EFFECT OF "THERMAL EXPLOSION"

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Spacecraft and meteoroid

• The shape is known and unchanged
• The material is known
• The mass is known and constant
• $V < 16 \text{ km/s} \ (\text{usually } 5 \ 7 \text{ km/s})$

• The shape is unknown and can vary
• The material is unknown
• The mass is unknown and can vary
• $V < 72 \text{ km/s} \ (\text{usually } 11 \ 72 \text{ km/s})$
Meteoroid undergoes

- Aerodynamic drag
- Mechanics loading
- Aerodynamic heating
- Radiation
- Ablation
- Fragmentation
- Explosion
Physical theory of meteors

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

\( M \) – mass,
\( V \) – velocity,
\( A \) – square middle section,
\( \rho \) – air density,
\( CH \) – heat transfer coefficient,
\( Q \) – specific heat of ablation
(Effective enthalpy)
Modern models of fracture meteoroids

1. «Early»
Stanukovich and Shalimov, 1961; ReVelle, 1979 – because of the aerodynamic heating.
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”.

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.
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.
Ivanov, Ryzhansky, 1995 – successive doubling of fragments.
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

\[ \frac{1}{1-2\nu} \text{grad div } u + \Delta u = -\frac{(\alpha + \beta)}{8G} \rho V^2 \frac{1}{R} k \]

\[ \sigma_r = \sigma(\theta), \quad \text{if } r = R \]

\[ \tau_{r\theta} = \tau(\theta), \quad \text{if } r = R \]

\( \sigma_r \) and \( \tau_{r\theta} \) are from aerodynamic solution of hypersonic flow

\( \nu \) - Poisson coefficients

\( r, \theta \) - spherical coordinates

\( k \) – flow direction unit vector
Stress state

\[ \varepsilon_{\alpha\beta} = \begin{cases} 
\varepsilon_r = \frac{\partial u_r}{\partial r} \\
\varepsilon_\theta = \frac{1}{r} \left( \frac{\partial u_\theta}{\partial \theta} + u_r \right) \\
\varepsilon_\phi = \frac{1}{r} (u_\theta \cot \theta + u_r) \\
\gamma_{r\theta} = \frac{1}{r} \frac{\partial u_r}{\partial \theta} + r \frac{\partial}{\partial r} \left( \frac{u_\theta}{r} \right) 
\end{cases} \]

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

\[ \tau_{\alpha\beta} = G \gamma_{\alpha\beta} ; \quad \alpha, \beta = r, \theta, \phi, \quad \alpha \neq \beta \]

Stress intensity

\[ \tau_i = \sqrt{I_2} = \sqrt{\frac{1}{6} \left[ \sigma_r - \sigma_\theta \right]^2 + \sigma_r - \sigma_\phi \right]^2 + \sigma_\theta - \sigma_\phi \right]^2 + \gamma_{r\theta} \left( \frac{\partial \gamma_{r\theta}}{\partial \theta} \right) \]

Solution of problem:
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 \( V \approx \text{const} \), then \( I_2 = I_2(\rho_c) \)

\[ \frac{\rho_c(h)}{\rho_c(H)} = e^{-\frac{h}{H}} \]

\[ h = -H \ln \left( \frac{\sigma_*}{\sqrt{3} \sqrt{I_2(H)}} \right)_{\text{max}} \]

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

\( \sigma_* = 50 \text{ atm}, \quad V = 30 \text{ km/s}, \quad h_{\text{start}} = 37,6 \text{ km}, \quad h_{\text{end}} = 26,6 \text{ km} \)
Thermoelastic stress
Problem of vanishing ball (Stephen problem)
Criteria of elastic fragmentation

Condition of no rising flow strength

\[
\frac{d}{dt} (\varphi V^2) \leq 0, \quad \text{где} \quad \rho = \rho_0 \exp\left(- \frac{h - V_0 t + at^2 / 2}{H}\right)
\]

\[
V(t) = V - at, \quad a = \frac{3V_0^2 \rho_0}{8r \rho_T} \exp\left(- \frac{h_*}{H}\right)
\]

\[
r \leq \frac{3}{4} \frac{H \rho_0}{\rho_T} e^{-\frac{h_*}{H}}
\]

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

\[ \frac{dN_m}{dm} = Cm^{\frac{k}{2}} \], \quad k = 1.2

\( N_m \) – number of particles of mass \( m \)

\( C \) – constant

Solution

\[ N_m = \frac{2}{3} \left( \frac{1}{m^{0.6}} - 1 \right), \quad \frac{m}{M} = \frac{m}{M} \]
Thermal explosion effect

\[ \begin{align*}
    m \frac{dV}{dt} &= \frac{1}{2} c_x \rho_g V^2 S \\
    \dot{i}^* \frac{dm}{dt} &= \frac{1}{2} c_H \rho_g V^3 S
\end{align*} \]

The particle will light until velocity \( V > V_* \)

\[ L = \int_{0}^{t_*} V dt = \frac{r_0}{A} \ln \left( 1 + \frac{V_0 - V_*}{V_*} \right), \quad A = \frac{3}{8} c_x \frac{\rho_g}{\rho_b} \]

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

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

\[ I_{\Sigma}(t) = \int_{m_n}^{1} N_{m_0} \frac{d}{dm_0} \left( -\tau \frac{V^2}{2} \frac{dm}{dt} \right) dm_0 \]
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.

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