Constructing the Solar System: A Smashing Success

Asteroids and Meteorites:
Our eyes in the early Solar System

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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

1. What are asteroids and meteorites?
2. Orbital properties of asteroids
3. How do we classify meteorites?
4. Proposed origins for different meteorite classes
   - How they are linked to asteroid families
5. Evidence of collisions on asteroids

Image courtesy of Ed Sweeney

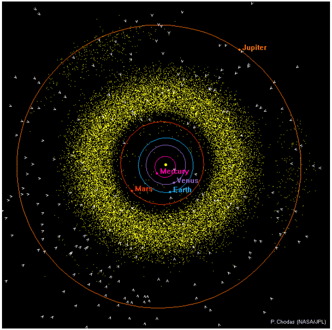


Image courtesy of Paul Chodas (NASA/JPL)

Part 1:
What are asteroids and meteorites?

Image courtesy of Ed Sweeney

What are asteroids and comets?

Asteroid

A relatively small, inactive, rocky body orbiting the Sun, usually between the orbits of Mars and Jupiter

Comet

A relatively small, at times active, object whose ices can vaporize in sunlight forming an atmosphere (and sometimes a tail) of dust and gas

Vesta: mean diameter = 525 km

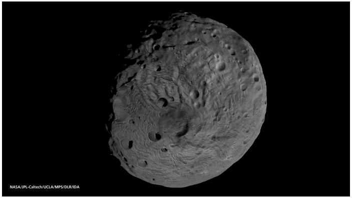


Image courtesy of NASA/JPL-Caltech/UCLA/MPS/DLR/IDA

Comet Hartley 2: 2.25km long

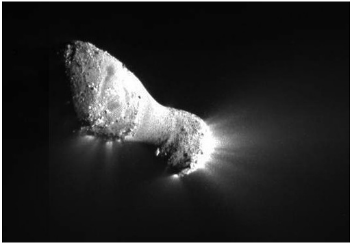


Image courtesy of NASA/JPL-Caltech/UMD

Asteroids are planetesimals that didn't grow into planets

- Last time, we learnt how **planetesimals** were formed
  - Small rocky bodies ∼ 1–100 km in size
- Next week we will learn how the planets grew from planetesimals
- Some planetesimals did not grow into planets
- Those that survived now form the **asteroid belt**

Examples of some asteroids, compared to the size of Mars

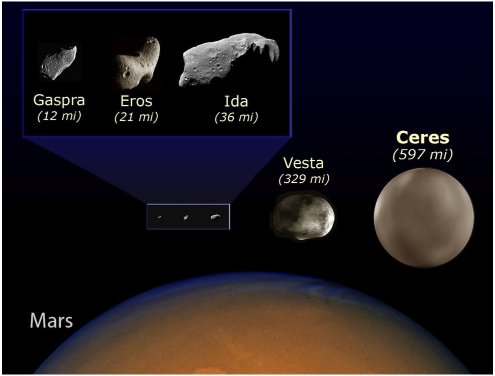
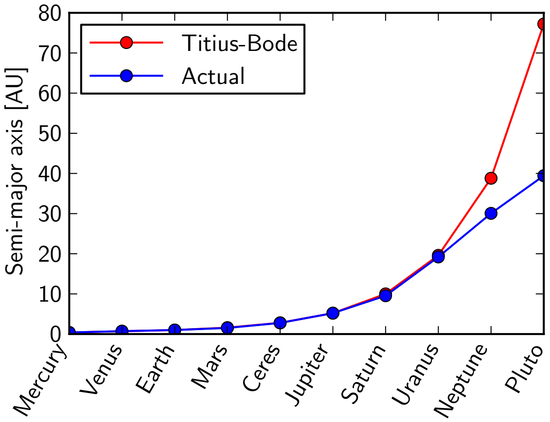


Image courtesy of NASA/JPL/STScI/JHU/APL

Discovery of Asteroids from 1980 to present

- First asteroid, Ceres, discovered in 1801 by Guiseppe Piazzi
- By 1980, we knew of ∼9000 asteroids
- Recently, with better observation, we know of half a million!



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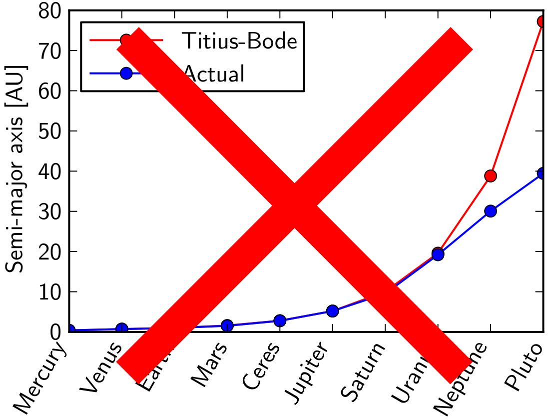

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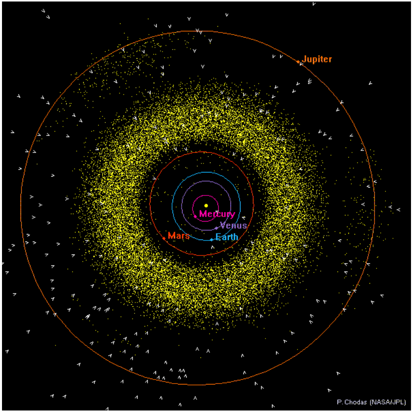
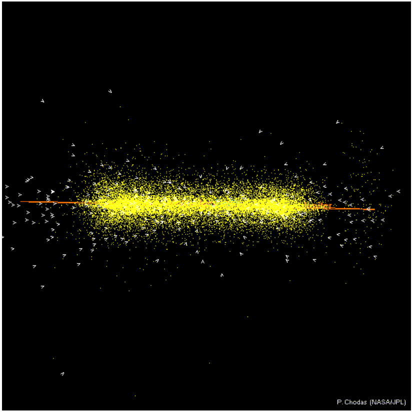
- By 1980, we knew of $\sim$9000 asteroids
- Recently, with better observation, we know of half a million!

In the lecture, I showed a movie of asteroid discovery from 1980 to the present day. You can view that movie in two places online:

- On YouTube — `http://www.youtube.com/watch?v=XaXcBUFapic`
- On Scott Manley's website — `http://star.arm.ac.uk/neos/1980-2010/`

Positions of asteroids and comets on October 1, 2008





Images courtesy of Paul Chodas (NASA/JPL)

Orbits of Asteroids and Comets

Positions of asteroids and comets on October 1, 2008

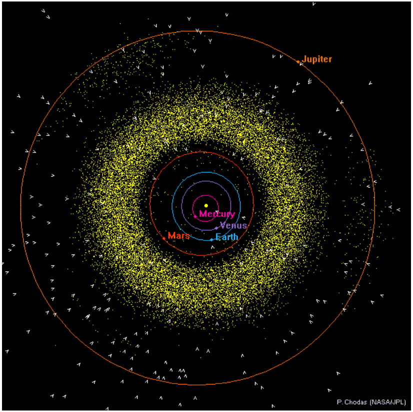


Image courtesy of Paul Chodas (NASA/JPL)

- Most asteroids are contained in the **main belt** between Mars and Jupiter
- Some follow a similar orbit to Jupiter (the **Trojans**)
- Comets tend to have much longer orbital periods, and much greater eccentricity than asteroids
- Their orbits taken them out to the region of the outer planets, and beyond

Orbital eccentricity and inclination

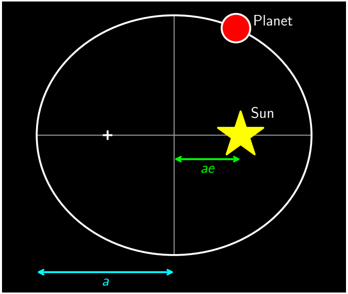
Eccentricity

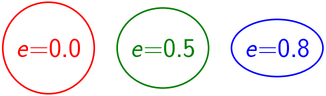
A planet's orbital eccentricity, e is a measure of how elliptical its orbit is

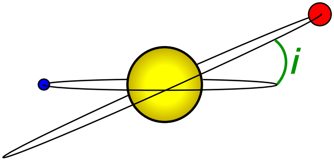
- $e = 0$ means the orbit is circular
- $0 < e < 1$ for an elliptical orbit

Inclination

The orbital inclination, i is the angle between the plane of the orbit of the planet and the ecliptic — which is the plane containing Earth's orbital path

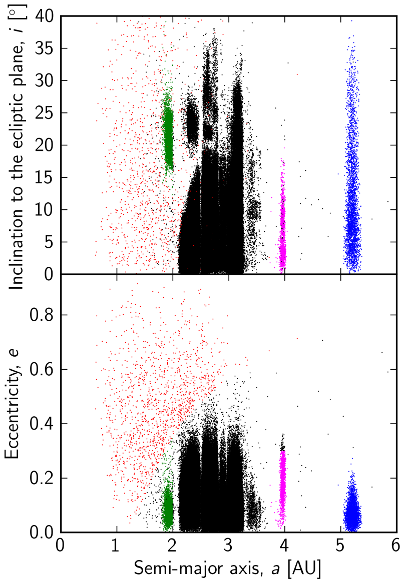






Asteroid families

- Some asteroids are grouped based on where they orbit. For example:
  - The **Hungaria** family orbit between 1.78 and 2 AU
  - The **Hilda** family orbit between 3.7 and 4.2 AU
  - The **Jupiter Trojan** family orbit between 5.05 and 5.35 AU
  - The **Near-Earth Objects** come within 1.3 AU of the Sun on their closest approach
- Why are there gaps where no asteroids orbit?



Kirkwood gaps

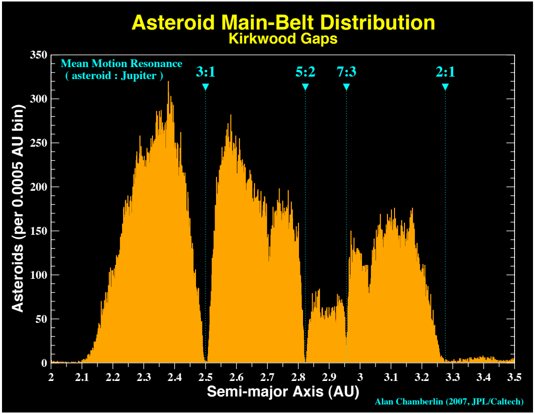


Image courtesy of Alan Chamberlin (NASA/JPL)

- Gaps in the asteroid belt appear at **mean motion orbital resonances** with Jupiter
- These gaps are known as **Kirkwood gaps**
- What is an orbital resonance?

Orbital resonance

- Imagine a child on a swing
- If I always give the child a push as the swing is going forward, all those pushes will **add up** to make the swing go higher
  - The velocity increases
- The same applies for asteroids in resonance with Jupiter
- A resonance of 3:1 means that the asteroid orbits the Sun 3 times for every orbit that Jupiter makes
- So, every third orbit, the asteroid gets a small **push** from Jupiter, which speeds it up
- It then can either:
  - Find a new stable orbit
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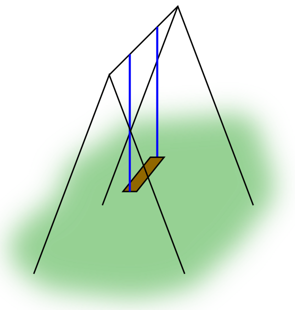

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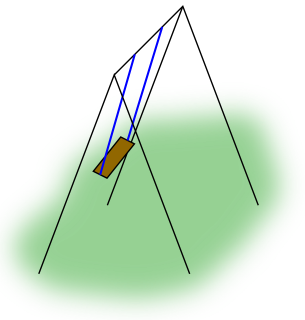

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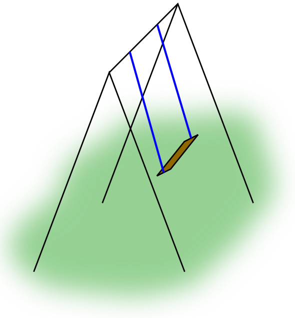

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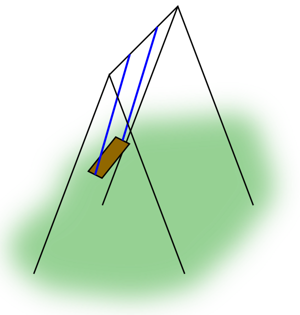

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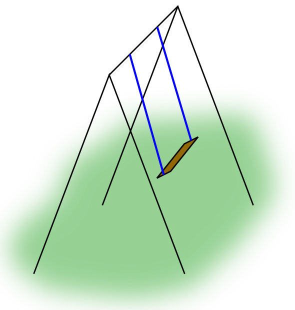

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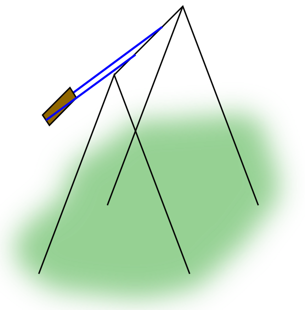

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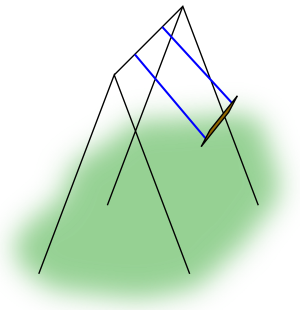

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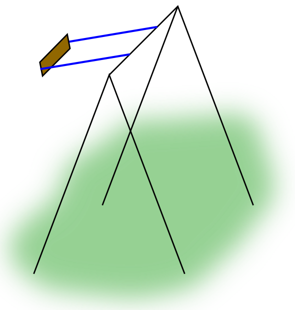

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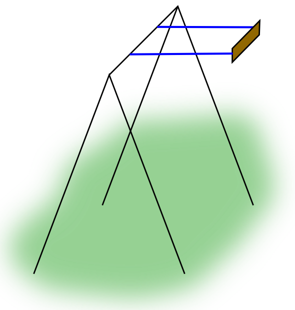

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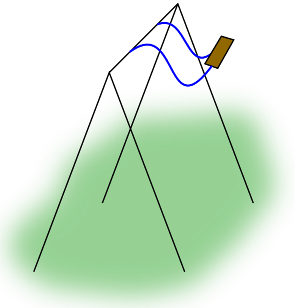

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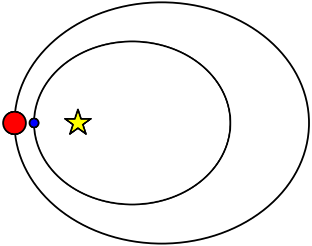

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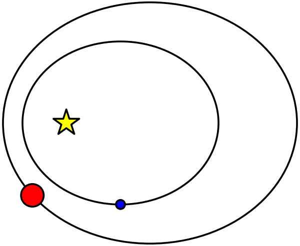

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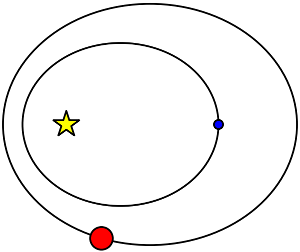

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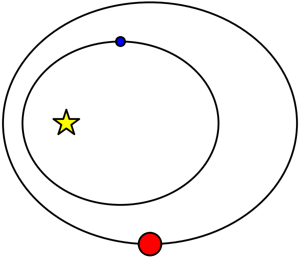

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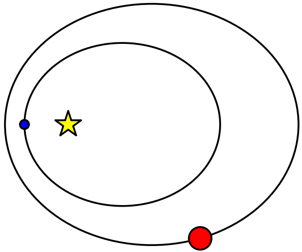

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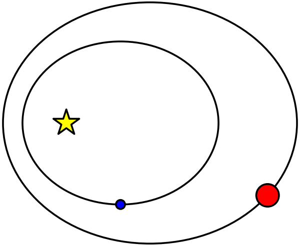

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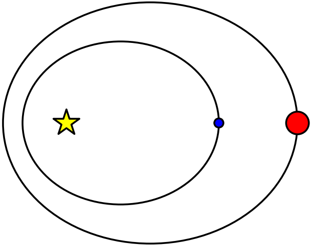

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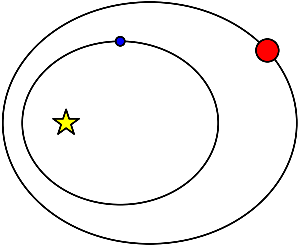

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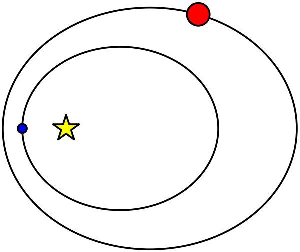

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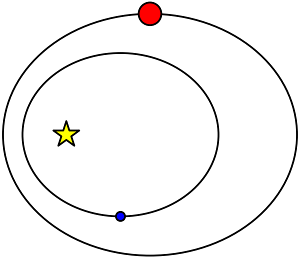

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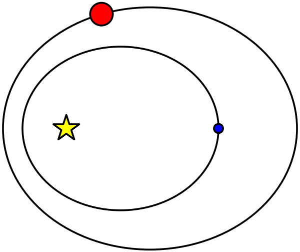

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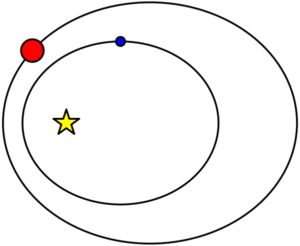
- If I always give the child a push as the swing is going forward, all those pushes will **add up** to make the swing go higher
  - The velocity increases
- The same applies for asteroids in resonance with Jupiter
- A resonance of 3:1 means that the asteroid orbits the Sun 3 times for every orbit that Jupiter makes
- So, every third orbit, the asteroid gets a small **push** from Jupiter, which speeds it up
- It then can either:
  - Find a new stable orbit
  - Fall into a planet-crossing orbit



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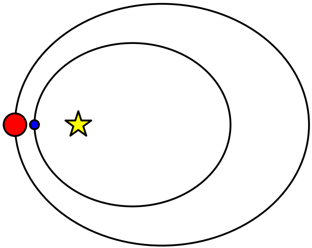

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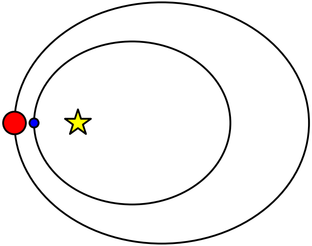
Planet Formation

We will look more at the role of orbital resonance in the formation of the planets, next week



What else can we find out about asteroids?

- It is possible to look at the light reflected from asteroids and tell something about their chemistry
- Different elements reflect and absorb light at different wavelengths
- However, to really understand that data, we need something to compare it to
- We do have some sample of asteroids on Earth: these samples are called **meteorites**

Ida

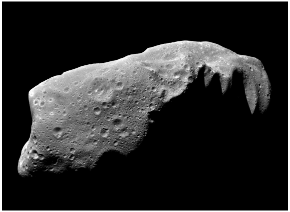


Image courtesy of NASA/JPL

Mathilde

Image courtesy of NASA

What are meteorites?

Leonid meteor shower, 2009

Image courtesy of Ed Sweeney

Holsinger Meteorite,
Meteor Crater, Arizona

Meteoroid

A small particle from a comet or asteroid orbiting the Sun

Meteor

The light phenomena which results when a meteoroid enters the Earth's atmosphere and vaporizes; a shooting star

Meteorite

A meteoroid that survives its passage through the Earth's atmosphere and lands upon the Earth's surface

Meteorites: Falls and Finds

Image courtesy of P. Jenniskens/SETI Institute

- Meteorites can be classified into two types depending on how we found them
- **Falls** and **Finds**

Meteorites: Falls and Finds

Image courtesy of P. Jenniskens/SETI Institute

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- **Falls** and **Finds**
- **Falls** are meteorites that have been observed falling to Earth, and are collected soon after
    - $\sim$ 500 meteorites of marble to basketball size are expected to fall each year and remain intact
    - Yet, only $\sim$ 5–6 are discovered and made available for scientists
- Example: Almahatta Sitta meteorite that fell in the Nubian Desert in Sudan in 2009

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Image courtesy of P. Jenniskens/SETI Institute

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Image courtesy of C. Corrigan/ANSMET

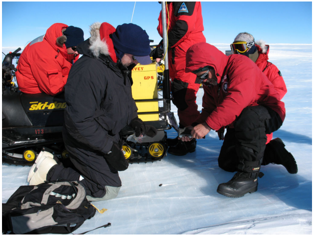


Image courtesy of ANSMET

- Meteorites can be classified into two types depending on how we found them
- **Falls** and **Finds**
- **Finds** are meteorites that were not observed falling to Earth, and are found later
    - Finds are $\sim$ 30 times more common
    - But, sometimes have been weathered
    - Some areas are better to look than others: e.g. deserts or Antarctica

Meteorites can be separated into two main classes

Differentiated meteorites and Chondritic meteorites

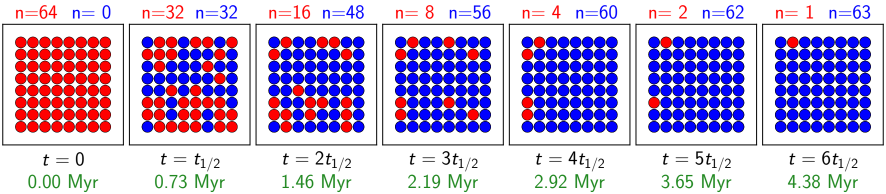
- **Differentiated meteorites**
  - Formed in planetesimals that melted shortly after
  - Some are metallic (usually a nickel-iron alloy)
    - Core of a melted planetesimal
  - Some are stony (called achondrites because they have no chondrules)
    - Outer layers of a melted planetesimal or planet
    - These include meteorites from the Moon, Mars and asteroids such as Vesta

Iron meteorite

Image courtesy of H. Raab

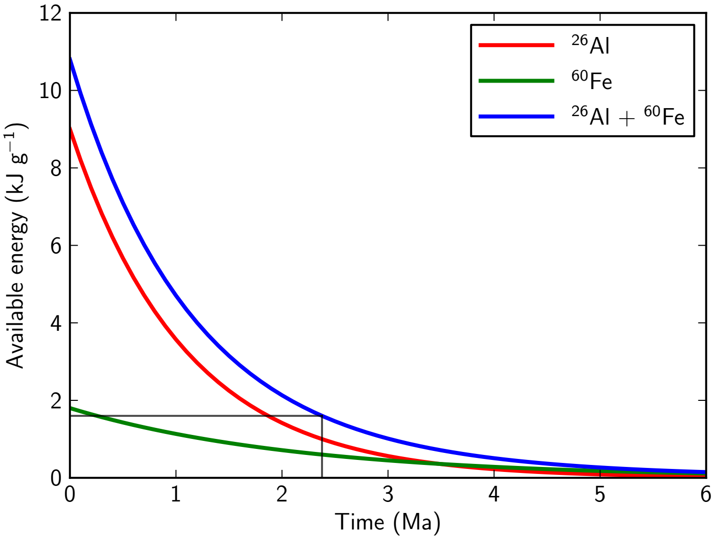
Planetesimals were heated after formation

- Differentiated meteorites were melted after their parent planetesimal formed
- Most of this heat came from the decay of radioactive material
- A major source of this heat is the decay of ^{26}Al to ^{26}Mg
  - Decays with a half-life of $t_{1/2} = 0.73$ Myr



- This heat source is only effective for the first 5 Myr or so

Radioactive decay is only effective for the first 5 Myr or so



- **Chondrites**, or **primative meteorites**
  - Chemical compositions that closely resemble the Sun
  - Except for volatile elements (e.g. H, He, C, N, O), the abundance of other elements are within a factor of 2 of the Sun's composition
  - They have not melted since they accreted

Chondrite

Image courtesy of H. Raab

Chondrites can tell us about the early Solar System

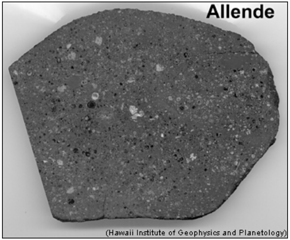


Image courtesy of Hawaii Institute of Geophysics and Planetology

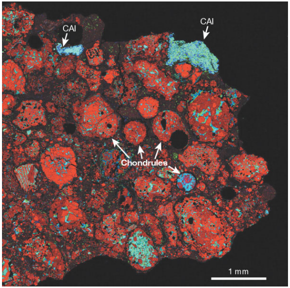
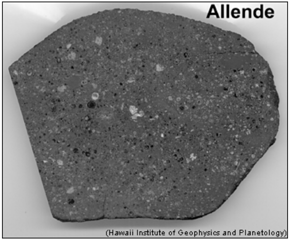


Image courtesy of Alexander Krot, University of Hawaii

- An important component of chondrites are called **Calcium-Aluminium-rich inclusions (or CAIs)**
  - CAIs are the oldest known objects to form in the Solar System
  - Formed approximately 4567 Myr ago
  - Formed at very high temperatures (> 1400 K or $2000°$F)

Chondrites can tell us about the early Solar System



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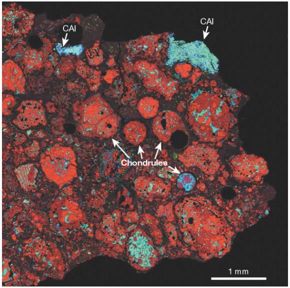
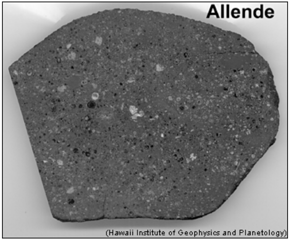


Image courtesy of Alexander Krot, University of Hawaii

- Chondrites get their names from one of their main components: **Chondrules**
  - Chondrules are small (mm-sized) spheres of silicate rock
  - They condensed from melt droplets
  - Formed at lower temperatures (< 1000 K or 1350°F)
  - Formed around 2 Myr after CAIs
  - There are lots of discussions about how chondrules formed, and still no consensus from the scientific community

Chondrites can tell us about the early Solar System



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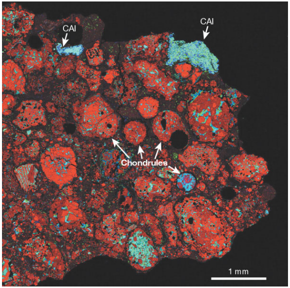


Image courtesy of Alexander Krot, University of Hawaii

- In between the chondrules and CAIs is a fine grained **matrix**
  - Mostly made up of silicate-rich material that formed across a range of Solar System locations
  - Studying the matrix material can tell us about the heating and cooling histories of the meteorites
  - Presolar grains that formed elsewhere before our Sun formed

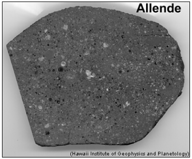
Chondrites can be classified by their chemical composition

- Three main classes are called Enstatite Chondrites, Ordinary Chondrites and Carbonaceous Chondrites
- Each of these classes can be further subdivided into groups
  - Enstatite chondrites have 2 groups
  - Ordinary chondrites have 3 groups
  - Carbonaceous chondrites have 9 groups
- Meteorites with each group have similar physical properties (e.g. chondrule sizes, mix of different components)
  - Each group represents materials that were mixed together and accreted at the same time and place
  - Probably from the same **parent body**

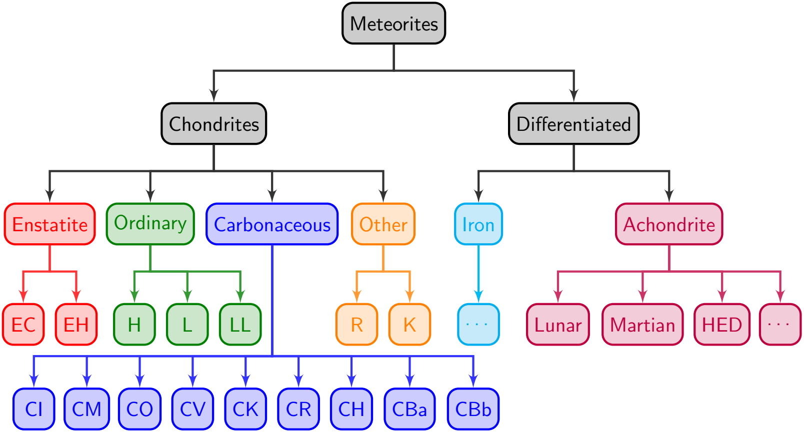
Enstatite

Ordinary

Carbonaceous



Meteorite groups



Differences between chondrite groups

How do we differentiate between enstatite, ordinary and carbonaceous chondrites?

Enstatite	Ordinary	Carbonaceous
1. High formation temperature	1. High formation temperature	1. Lower formation temperature
2. Low water and oxygen content	2. Medium water content	2. High water content
3. Little to no aqueous alteration	3. Mild aqueous alteration	3. Aqueous alteration is common
4. High levels of heating	4. Medium levels of heating ($> 500°C$)	4. Low levels of heating ($< 200°C$)

Likely scenario:

Formed close to the Sun ⟶ **Formed far from the Sun**

What do we know about where an asteroid formed?

- Planetesimals formed in the protoplanetary disk
- Those close to the Sun would have been hotter than those far away
- Asteroids that formed close to the Sun probably wouldn't have any water (it not have condensed in the hotter regions near the Sun)
- Those far away from the Sun, where the temperature was lower, may contain water (it could have condensed as ice from the gas)

Ida

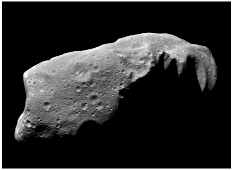


Image courtesy of NASA/JPL

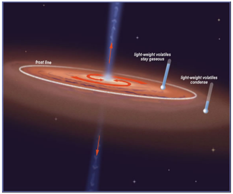


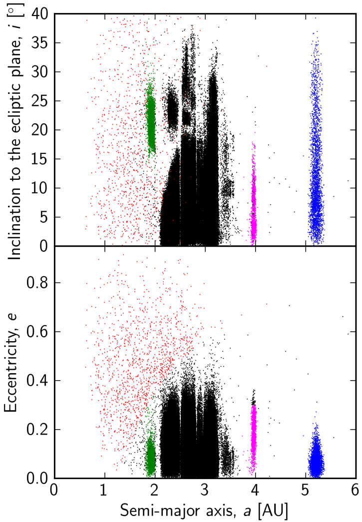
Image courtesy of the Lunar and Planetary Institute

Enstatite — Ordinary — Carbonaceous

Formed close to the Sun ⟶ Formed far from the Sun

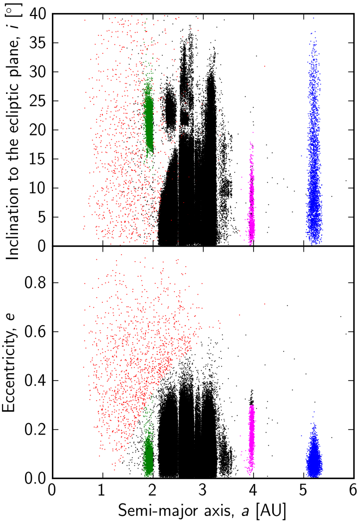
Meteorites are samples of asteroids

- E-type asteroids are similar in composition to enstatite chondrites
  - Hungaria family are E-type
  - They orbit at ∼1.8 AU
- S-class (stony) asteroids can be linked to the ordinary chondrites
  - They orbit at around 2.1 – 2.8 AU
- C-class asteroids are linked to the carbonaceous chondrites
  - They orbit at distances of > 2.7 AU
  - They contain water-bearing minerals



Meteorites are samples of asteroids

- Groups of meteorites are linked to particular regions of the asteroid belt
  - However, the regions overlap a little
  - So, perhaps they were mixed after their formation
  - We will talk more about this mixing next week



Part 2:

Evidence of impacts on asteroids and meteorites

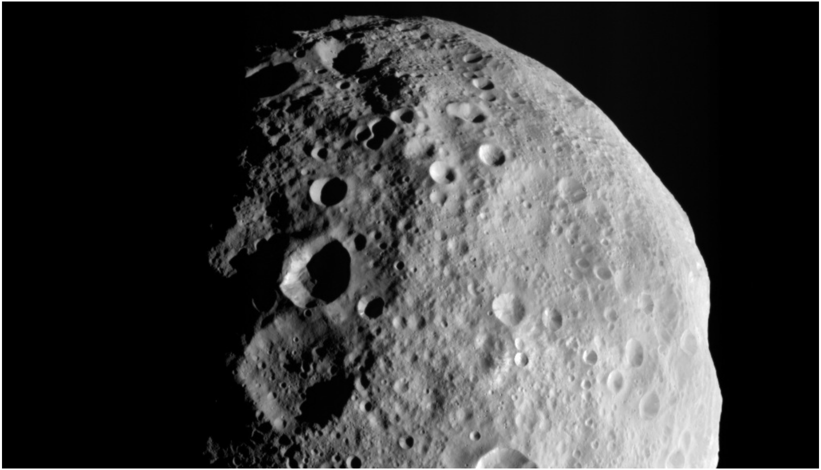


Image courtesy of NASA/JPL-Caltech/UCLA/MPS/DLR/IDA

All asteroids have one feature in common: Impact Craters

In the lecture, I played a video of Dawn's virtual flight over Vesta. You can view that video online here:

http://www.jpl.nasa.gov/video/index.php?id=1080

Collisions have long lasting effects

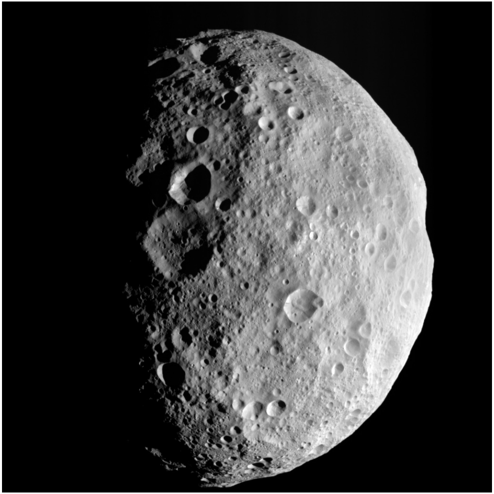
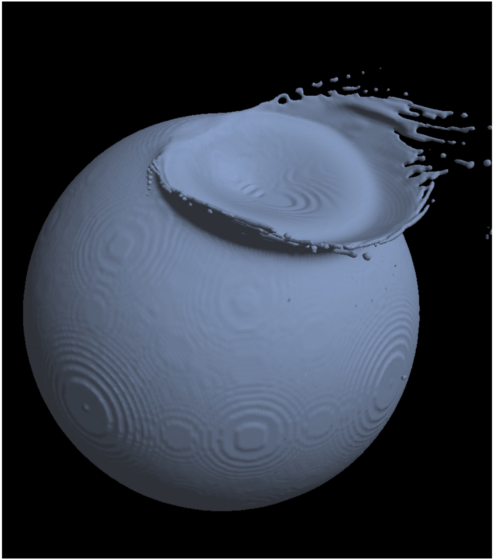


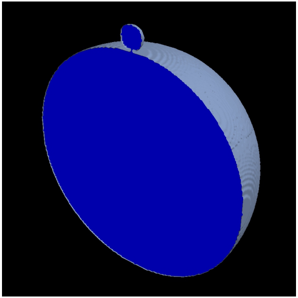
Image courtesy of NASA/JPL-Caltech/UCLA/MPS/DLR/IDA

- All asteroids show the effects of collisions on their surfaces
- Impacts also have effects that can be seen in meteorites
- A collision at fast enough velocity causes a **shock wave** to travel through the asteroid
- The effects of that shock wave can be observed in meteorites

Collisions cause shock waves



- Collision between two asteroids forms a crater on the surface
- Inside the asteroid, high pressures are experienced because of the shock wave



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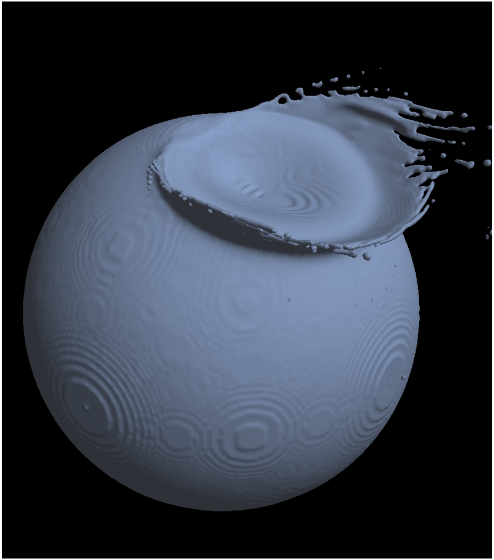

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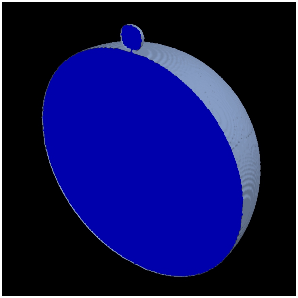

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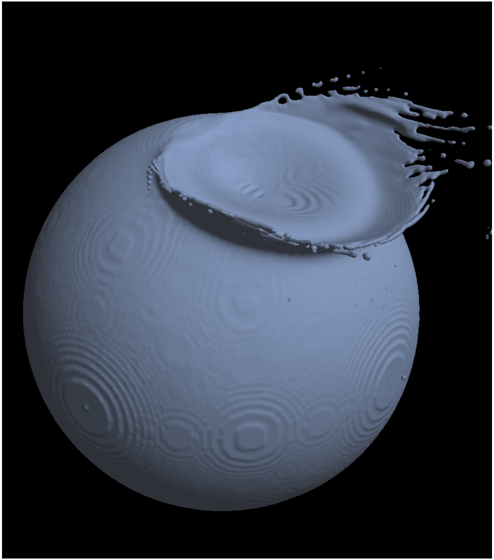

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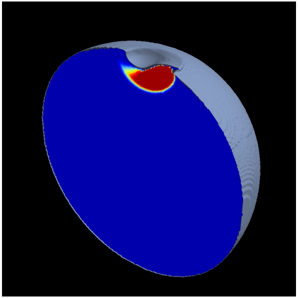

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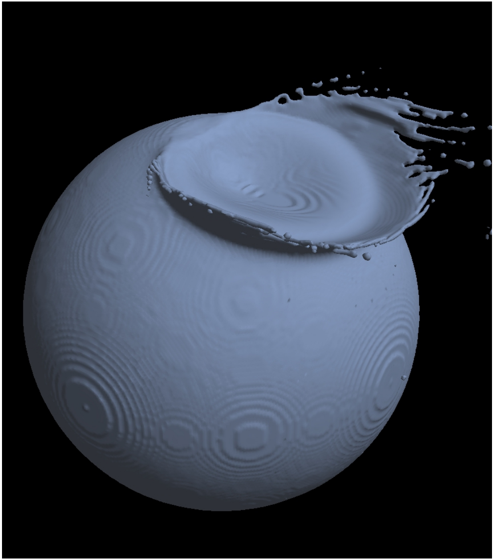

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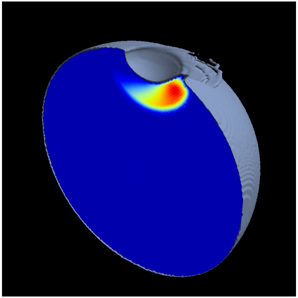

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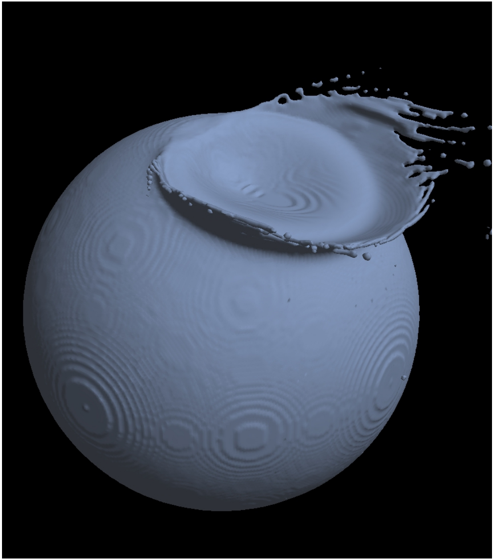

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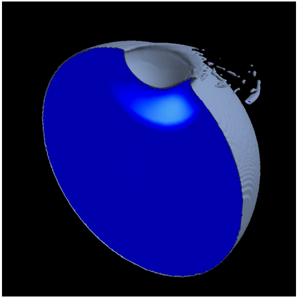

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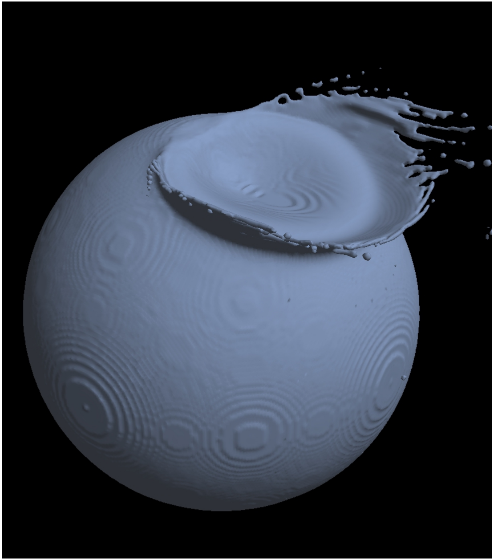

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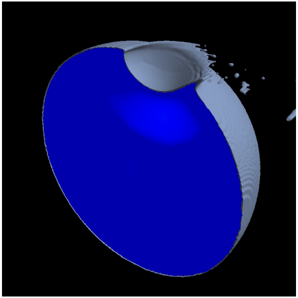

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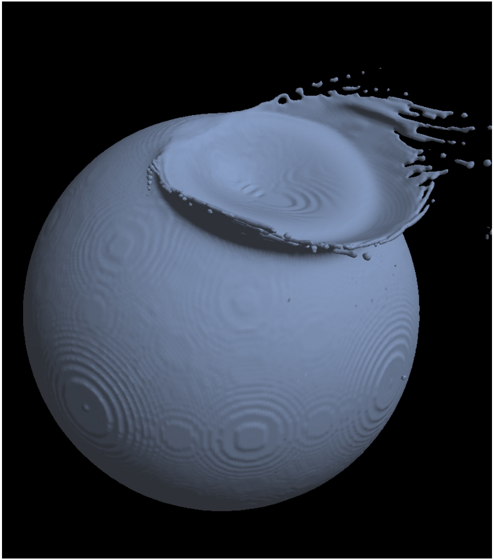

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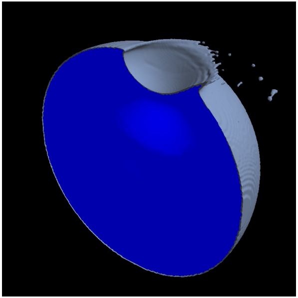


Shock waves alter the minerals in a meteorite

- The high pressure created by the impact event can melt materials
- In some cases, small particles of melt have the effect of **blackening** the meteorite
- Impacts can also cause **metamorphism** in meteorites, e.g.
  - Planar deformation features
  - Shocked quartz

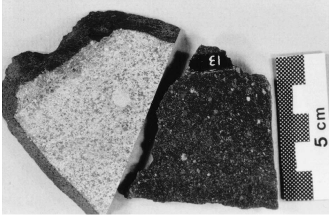


Image courtesy of Consolmagno & Britt (2004)

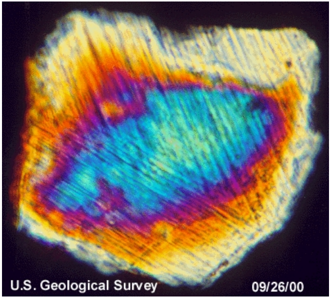
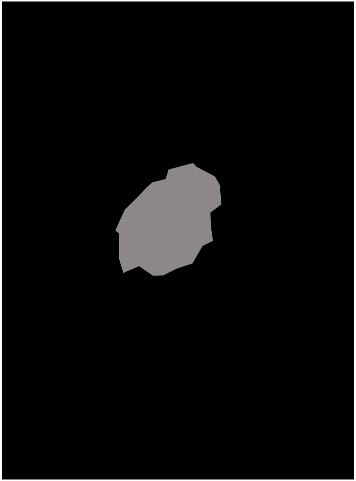


Image courtesy of USGS

Impacts can also break apart asteroids

- In space, there is constant background radiation, called **galactic cosmic rays**
- These rays provide enough energy to form some short-lived radioactive isotopes, which decay quickly
- But, they can only do this in the upper few inches of the asteroid or meteoroid
- Since we know the half lives of these isotopes, we can determine how long the material has been exposed in space
- A short **cosmic ray exposure age** means the asteroid was only recently disrupted



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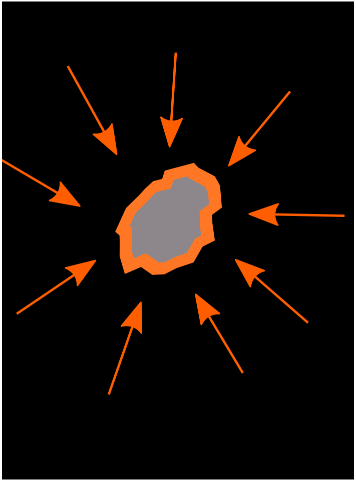

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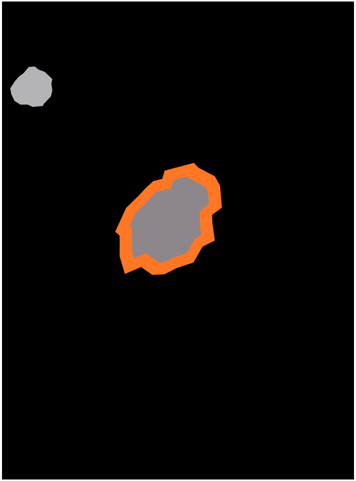

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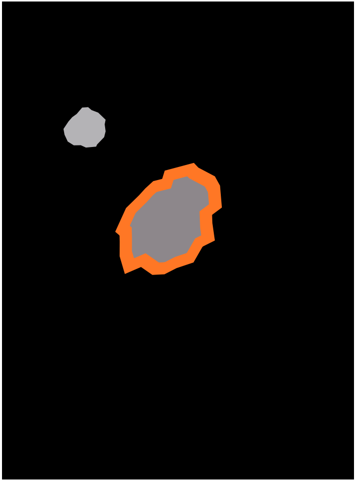

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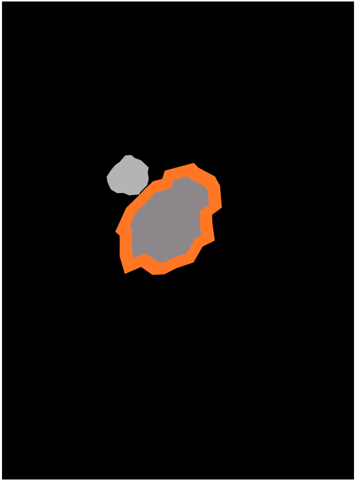

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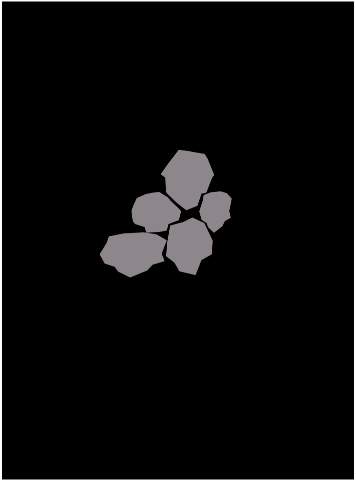
- A short **cosmic ray exposure age** means the asteroid was only recently disrupted



Impacts can also break apart asteroids

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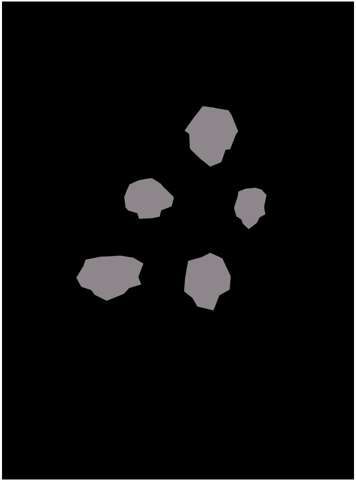

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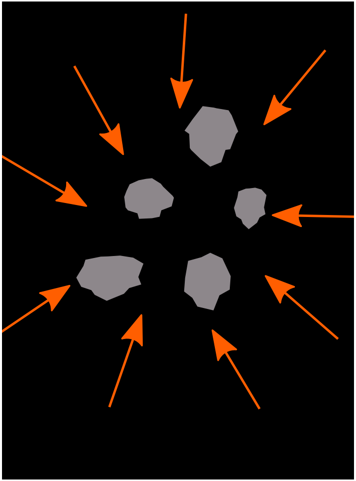

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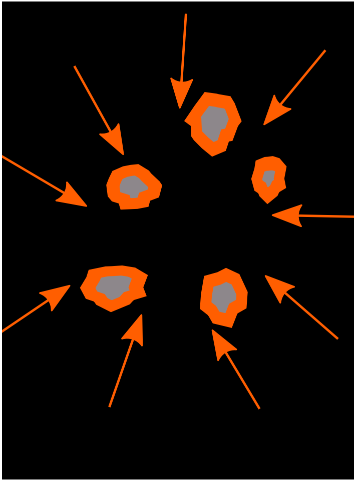

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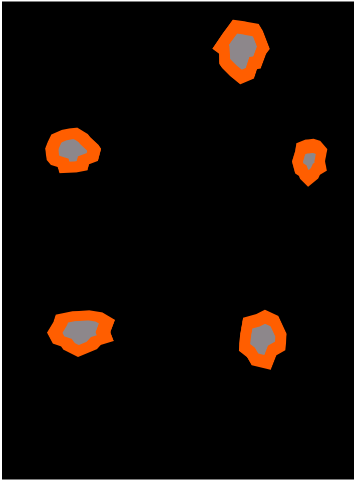

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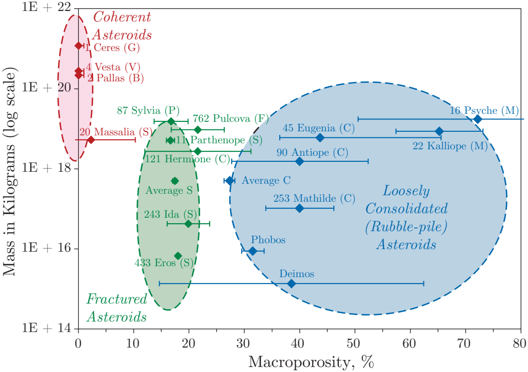
Collision Processes

We well look at collisions in more detail in a couple of weeks time

Low density asteroids are evidence of breakup events



Adapted from Britt et al. (2002) in *Asteroids III*

- Some asteroids have high porosity (low density)
  - Impacts should have crushed some of that pore space out
- They have a **macroporosity**, because they have been broken apart and reformed

Summary of today's lecture

- Meteorites are samples of asteroids and planets
- They can tell us about the conditions under which asteroids formed
- They also record the collisional history of asteroids
- They are one of our best sources of information about the early Solar System

- Next week: **Building the Planets**

Image courtesy of H. Raab

Image courtesy of NASA

Thank you

Questions?