





- Asteroids are rocky leftovers of planet formation.
- Largest is Ceres, diameter ~1,000 km
- 150,000 in catalogs, and probably over a million with diameter >1 km.
- Small asteroids are more common than large asteroids.
- All the asteroids in the solar system wouldn't add up to even a small terrestrial planet.



Asteroids are cratered and not round



Types of Asteroids (based on composition)

- C-type: large fraction of carbon - dark (low reflectivity), 75% of all asteroids
 - remnants of solar system formation?
- S-type: large fraction of silicates - standard rocky material, 15% of asteroids
- M-type: large fraction of iron, nickel - standard rocky material, ~10% of asteroids

Missions to Asteroids

- Galileo (en route to Jupiter)
 - flyby of Gaspra, Ida (S-types)
- NEAR (Near Earth Asteroid Rendezvous):
- flyby of Mathilde (C- type)
- orbited Eros (and landed!)





Dimensions: 16 x 12 km(about the same size as Deimos) - colors have been enhanced

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Asteroid Orbits



- Most asteroids orbit in a belt between Mars and Jupiter
- *Trojan asteroids* are in Jupiter's orbit
- Orbits of *near-Earth asteroids* cross Earth' s orbit

Thought Question

Why are there very few asteroids beyond Jupiter's orbit?

- A. There was no rocky material beyond Jupiter's orbit.
- B. The heaviest rocks sank towards the center of the solar system.
- C. Ice could form in the outer solar system.

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D. A passing star probably stripped away all of those asteroids, even if they were there at one time.

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- Rocky planetesimals between Mars and Jupiter did not accrete
- Jupiter's gravity, resonances, stirred up asteroid orbits and prevented their accretion into a planet.

Where do meteorites come from?



Meteor Terminology

- Meteoroid: a rock in space
- Meteor: a bright trail left by a meteoroid falling through the atmosphere ("shooting star")
- Fireball: a very bright meteor
- Meteorite: A rock from space that survives the Earth's atmosphere and is found on the ground.



Meteorite Types

- 1) Primitive: Unchanged in composition since they first formed 4.6 billion years ago.
- 2) Processed: Younger, have experienced processes like volcanism or differentiation.

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Meteorites from Moon and Mars

- A few meteorites arrive from the Moon and Mars
- Composition differs from the asteroid fragments.

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• A cheap (but slow) way to acquire moon rocks and Mars rocks.







Comet Facts

- Formed beyond the frost line, comets are icy counterparts to asteroids.
- Nucleus of comet a "dirty snowball"
- Most comets do not have tails.
- Most comets remain perpetually frozen in the outer solar system.
- Only comets that enter the inner solar system grow tails.







Giotto Image of Halley's Nucleus











Comets eject small particles that follow the comet around in its orbit and cause meteor showers when Earth crosses the comet's orbit.







Only a tiny number of comets enter the inner solar system - most stay far from the Sun

Oort cloud: On random orbits extending to about 50,000 AU

Kuiper belt: On orderly orbits

from 30-100 AU in disk of solar system



- Kuiper belt comets formed in the Kuiper belt: flat plane, aligned with the plane of planetary orbits, orbiting in the same direction as the planets.
- Oort cloud comets were once closer to the Sun, but they were kicked out there by gravitational interactions with jovian planets: spherical distribution, orbits in any direction.

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Neptune. 2005 EY Quagar

Other Icy Bodies - "Dwarf Planets"

- There are many icy objects like Pluto on elliptical, inclined orbits beyond
- The largest of these, Eris, was discovered in 2005, and is even larger than Pluto.

Kuiper Belt Objects



• These large, icy objects have orbits similar to the smaller objects in the Kuiper Belt that become short period comets

What are the large objects of the Kuiper belt like?



What is Pluto like?

- Its moon Charon is nearly as large as Pluto itself (probably made by a major impact)
- Pluto is very cold (40 K)
- Pluto has a thin nitrogen atmosphere that will refreeze onto the surface as Pluto's orbit takes it farther from the Sun.



- Most have been discovered very recently so little is known about them.
- NASA' s *New Horizons* mission will study Pluto and a few other Kuiper Belt object in a planned flyby.

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Pluto and Eris

- Pluto's size was overestimated after its discovery in 1930, and nothing of similar size was discovered for several decades
- Now other large objects have been discovered in Kuiper Belt, including Eris
- The International Astronomical Union (IAU) now classifies Pluto and Eris as *dwarf planets*

Eris Pluto 2005 FY9

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2003 EL6[.]

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Are Pluto and Eris planets?





Comet SL9 caused a string of violent impacts on Jupiter in 1994, reminding us that catastrophic collisions still happen.

Tidal forces tore it apart during a previous encounter with Jupiter

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Animation of impact with Jupiter

Dusty debris at an impact site







Mass Extinctions

- Fossil record shows occasional large dips in the diversity of species: *mass extinctions*.
- Most recent was 65 million years ago, ending the reign of the dinosaurs.

Iridium: Evidence of an Impact

- Iridium is very rare in Earth surface rocks but often found in meteorites.
- Luis and Walter Alvarez found a worldwide layer containing iridium, laid down 65 million years ago, probably by a meteorite impact.
- Dinosaur fossils all lie below this layer



Consequences of an Impact

- Meteorite 10 km in size would send large amounts of debris into atmosphere.
- Debris would reduce sunlight reaching Earth's surface.
- Resulting climate change may have caused mass extinction.

Likely Impact Site



 Geologists have found a large subsurface crater about 65 million years old in Mexico



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Comet or asteroid about 10 km in diameter approaches Earth











Facts about Impacts

- Asteroids and comets have hit the Earth.
- A major impact is only a matter of time: not IF but WHEN.
- Major impacts are very rare.
- Extinction level events ~ millions of years.
- Major damage ~ hundreds of years.



Tunguska, Siberia: June 30, 1908 A ~40 meter object disintegrated and exploded in the atmosphere



Meteor Crater, Arizona: 50,000 years ago (50 meter object)



The asteroid with our name on it

- We haven't seen it yet.
- Deflection is more probable with years of advance warning.
- Control is critical: breaking a big asteroid into a bunch of little asteroids is unlikely to help.
- We get less advance warning of a killer comet...

What are we doing about it?

• Stay tuned to