Ablation of small iron meteoroids
first results

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talk outline
• introduction
• mathematical model
• boiling of iron drop
• breakup of liquid iron drop
• immediate removal of liquid layer
• conclusions
Small iron meteoroids


Hypothesis:

- Fe meteoroid – high thermal conductivity
- throughout heating and complete melting
- fast ablation of liquid iron drop

Unusual light curves

Low $v$, $h_{beg}$, short trajectories

~ 0.7-2.2 mm

Only Fe lines in spectra

Borovička et al. (2005), fig. 7
The model

• Spherical meteoroid,
• Radially symmetric temperature field
• Thermophysical parameters for pure iron (not Ni-Fe alloy, not oxides)
• Heat diffusion problem - numerically
• Deceleration of meteoroid
• Density of atmosphere: NRLMSISE
• Free molecular flow regime

• Ablation process

1. Vaporization of liquid iron

2. Breakup of liquid iron drop due to aerodynamic loading

3. Immediate removal of liquid layer from the meteoroid surface
Vaporization of liquid iron - model

example: temperature profile in 10mm meteoroid (too big!)

Preheating

Heat diffusion equation: $\rho c \dot{T} = \nabla \cdot (K \nabla T)$

Boundary condition in the center: $\nabla T = 0$

Surface boundary condition:

$$K \nabla T + \varepsilon \sigma T^4 = \frac{1}{8} \Lambda \rho_A v^3$$
Vaporization of liquid iron - model

Melting… $T(R(t)) \geq T_{\text{fusion}} = 1811$K

Heat diffusion equation: $\rho c \dot{T} = \nabla \cdot (K \nabla T)$

Boundary condition in the center: $\nabla T = 0$

Moving phase boundary $s(t)$:

$$l_F \rho_S \dot{s} = K_S \nabla T|_{s^-} - K_L \nabla T|_{s^+}$$

$$T(s(t)) = T_{\text{fusion}}$$

Evaporation rate (Hertz-Knudsen equation):

$$\dot{m} = -\eta p_0 \sqrt{\frac{M}{2\pi R T}} 4\pi R^2$$

Surface boundary condition:

$$K \nabla T + \varepsilon \sigma T^4 = \frac{1}{8} \Lambda \rho_A v^3 + \dot{m} \ell_V$$

$p_0(T)$ – vapor pressure

$\ell_F$ – latent heat of fusion

$\ell_V(T)$ – latent heat of vaporization
Vaporization of liquid iron - model

Boiling… \( T(R(t)) = T_{\text{boiling}(p)} \)

Heat diffusion equation: \( \rho c \dot{T} = \nabla \cdot (K \nabla T) \)

Boundary condition in the center: \( \nabla T = 0 \)

Moving phase boundary \( s(t) \):

\[
\ell_{fp} \rho_S \dot{s} = K_S \nabla T|_{s-} - K_L \nabla T|_{s+}
\]

\( T(s(t)) = T_{\text{fusion}} \)

Evaporation rate – from surface boundary condition:

\[
\dot{m} = -\frac{1}{\ell_v} \left( \frac{1}{8} \Lambda \rho_A v^3 - K \nabla T - \varepsilon \sigma T^4 \right)
\]

\( T(R(t)) = T_{\text{boiling}(p)} \)

Radiation:

\[
I = -\frac{1}{2} \tau \dot{m} v^2
\]
Iron material parameters

- Density vs. temperature
- Thermal capacity vs. temperature
- Thermal conductivity vs. temperature
- Emisivity vs. temperature
Iron material parameters
Vaporization of liquid iron - results

Model parameters:

- $m_\infty, v_\infty, z$ – from observations
- heat transfer coefficient $\Lambda = 1$
- drag coefficient $\Gamma = 1/4$
- evaporation efficiency $\eta = 1$
- radiative efficiency $\tau = 0.01$

Borovička et al. (2005)

Observations: Fusion starts, completely melted, boiling surface.
Breakup of liquid iron drop - results

- Due to aerodynamic loading
- Breakup conditions described by Weber number:

\[ We = \frac{2R\rho v^2}{\sigma} \geq 12 \]

- $2R$ – drop size
- $\rho v^2$ - dynamic pressure
- $\sigma$ - surface tension
Immediate removal of liquid layer - results

Borovička et al. (2005)
Light curves comparison

synthetic light curves for two different meteoroid masses deduced from photometry (solid and dashed lines)

immediate removal of liquid layer

observed meteor

vaporization of liquid layer
Conclusions + future work

• *Vaporization of liquid Fe drop* or *Breakup of liquid Fe drop* can not explain observed iron meteors (too slow or occurs too late).

• Immediate removal of liquid Fe layer – can explain come features

• We will focus on *dynamics of layer of liquid Fe and its shedding* from the meteoroid.

Assumed model improvements:

• Oxidation of molten layer

• Termophysical parameters for Ni-Fe alloy (and oxides) instead of pure Fe.

• Variation of model parameters \((\Lambda, \tau)\) and initial masses.

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