EFFECT OF "THERMAL EXPLOSION"

Lidia Egorova

МГУ им. М.В.Ломоносова
ИНСТИТУТ МЕХАНИКИ
INSTITUTE OF MECHANICS
LOMONOSOV MOSCOW STATE UNIVERSITY

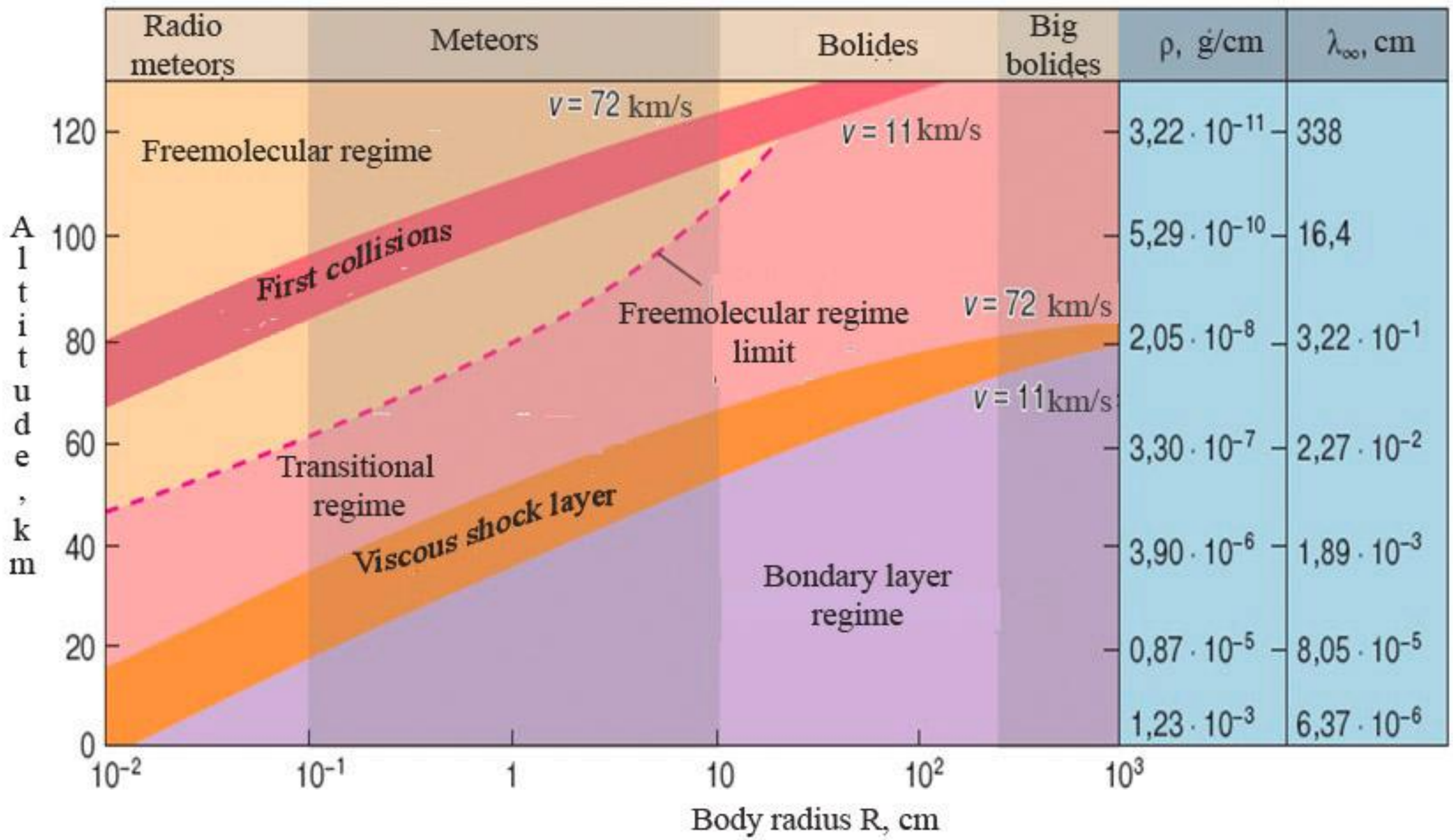
Spacecraft and meteoroid

- The shape is known and unchanged
- The material is known
- The mass is known and constant
- V<16 km/s (usually 5 7 km/s)

- The shape is unknown and can vary
- The material is unknown
- The mass is unknown and can vary
- V<72 km/s (usually 11 72 km/s)

Meteoroid undergoes

- Aerodynamic drag
- Mechanics loading
- Aerodynamic heating
- Radiation
- Ablation
- Fragmentation
- Explosion



Tirskii*,*G.A., Interaction between Cosmic Bodies and the. Earth's and Planet's Atmosphere, Soros Educational Journal, v.6, 2, 2000 (in Russian)

Physical theory of meteors

$$M\dot{V} = -\frac{1}{2}AC_D\rho V^2, \quad Q\dot{M} = -\frac{1}{2}AC_H\rho V^3,$$

M **– mass,**

V **– velocity,**

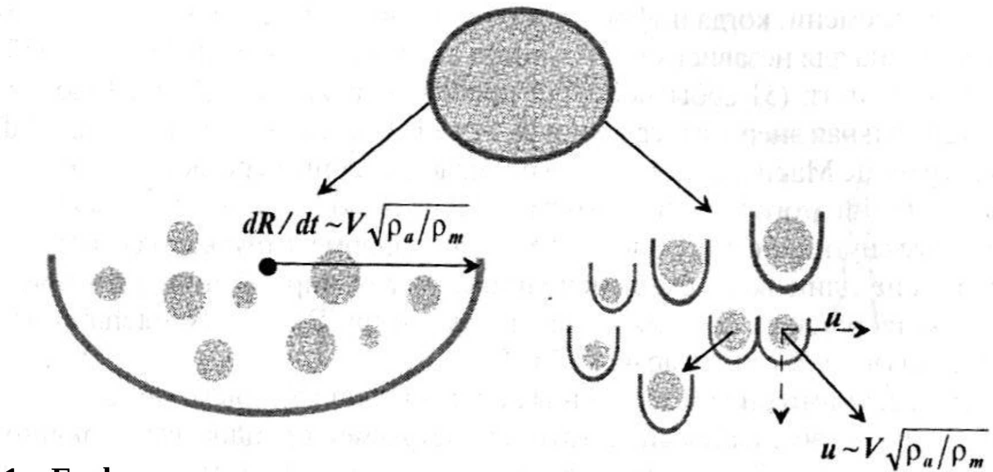
A **– square middle section ,**

ρ **– air density,**

CH **– heat transfer coefficient,**

Q **– specific heat of ablation**
(effective enthalpy)

Modern models of fracture meteoroids



1. «Early»

Jaccia, 1955; Levin, 1962-63; Simonenko 1973-74 – fragments separation from the main body.

Stanukovich and Shalimov, 1961; ReVelle, 1979 – because of the aerodynamic heating.

Cook, 1960; Lebedinets and Portnyagin, 1967 – unstable liquid drop.

McCrosky and Ceplecha, 1969 – because of the previous cosmic collisions.

Petrov and Stulov, 1976 – because of extremely low density of the body.

2. Catastrophic

Pokrovsky, 1964-66 – "explosion".

Jones and Kaiser, 1967; McCrosky and Ceplecha, 1969 – thermal shock.

Fujiwara, 1989; Jenniskens, 1994 – instantaneous disintegration into fragments.

ReVelle, 1999-2001 – modification of a single body model.

3. Hydrodynamic

Grigorian, 1976-79; Bronshten, 1985 – the propagation of fragmentation front.

Hills and Goda, 1993 – the expansion of debris cloud.

Korobeinikov, Chushkin, Shurshalov, 1986-98 – the fragmentation from inside.

Melosh, 1981; V.A.Ivanov, 1986-88 – the exploitation of body geometry specifics.

Chyba, Thomas, Zahnle, 1992-93 – the flattering of cylindrical body.

Svetsov, Nemchinov, Teterev, 1995; Shuvalov, Artem'eva, Trubetskaya, 2000 – numerical modeling.

4. Progressive, discrete

Fadeenko, 1967 – comparison of body strength with aerodynamic load.

Baldwin and Sheaffer, 1971; Tsvetkov, Skripnik 1991; Stulov, 1998; Artem'eva, Shuvalov, 2001 – the application of statistical theory of strength (Weibull, 1939).

Ivanov, Ryzhansky, 1995 – successive doubling of fragments.

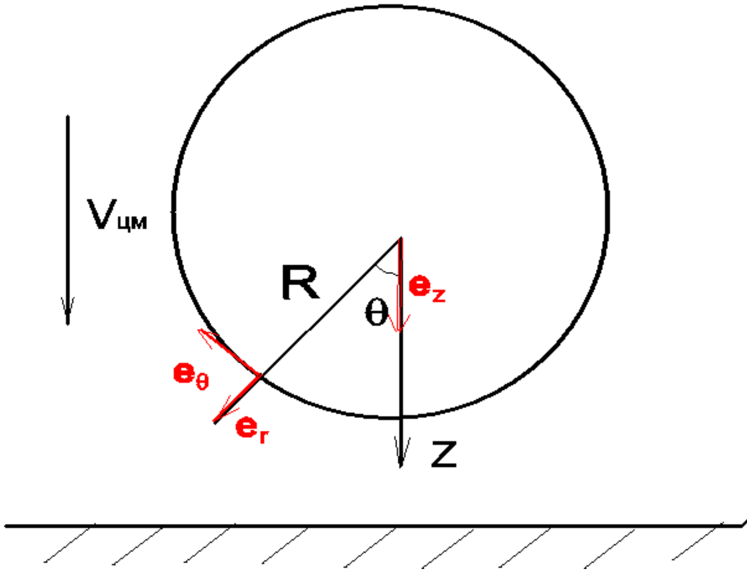
Ceplecha, Spurny, Borovička, and Keclikova, 1993 – gross-fragmentation.

Thermal explosion

is a very fast energy transfer to the atmosphere with the conversion of the whole body mass into vapor

Elastic theory equation set

$$\begin{cases} \dfrac{1}{1-2\nu}\,\mathrm{grad}\,\mathrm{div}\,\mathbf{u} + \Delta\mathbf{u} = -\dfrac{}{8G}(\alpha+\beta)\rho V^2 \dfrac{1}{R}\mathbf{k} \\ \sigma_r = \sigma(\theta), \quad if\ \ r = R \\ \tau_{r\theta} = \tau(\theta), \quad if\ \ r = R \end{cases}$$



σ_r and $\tau_{r\theta}$ are from aerodynamic solution of hypersonic flow

ν - Poisson coefficients

r, θ - spherical coordinates

k –flow direction unit vector

Stress state

$$\varepsilon_{\alpha\beta}=\begin{cases}\varepsilon_r=\dfrac{\partial u_r}{\partial r}\\[2mm]\varepsilon_\theta=\dfrac{1}{r}\left(\dfrac{\partial u_\theta}{\partial\theta}+u_r\right)\\[2mm]\varepsilon_\varphi=\dfrac{1}{r}(u_\theta\,\mathrm{ctg}\,\theta+u_r)\\[2mm]\gamma_{r\theta}=\dfrac{1}{r}\dfrac{\partial u_r}{\partial\theta}+r\dfrac{\partial}{\partial r}\left(\dfrac{u_\theta}{r}\right)\end{cases}$$

$$\sigma_\alpha=2G\left\{\varepsilon_\alpha+\frac{\nu\sum_{i=1}^{3}\varepsilon_i}{1-2\nu}\right\}$$

$$\tau_{\alpha\beta}=G\gamma_{\alpha\beta}\,;\qquad \alpha,\beta=r,\theta,\varphi,\qquad \alpha\neq\beta$$

Stress intensity

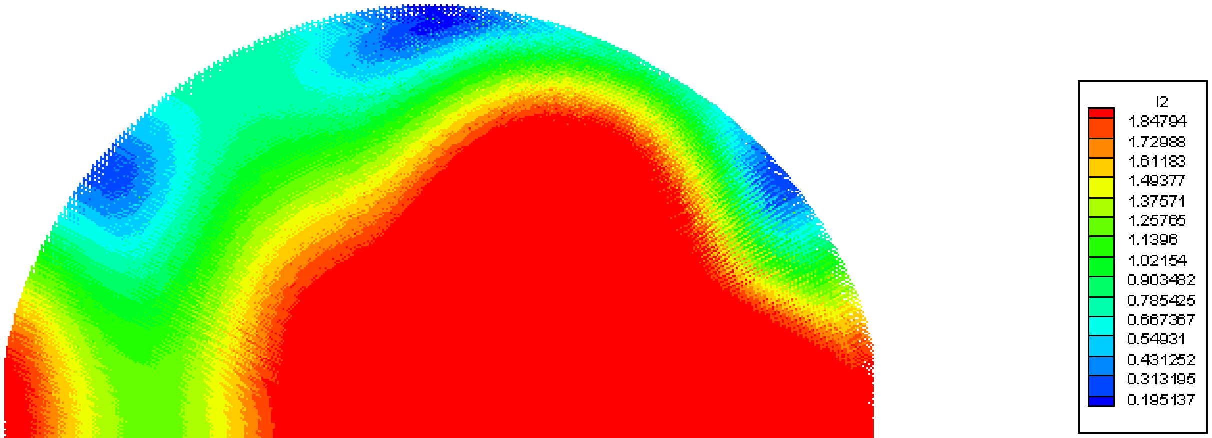
$$\tau_i=\sqrt{I_2}=\sqrt{\frac{1}{6}\left[\ \sigma_r-\sigma_\theta\ {}^2+\ \sigma_r-\sigma_\varphi\ {}^2+\ \sigma_\theta-\sigma_\varphi\ {}^2+\tau_{r\theta}^2\right]}$$

Solution of problem:

L.A.Egorova The stress–strain state and disintegration of a meteoroid moving through the atmosphere/Journal of Applied Mathematics and Mechanics, 2011,

DOI: 10.1016/j.jappmathmech.2011.07.015

Stress intensity



The condition of safety: the dense of shape change potential energy less then critical one

$$\sqrt{3}\tau_i = \sqrt{3}\sqrt{I_2} < \sigma_*$$

If $V \cong const$, then $I_2 = I_2(\rho_г)$

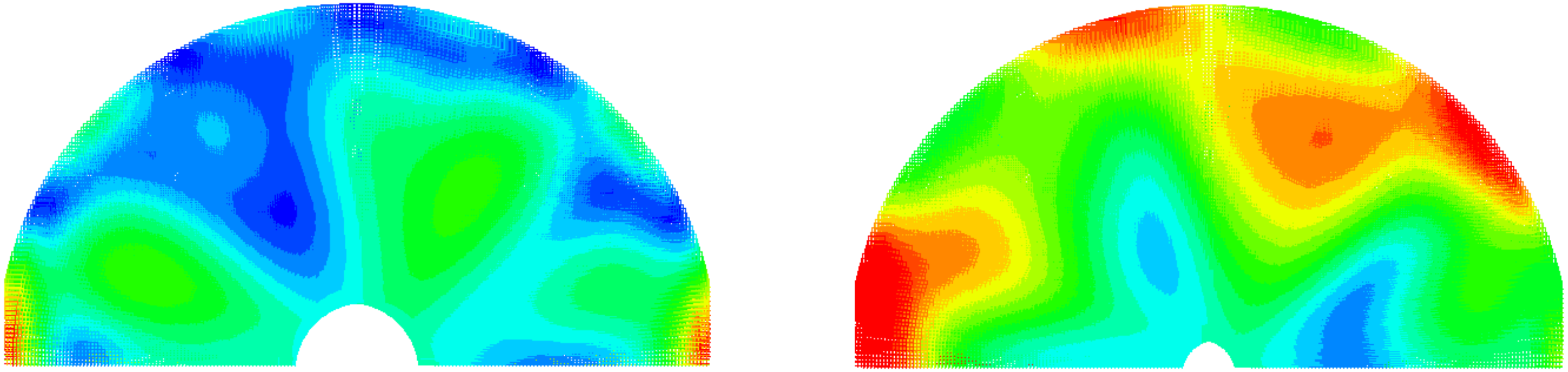
$$\frac{\rho_г(h)}{\rho_г(H)} = e^{-\frac{h}{H}}$$

$$h = -H \ln \frac{\sigma_*}{\sqrt{3}\ \sqrt{I_2(H)}_{max}}$$

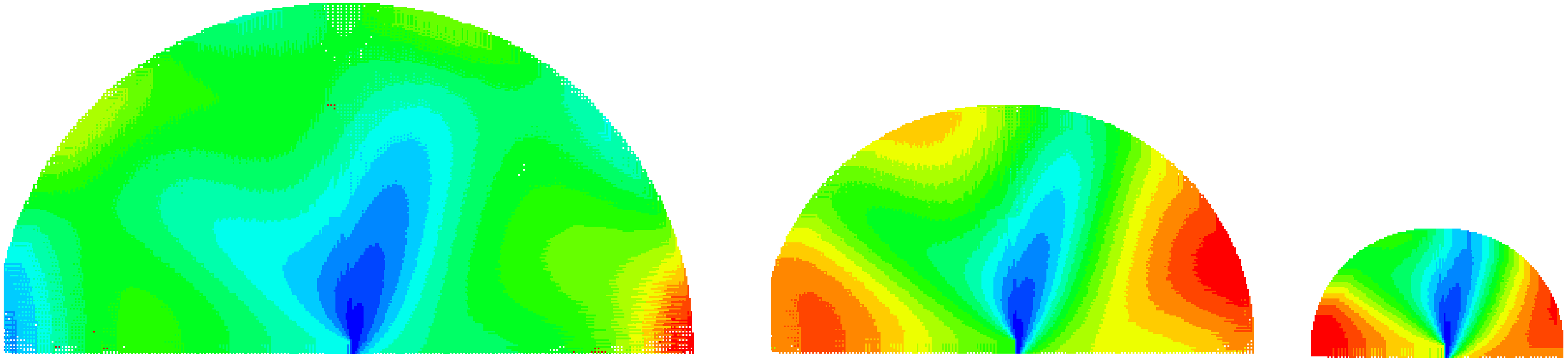
$\sigma_* = 700\ atm,\quad V = 30\, km/s,\quad h_{start} = 7{,}868\, km$ Falls to the surface

$\sigma_* = 50\ atm,\quad V = 30\, km/s,\quad h_{start} = 37{,}6\, km,\quad h_{end} = 26{,}6\, km$

Thermoelastic stress



Problem of vanishing ball (Stephen problem)



Criteria of elastic fragmentation

Condition of no rising flow strength

$$\frac{d}{dt}\left(\rho V^2\right) \le 0, \quad \text{где} \quad \rho = \rho_0 \exp\left(-\frac{h - V_* t + at^2/2}{H}\right)$$

$$V(t) = V - at, \quad a = \frac{3V_*^2 \rho_0}{8r\rho_T} \exp\left(-\frac{h_*}{H}\right)$$

$$\boxed{r \le \frac{3}{4} \frac{H\rho_0}{\rho_T} e^{-\frac{h_*}{H}}}$$

No fragmentation occur

due to elastic stress

$$h_* = -H \ln \frac{\sigma_* 2\sqrt{2}}{\alpha \rho_0 V^2 \sqrt{\Sigma_{\max}}}$$

Spectrum of pieces for the body crashed by explosion

Nemtchinov I.V., Popova O.P., Teterev A V. Entering the large meteotroids into atmosphere: theory and practice. // Inzhen. Phis. Zhurn. 1999. V. 72, 6. Pp. 1233 - 1265. (in Russian)

$$\frac{dN_m}{dm} = Cm^{\frac{k}{3}-2}, k = 1.2$$

N_m – number of particles of mass m

C – constant

Solution

$$N_m = \frac{2}{3}\left(\frac{1}{\overline{m}^{0.6}} - 1\right), \quad \overline{m} = \frac{m}{M}$$

Thermal explosion effect

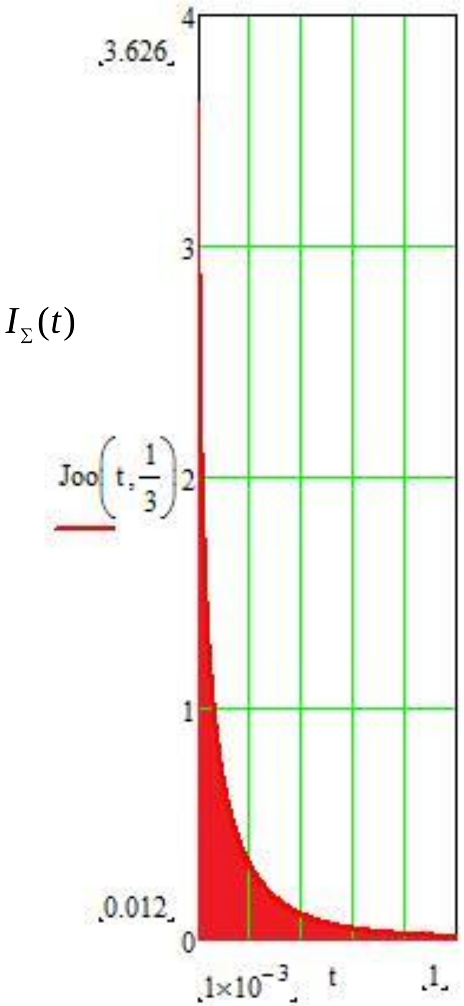
$$\begin{cases} m\dfrac{dV}{dt} = \dfrac{1}{2}c_x\rho_g V^2 S \\ i^*\dfrac{dm}{dt} = \dfrac{1}{2}c_H\rho_g V^3 S \end{cases}$$

The particle will light until velocity >V_*

$$L = \int_0^{t_*} V dt = \frac{r_0}{A}\ln\left(1 + \frac{V_0 - V_*}{V_*}\right), \quad A = \frac{3}{8}c_x\frac{\rho_g}{\rho_b}$$

$$t_* = \frac{8(V_0 - V_*)\rho_b}{3c_x\rho_g V_0 V_*}R$$

Luminosity



$$I = -\tau \frac{V^2}{2} \frac{dM}{dt}$$

$$I_{\Sigma}(t) = \int_{m_*}^{1} N_{m_0} \frac{d}{dm_0} \left(-\tau \frac{V^2}{2} \frac{dm}{dt} \right) dm_0$$

Conclusions

The body moving in the planet atmosphere is under the influence of the aerodynamic loads, the forces of inertia and the heat flux. As a result, the body undergoes ablation and even could be completely destroyed.

First of all, the stressed state within the body at any time is determined through an accurate solution of the Lamé equations.

During the flight of small fragments the thermo elastic forces become significant.

Finally, «thermal explosion» due to the rapid evaporation of small fragments cloud with a typical range of sizes of fragments was considered.

The work receive financial support from FASI, State contract 02.740.11.0615.