Asteroid entry in Venusian atmosphere: pressure and density fields effect on crater formation

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Objectives

• Look at times scales of overpressure compared to cratering.

• What are the transient pressure and density due to atmospheric entry?

• Does shock wave evacuate ambient gas?

• Does transient atmospheric disturbance "settle down" during cratering?

• Can the pressure/density field be approximated as quasi-static?

• How does disturbance scale with impactor size?

• What is the role of atmospheric thickness?
General approach

- Perform inexpensive exploratory calculations (Phase 1).
- Experiments to validate code and observe crater growth.
- Follow up with more realistic coupling calculation (Phase 2).
MAZe Code Description

- CFD code developed and continually evolving under various government contracts (DNA, NASA/JPL, NSF/USGS)
  - Formation of dust, water, ice clouds from nuclear and high explosives
  - Fireball expansion, airblast propagation, boundary layer analysis

- Relevant capabilities
  - Adaptive zoning automatically refines the grid where "needed"
  - TVD (Total Variation Diminishing) finite differencing
    - Employs linearized Riemann solver, second-order accurate, flux limiting
  - Multiphase physics treats the mutual interactions between a gas mixture and the solid/liquid particles contained in that gas
  - ALE (Arbitrary Lagrangian Eulerian) grid techniques track physical interface between different type materials
MODELING ASSUMPTIONS
Venus Atmosphere

- Temperature profile from Seiff (1983)
  - 90 bar pressure, 733 K temperature at surface,
  - Treated as 100% CO2

- Non-ideal gas EOS (equation-of-state)
  - Variable \( \gamma \), of form \( P = \rho (\gamma - 1) e \)
  - Requires \( \gamma \)-vs-T, \( \gamma \)-vs-e
    - 111 K < T < 3000 K fit from gas tables (Keenan and Kaye, 1945)
    - Assume \( \gamma = 1.15 \) for T > 3000 K
Approach (Phase 1)

- Asteroid penetration through Venusian atmosphere
  - Calculate bow shock environment ahead and behind body
    - pressures, temperatures
    - include deceleration of asteroid

- Treat asteroid as spherical, rigid body
  - 1 km diameter, 2 gm/cc density \(\Rightarrow\) Mass \(\sim 10^{15}\) gm

- Transparent boundary
  - Asteroid passes through planet surface without distortion

- Minimum zone size
  - 0.125 km for 1-km diameter impactor
Look at 2 impactor sizes

- 1 km diameter and 10 km diameter.
- Initial velocity equal to 20 km/s for each.
- Start leading edge at 40 km altitude.
- 10-km body impacts at 19.5 km/s; transit time = 2.01 sec.
- 1-km body impacts at 15.7 km/s; transit time = 2.16 sec.
- Peak pressure is 125 kbar and 75 kbar respectively.
- Disturbance is due to the bow wave only.
Case VEN01 10 km diameter at 20 km/s on Venus

Pressure time histories at various ranges along ground surface

Time (sec)
Case VEN02 1 km diameter at 20 km/s on Venus

Pressure time histories at various ranges along ground surface

Scaled-Time = (t - 2.16) * 11.55 + 2.01
where 11.55 is ratio of KE at impact
2.16 is impact time of 1-km body
2.01 is impact time of 10-km body

Scaled-Range

<table>
<thead>
<tr>
<th>Scaled-Range</th>
<th>Range (km)</th>
</tr>
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<tbody>
<tr>
<td>8.09</td>
<td>r0.7km</td>
</tr>
<tr>
<td>10.4</td>
<td>r0.9</td>
</tr>
<tr>
<td>17.3</td>
<td>r1.5</td>
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<tr>
<td>23.1</td>
<td>r2.0</td>
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<tr>
<td>28.9</td>
<td>r2.5</td>
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<tr>
<td>34.7</td>
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<td>40.4</td>
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<td>46.2</td>
<td>r4.0</td>
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<tr>
<td>52.0</td>
<td>r4.5</td>
</tr>
<tr>
<td>57.8</td>
<td>r5.0</td>
</tr>
</tbody>
</table>
Case VEN02: 1 km diameter at 20 km/s on Venus r09 venp1

Density time histories at various ranges along ground surface

- $r_{6km}$
- $r_7$
- $r_8$
- $r_9$
- $r_{10}$
- $r_{15}$

Time (sec)

Density (gm/cc)
Case VEN02 1 km diameter at 20 km/s on Venus

Density time histories at various ranges along ground surface

- $r_{0.5km}$
- $r_1$
- $r_2$
- $r_3$
- $r_4$
- $r_5$

Density (gm/cc)

Time (sec)
Case VEN02  1 km diameter at 20 km/s on Venus  r09 vepnlt1
Pressure time histories at various ranges along ground surface

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>Graph Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>r6</td>
<td>Solid</td>
</tr>
<tr>
<td>r7</td>
<td>Dashed</td>
</tr>
<tr>
<td>r8</td>
<td>Solid</td>
</tr>
<tr>
<td>r9</td>
<td>Dotted</td>
</tr>
<tr>
<td>r10</td>
<td>Dashed</td>
</tr>
<tr>
<td>r15</td>
<td>Solid</td>
</tr>
<tr>
<td>r20</td>
<td>Dashed</td>
</tr>
<tr>
<td>r25</td>
<td>Dotted</td>
</tr>
<tr>
<td>r30</td>
<td>Dashed</td>
</tr>
</tbody>
</table>

- Time (sec)
- Pressure (bar)
Case VEN02: 1 km diameter at 20 km/s on Venus.

Pressure time histories at various ranges along ground surface.
Case VEN01 10 km diameter at 20 km/s on Venus

Density time histories at various ranges along ground surface
Vacuum or small $\Pi_P$ scaling laws

Coupling Parameter: $C \propto aU^\mu$

\[ \pi_v \pi_2^\alpha = A \]

Final Crater Size

\[ \log \left( \frac{V_P}{M} \right) \]

slope = $-\frac{3\mu}{2 + \mu} = -\alpha$

Formation Time

\[ \log (UT/a) \]

slope = $-\frac{1 + \mu}{2 + \mu}$

Crater Growth

\[ \log \left( \frac{R}{a} \right) \]

slope = $\frac{\mu}{1 + \mu}$

log \( (Ut/a) \)

Dependence of exponents on material type

<table>
<thead>
<tr>
<th>Material Type</th>
<th>$\alpha$</th>
<th>$\mu$</th>
<th>Crater Size</th>
<th>Form Time</th>
<th>Rate of Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mom. Limit</td>
<td>3/7</td>
<td>1/3</td>
<td>0.429</td>
<td>0.571</td>
<td>0.250</td>
</tr>
<tr>
<td>Dry Soil</td>
<td>0.507</td>
<td>0.407</td>
<td>0.507</td>
<td>0.585</td>
<td>0.289</td>
</tr>
<tr>
<td>Wet Soil</td>
<td>0.600</td>
<td>0.500</td>
<td>0.600</td>
<td>0.600</td>
<td>0.333</td>
</tr>
<tr>
<td>Water</td>
<td>0.650</td>
<td>0.553</td>
<td>0.650</td>
<td>0.608</td>
<td>0.356</td>
</tr>
<tr>
<td>Energy Limit</td>
<td>3/4</td>
<td>2/3</td>
<td>0.750</td>
<td>0.625</td>
<td>0.400</td>
</tr>
</tbody>
</table>

A schematic illustration of how some of the power-law scaling relationships, which result from a point-source coupling parameter, are interrelated by the scaling exponent, $\mu$. 
Vacuum crater size, time, and growth

- **Impactor Size**
  - 1-km dia
  - 10-km dia

- $\pi_2$
  - $3.57 \times 10^{-5}$
  - $3.57 \times 10^{-4}$

- Final crater size
  - 3.9 km
  - 26.5 km

- $R/a$
  - 7.8
  - 5.3

- Time of formation
  - 18.2 sec
  - 47.5 sec

- $\pi_T = UT/a$
  - 312
  - 190

- Growth (km, sec)
  - $R = 1.70t^{0.287}$
  - $R = 8.76t^{0.287}$
Test for cube-root scaling

small 0.5% volume and large 1.5% volume

small 1.7% volume and large 5.4% volume
Test for cube-root scaling (cont.)
Need better interpolation and longer times

small 5% volume and large 16% volume

small 17% volume and large 53% volume
Gravity-scaled crater growth

1.2% volume

10% volume
Gravity-scaled crater growth (cont.)

20% volume

75% volume
Pressure effect on crater size

Scaling law: \( \pi_v \pi_2^\alpha = A \)

Earth 10 km-Venus-1km

\[ \frac{P}{\rho g a} \pi_2^{\alpha/3} \]
Density (drag) effect on crater size

Scaling law: \( \pi_v \pi_2^\alpha = A \)
Approach for Phase 2 (currently underway)

- Calculation of coupled impact, cratering, ejecta, and airblast
  - Determine partitioning of impactor kinetic energy into airblast
  - Track airblast out to times and ranges beyond crater

- Assume impactor reaches surface intact

- Treat body as "swarm" of various size "particles"
  - EOS includes hydrodynamic pressures under compression

- Calculate momentum transfer to ground using ALE logic
  - Formation of impact crater and ejecta

- EOS includes high-pressure vaporization of impactor and ground
  - Vaporized material available for airblast
Summary

• This is a hard problem, all effects lead to smaller craters!
  1) Increased pressure/drag on crater formation
  2) Slowdown of impactor due to entry drag
  3) Breakup of impactor due to pressure distribution

• Progress has been made in isolating variables.

• Preliminary forms for scaling laws have been developed.

• Improved calculations for transient pressure and density underway.

• Shooting light gas gun into high pressure chamber demonstrated.

• Equivalent explosive experiments provide supporting data.

• Objective is to obtain useful scaling relationships for:
  Crater formation when atmospheric effects are important.
1-km Diameter Impactor into Venus

20 km/s Initial Velocity  time = 9 sec

Pressure

Level P(bar)

8  2.18E2
7  1.51E2
6  1.04E2
5  7.19E1
4  4.97E1
3  3.43E1
2  2.37E1
1  1.64E1

Density

Level R

5  8.50E-2
4  2.80E-2
3  9.22E-3
2  3.04E-3
1  1.00E-3

Radius (km)
10-km Diameter Impactor into Venus

20 km/s Initial Velocity  time = 20 sec

Pressure

Density

Radius (km)
### Target EOS for Phase II

**Quartz**

- **Initial Density**: $2.5 \text{ gm/cm}^3$
- **Air-filled void volume**: 8%
- **Initial Bulk Modulus**: 0.45 Mb
- **Maximum Bulk Modulus**: 0.75
- **Vaporization Activation Energy**: $1.7 \times 10^{10} \text{ ergs/gm}$
- **Initial Shear Modulus**: 0.173 Mb
- **von Mises Limit in Compression**: 0.017 Mb
- **Cohesion**: 50 bars
- **Slope of Mohr Coulomb Surface**: 0.75
- **Poisson’s Ratio**: 0.33