The Role of Phase Changes on the Thermodynamics and Mechanics of Impact Cratering in H$_2$O Ice

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Impact craters reflect target properties

Morphological differences from target properties:
- Depth to diameter ratios
- Central features
- Ejecta structures

Diversity of features is greater on icy bodies.

Use morphologies to infer target information?

What will we see after Deep Impact?
Need to understand the many pieces of the messy cratering process

Assuming we know the impact conditions and target composition......

Shock thermodynamics
  Equation of state
  Temperature field; phase changes
  Mixtures/heterogeneity

Cratering mechanics
  Constitutive relations; fracturing
  Phases; mixtures

Gula and Achelous, Ganymede (40 km)
Why is ice so complicated?
So many polymorphs!
Phase changes on shock loading and unloading.

At least 12 stable phases known.

At least 9 metastable phases known (Ic, IV, IX, LDA, HDA, V-HDA, VII’, XII, XIV).

Triple point
612 Pa, 273 K

Critical point
22 MPa, 647 K

Figure modified from Petrenko & Whitworth
Shock Hugoniot measurements in ice

3-wave structure in 100 K H₂O Ice

Faraday’s Law: induced voltage \( V = B L u_p \)

Stewart & Ahrens 2003, 2005
5 regions on the ice Hugoniot

$T_0 = 263$ K dashed line; $T_0 = 100$ K solid line

Stewart & Ahrens 2003, 2005
Another H$_2$O phase diagram

Experimentally determined phase boundaries

(Liquid and vapor EOS from Wagner & Pruss 2002)
H$_2$O Ice Hugoniot

5 regions on the Hugoniot
Low and high temperature (100 & 263 K) ice Hugoniotics are different

Some low temperature, low pressure phases (ices II, III, V) excluded by strength
What happens on release?
Shock-induced melting & vaporization

Want to model impact cratering in ice

Need a full model EOS
The 5-Phase H$_2$O EOS

Tabular EOS
- P, E, S on a ρ-T grid
  Senft & Stewart 2008

Liquid & Vapor
- Wagner & Pruss 2002 (NIST)
- Ice Ih
  Feistel & Wagner 2006
- Ice VI and VII
  Stewart & Ahrens 2005

Good match to P-V Hugoniots for liquid, ice, porous ice
Shock Temperature Experiments
Pyrometry on polycrystalline H$_2$O ice and an ice-quartz mixture

Shock pressure calculated from impedance match solution.
~1 millitorr in sample chamber.
Driver cooled to ~165 K.

Harvard 40-mm gas & powder gun

Stewart, Seifter, & Obst 2008
Kraus, Stewart, Seifter, & Obst 2010
Radiance Data on Shocked Ice

Shock Temperatures and 5-Phase EOS

Excellent agreement between model and data.
Shock Temperatures and 5-Phase EOS

Release temperatures much higher than expected......
Post-shock temperatures lie on the saturation vapor curve. Full release time scale depends on volume expansion rate.
Phase changes during uniaxial decompression

Uniaxial release of shocked H$_2$O

Maximum decompression determined by inertia in the flow (stuck at vapor curve)

Only leading edge fully decompresses (optically thin and colder)

Decompression depends on the expansion rate (and geometry)
Phase changes during uniaxial decompression

Uniaxial release of shocked H₂O

Maximum decompression determined by inertia in the flow (stuck at vapor curve)

Only leading edge fully decompresses (optically thin and colder)

Decompression depends on the expansion rate (and geometry)

(ignoring edge effects)
Derived criteria for shock-induced melting and vaporization for any initial P & T using the entropy method.
Back to impact cratering......

From the lab work:
- improved understanding of shock-induced phase changes
- improved model EOS

Need modeling for:
- volumes of melt & vapor
- crater formation
- final temperature field

Steinheim crater, Mars (10 km)
Volume of melt and vapor depends on impact conditions and pressure decay profile.

CTH code calculations of shock pressure at each initial position using 5-Phase EOS.

Kraus & Stewart, in prep.
Scaling laws for melt and vaporization

\[
\frac{M_{\text{melt}}}{M_{\text{projectile}}} = F \text{ (impact velocity, angle, porosity, temperature)}
\]

Good news:

\(M_{\text{melt}}\) is within a factor of 2 for full range of angle, porosity, and temperature

Close to energy scaling

(Bjorkman and Holsapple, 1987)

Bad (interesting?) news:

Up to a factor of 10 difference depending on the thermodynamics in a mixture

(Turtle & Pierazzo 2001)

Kraus & Stewart, in prep.
Modeling full crater formation

D=2 km, V=15 km/s, T=120 K, Ganymede gravity

Black points are Lagrangian tracer particles
Gray density <0.9 g/cm^3

Quasi-static strength model for ice (Senft & Stewart 2008, Collins et al. 2004)
Crater collapse modeled with acoustic fluidization (Senft & Stewart, in revision)
Crater formation using 5-Phase EOS

D=2 km, V=15 km/s, T=120 K, Ganymede gravity
40 km diameter final crater
5-Phase EOS vs Simple Single Phase EOS

- 2.5 s
- 20 s
- 65 s
- 400 s

Density: 0.9 g/cm³ to 1.2 g/cm³

Shock wave front
Crater formation using 5-Phase EOS

D=2 km, V=15 km/s, T=120 K, Ganymede gravity
40 km diameter final crater

(Senft & Stewart, in revision)
Phase changes in ice leads to **discontinuous excavation**

Ice is shocked to different phases with distance from impact

Different unloading paths leads to a discontinuity in material velocities

Most highly shocked material is slower – it is concentrated within the collapsing crater

Shock-induced phase changes modify the dynamics of excavation flow
With the phase changes, adjacent materials have different loading and release paths.
Central feature is a product of phase changes
Ice at the melting point is concentrated in crater floor
Example thermodynamic paths

- Shocked to ice VI
  - Material is in the ‘central plug’

- Shocked to supercritical fluid
  - Material is in the ‘hot plug’

Color indicates time.
Is there observational support for discontinuous excavation?

Central pit craters on Ganymede and Callisto

D=73 km                   D=64 km                   D=62 km
Hot plug diameter and size range agree with central pit crater observations

Discontinuous excavation not significant in small craters (small volume shocked to high pressure solid phases); larger craters influenced by subsurface ocean.

(Alzate & Barlow 2009, submitted)
Discontinuous excavation and the origin of central pit/dome craters?

Width of hot plug is same as central pits
Size range of craters with hot plugs same as central pits (about 25-150 km diameter)
Pits observed on Callisto & Ganymede but not other icy satellites (resurfacing or not enough melted material)
Expect variations with impact velocity  
   Less melt at very low and very high impact velocities
(Do not expect central pits on Pluto)
Hot plug evolution into a pit/dome is TBD (e.g., hydrologic model presented at LPSC 2010 by Elder et al.)
Want lab verification (in progress)
Conclusions

• H$_2$O is full of surprises!
• Importance of phase changes on loading and release
• Laboratory data + modeling led to discovery of a new phenomena: discontinuous excavation
  – Phase transitions change the dynamics of impact cratering
• Discontinuous excavation leads to hot plug in crater floor
  – Hot plug characteristics similar to central pit craters
  – Most of the melt is concentrated in the plug
• Starting to be able to infer gross target properties from impact craters

What else are we missing by an incomplete understanding of phase changes?
Need more exploration in the lab.

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