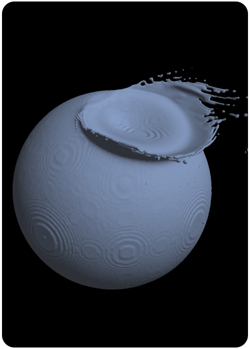
Constructing the Solar System: A Smashing Success

When Asteroids Collide

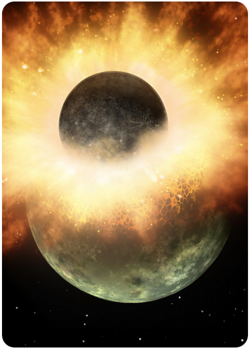


Thomas M. Davison

Department of the Geophysical Sciences

THE UNIVERSITY OF CHICAGO

Compton Lecture Series
Autumn 2012



Compton Lecture Series Schedule

1	10/06/12	A Star is Born
2	10/13/12	Making Planetesimals: The building blocks of planets
3	10/20/12	*Guest Lecturer: Mac Cathles*
4	10/27/12	Asteroids and Meteorites: Our eyes in the early Solar System
5	11/03/12	Building the Planets
6	11/10/12	When Asteroids Collide
7	11/17/12	Making Things Hot: The thermal effects of collisions
	11/24/12	No lecture: Thanksgiving weekend
8	12/01/12	Constructing the Moon
	12/08/12	No lecture: Physics with a Bang!
9	12/15/12	Impact Earth: Chicxulub and other terrestrial impacts

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Today's lecture

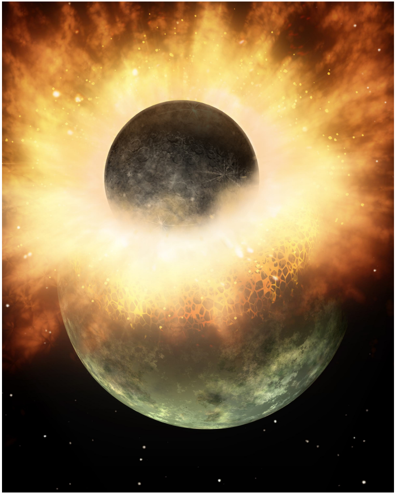
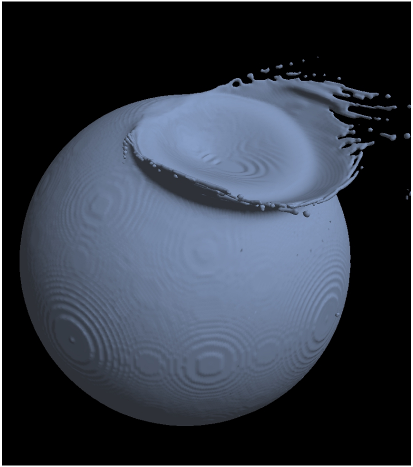


Image courtesy of NASA

- Range of outcomes of collisions between planetesimals
- Impact processes
- Disruption of planetesimals by impact
- Heating in impacts

Collisional outcomes



- Cratering/Merging
  - Low energy — impactor too small or velocity too low to cause disruption
- Disruption
  - Higher energy — breaks apart the larger body
- Hit-and-Run
  - Oblique angle — little mixing of material

Collisional outcomes

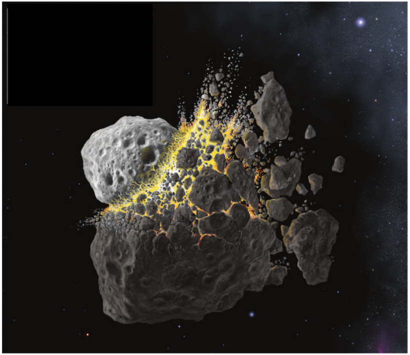


Image courtesy of Don Davis/SWRI/Nature Publishing Group

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Collisional outcomes

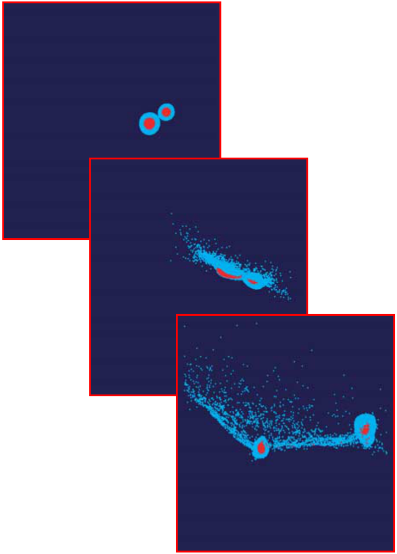

Image courtesy of Asphaug et al. (2006) *Nature*

- Cratering/Merging
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Catastrophic Disruption

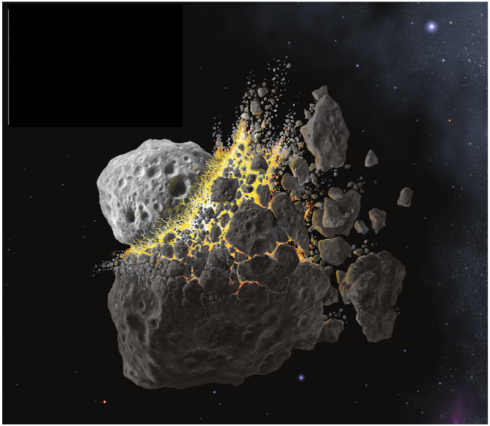


Image courtesy of Don Davis/SWRI/Nature Publishing Group

Catastrophic disruption

Catastrophic disruption is defined as an impact in which the largest remaining fragment of the target body is less than half the mass of the original target body

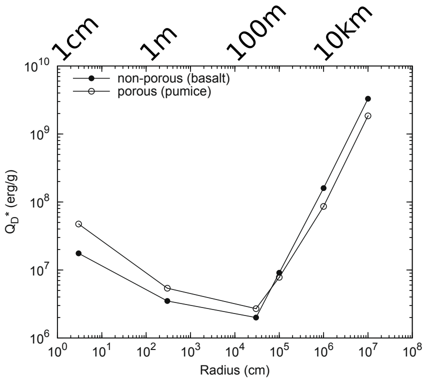


Image courtesy of Jutzi et al. (2010) *Icarus*

$$\frac{\text{Kinetic energy of impactor}}{\text{Mass of target}} = \frac{1}{2}\frac{m_i v_i^2}{m_t} > Q_D^\star$$

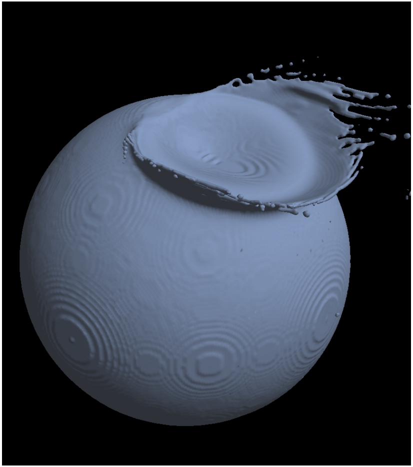
- If the impact energy is high enough, the collision will break apart the target asteroid
- Lots of work has been done to quantify the **disruption threshold**
- Depends on physical properties of target, e.g.
  - Size (strength or gravity)
  - Porosity

Part 1:
Introduction to impact cratering

Image courtesy of Wikimedia Commons

Cratering

- If the impact energy is below the disruption threshold, an impact crater will be formed
- The cratering process can be broken down into several stages
  - Contact and compression
  - Excavation
  - Modification



Contact and compression

- Begins with contact between the impactor and the target
- Relative velocity greater than speed of sound (**hypervelocity**)
- Impactor penetrates surface and slows down
- Target material speeds up
- Shock wave is sent into the target and impactor as a result of the changing velocities

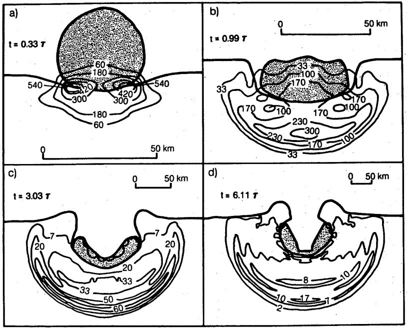


Image courtesy of *Impact Cratering: A Geologic Process*, H.J. Melosh (1989)

- Material behind shock wave at very high pressures
- Once shock wave reaches back of impactor, a release wave is started
- Release wave travels back through impactor into target, releasing material from high pressure state

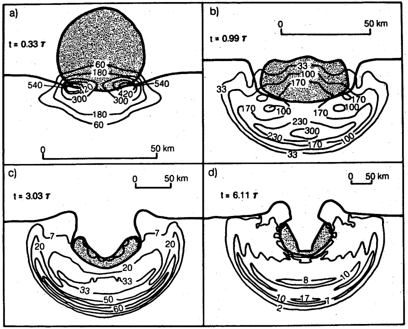


Image courtesy of *Impact Cratering: A Geologic Process*, H.J. Melosh (1989)

Excavation

- Shock wave travels into material, weakening it
- Shock wave (and the following rarefaction wave) set the material in motion
- Material flows away from impact point — opening a crater
- Material near surface flows up and out of crater
- Material below that moves downwards and outwards

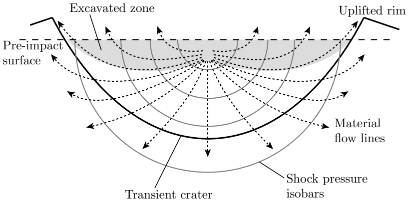


Image adapted from *Traces of Catastrophe*, B.M. French (1998)

Excavation

- The excavation phase ends when the crater stops growing
- Known as the **transient crater**
- Excavating flow decelerated by the gravity and strength of the target

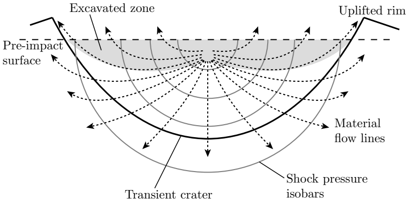


Image adapted from *Traces of Catastrophe*, B.M. French (1998)

Modification

- Modification after the formation of the transient crater depends on the size of the crater
- Small transient craters form **simple** craters in which the crater walls can slump to form a breccia lens
- Larger transient craters form **complex** craters with a central uplift and a flat crater floor

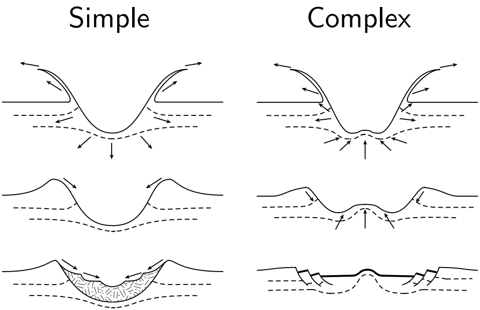


Image adapted from Melosh (1989) and French (1998)

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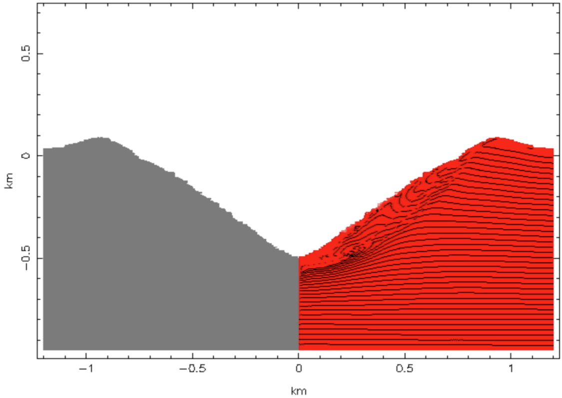
Simple crater



- Simple, bowl-shaped final crater
- After transient crater forms, crater walls slump towards center

In the lecture, I showed a movie of simple crater formation. You can view that movie here: http://geosci.uchicago.edu/~tdavison/comptonlectures/Lecture5_Simple.avi

Simple crater

Barringer Crater, Arizona

Image courtesy of Wikimedia Commons

- Simple, bowl-shaped final crater
- After transient crater forms, crater walls slump towards center

Craters on Lutetia

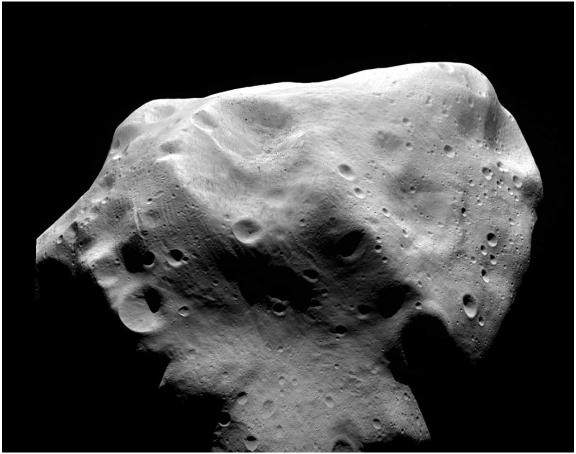
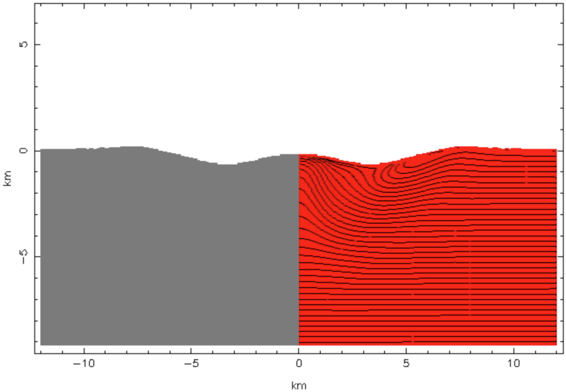


Image courtesy of ESA

- Simple, bowl-shaped final crater
- After transient crater forms, crater walls slump towards center

Complex crater



- Complex final crater
- Central uplift after transient crater leads to peak in center of final crater

In the lecture, I showed a movie of complex crater formation. You can view that movie here:
http://geosci.uchicago.edu/~tdavison/comptonlectures/Lecture5_Complex.avi

Complex crater

Tycho Crater on the Moon

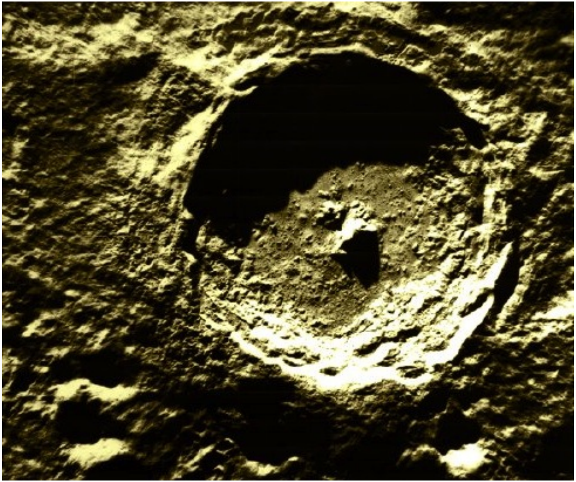
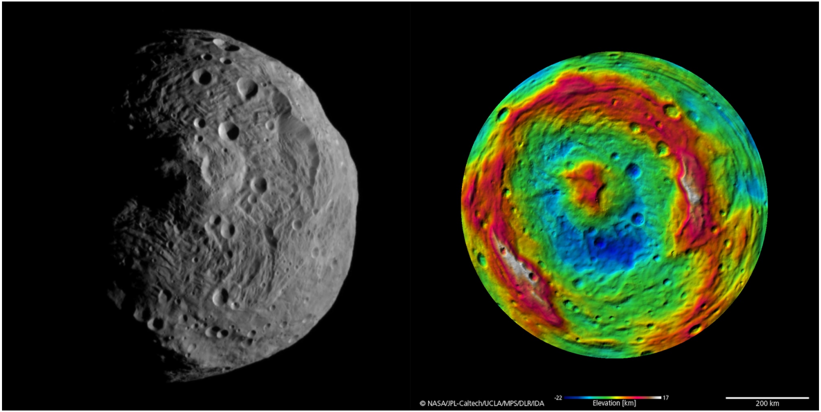


Image courtesy of NASA

- Complex final crater
- Central uplift after transient crater leads to peak in center of final crater

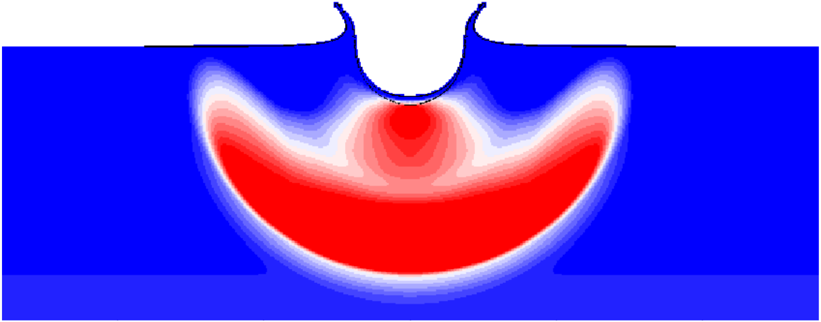
Rheasilvia on Vesta: a complex crater?



Images courtesy of NASA/JPL-Caltech/UCLA/MPS/DLR/IDA

In the lecture, I showed a movie from Martin Jutzi of an impact on Vesta forming a feature similar to Rheasilva. That movie can be viewed here: http://vimeo.com/19578888

Part 2:
Shock wave physics



Shock waves

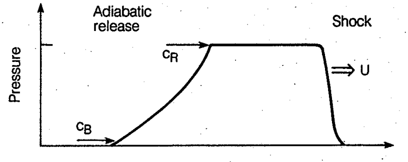


Image courtesy of Melosh (1989)

- Shock wave is a near instantaneous jump in pressure, density and energy
- Material stays at this high pressure state until **released** from that state, by a release wave
- A shock wave increases the entropy of the material
- During release, entropy is conserved

Shock waves are what cause heating in a collision

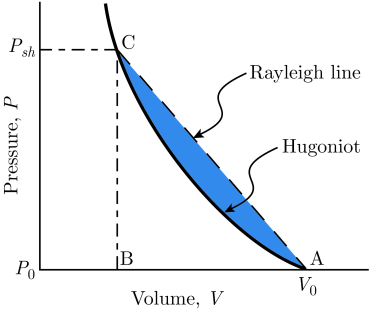


Image adapted from Sharp and de Carli (2006)
Meteorites and the Early Solar System II

- The increase in entropy during a shock event is what causes heating
- Material shocked to high shock pressure (P_{sh}), to a point on a Hugoniot
  - Hugoniot is specific to material
- The releases back to ambient pressure (P_0)
- Waste heat is a measure of the amount of heat deposited in the collision

Planetesimals were created porous

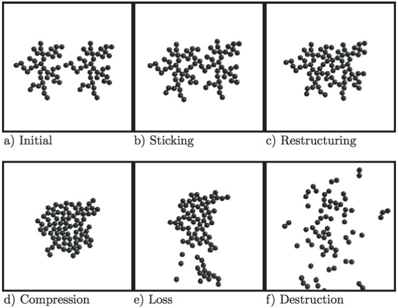


Image courtesy of Dominik and Tielens (1997)

- Recall from previous lectures: Planetesimals contained significant porosity as they accreted
- Porosity has significant effect on shock wave physics

More waste heat in porous materials

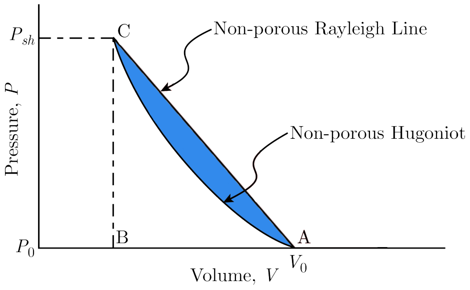


Image adapted from Sharp and de Carli (2006)
Meteorites and the Early Solar System II

- Non-porous material has a particular waste heat for a given shock
- An equal mass of porous material has a greater initial volume
- More work done in raising porous material to given shock pressure
  - Crushing out pore space
- More waste heat in porous collision

More waste heat in porous materials

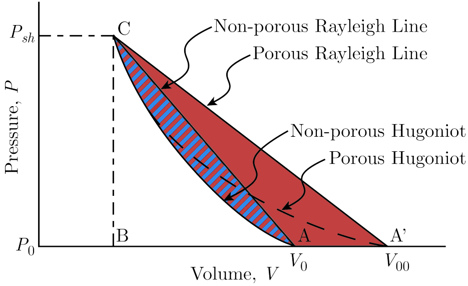
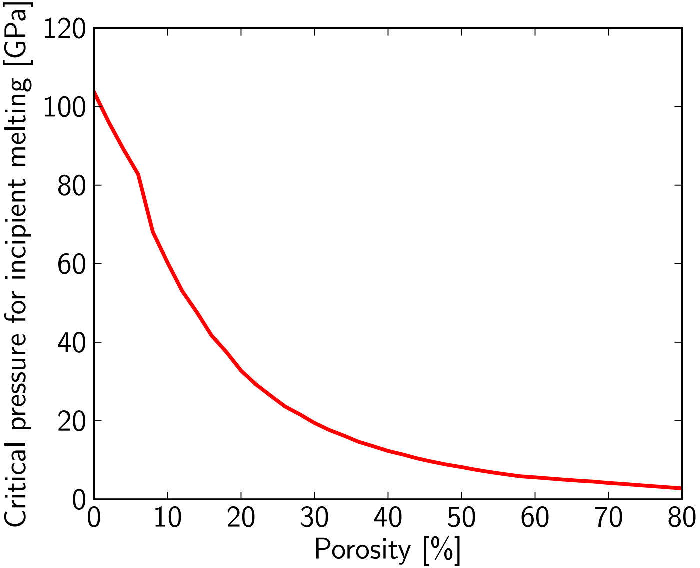


Image adapted from Sharp and de Carli (2006)
Meteorites and the Early Solar System II

- For a given shock pressure, more waste heat produced in porous material
- Or, lower pressure required to produce same temperature increase

- Non-porous material has a particular waste heat for a given shock
- An equal mass of porous material has a greater initial volume
- More work done in raising porous material to given shock pressure
  - Crushing out pore space
- More waste heat in porous collision

Critical pressure for melting is lower in porous materials

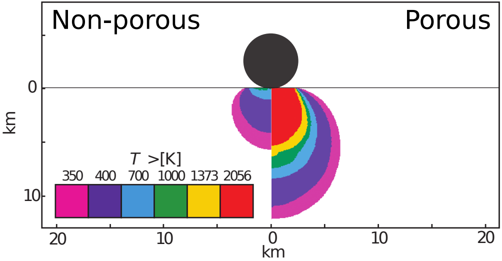


More heat in porous material

- More work is required to crush out pores
- Shock wave attenuated sooner in porous material
- Smaller volume of material affected by shock wave
- Which effect is dominant in collisions between planetesimals?

In the lecture, I showed a movie of shock wave attenuation in porous and non-porous materials. That movie can be viewed here:

http://geosci.uchicago.edu/~tdavison/comptonlectures/Lecture5_ShockWave.avi



Part 3:
Which impact parameters are important for collisional heating?

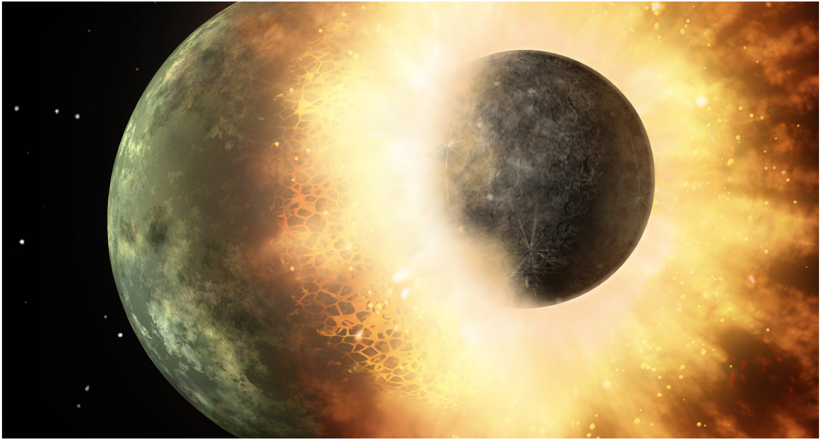
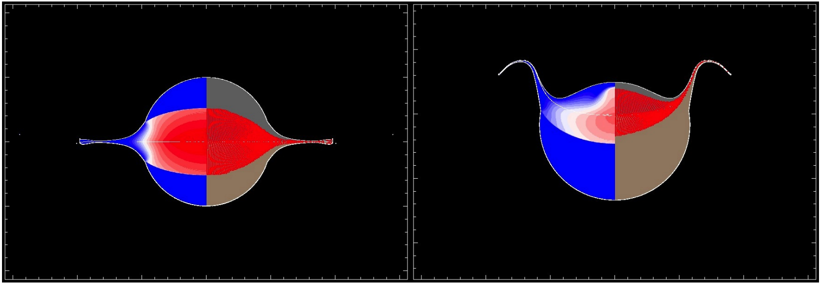


Image courtesy of NASA

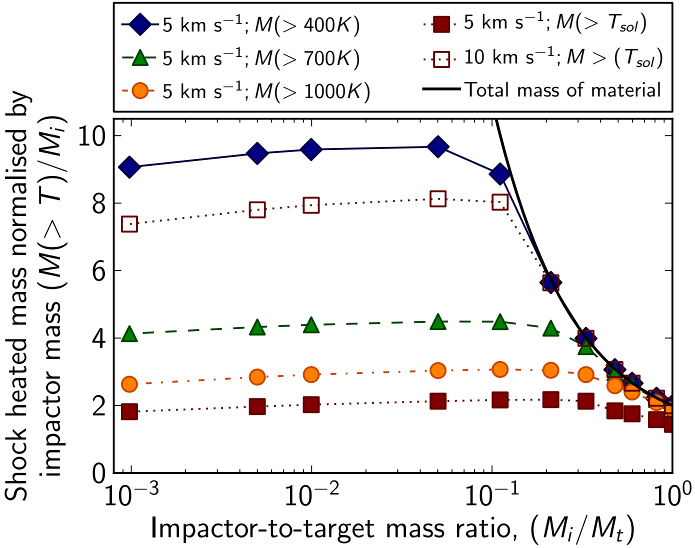
Impactor size



In the lecture, I showed a movie of two collisions, one between equal sized bodies, and one between a small impactor and a larger target. That movie can be viewed here:

http://geosci.uchicago.edu/∼tdavison/comptonlectures/Lecture5_ImpactorSize.mov

Impactor size



Impactor size

In the lecture, I showed three movies of collisions involving different sized impactors. They can be viewed here:

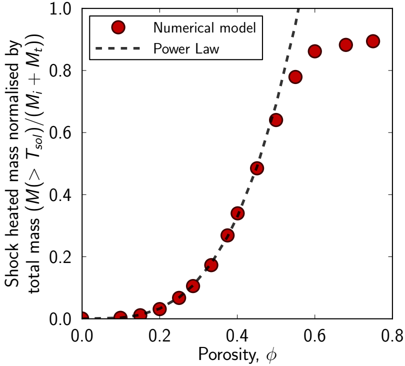
- http://geosci.uchicago.edu/~tdavison/comptonlectures/Lecture5_Collision1.mov
- http://geosci.uchicago.edu/~tdavison/comptonlectures/Lecture5_Collision2.mov
- http://geosci.uchicago.edu/~tdavison/comptonlectures/Lecture5_Collision3.mov

Porosity

In the lecture, I showed a movie of three collisions with targets of different porosities. That movie can be viewed here:

http://geosci.uchicago.edu/~tdavison/comptonlectures/Lecture5_Porosity.mov

Porosity



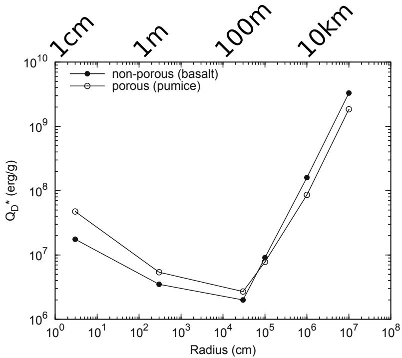
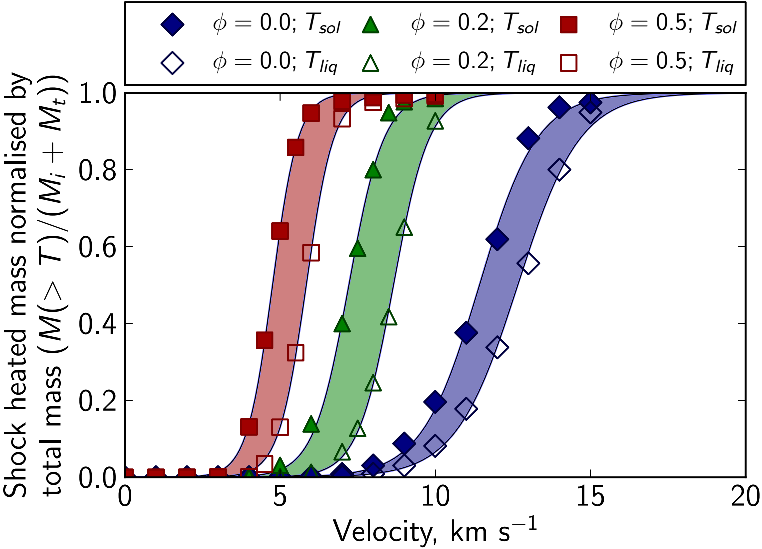


Image courtesy of Jutzi et al (2010) *Icarus*

Velocity



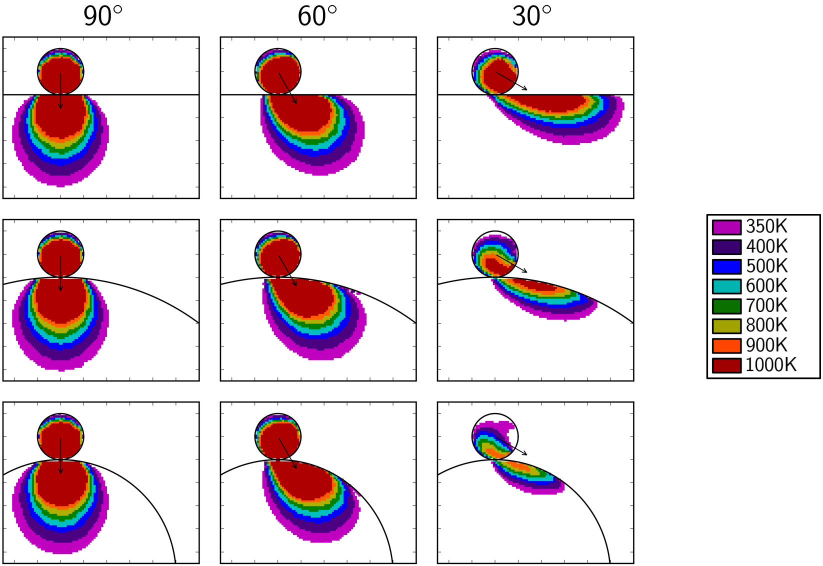
$\phi = 0.0$; T_{sol}
$\phi = 0.2$; T_{sol}
$\phi = 0.5$; T_{sol}
$\phi = 0.0$; T_{liq}
$\phi = 0.2$; T_{liq}
$\phi = 0.5$; T_{liq}
Shock heated mass normalised by total mass $(M(>T)/(M_i + M_t))$
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
Velocity, km s^{-1}

Impact angle

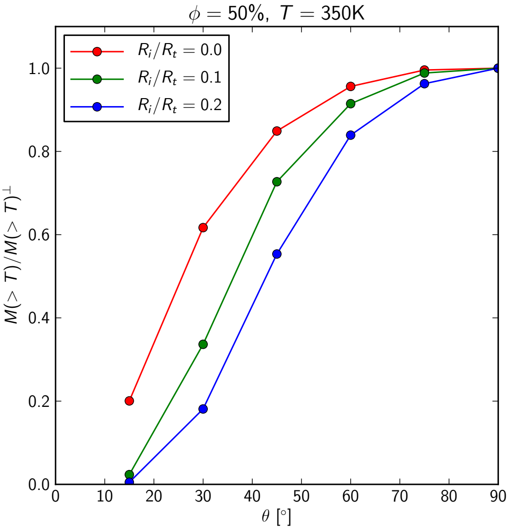
In the lecture, I showed a movie of collisions at different impact angles. That movie can be viewed here:

http://geosci.uchicago.edu/~tdavison/comptonlectures/Lecture5_3D.mov

Impact angle



Impact angle



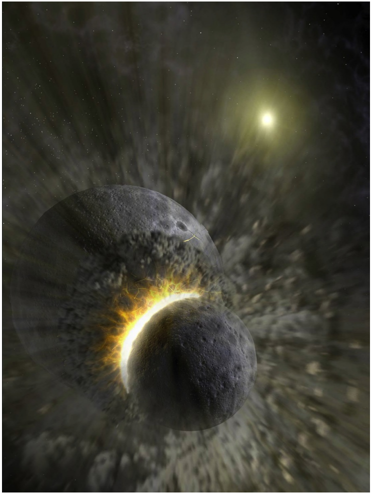


Image courtesy of NASA

- Can quantify collateral effects of most collision scenarios using computer models
- Collisions can have significant effect on target body
  - Ranging from catastrophic disruption to cratering or grazing events
- Assuming planetesimals were porous early in their lifetimes, collisions could provide a significant source of heat
  - How much compared to other sources?
  - Next week's lecture will focus on this question

Thank you

Questions?