Laboratory simulation of micrometeoroid ablation


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Motivation

• Understanding Earth’s cosmic dust environment (sources and evolution of interplanetary dust particles)
• Total meteoric material input to Earth’s atmosphere
• Sensitivity of meteor radars to mass, composition and velocity (uncertainties of $\beta$–ionization probability)
• Meteoric ablation delivers exotic material to the MLT region (relevant to NLC/PMC, atmospheric chemistry, meteoric smoke particles, etc.)

Here we report the results on a recent experimental campaign in a newly developed experimental facility (Thomas et al., GRL, 2016)
The understanding of the ablation process is paramount

**Table:** Estimates of the global IDP input rate to the Earth’s atmosphere (increasing order).

<table>
<thead>
<tr>
<th>Technique</th>
<th>IDP input [t/d]</th>
<th>Reference</th>
<th>Potential Problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micrometeorites in polar ice</td>
<td>4 ± 1</td>
<td>Taylor et al. [1998]</td>
<td>Lower limit, since most IDPs ablate</td>
</tr>
<tr>
<td>High performance radars</td>
<td>5 ± 2</td>
<td>Mathews et al. [2001]</td>
<td>Possible velocity bias</td>
</tr>
<tr>
<td>Fe in Antarctic ice core</td>
<td>15 ± 5</td>
<td>Lanci et al. [2007]</td>
<td>Very little wet deposition by snow</td>
</tr>
<tr>
<td>Na layer modeling</td>
<td>10 - 30</td>
<td>Plane [2004]</td>
<td>Depends on vertical eddy diffusion</td>
</tr>
<tr>
<td>Fe/Mg in stratos. sulphate layer</td>
<td>22 – 104</td>
<td>Cziczo et al. [2001]</td>
<td>Data limited geographically</td>
</tr>
<tr>
<td>Aerosols at South Pole</td>
<td>30</td>
<td>Tuncel &amp; Zoller [1987]</td>
<td>Data limited geographically</td>
</tr>
<tr>
<td>Optical extinction measurements</td>
<td>40</td>
<td>Hervig et al. [2009]</td>
<td>Questionable refractive indices</td>
</tr>
<tr>
<td>Zodiacal dust cloud model</td>
<td>41±14</td>
<td>Nesvorny et al. [2011]</td>
<td>Needs to be constrained by radars</td>
</tr>
<tr>
<td>Conventional meteor radars</td>
<td>44</td>
<td>Hughes [1978]</td>
<td>Extrapolation</td>
</tr>
<tr>
<td>Os in deep-sea sediments</td>
<td>101 ± 36</td>
<td>Peuker-Ehrenbrink [1996]</td>
<td>Focusing by ocean currents</td>
</tr>
<tr>
<td>Long Duration Exposure Facility</td>
<td>110 ± 55</td>
<td>Love &amp; Brownlee [1993]</td>
<td>Sensitive to particle velocity</td>
</tr>
<tr>
<td>Lidar Fe/Na and vertical wind meas.</td>
<td>150± 38</td>
<td>Huang et al. [2015]</td>
<td>Ablation/transport model dependence</td>
</tr>
<tr>
<td>Fe in Greenland ice core</td>
<td>175 ± 68</td>
<td>Lanci &amp; Kent [2006]</td>
<td>Wet deposition may be important</td>
</tr>
<tr>
<td>Ir and Pt in Greenland ice core</td>
<td>214 ± 82</td>
<td>Gabrielli et al. [2004]</td>
<td>Wet deposition may be important</td>
</tr>
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<td>Ir in deep-sea sediments</td>
<td>214</td>
<td>Wasson &amp; Kyte [1987]</td>
<td>Focusing by ocean currents</td>
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</table>

After JMC Plane, 2012
Funded by NASA, Solar System Exploration Research Virtual Institute (SSERVI) program

Check out: IMPACT.COLORADO.EDU
Testing and calibration (dust accelerator)

3 MV Pelletron

Accelerated dust:
• 0.01-2 micron
• 1-60 km/s
• Various materials
Particle mass vs. velocity distribution

Dust material samples:
- Iron
- Carbon
- Olivine (coated)
- ........
Research and development enabled by the dust accelerator

Dust detector and analyzer instrument development

Lunar Dust EXperiment on LADEE

Hyperdust: advanced dust telescope

Hypervelocity impact studies

Ice target impact studies

Laboratory simulation of dust impact signals detected by spacecraft
The ablation facility

- Ablation chamber (~40 cm)
- Differential pumping
- Two 500 l/s turbo-pumps
- Dust
The ablation facility

- Ablation chamber (~40 cm)
- Four optical ports
- Differential pumping
- Dust
What’s inside the ablation chamber

Segmented charge collectors

Impact Detector
Shield
CSAs and E-field
Skimmer

15-200 mTorr

10^{-3} Torr
10^{-5} Torr

10^{-7} Torr

Dust

B

Velocity: 19.1 km/s
Mass: 5.4e-18 kg

C

Position (cm)

Elementary Charges (Thousands)

Channel Number

Dust
How good is the collection efficiency?

• Monte Carlo simulation (Fe + N₂)
• Hard-sphere collision model
• Ions collected close to location of birth
• >99% of ions collected
IONIZATION EFFICIENCY
**Historical overview of prior measurements of ionization efficiency**

1- Ionization cross section measurements

- **Na$^+$ beam**
- Na beam, ioniz.
- CX coll.

**Elements:** Na, K
**Gases:** N$_2$, O$_2$, etc.

- Bydin & Bukhteev, 1960
- Moutinho et al., 1971
- Cuderman et al., 1972
- Kleyn et al., 1978

2- Dust accelerator/ablation measurements

- **Fe, Cu, LaB$_6$**
- Gases: N$_2$, CO$_2$, Ar, air, etc.

- Slattery and Friichtenicht, 1966
- Friichtenicht et al., 1967
- Friichtenicht and Becker, 1971
Jones (1997) – the standard reference

- Ionization efficiency, $\beta_0$
- Two assumptions made
  1: $\sigma_{el} \sim 1/v^{0.8}$
  2: $\sigma_{ion} \sim (v - v_0)^2$
- Assumed form
- Where

$$\beta_0 = \frac{\sigma_{ion}}{\sigma_{tot}}$$
$$\sigma_{tot} = \sigma_{el} + \sigma_{ion}$$

$$\beta_0 = \frac{c(v - v_0)^2 v^{0.8}}{1 + c(v - v_0)^2 v^{0.8}} \quad \beta_0 \leq 1$$

$$v_0^2 = \frac{2(m + M)}{mM} \varphi_{IE}$$
Jones model – II.

### Table 1. Ionization parameters for elements assumed to be present in the composition of a cometary meteoroid.

<table>
<thead>
<tr>
<th>Element</th>
<th>%</th>
<th>$p$</th>
<th>$v_0$</th>
<th>$c \times 10^6$</th>
<th>$\mu$</th>
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<tr>
<td>O</td>
<td>45</td>
<td>0.617</td>
<td>16.7</td>
<td>4.66</td>
<td>0.57</td>
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<tr>
<td>Fe</td>
<td>15</td>
<td>0.059</td>
<td>9.4</td>
<td>34.5</td>
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<tr>
<td>Mg</td>
<td>9</td>
<td>0.082</td>
<td>11.1</td>
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<td>0.86</td>
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<td>Si</td>
<td>31</td>
<td>0.242</td>
<td>11.0</td>
<td>18.5</td>
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<tr>
<td>Cu</td>
<td>–</td>
<td>–</td>
<td>9.1</td>
<td>15.3</td>
<td>2.25</td>
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- Jones calculates $\beta$, the total ionization probability allowing subsequent ionizing collisions
- Hard-sphere collision model assumed

\[
\beta(v) = \beta_0(v) + (1 - \beta_0(v)) \frac{(1 + m)^2}{2v^2\mu} \int_{v_0}^{v} \beta(v')v' dv'
\]

Inelastic collisions ignored

$\sim 2 \times$ at high impact velocities
Jones model – III. – Fe

Slattery & Friichtenicht (1967) data span (20 – 45 km/s)

\[ \beta_0 = \frac{c(v - v_0)^2 v^{0.8}}{1 + c(v - v_0)^2 v^{0.8}} \]
From Vondrak et al., 2008, for ionization in N2

Slattery and Friichtenicht (1967) data

The Jones model (1997)

\[
\beta_0 = \frac{c(v - v_0)^2 v^{0.8}}{1 + c(v - v_0)^2 v^{0.8}}
\]

\[
v_0^2 = \frac{2(m + M)}{mM} \varphi_{IE}
\]

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Ionization efficiency, Fe + N₂, complete ablation

Complete ablation: $\beta = \frac{Q_{\text{TOTAL}}}{(\# \text{ atoms})}$

- $> 20 \text{ km/s}$, $> 15 \text{ mTorr}$
- Complete ablation occurs
- Velocity change is small
- Collected pos/neg charges are equal
- Previous measurements
- New fit using Jones (1997)

Thomas et al., GRL, 2016
Ionization probability of Fe in various gases

\[ \beta_0 = \frac{c(v - v_0)^2 v^{0.8}}{1 + c(v - v_0)^2 v^{0.8}} \]

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<th>Gas</th>
<th>Parameter $c \times 10^6$</th>
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<td>$N_2$</td>
<td>20.4</td>
</tr>
<tr>
<td>Air</td>
<td>19.7 (34.5 from Jones et al. (1997))</td>
</tr>
<tr>
<td>$CO_2$</td>
<td>18.6</td>
</tr>
<tr>
<td>He</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Results in Thomas et al., GRL, 2016
HOW WELL CAN WE MATCH THE ABLATION PROFILE USING MODELS?
Ablation model (after Vondrak et al., 2008)

\[
\frac{dV}{dt} = -\Gamma V^2 \frac{3\rho_a}{4\rho_m R}
\]

Momentum equation, \( \Gamma = \text{molecular drag coefficient} \)

\[
\frac{dm_i^A}{dt} = \gamma p_i S \sqrt{\frac{\mu_i}{2\pi k_B T}}
\]

Mass loss rate, \( \gamma = \text{uptake coefficient} \)

\[
\frac{1}{2} \pi R^2 V^3 \rho_a \Lambda = 4\pi R^2 \varepsilon \sigma (T^4 - T_{\text{env}}^4) + \frac{4}{3} \pi R^3 \rho_m C \frac{dT}{dt} + L \frac{dm}{dt}
\]

Energy conservation (heating) equation

\( \Lambda \) – heat transfer coefficient

Ionization rate: \((dm/dt) \times \beta \)

\( \beta = \text{Ionization efficiency} \)
Solutions to the ablation model

‘Fast’ particle: **18.6 km/s**, 50 nm in radius

‘Slow’ particle: **10.4 km/s**, ~70 nm in radius

Generated charge = \((\frac{dm}{dx}) \times \beta\)

Incomplete ablation \(\rightarrow\) uncertainty of mass loss
Monte Carlo analysis of experimental data

Best fits:

\[ \Lambda = 0.42 - 0.48 \]

Particle 1: \( r_0 = 39 \text{ nm}, v_0 = 30 \text{ km/s} \)

Particle 2: \( r_0 = 40 \text{ nm}, v_0 = 26 \text{ km/s} \)

Particle 3: \( r_0 = 41 \text{ nm}, v_0 = 29 \text{ km/s} \)

Particle 4: \( r_0 = 42 \text{ nm}, v_0 = 33 \text{ km/s} \)

Chamber Pressure: 48.9 mTorr
The difficulty of determining $\beta$ at velocities < 20 km/s

- Velocity: 10.4 km/s
- Radius: 70 nm
- Material: Fe
- Gas: $N_2$
- Best fit parameters
  - $\Lambda$: $\approx 0.55$
  - $\Gamma$: $\approx 0.75$

$\beta$ is strongly varying with velocity

Difficult to untangle dependence on $\beta(v)$ and ($\Gamma, \Lambda$)
Ongoing improvements: optical velocity measurement
(with the help of Bob Marshall)

Photomultiplier detectors with overlapping Field-of-View
Summary/Conclusions

• The dust accelerator enables the experimental investigation of the ablation process
• First set of measurements at higher velocity and complete ablation performed, ionization efficiency determined.
• Updates to the facility under way to extend measurements to lower velocities
BACKUP SLIDES
Fast particle

![Graph showing the relationship between ionization efficiency and velocity for a fast particle. The graph includes a line for Jones model (Fe) and a data point indicating a measured value.](image-url)
Need to consider change of velocity during the ablation process.

The calculation of mass loss over each collection plate is dependent on the ablation model and parameters used (uncertainty).

Need to analyze a large assemble of particles for reliable find the fitting parameters.

\( \beta \) will depend on parameters in the ablation mode and the assumed shape of \( \beta(v) \).
CABMOD and Hood and Horanyi (1991) are similar

Compared model by Hood and Horanyi (1991) to CABMOD (Vondrak et al, 2008).

\[ v_0 = 25.8 \text{ km/s}, \ r_0 = 40.3 \text{ nm}, \ P = 16.0 \text{ mTorr}, \ N_2 \text{ Gas} \]

\[ v_0 = 25.1 \text{ km/s}, \ r_0 = 57.5 \text{ nm}, \ P = 48.9 \text{ mTorr}, \ N_2 \text{ Gas} \]
More careful analysis needed at low velocities