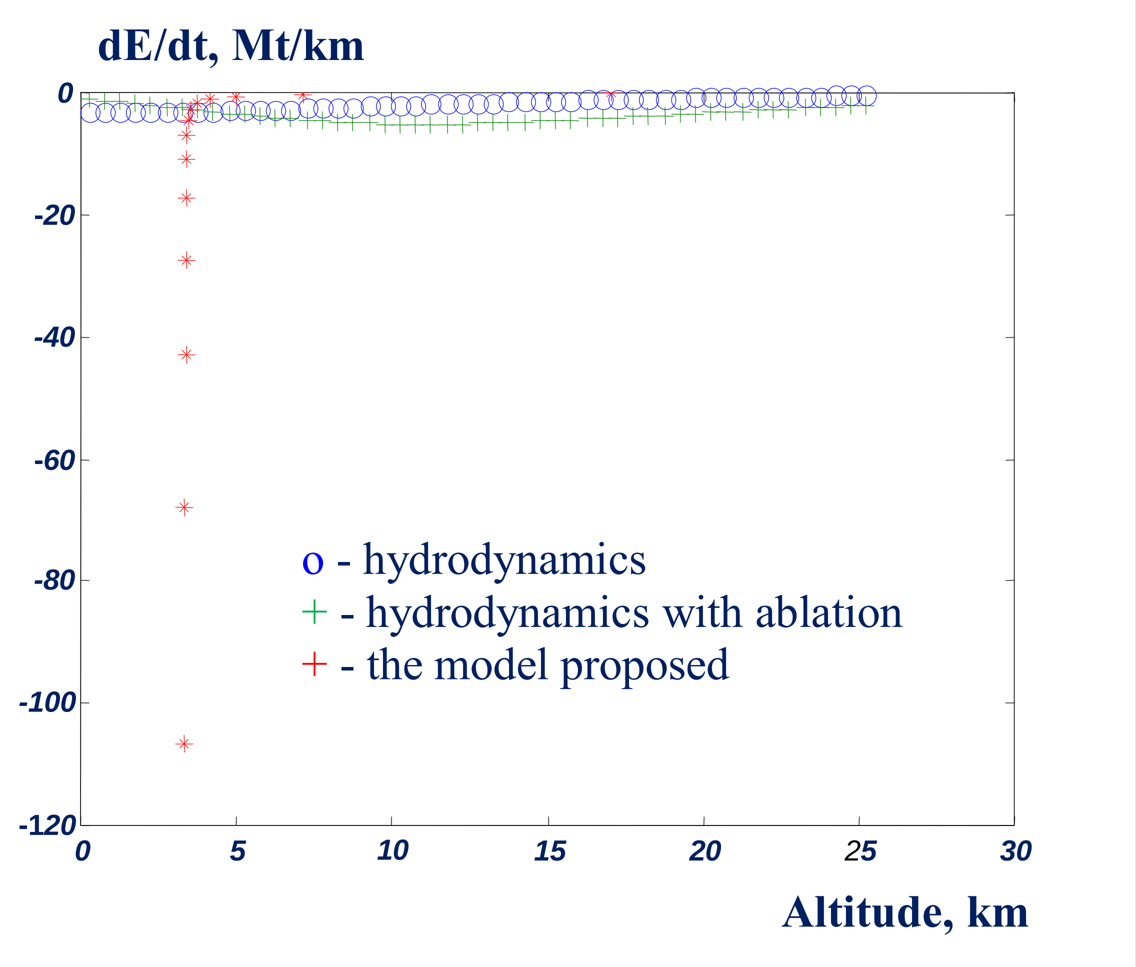
Energy of the meteorite versus altitude

COMPARISON OF DIFFERENT MODELS



Energy loss rate versus time

COMPARISON OF DIFFERENT MODELS



Energy loss rate versus altitude

TUNGUSKA METEORITE

Radius **46 m**, velocity **20 km/sec**, angle of fall **45°**.
Total energy - **20 Mt**, atmospheric parameters **ρ=1.4.10-3 g/cm3** and **h=7 km**.
Limiting altitude up to which meteorite fragments fly - **21 km**.
Explosive method provides release of about **16 Mt** energy.

Forest fall in the region of Tunguska explosion.
(based on materials of the expedition headed by
L. Kulik, 1927)

CONCLUSION

The model of asteroid explosion and fragmentation in the Earth atmosphere has been developed.

Based on the proposed model of asteroid explosion and fragmentation in the atmosphere, the size of an icy meteorite able to reach the Earth surface has been estimated as ~ 200 meters. In the case the meteorite does not reach the Earth, it looses its kinetic energy explosively – a major part of energy is lost within a distance equal to several meteorite sizes.

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