Artificial Meteor and Chelyabinsk Ablation Test using Arc-heated Wind Tunnel

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Explosion phase at 62.7 km: numerous strong emissions were seen in the visible spectrum. Exotic lines; Cu I (5700 and 5782 Å), Zn I lines (4680, 4722, and 4811 Å), Mo I (5506 and 5533 Å), Xe I (4624 and 4671 Å).
• The maximum absolute magnitude of the fireball of -12.6 was reached at a height of 67 km
• The dynamic pressures acting on the spacecraft at the fragmentation points were only 1–50 kPa
• No spacecraft fragment was seen to survive below a height of 47 km
• The integral luminous efficiency of the spacecraft was 1.3% and the capsule was 0.03%

<table>
<thead>
<tr>
<th>Geocentric orbit</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Eccentricity</td>
<td>1.32</td>
</tr>
<tr>
<td>Inclination</td>
<td>34.52°</td>
</tr>
<tr>
<td>Right ascension of the ascending node</td>
<td>7.58°</td>
</tr>
<tr>
<td>Pericenter distance</td>
<td>6310 km</td>
</tr>
<tr>
<td>Longitude of pericenter</td>
<td>255.58°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heliocentric orbit (J2000.0)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Semimajor axis</td>
<td>1.278 AU</td>
</tr>
<tr>
<td>Perihelion distance</td>
<td>0.9824 AU</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.231</td>
</tr>
<tr>
<td>Inclination</td>
<td>1.59°</td>
</tr>
<tr>
<td>Argument of perihelion</td>
<td>145.63°</td>
</tr>
<tr>
<td>Longitude of the ascending node</td>
<td>82.360°</td>
</tr>
</tbody>
</table>

Borovická, Abe, Shrbený, Spurný, Bland, 2011
To understand ablation processes of atmospheric entry, artificial meteor test is carried out using JAXA’s facility.

JAXA/ISAS Arc-heated Wind Tunnel
High enthalpy conditions
T~10,000K, V~6km/s, 0.6MPa

UV-VIS-NIR spectroscopy

\[
\frac{dT_m}{dt} = \frac{A}{cm^{1/3}\rho_m^{2/3}} \left( \frac{C_h \rho_a V^3}{2} - 4\sigma \epsilon (T_m^4 - T_a^4) - L \frac{dm}{dt} \right)
\]
Strength of Meteoroids by MU Radar Meteor head-echo

- **Very slow speed**
- **fragile dust balls**
- **Very weak**
- **Strong**
- **(refractory)**
- **Perseids**
- **109P/Swift-Tuttle**
- **Geminids**
- **3200 Phaethon**
- **very strong Geminids; not depending on size**

*S. Abe, J. Kero, T. Nakamura et al. (in prep)*
High speed camera
Phantom v711

JAXA/ISAS Arc-heated Wind Tunnel

Spectroradiometer & Spectrograph
OceanOptics QEPro, HR4000CG-UV-NIR
Chelyabinsk Meteorite; 2013/2/15

Diameter~19m, Mass~10,000ton
Entry velocity=19km/s
Absolute magnitude; -26~-30Vmag (10times of Sun)
Kinetic energy; 500Kton TNT=33xHiroshima
Chelyabinsk samples light and dark lithology in the cm scale.

(W); Light (White) sample

(B); Dark (Black) sample

T. Arai, S. Abe et al.
LPI (2014) 2860.
Artificial Meteor Test using JAXA Arc-heated wind tunnel
Chelyabinsk (LL5)

UV-VIS Spectrum (1/30s)
Fe+Mg+Al+C (FMAC) with Sabo
UV-VIS Spectrum (1/30s)
Blackbody is dominant for low-velocity meteors.
**FMAC**

- **Na**
- **Mg**
- **Fe**
- **Fe+**

**Differential ablation**

*Intensity vs. Time [s]*
T \sim 10,000 \text{ K}, v \sim 6\text{ km/s}

Heating rate \sim 30 \text{ MW/m}^2

High speed imaging (exp=10\mu s, 1000 fps)
Chelyabinsk

High speed imaging (exp=10µs, 1000 fps)
Mass Loss Rate, $dm/dt$

Y-axis: Rest of mass [\%]  
X-axis: Time [s]

- **type1**: moderate
- **type2**: steady
- **type3**: gentle

Fe+Mg+Al+C (17.7\%)

Fe+Mg+Al+C (29.2\%)

Chelyabinsk (W)

Chelyabinsk (B)

3D printer (10.0\%)

3D printer (20.0\%)
**Fragmentation**

\[ N = a \times L^{-\alpha} \]

\[ \alpha = 1.67 \]

\[ \alpha = 1.50 \]

Košice: \( \alpha = 1.53 \)

Sutter’s Mill: \( \alpha = 1.51 \)

Bassikounou: \( \alpha = 1.32 \)

(V. Vinnikov et al. 2014)
Fe+Mg+Al+C (FMAC) : Maximum compressive stress as a function of Porosity (ultimate strength)

\[ y = -3.546x + 147.443 \]

stress-strain diagram

Porosity [%] vs. Compressive Stress [MPa]

movie (16x)
oroid.

We have therefore no Na I (1), and FeI (15) multiplets in Geminid and spectrum, and retrograde orbit (tics of this population: high material strength, no Na in the 8.2.2. Cometary Na-free meteoroids pretation implies that the Geminid meteoroid stream was not a separate body. Younger meteoroids which have suffered oroid, i.e., with the time the meteoroid is orbiting Sun as that the Na content is correlated with the age of the mete-

We suggest the explanation have nearly normal content of Na. The wide spread of Na of them can be classified as Na-poor and some Geminids Geminid meteors really fall into the Na-free class but most diagram to see their spectral classification (Fig. 17). Some

We therefore plotted Geminids in the Mg–Na–Fe ternary 07 AU) are also found. Another meteoroid stream, the Geminids, also have small perihelion distance: (Spurn
techin fireball!
and angular speed. In addition, we have one good example with known orbits but another 4 single station meteors may three meteoroids of this population among the meteoroids

The other part of Na-free meteoroids have perihelia close (D)

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diagram (Fig. 17 together with Geminids. The discovery of differentiated meteoroids on (LNT)

(Levison et al., 2002)—during the processes responsible for the release of sodium from the content of Na. Ion sputtering, nevertheless, is one of cosmic ray produced cometary crust (e.g.,Strazzula et al., 1991) deal only with organic elements and do not predict the possibility that Na-free meteoroids come from the pri-

crater surface(Levison et al., 2004). The long ex-

sponding to meteoroids larger than (D)

Harris et al., 2001). The relatively high proportion of Na-free meteoroids among sporadic meteoroids on Halley type or-

Similarly to the population of Na-free meteoroids, the Monocerotids form a transitional material between Na-free major axis (D)

Monocerotid stream was deficient in bright meteors, corre-

Perseids (59km/s) ○

Taurids (29km/s) ▽

Leonids (71km/s) ▼

α Capricornids (23km/s) ▲

S. δ Aqua (41km/s) ◆

20

15

Perseids

Geminids

Sporadic

LL5

CM2

Olivine (13.7%)

Fe+Mg(34.5%)

FMAC1(29.2%)

FMAC1(17.7%)

FMAC2(44.4%)

(Vojacek, V., et al., 2015) ground velocity

Draconids (20km/s) □

Orionids (66km/s) ■

Geminids (35km/s) ○

Quadrantids (41km/s) ●

Lyrids (49km/s) △

Perseids (59km/s) ◆

Leonids (71km/s) ▼

α Capricornids (23km/s) ▲

S. δ Aqua (41km/s) ◆

This study

α

a

⩾
Comparison between Artificial meteor and Geminids

FMAC1 (29.2%)
FMAC1 (17.7%)
FMAC2 (44.4%)
Geminids

Time evolution of Na/Mg/Fe ratio
Color changes with time.
Artificial Meteors for Business & Science
ALE Co. Ltd., Tokyo Metropolitan Univ., Nihon Univ., Teikyo Univ.
Thank You

On-demand Meteor Shower

First test in 2018
Chelyabinsk (6.0%) \( T = 2473 \pm 31 \) [K]

Olivine (13.7%) \( T = 2442 \pm 35 \) [K]

Jbilet Winselwan (CM2)

LL5 (6.0%)

CM2 (23.0%)

オリビン (13.7%)
Differential ablation (Na early release) signature of structure & volatility of meteoroids

S. Abe (2009), Meteoroids and Meteors - observations and connection to parent bodies, Springer
Vibration-rotation temperature of ~13,000 K for N$_2^+$ (1$^-$) and CN is reasonable.
• The vibration temperature of molecular $N_2^+ (1^-)$ as dramatically changed from 4,000 K @ 92.5km to 13,000 K @ 82.9km.

• The observed spectra are a superposition of the post shock plasma radiation which is mixed with a shock layer heating and downward plasma. Thus, it is logical to understand that the high temperature region was induced by a shock layer of the spacecraft which rapidly grew between 92.5 km and 82.9 km in height.

• $N_2^+ (1^-)$ bands originated from the spacecraft was much stronger than CN bands originated from the capsule in which Carbon was the major erosion product of the Carbon-Phenol heat shield of the capsule as seen by the Stardust capsule (Jenniskens 2010; Winter & Trumble 2011).
Discovery of Molecular Bands in Leonid Fireball (-5 mag.)

\[ \text{Atoms} + \text{N}_2^+ + \text{OH} \]

**Atom; 4500K**  
**N}_2^+; 10000K**

\[ \text{N}_2^+ \text{ was expected for the SRC emission.} \]

- Bow shock
- Recompression shock
- Wake core
- Thermochemical non-equilibrium state
- Neck
- Backward flow

Observed number of meteors, normalized by beam area, versus RCS (Radar Cross Section) and radial distance from beam centre.

>150k meteoroids were detected during 2009-2015

3,000 - 4,000 meteor head echoes / day
Data rate ~ 20GB/hour
average σ of velocity ~ 0.25 km/s
average σ of perihelion = 0.003 AU