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
    - $111 \text{ K} < T < 3000 \text{ K}$ fit from gas tables (Keenan and Kaye, 1945)
    - Assume $\gamma = 1.15$ for $T > 3000 \text{ K}$
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

- $r_{6km}$
- $r_{8}$
- $r_{10}$
- $r_{15}$
- $r_{20}$
- $r_{25}$
- $r_{30}$
- $r_{40}$
- $r_{50}$
- $r_{60}$

Time (sec)
Case VEN02 1 km diameter at 20 km/s on Venus r05 venpl

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

8.09  r0.7km
10.4  r0.9
17.3  r1.5
23.1  r2.0
28.9  r2.5
34.7  r3.0
40.4  r3.5
46.2  r4.0
52.0  r4.5
57.8  r5.0
Case VEN02 1 km diameter at 20 km/s on Venus

Density time histories at various ranges along ground surface

- r6km
- r7
- r8
- r9
- r10
- r15

Time (sec) vs. Density (gm/cc)
Case VEN02 1 km diameter at 20 km/s on Venus r09 venpt1

Density time histories at various ranges along ground surface

![Graph showing density time histories at various ranges along ground surface.](image-url)
Case VEN02 1 km diameter at 20 km/s on Venus r09 venpl1

Pressure time histories at various ranges along ground surface

Pressure (bar)

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

Pressure time histories at various ranges along ground surface

[Graph showing pressure time histories with various ranges labeled as r0.5km, r1, r2, r3, r4, and r5.]
Case VEN01 10 km diameter at 20 km/s on Venus rt>7 venp1

Density time histories at various ranges along ground surface

Time (sec)

Density (gm/cc)
Vacuum or small $\pi_p$ scaling laws

Coupling Parameter: $C \propto a U^\mu$

\[
\pi_v \pi_2^\alpha = A \quad \text{(Final Crater Size)}
\]

\[
\log \left( \frac{V_p}{A} \right) = \frac{3\mu}{2 + \mu} = -\alpha \quad \text{(slope)}
\]

\[
\log \left( \frac{V_p}{a} \right) = \log \left( \frac{ga}{U^2} \right) \quad \text{(log (ga/U^2))}
\]

\[
\pi_v \pi_2^\alpha = A \quad \text{(Formation Time)}
\]

\[
\log \left( \frac{UT}{a} \right) = \frac{1 + \mu}{2 + \mu} \quad \text{(slope)}
\]

\[
\log \left( \frac{UT}{a} \right) = \log \left( \frac{ga}{U^2} \right) \quad \text{(log (ga/U^2))}
\]

Crater Growth

\[
\log \left( \frac{R}{a} \right) = \frac{\mu}{1 + \mu} \quad \text{(slope)}
\]

\[
\log \left( \frac{U_T}{a} \right) \quad \text{(log (Ut/a))}
\]

<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>
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<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>
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<tr>
<td>Water</td>
<td>0.650</td>
<td>0.553</td>
<td>0.650</td>
<td>0.608</td>
<td>0.356</td>
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<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>

Dependence of exponents on material type

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, $\mu$. 

\[
\text{log (Ut/a)}
\]
**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: \[ \pi_v \pi_2^\alpha = A \]
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

Radius (km)

Pressure

Density

Level R

Level P(bar)

Radius (km)
10-km Diameter Impactor into Venus

20 km/s Initial Velocity  time = 20 sec

Pressure

<table>
<thead>
<tr>
<th>Level</th>
<th>P(bar)</th>
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<tbody>
<tr>
<td>8</td>
<td>2.53E2</td>
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<td>7</td>
<td>2.19E2</td>
</tr>
<tr>
<td>6</td>
<td>1.85E2</td>
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<tr>
<td>5</td>
<td>1.52E2</td>
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<tr>
<td>4</td>
<td>1.18E2</td>
</tr>
<tr>
<td>3</td>
<td>8.42E1</td>
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<tr>
<td>2</td>
<td>5.05E1</td>
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<tr>
<td>1</td>
<td>1.68E1</td>
</tr>
</tbody>
</table>

Density

<table>
<thead>
<tr>
<th>Level</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>7.21E-2</td>
</tr>
<tr>
<td>7</td>
<td>2.82E-2</td>
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<tr>
<td>6</td>
<td>1.10E-2</td>
</tr>
<tr>
<td>5</td>
<td>4.30E-3</td>
</tr>
<tr>
<td>4</td>
<td>1.68E-3</td>
</tr>
<tr>
<td>3</td>
<td>6.55E-4</td>
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<tr>
<td>2</td>
<td>2.56E-4</td>
</tr>
<tr>
<td>1</td>
<td>1.00E-4</td>
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</table>
## Target EOS for Phase II

*Quartz*

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