Super-orbital entry of artificial asteroids (Apollo, Hayabusa) and CFD/Radiation/Thermal analysis of the entry of Chelyabinsk meteorite

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Outline

• Elements on super-orbital re-entries: Apollo, Genesis, Stardust, and Hayabusa.

• Trajectory analysis of Chelyabinsk and St Valentine meteoroid entries;

• CFD/Thermal/Radiation entry analysis.

• Conclusions.
Apollo - 1

• To prepare manned return mission to Moon, two prototype vehicles were flown: Apollo 4 and 6.

• TPS was made of AVCOAT a highly ablative and catalytic material. The entry regime was sufficient to provoke a strong pyrolysis gas injection.

• Vehicles where equipped with radiometers (4) and calorimeters (27).

• Apollo 6 trajectory was degraded due to an unsuccessful attempt to reignite Saturn 5.
• Usually the numerical rebuilding found in the literature compare well with the flight data.

• At peak heating convective and radiative heating were 3.5 and 1.7 MW/m². 2/3 of the convective heating was due to absorption of radiation in the boundary layer (intrinsic components were 1.1 and 4.1 MW/m²).

Rates of surface vaporization and pyrolysis gas at Apollo 4 stagnation point (Park, 2004).
Russian missions

- Sample return mission to the Moon: Luna 16. Entries have also been performed into Venus atmosphere (Venera, Vega).

- No flight data published on these different missions.

- In the frame of ISTC, developments were carried out to assess the blockage for Mars sample return.

- Blowing effect on heterogeneous catalysis assessed numerically and experimentally at IPM for Mars entry conditions.
Genesis

- Little data is available in the literature on Genesis particularly for aerothermodynamics and heat-shield design, indeed most of the works performed on ablation and aerothermodynamics heating were not published.

- TPS was made of carbon-carbon.

- Most of the TPS was ablated during re-entry. Peak ablation rate was 0.5 kg/s (0.2 for Stardust). Ablation was due to oxidation leading to carbon atoms and CO.
Stardust-1

• At 12.6 km/s Stardust entry was the fastest ever attempted into Earth atmosphere.

• TPS was made of PICA a lightweight ceramic ablator close to carbon phenolic with the same elemental composition. Backcover was made of SLA 561.

• Heat-flux during entry has been computed using a loosely coupled approach accounting for radiation and ablation.

• At wall, fully catalytic and equilibrium catalytic conditions were used.
Ablation products:

- Dominant ablation species were CO and C$_3$, secondary products were C, HCN, CN and H.
- Main absorbing species was C$_3$.
- CO lowers significantly the wall enthalpy.
Turbulence effects:

• Turbulent and laminar injection rates computed by Gupta (1999).

• Strong impact of turbulence on the injection rate.

Mass injection rate at peak heating (Gupta, 1999).
• Blockage efficiency is 35% for a laminar flow.

• For turbulent computations, reduction of heat flux is still 35% at stagnation point but only 13% on the conical flank, Turbulence effects offset the blockage.

Mass injection rate at peak heating (Gupta, 1999).
As previously, blockage efficiency is around 35%.

Maximum of heat-flux decreases from 11 MW/m$^2$ to 6.4 MW/m$^2$.

Radiative heating was around 10% of total heating at stagnation point, 7% at the shoulder.

Mass injection rate at peak heating (Olynick et al, 1999).
Stardust - 6

- Airborne observation campaign was performed during capsule re-entry.

- Post-flight analysis carried out focusing on in-flight radiation measurements.

- CFD + radiation analysis done by Boyd & Jenniskens (JSR 2010) for high altitude part of the trajectory. Good agreement found with flight data for $\text{N}_2^+$ radiation.

Measured and computed spectra for air molecular bands at 81 km (Boyd, 2010).
Hayabusa -1

• Sample return mission to the asteroid Nereus, with a sample return capsule of 20 kg.

• Due to the lack of flight data for a high-speed Earth entry and to the similarity with a Venus entry, JAXA has undertaken a large effort based on the data obtained during the Pioneer-Venus mission and the tools used to design the TPS have been validated with this data.

• Ahn & Park (1997) have investigated the suitability of a carbon phenolic TPS for this mission.
Hayabusa - 2

- TPS investigations were performed accounting for convective blockage.

- Convective blockage was determined using boundary layer analysis. The approach was based on several hypothesis:
  - Most significant reaction is the combustion of carbon producing CO.
  - Catalytic recombination of oxygen and nitrogen were neglected.
  - No surface nitridation.
  - Carbon char sublimates and the main product is C$_3$. 
Hayabusa - 3

- Turbulent transition was assumed to occur at the sonic point (30° location). Radiative flux was reaching a value of 4 MW/m² at stagnation point for a total of 12 MW/m². At the frustum edge total flux was 23 MW/m² due to turbulent heating.

- Airborne observation campaign carried out during re-entry flight.
Hayabusa - 4

- **Post-flight TPS analysis** performed (Suzuki et al, JSR 2014):
  - CFD reconstruction + Thermal response + Radiation;
  - Surface recession 2mm;
  - Good agreement found for surface temperature

Measured and computed surface temperatures (Suzuki et al, 2014).
Summary

• A first survey of the available data for high-speed Earth entry has been carried out.

• There is a lack of in-flight measurements for such entries: only flight data for Apollo 4 is available. Other data are from airborne observations.

• Concerning ablation: moderate injection rates. Cooling effect due to blowing offset, at least partially by turbulence.
Meteoroids
### Selected cases

<table>
<thead>
<tr>
<th>Chelyabinsk</th>
<th>“St Valentine”</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>06/02/2016</td>
</tr>
<tr>
<td>Well documented</td>
<td>Less documented</td>
</tr>
<tr>
<td>Very large (&gt;15m diameter)</td>
<td>Smaller (~5m diameter)</td>
</tr>
<tr>
<td>Composition: chondrite</td>
<td>Composition: unknown</td>
</tr>
</tbody>
</table>
Chelyabinsk

- Origin: Asteroid (chondrite with ~10-30% iron)
- Entry velocity: 19160±150 m/s at 100 km
- Entry angle: 18.2°
- Mass ~ 7-13 $10^6$ kg
- Diameter ~ 15-19 m
- Observed radiation pike: 54.8° N, 61.1° E, 23.3 km (18.3 km/s)
- Estimated dissipated energy: 440 kt
- Explosion altitude: 15-20 km
Chelyabinsk – Trajectory analysis

\[ \beta = \frac{\text{Mass}}{\text{Cd} \times \text{Section}} \]

<table>
<thead>
<tr>
<th>Diamètre</th>
<th>19 m</th>
<th>15 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Masse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13,10^6 kg</td>
<td>48,8</td>
<td>78,3</td>
</tr>
<tr>
<td>7,10^6 kg</td>
<td>26,2</td>
<td>42,1</td>
</tr>
</tbody>
</table>
Chelyabinsk - Radiation correlations

![Graph showing radiation correlations with altitude.](image)
Chelyabinsk - Influence of the lift

![Graph showing velocity and radiative heat transfer as a function of altitude with different lift/drag ratios.](image)

- Observed explosion
- Height (km): 60, 40, 20, 0
- Velocity (km/s): 20, 18, 16, 14, 12, 10, 8
- Radiative heat transfer (GW/m²): 1200, 1000, 800, 600, 400, 200, 0

- L/D = 0
- L/D = 0.1
- L/D = 0.2
- L/D = 0.3
- L/D = 0.32
St Valentine

- Observed radiation pike: 30.4° S, 25.5° W, 31.0 km
- Observed velocity at radiation pike: 15.6 km/s
- Entry angle: 39.8°
- Heading angle: 35.7° (from North)
- Diameter: 2-8 m
- Estimated dissipated energy: 13 kt
- Explosion altitude: 23 km
St Valentine - Diameter estimation

Calculated mass (from energy) : 224 t

<table>
<thead>
<tr>
<th>Diameter (m)</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>53,6</td>
</tr>
<tr>
<td>3</td>
<td>15,9</td>
</tr>
<tr>
<td>4</td>
<td>6,70</td>
</tr>
<tr>
<td>5</td>
<td>3,43</td>
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<tr>
<td>6</td>
<td>1,98</td>
</tr>
<tr>
<td>7</td>
<td>1,25</td>
</tr>
<tr>
<td>8</td>
<td>0,84</td>
</tr>
</tbody>
</table>

Metals → Rocks → Dirty ice
St Valentine - Velocity and heating

(Tauber and Sutton correlations)
St Valentine - Radiation correlations
## Calculation points

<table>
<thead>
<tr>
<th>Event</th>
<th>Altitude (km)</th>
<th>Meteor velocity (km/s)</th>
<th>Atmosphere temperature (K)</th>
<th>Atmosphere density (kg/m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed radiation pike</td>
<td>31</td>
<td>16,0</td>
<td>227,5</td>
<td>0,0159</td>
</tr>
<tr>
<td>Observed explosion</td>
<td>23</td>
<td>15,2</td>
<td>219,6</td>
<td>0,0546</td>
</tr>
<tr>
<td>Calculated conv. pike</td>
<td>18</td>
<td>13,9</td>
<td>216,6</td>
<td>0,115</td>
</tr>
<tr>
<td>Calculated radiation pike</td>
<td>17</td>
<td>13,4</td>
<td>216,6</td>
<td>0,141</td>
</tr>
</tbody>
</table>

### St Valentine

<table>
<thead>
<tr>
<th>Event</th>
<th>Altitude (km)</th>
<th>Meteor velocity (km/s)</th>
<th>Atmosphere temperature (K)</th>
<th>Atmosphere density (kg/m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed rad. pike</td>
<td>23.3</td>
<td>18.9</td>
<td>219.6</td>
<td>0.0550</td>
</tr>
<tr>
<td>Observed explosion</td>
<td>20</td>
<td>18.7</td>
<td>216.7</td>
<td>0.0886</td>
</tr>
</tbody>
</table>
Computational conditions

Non ablative calculations
Non catalytic surface
Laminar conditions

Park's model:

11 species: N$_2$, O$_2$, N, O, NO, N$_2^+$, O$_2^+$, N$^+$, O$^+$, NO$^+$, e-

16 reactions

Other points: altitude points at 80, 60 and 40 km.
St Valentine- Mesh

120×160 cells
St Valentine – Pressure & Mach number
St Valentin - Stagnation line temperature and species

- Temperature [K] and VIB temperature [K]
- Molar fractions of various species:
  - N2
  - N
  - O2
  - O
  - NO
  - N2+
  - N+
  - O2+
  - O+
  - NO+
  - e−
CFD: Mixture composition
St Valentin - Mixture composition (2)
St Valentin - Mixture composition (3)
Chelyabinsk- Mesh

120 ×160 cells
First cell less than 10 µm
Time steps 0.1 to 0.2 CFD number
Convergence up to $10^{-2}$
Chelyabinsk- Pressure & Mach
Chelyabinsk- Temperatures
Chelyabinsk - Mixture composition (1)
Chelyabinsk - Mixture composition (2)

N$^+$

O$^+$

Pres-03-2017v2 - Ph. Reynier - 7 Oct. 2017
Chelyabinsk - Mixture composition (3)
Chelyabinsk - Stagnation line temperature and species
Radiation

Calculations carried out with PARADE at stagnation point for Chelyabinsk

• Wavelengths: 100 to 4000 nm – 10000 points discretisation

• Molécules:
  - $N_2$ (1p, 2p, bh2, bh, lbh, cy, wj, w, eX)
  - $O_2$ (Schumann-Runge)
  - NO (beta, gamma, delta, epsilon)
  - $N_2^+$ (1n, mei)

• Atomes: N, O, N$^+$, O$^+$
St Valentine - Radiation along stagnation line
Chelyabinsk - Radiation along stagnation line

![Graph showing emission coefficient vs wavelength]
## Species involved

<table>
<thead>
<tr>
<th>Species</th>
<th>Strongly visible</th>
<th>Weakly visible</th>
<th>No data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Presence in large quantity (&gt;10%)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>I</td>
<td>II</td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>I / II</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FeO</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td><strong>Presence in medium quantity (~1%)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>I</td>
<td>II</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>I / II</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>I</td>
<td>II</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td></td>
<td>I / II</td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In blue not available with PARADE – Red: lack of data
## Species involved (2)

<table>
<thead>
<tr>
<th>Species</th>
<th>Strongly visible</th>
<th>Weakly visible</th>
<th>No data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti</td>
<td>I</td>
<td>II</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>I / II</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>K</td>
<td>I</td>
<td>II</td>
<td></td>
</tr>
<tr>
<td>Co</td>
<td>I / II</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mg</td>
<td>I</td>
<td>II</td>
<td></td>
</tr>
<tr>
<td>C$_2$</td>
<td></td>
<td>I / II</td>
<td></td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Na$_2$O</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>K$_2$O</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Might appear during entry</td>
<td>CN</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>SiO</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
Radiation – Summary

• Calculations carried out for Chelyabinsk
  - Without VUV radiative flux of 9.18 Gw/m²
  - With VUV radiative flux more than 11 Gw/m²

• Calculations for St Valentine: on-going
• Species missing have been identified
Thermal Analysis - 1

- Performed using Elmer, a multiphysic software.
- The tool has been interfaced with the convective heating profile.
- Meteoroids considered to be chondrites at an initial temperature of 100 K, density of 300 kg/m$^3$, thermal capacity of 800 J.kg$^{-1}$.K$^{-1}$, and thermal diffusion 2 W.m$^{-1}$.K$^{-1}$.
- $\frac{1}{4}$ of the meteoroid has been computed to save some computational effort.
Temperature computed within St Valentine
• Only convective heating accounted for.
• The total entry time within the atmosphere is very short: less than 10 s.
• Only the outside layer of the meteoroid (here St Valentine) has the time to reach an high temperature (the order of 1600 K).

Need to account for radiation.
Conclusions - 1

• Brief survey of data for superorbital entries
• Trajectory analysis and assessment of the influence of different parameters.
• CFD calculations using TINA for Chelyabinsk and St Valentine meteoroids for flow-field predictions and convective heating.
• Radiation calculations using PARADE and identification of the missing species.
• Coupling with ELMER and thermal analysis.
Conclusions - 2

• Reliability of existing stagnation point heating correlations.
• Need for a more deeper investigation of radiative heating accounting for radiative blockage.
• Opacity of the material.
• Improve calculations with ELMER accounting for radiative heating.
• Need to upgrade PARADE adding additional species and molecules.