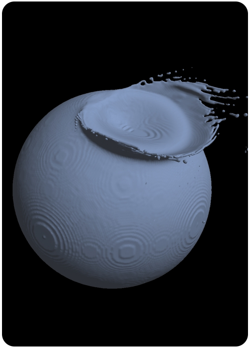
Constructing the Solar System: A Smashing Success

Making Things Hot:
The thermal effects of collisions

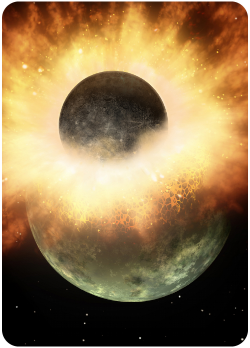


Thomas M. Davison

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

Today's lecture

- Evidence of heating in planetesimals
- Possible heat sources in planetesimals
  - Radioactive decay
  - Impacts
- Modeling heating on the H Chondrite parent body

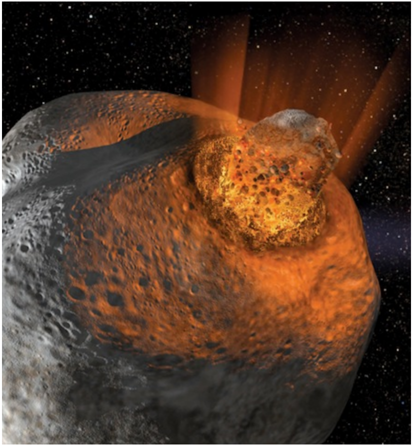
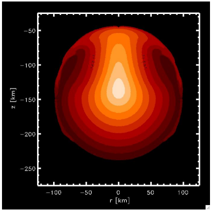


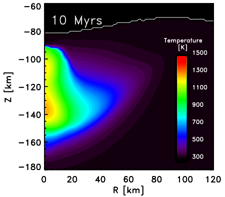
Image courtesy of Don Davis/Nature Publishing Group

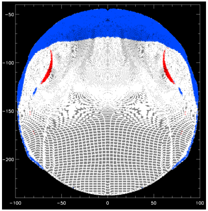
Acknowledgments

Many of the results I will show you today are the product of a collaborative research effort

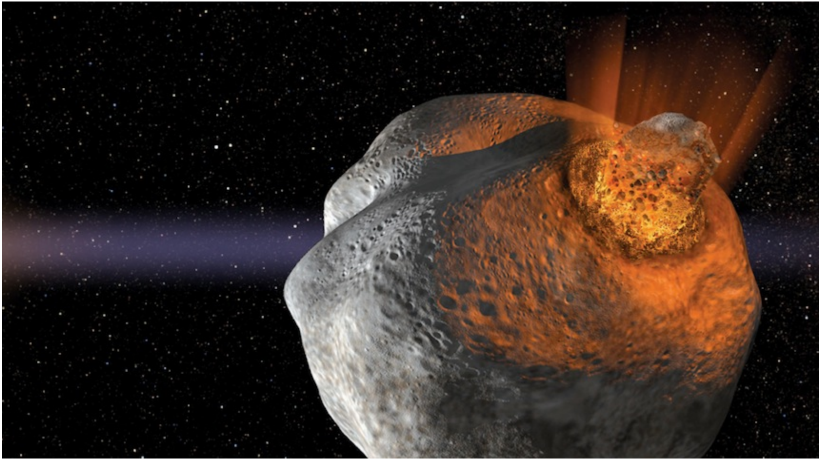
Fred Ciesla	University of Chicago
Gareth Collins	Imperial College London
David O'Brien	Planetary Science Institute







Part 1:
Heating in planetesimals

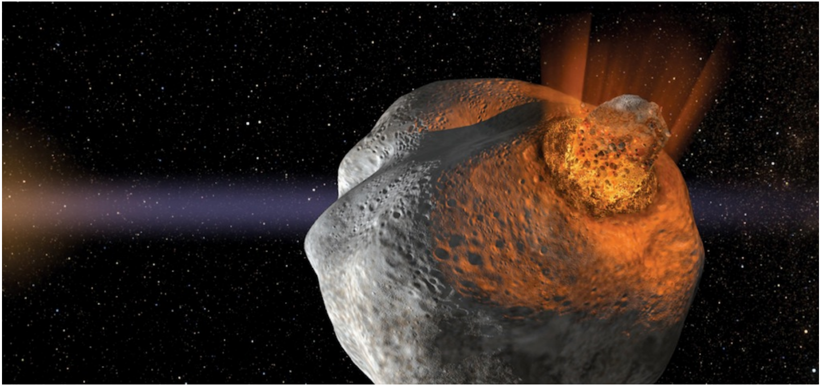


Images courtesy of Don Davis/Nature Publishing Group

Planetesimals got hot early in their lifetimes

Evidence from meteorites shows that planetesimals would have been heated early on, e.g.:

- Metamorphism in chondritic meteorites
- Differentiation and melting of iron and achondrite meteorites



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Metamorphism

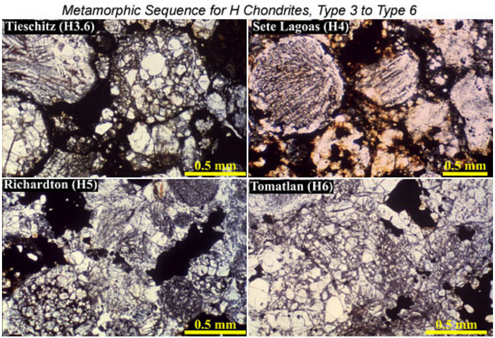


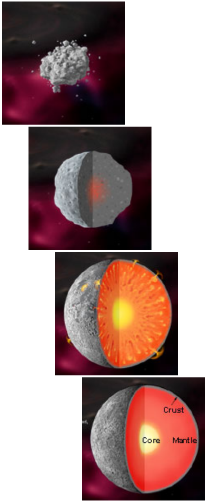
Image courtesy of Gary Huss

- Evidence in meteorites of **metamorphism**
- Regions that got hotter than they were at formation
- e.g. relationship between **chondrules** and **matrix**

Type 3	Sharp boundaries to chondrules
Type 4/5	Some chondrules visible, fewer sharp edges
Type 6	Chondrules poorly delineated

↓ Increasing metamorphism

Differentiation



Images courtesy of Smithsonian National Museum of Natural History

- Some asteroids show evidence of **differentiation**
  - Those that formed the iron and achondrite meteorities
- If the material is hot enough to melt, the heavier elements (i.e. metal) sink to form a core
- Chemistry of the rocky (silicate) mantle is different to chondrites
  - i.e. shows the asteroid was melted

Heat sources in planetesimals

- Several sources of heat suggested for the early Solar System
  1. Electromagnetic induction
  2. Short-lived radionuclide decay
  3. Impacts

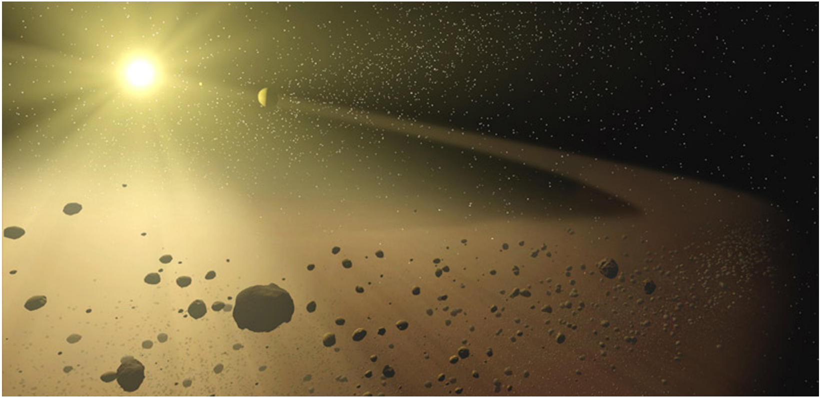


Image courtesy of NASA/JPL-Caltech

Electromagnetic induction is not a good candidate

- Magnetic field generated by Sun
- Planetesimals move through field, inducing an electric current
  - → Electric current heats up material

- But, magnetic field is from T Tauri phase of Sun's evolution
- Solar wind in this phase is dominant at the poles
  - → Not in the same plane as our disk of planetesimals
  - → Unlikely to cause much heating

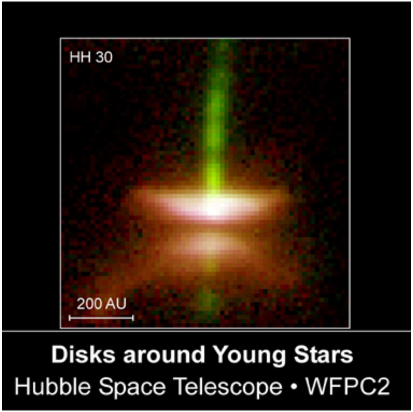


Image courtesy of STScI/JPL/NASA

Planets are heated by long-lived radionuclides

- Planets like the Earth receive much of their heat from radioactive decay
- Its why we have a hot core, and a geologically active planet
- In planet sized objects, the surface area is small compared to the volume
- Long lived radionuclides provide most heat

Isotope	Half life
^{238}U	4.5 billion years
^{235}U	0.7 billion years
^{232}Th	14 billion years
^{40}K	1.3 billion years

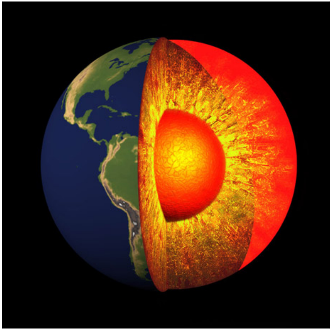


Image courtesy of Jason Reed/Photodisc/ Alamy/National Geographic

Planetesimals require short-lived radioisotopes

- Radiometric dating of meteorites show they were heated very early on
  - In the first ∼10 million years
- Too soon for the long-lived isotopes to have an effect
- Short-lived isotopes can provide heat on planetesimals

Isotope	Half life
^{26}Al	0.7 million years
^{60}Fe	2.6 million years

$^{26}\mathrm{Al} \rightarrow {}^{26}\mathrm{Mg} + \mathrm{Heat}$

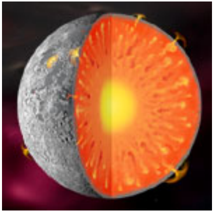
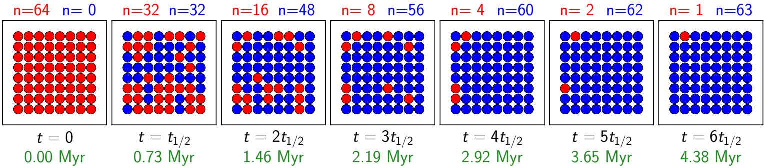


Image courtesy of Smithsonian National Museum of Natural History



The earlier an object formed, the hotter it became

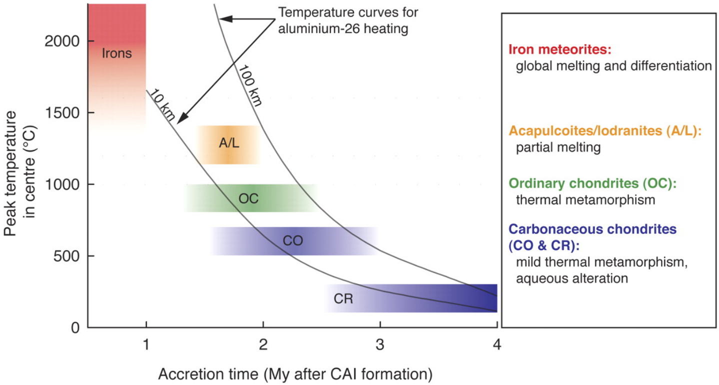


Image courtesy of Kleine & Rudge (2011) *Elements*

- Objects that formed early had higher abundance of short-lived radionuclides to heat them
- In later forming objects, the radionuclides had already decayed away

How would this heat affect the planetesimal?

- Formation of an **onion-shell** structure
- Hottest material in the center
- Progressively cooler material (and therefore lower petrologic type) further from the center

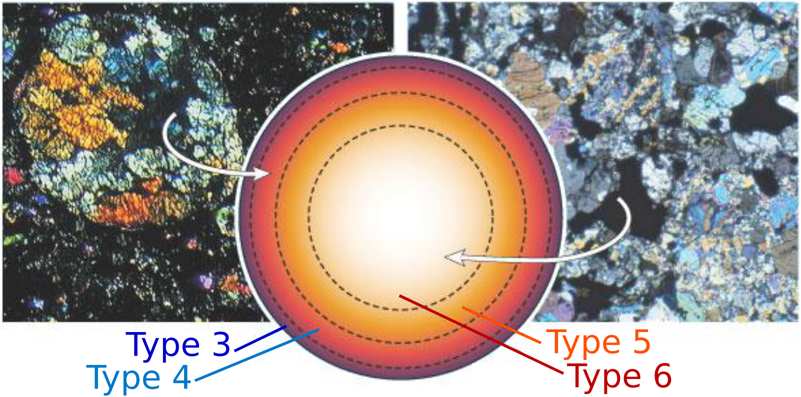


Image courtesy of Wood (2003) *Nature*

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Implications of the onion shell structure

- Material closest to surface loses heat to space quickly
- Hotter material, buried deeper, cools more slowly
- Should be a correlation between cooling rate measurements and peak temperature estimates

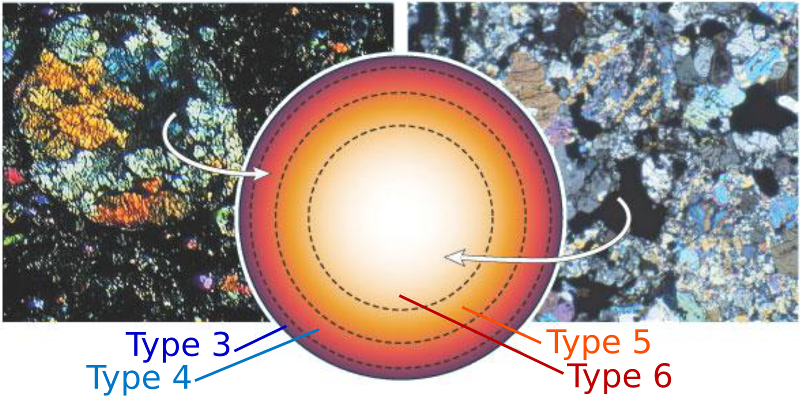

Image courtesy of Wood (2003) *Nature*

Modeling the onion shell

- Using computer models, we can simulate the evolution of an onion shell structure
- Several ways to quantify and compare with meteorites

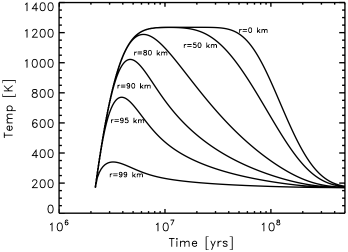

Image courtesy of Fred Ciesla

Peak temperature	Metamorphic grade
Cooling rate	Nickel concentration in metallic grains
Closure time	Radiometric age that grains cooled below a given temperature

- Extensive modeling for H chondrite parent body

Cooling rates can be inferred from metal grains

Available online at www.sciencedirect.com

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Geochimica et Cosmochimica Acta 74 (2010) 5410–5423

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Thermal constraints on the early history of the H-chondrite parent body reconsidered

Keith P. Harrison *, Robert E. Grimm

Southwest Research Institute, 1050 Walnut St., Ste 300, Boulder, CO 80302, USA

- Nickel concentrations within metal grains change depending on the cooling rate
- For the H chondrite parent body, models suggest:
  - Type 3 cooled at 0–50 K/Ma
  - Type 4/5 cooled at 20–40 K/Ma
  - Type 6 cooled at 3–20 K/Ma
- Harrison and Grimm's model can match 62 out of 71* cooling rate measurements

Cooling rates can be inferred from metal grains

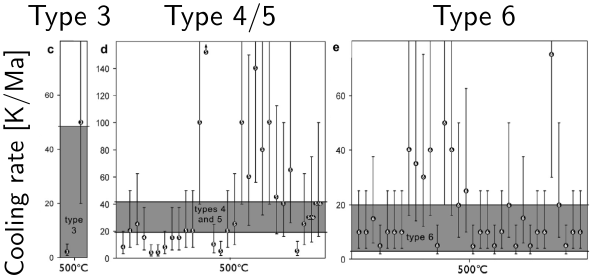

Image courtesy of Harrison & Grimm (2010) *Geochim Cosmochim Acta*

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Thermal history of the H Chondrite parent body

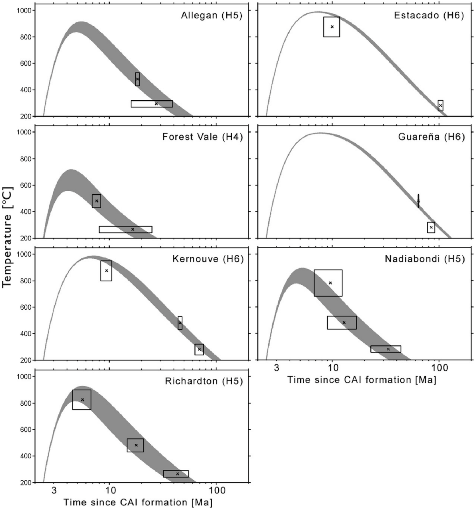

Image courtesy of Harrison & Grimm (2010) *Geochim Cosmochim Acta*

- 8 meteorites with multiple closure time data
- Harrison & Grimm were able to match 7 of them with onion shell
- Speculate that anomalies were due to impacts disturbing the onion shell
  - i.e. mix up the layers of petrologic types
- Could impacts do more than just disturb the onion shell?

Part 2:
Quantifying the long-term effects of impacts

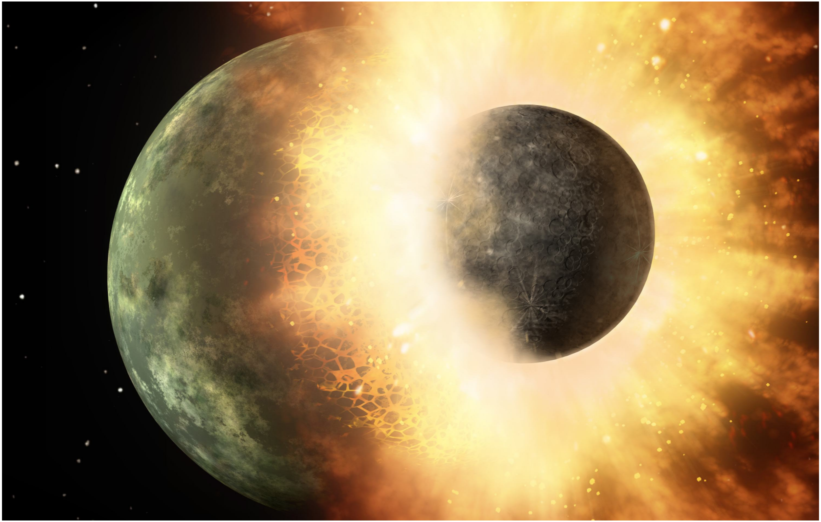

Image courtesy of NASA

Previously, it was thought impacts heating was negligible

Constraints on the role of impact heating and melting in asteroids

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[2]Museum für Naturkunde, Humboldt Universität, 10115 Berlin, Germany
[3]Seismological Laboratory 252-21, California Institute of Technology, Pasadena, California 91125, USA
[†]Also associated with the Hawaii Center for Volcanology
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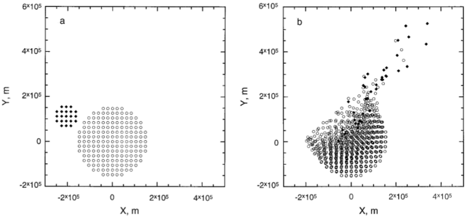
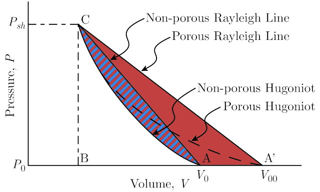
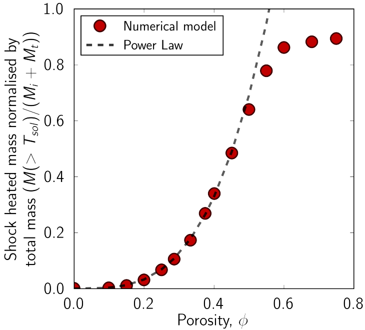


Image courtesy of Love & Ahrens (1996) *Icarus*

- Seminal paper in 1997
- Used numerical models, theoretical considerations and observations of craters
- Showed that a single impact could not raise the global temperature by more than a few degrees
- But, no porosity

Recall: Porosity greatly increases heating in collisions

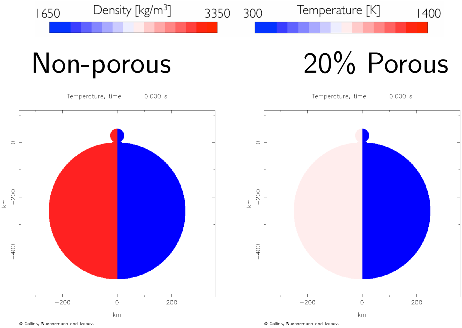




- Porosity increases the **waste heat** produced by a shock wave
- Last week we saw how that means much more heat is produced in porous collisions

- Could this change our conclusions about the role of impacts in the thermal evolution of planetesimals?

Porosity changes the cratering process



This movie can be downloaded from:

http://geosci.uchicago.edu/~tdavison/comptonlectures/Lecture6_Porosity.mov

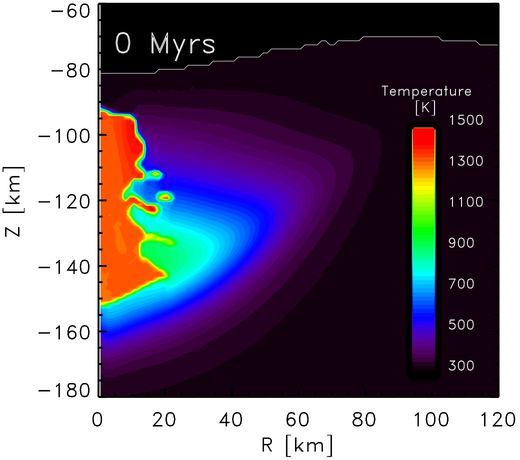
Porosity leads to:

- More heating
- Higher retention of heated material
- Deeper burial of heated material
- More thermal insulation of buried, heated material

What happens to the heat after the impact

- Solve heat equation: $\rho C_p \frac{\partial T}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(Kr^2\frac{\partial T}{\partial r}\right) + A_0\left(r,t\right)$
- Find what happens over millions of years

Time	T_{peak}
10 Ma	1100 K
20 Ma	900 K
50 Ma	800 K
100 Ma	600 K



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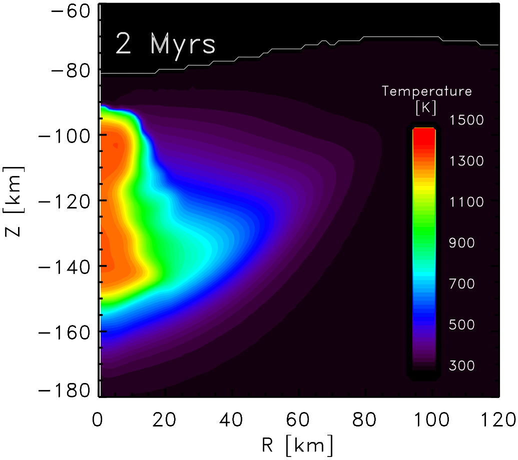

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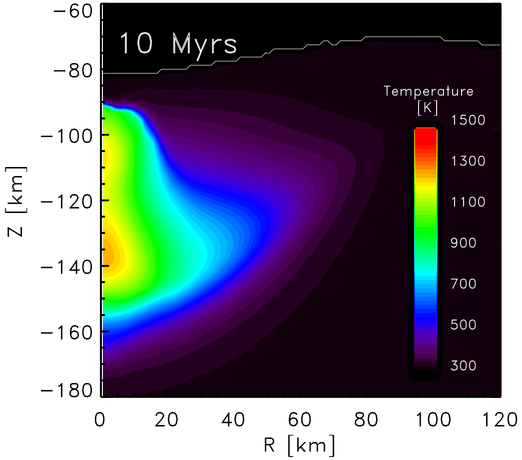

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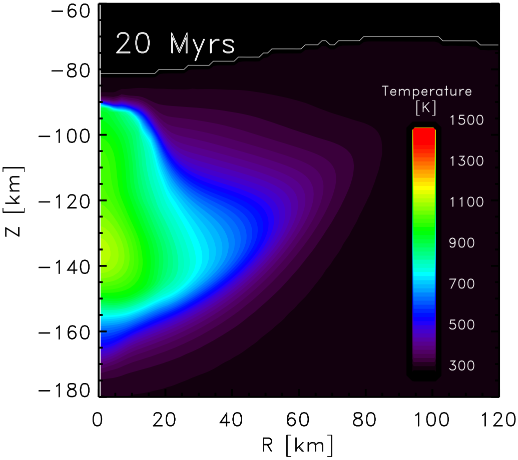

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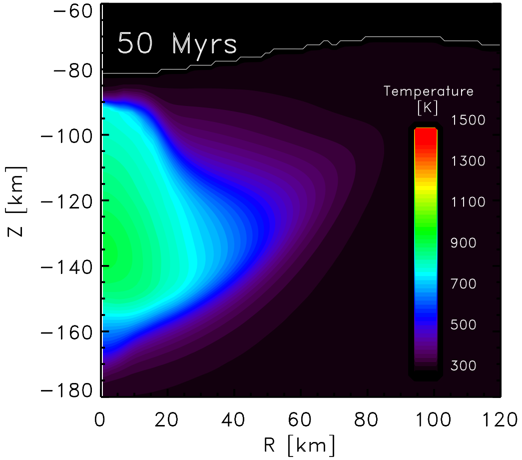

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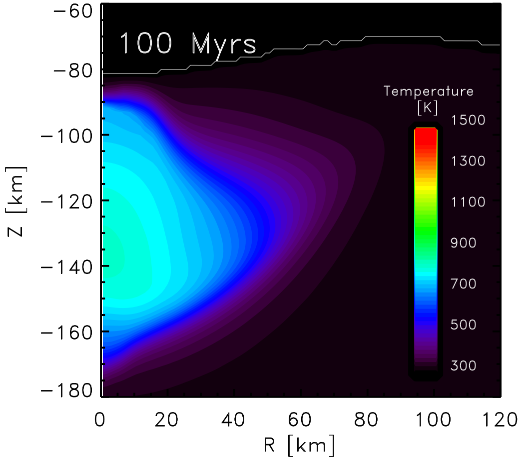
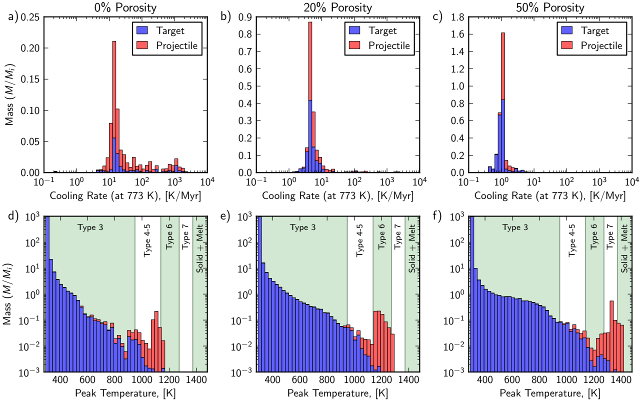
This is a local, not global, heat source



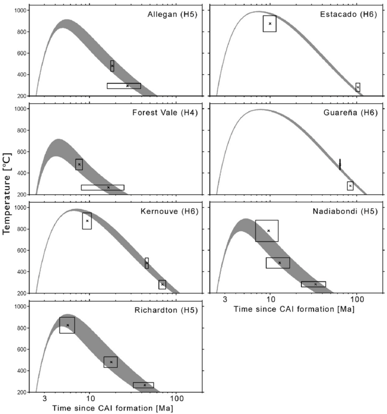
What are the cooling rates like post-impact?

- Cooling rates calculated at 500°C
- Average cooling rates ∼ 1 – 35 K/Ma
- Peak temperatures fit a wide range of petrographic types
  - from type 3 up to melt

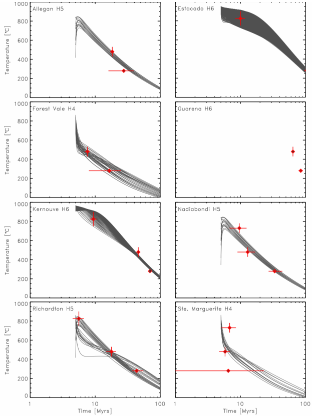


How does the thermal history compare to the onion shell?

Onion Shell

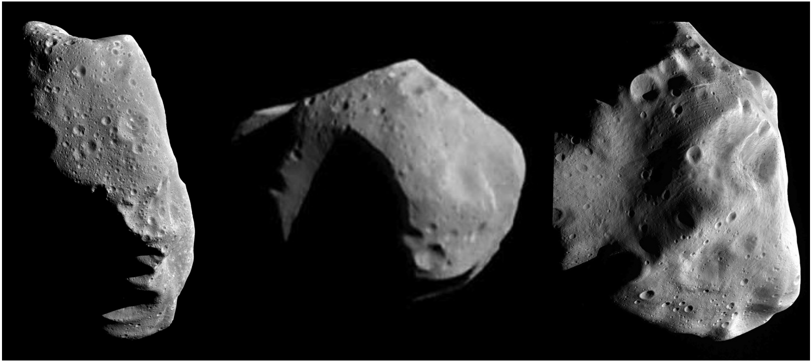


Impact



- This particular impact has material with thermal paths that can fit 7 out of 8 meteorites too!
  - Imagine what a range of other impacts could do
- Is this impact typical of what we expect on a parent body?

Part 3:
The effect of multiple impacts



Images courtesy of NASA/JPL/ESA

Asteroids show evidence of many cratering events

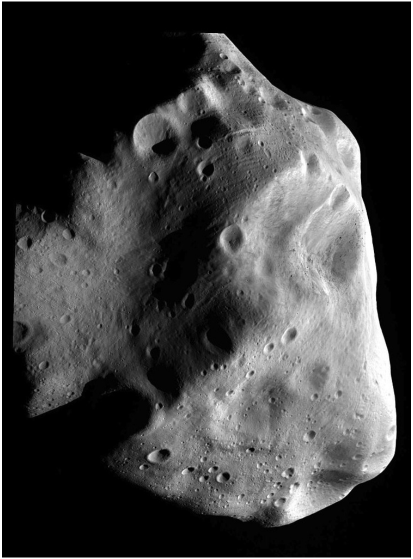


Image courtesy of ESA

- How many impacts do we expect on a parent body?
- What range of impact velocities and projectile sizes are likely?
- What is a typical impact like?

- What is the overall effect of all these impacts?

Legend

- **Jupiter**
- **Embryos/Planets**
- **Planetesimals**

In the lecture I showed a movie of an N-Body simulation created by David O'Brien. That simulation can be viewed online here:
http://www.psrd.hawaii.edu/WebImg/OBrien_movie_cjs_simulation.gif

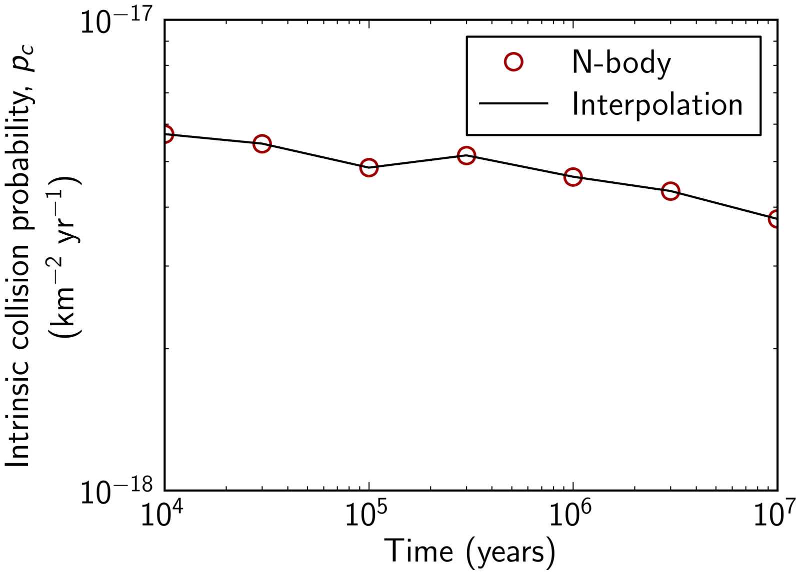
- Within 10's of millions of years, several planets form
- Stable orbits
- Terrestrial planet region 0.5 – 2 AU

The changing planetesimal population

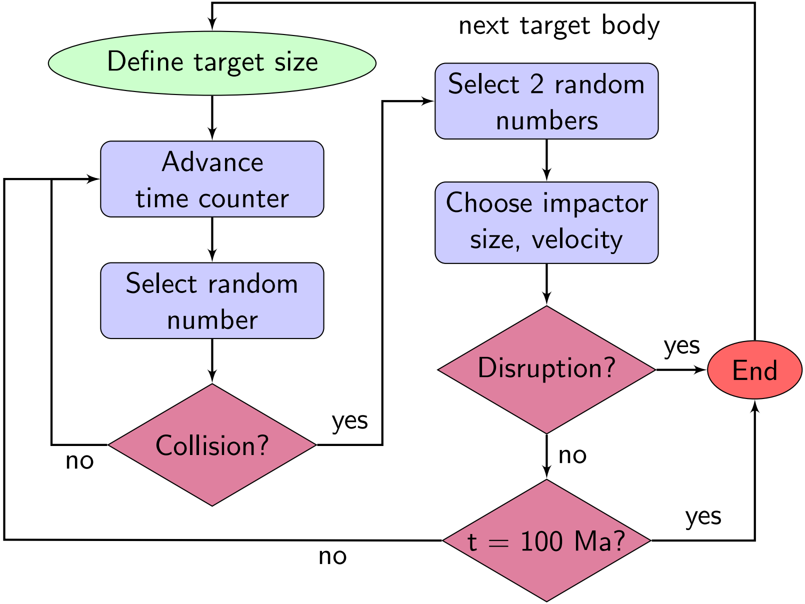
In the lecture, I showed two movies: The changing size-frequency distribution of the planetesimal population with time, and the changing velocity-frequency distribution of collisions between planetesimals, with time. Those movies can be downloaded here:

http://geosci.uchicago.edu/~tdavison/comptonlectures/Lecture6_SFDTime.mov
http://geosci.uchicago.edu/~tdavison/comptonlectures/Lecture6_VFDTime.mov

The changing planetesimal population



Monte Carlo model determines collisional histories



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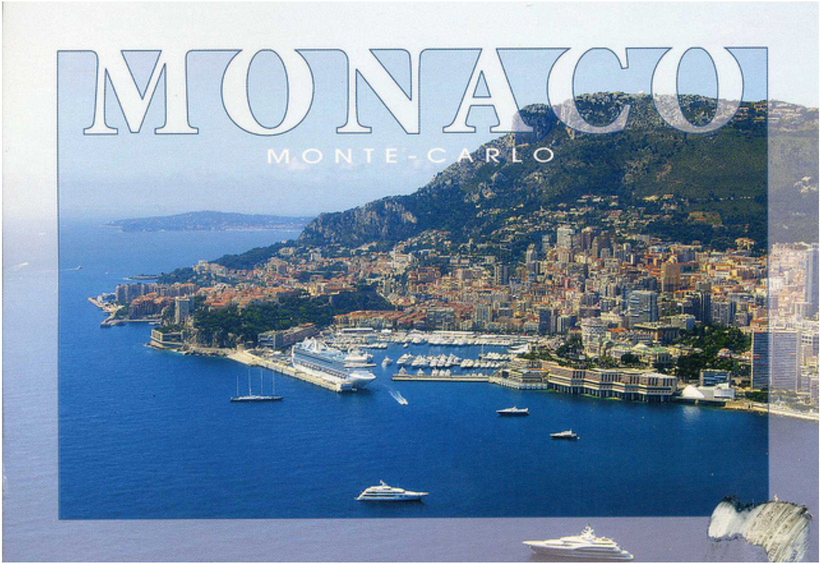
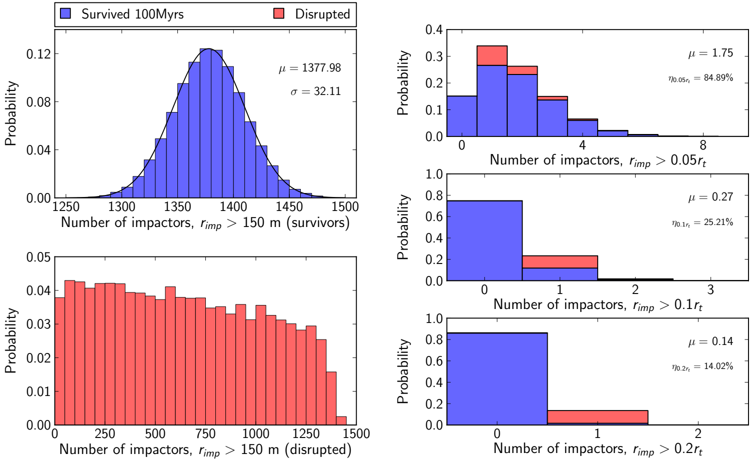


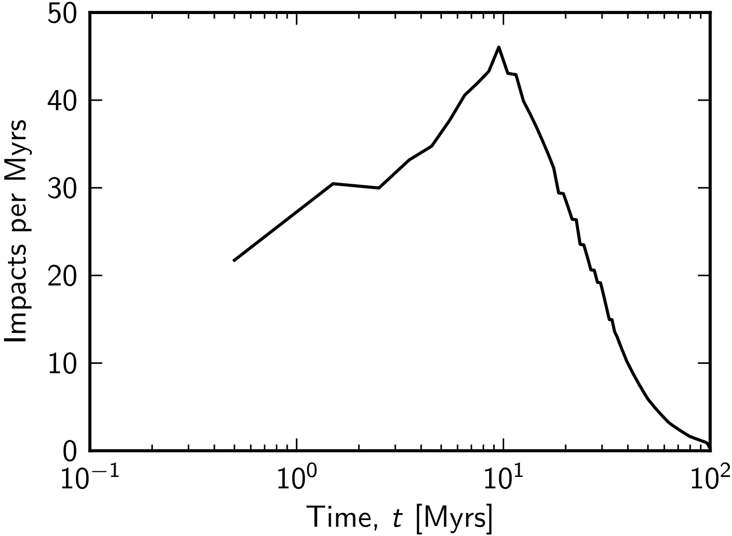
At least one thousand impacts expected

Several large impacts per parent body



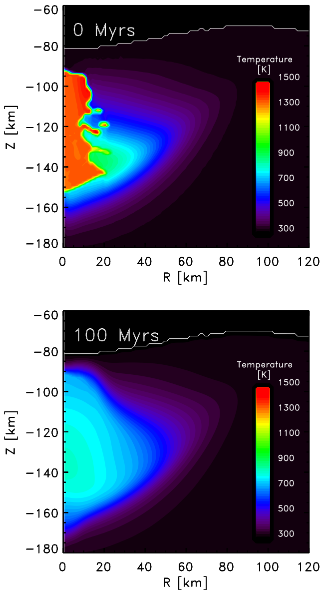
Most impacts happened early

Same time as ^{26}Al was active

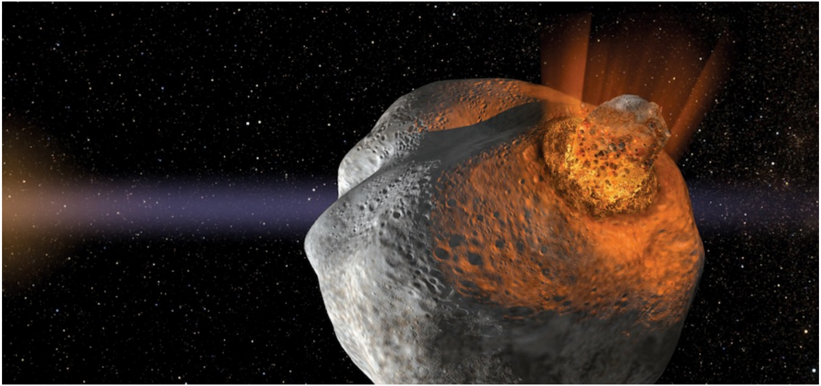


Summary

- Impacts could cause significant heating
- Thermal signatures from impacts can match those that we measure in meteorites
- Impact heating is typically localized, radionuclide decay is global
- Meteorites are only small samples — no need for heating to be a global process
- Previous estimates of parent body sizes and early Solar System conditions need to be revised
    - Account for the effect of impacts on the thermal evolution of planetesimals



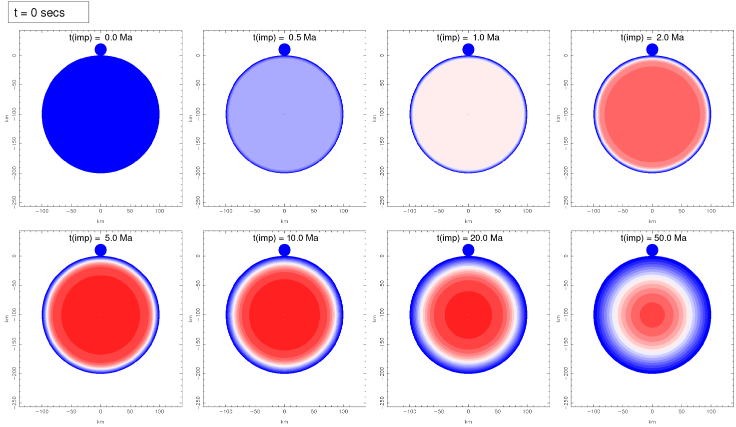
Part 4:
Still more to be done!



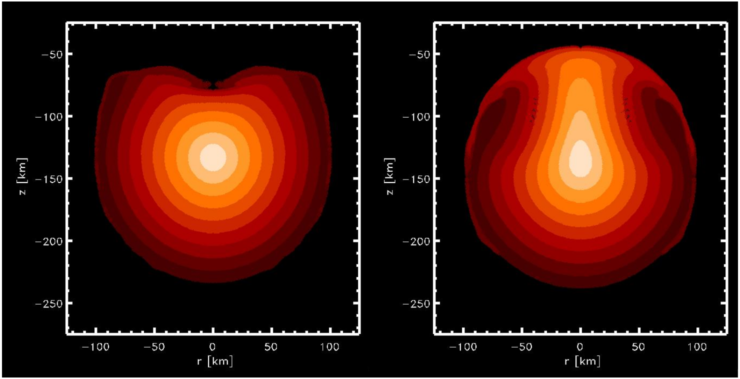
Images courtesy of Don Davis/Nature Publishing Group

How do the two processes combine?
Simulations of impacts into a pre-heated target

In the lecture, I showed a movie of collisions into target with different thermal structures. That movie can be viewed here:
http://geosci.uchicago.edu/∼tdavison/comptonlectures/Lecture6_TempGrad.mov



Impacts affect pre-warmed planetesimals in different ways



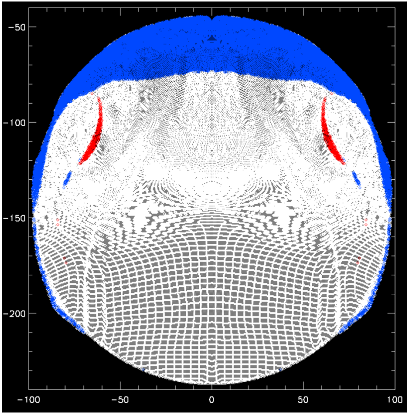
- Only disturbs near-surface region
- Center of body relatively unaffected

- Disturbs region much deeper in the body
- Warm material brought from center of body to surface

Cooling rates are also affected

Cooling rates at 500°C:

- Increased by >2.5 times
  - 13% by mass of target body
- Decreased by >2.5 times
  - 0.8% by mass of target body



- Unexpected result: Not just heating done by impacts
  - Also accelerates cooling of large volume of material
  - Important for large bodies that stay hot longer and experience more collisions
  - Can easily explain cooling rate observations from meteorites

Thank you

Questions?