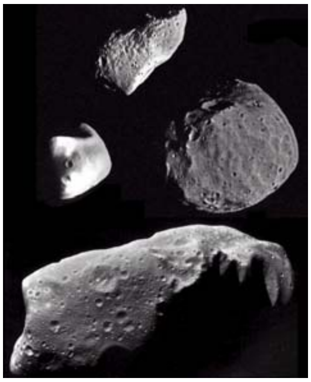
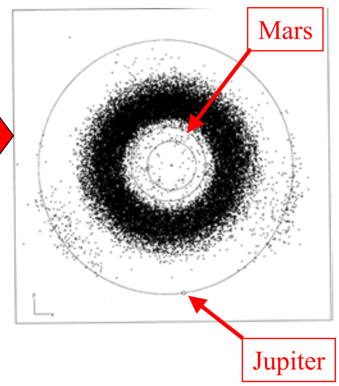


Asteroids

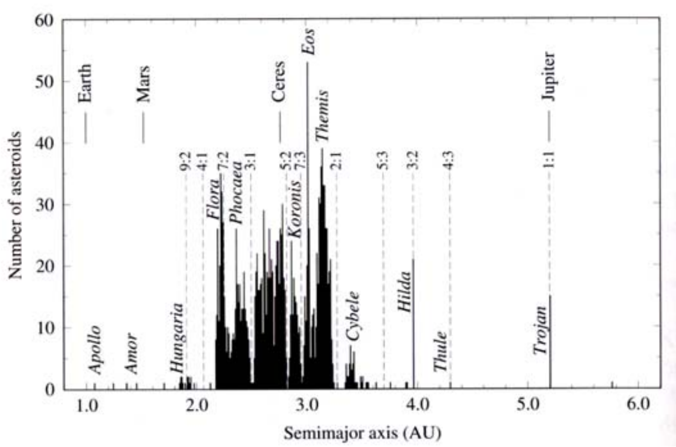
- Small, rocky objects in orbit around the Sun.
  - Sizes up to hundreds of km.
  - 26 known ones with sizes > 200 km.
- 250,000 currently have designations.
  - + estimated > 1 million asteroids < 1 km in size.
- But total mass probably less than mass of Moon.

The Asteroid Belt

- semi-major axis 2.2 - 3.3 au.
- Between orbits of Mars and Jupiter
- Includes 75% of known asteroids.
- Mostly orbiting sun in same direction of planets, and in plane of solar system.



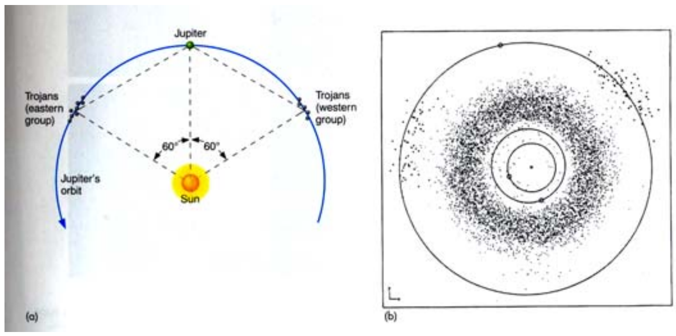
Jupiter's tidal effects are important



- Gaps in asteroid belt correspond to resonances with orbital period of Jupiter.

Trojan Asteroids

- In same orbit as Jupiter, but leading or trailing Jupiter by 60º
  - Gravitationally stable position.

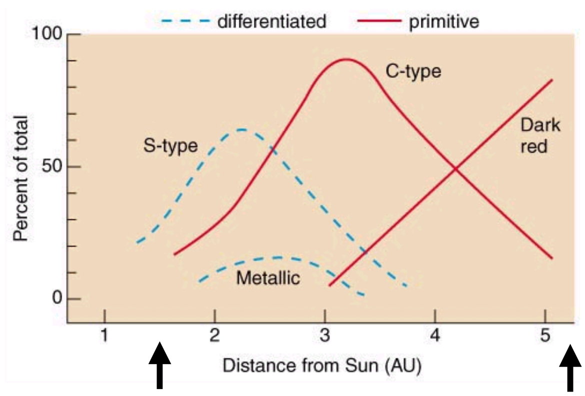


- Similar case exists for Mars.
  - also perhaps for Venus and Earth.
- Also, a few asteroids are known in outer solar system.
  - Pluto, Triton may belong in this list (but probably not).

Most Asteroids are "Dark"

- Low reflectivity (3-4%)
- Primitive bodies
  - chemically unchanged since initial formation of Solar System
- Most are carbon-rich "C-type"
- Also stony "S-type",
  - dark carbon compounds missing.
- A few metal-rich "M-type"
  - Especially reflective at radar wavelengths.
  - Remnants of a differentiated body.
  - Collisions with Earth ➔ giant iron/nickel deposits.

Where Different Types of Asteroids are Found



Mars

Asteroid belt

Jupiter

Asteroids seen from Galileo

Gaspra compared to Phobos & Diemos (the 2 moons of Mars)

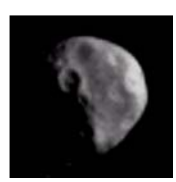
Gaspra

19x12x11 km.
Rotation: 7 hrs.
Orbit: 1.4 AU
Composition: S-type

Few craters
➔ recently formed from breakup of larger body.

Ida and Dactyl

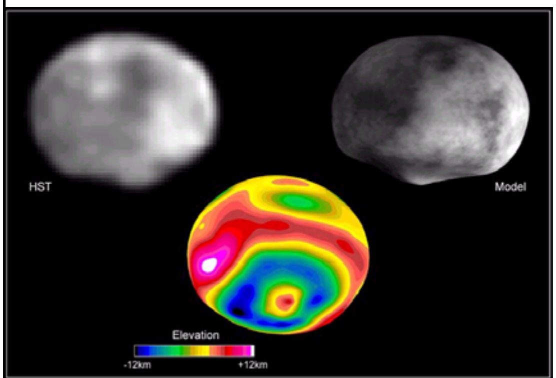
52 km long.
Rotation: 4.5 hrs
Orbit: 1.8 AU
Composition: S type.



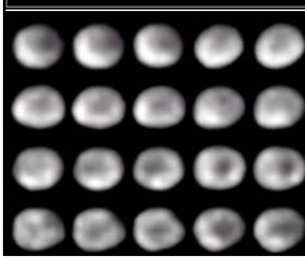
Dactyl (Ida’s little companion)

- Member of group resulting from breakup of heavier body.
- Heavy cratering ➔ happened long ago.

Vesta

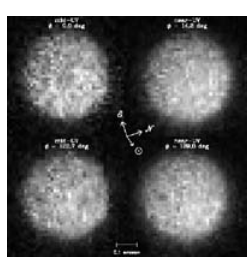


- Studied with Hubble Space Telescope.
- 500 km diameter
- Volcanic surface
  - basaltic rocks
  - 30% reflectivity.
  - Visible to naked eye (barely).
- Source of ~ 30 meteorites found on Earth.
  - Same unusual composition as Vesta.
  - radioactive decay ➔ 4.4 - 4.5 billion yrs old



Ceres

- The largest asteroid
  - 940 km diameter.
- Estimated to contain ~ half the total mass of the asteroids.
- Orbit: 2.8 AU
- C-type.

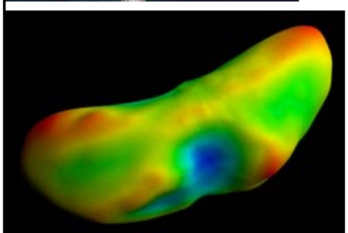


HST images in ultraviolet

Infrared image, taken from Earth

433 Eros

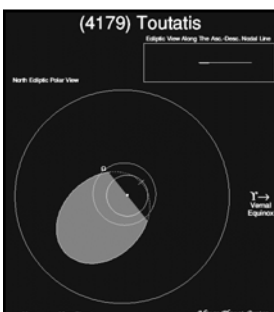
- Near Earth asteroid
  - 1.13 to 1.78 AU
- S-type
- 35 x 15 x 13 km
- NEAR spacecraft orbited for 1 year, then landed (Feb. 2001).



Colors show elevation (blue=low)

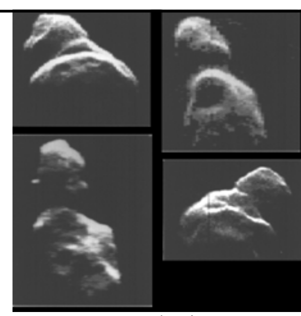
Science goal:
Chemical composition.
Is 433 Eros from differentiated body?

124 km orbit movie



Toutatis

An Earth-Crossing Asteroid



1992 radar image:
2 objects in contact, each about 4x2.5 km.

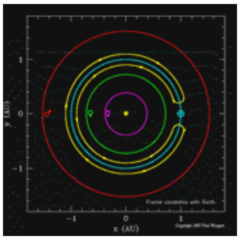
- Discovered in 1989
- Very irregular orbit
- 2004 approach will bring it to 1.5 million km from Earth.
  - From Toutatis, Earth will have same angular size as we see for Moon.

Earth-approaching asteroids:
75% chance of gravitational ejection.
25% chance of impact.

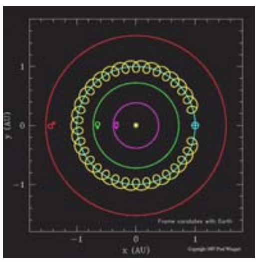
Close Approaches

Date	Distance / Distance to Moon
1996 Nov. 29	14
2000 Oct. 31	29
2004 Sept.29	4
2008 Nov. 9	20

Asteroid orbits as seen from Earth



Simple “horseshoe” orbit.



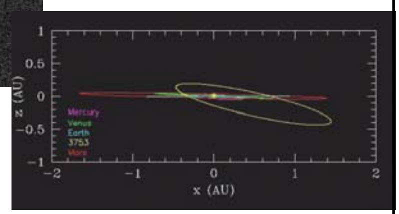
Spiral horseshoe orbit similar to that of Cruithne.

3753 Cruithne

- Another Earth-orbit crossing asteroid.
- No danger of collision… does not even come very close.
  - Due to high inclination of asteroid’s orbit
- Similar to Pluto - Neptune situation.

Movie: orbit in inertial frame

Movie: orbit seen from Earth



Side view of actual orbit.

Comets

- Small icy nucleus.
- “Dirty snowball” model
  - mostly water ice
  - + other ices
  - mixed with silicate grains and dust
- Outer layers of nucleus vaporize when comet approaches sun.
  - Little geysers and eruptions observed.
  - Comet’s head (Coma) often as large as Jupiter
    - up to 250,000 km diameter.
    - Primarily H_2O gas.
    - + few percent CO, CO_2 and hydrocarbons.
  - Huge hydrogen clouds around head can get bigger than sun.

45 minute animation

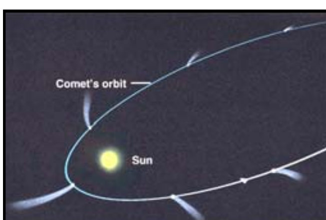
Hale-Bopp (1997)

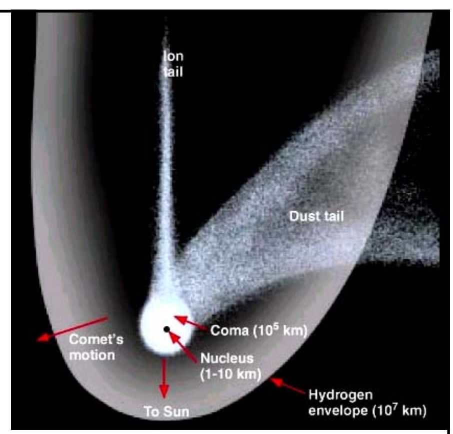
Comet Hale-Bopp February 7, 2000

This fading super comet continues to be visible in small telescopes almost 5 years after it was discovered. Despite now being out beyond the orbit of Saturn, the comet continues to display a strong coma.
The image is a combination of 3, 3-minute exposures using a 416xt CCD and a 12" f/6 newtonian telescope at prime focus. Taken by Maurice Clark

Comet Hale Bopp (1995 o1)
april 9, 1997

Tails

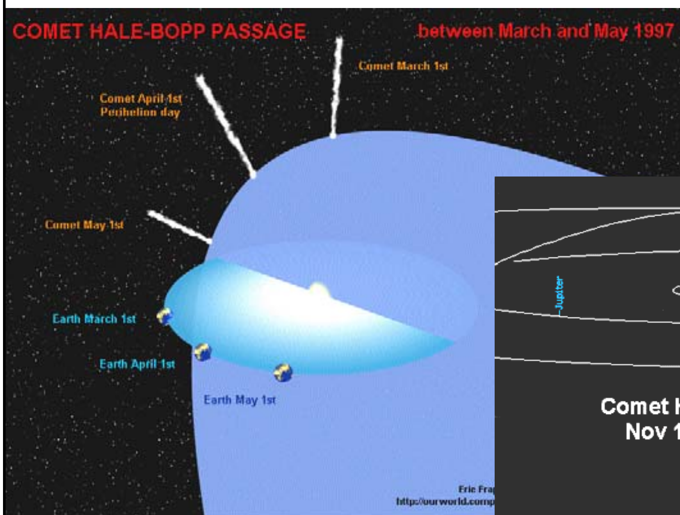


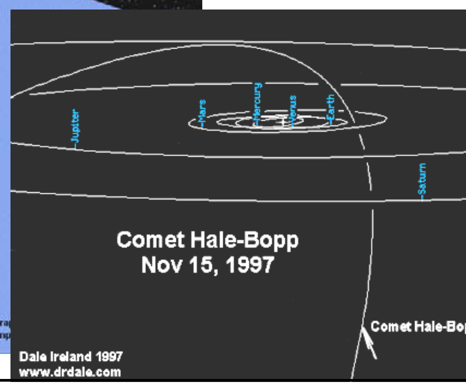


- dust tail
  - up to 10 million km long
  - smoke-sized dust particles
  - driven off nucleus by escaping gases
  - pushed outwards by Sun's radiation
  - competing force of Sun's gravity ➔ curve in tail.
- ion tail
  - Up to 100's of millions km long
  - small charged particles, pushed out by charged particles from Sun (solar wind).

Hale-Bopp's orbit

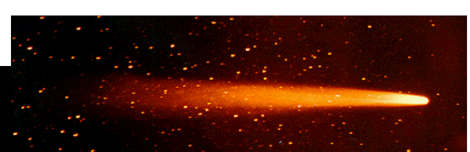
- 4200 yrs since last appearance
- 2400 yrs to next passage
- perihelion: 0.914 au
- inclined 90^{o} to plane of solar system

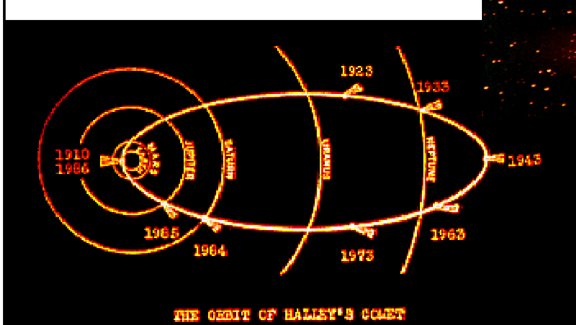




Halley's comet

- first observed 239 BC
- 76 year average period
- most recent visit 1986
- fizzled out last time around

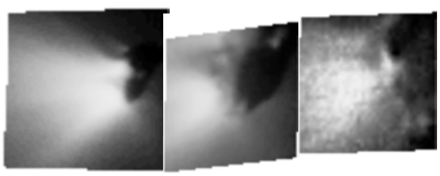


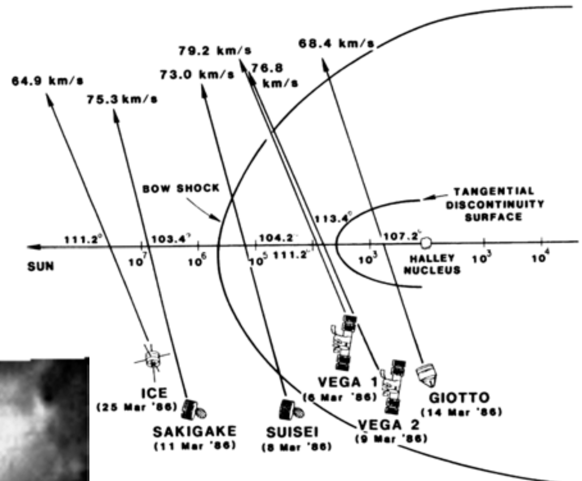


Earth Attacks!

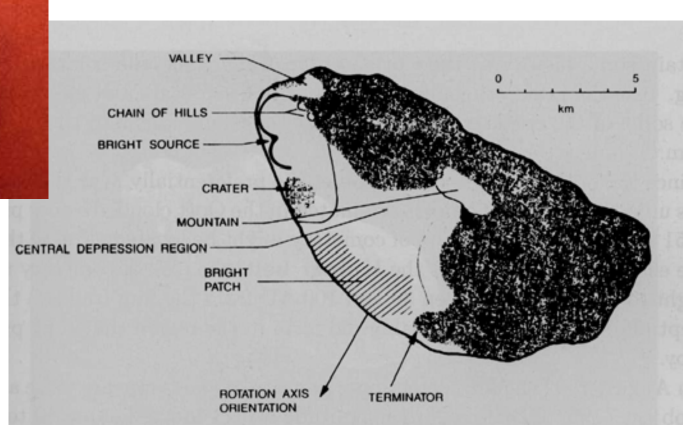
- 1986: The Space Flotilla moves in on Halley…

Giotto images



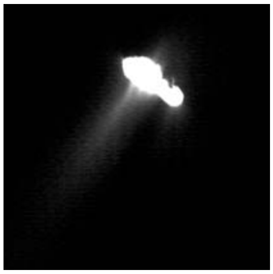


Sketch of Halley's nucleus.

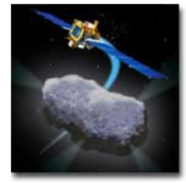


Deep Space 1
Encounter with Comet Borrelly

Sept. 22, 2001



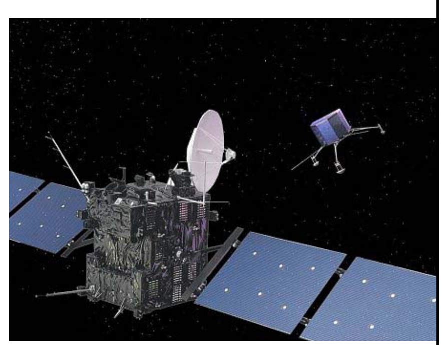
Worn-out technology demo spacecraft meets little-known comet.



The nucleus, from 2200 km (1400 miles)

Future exploration --- Rosetta

- European Space Agency mission
- to Comet Churyumov-Gerasimenko
- Will send Lander to surface of nucleus.



Launch February 20

Rendezvous November 2014

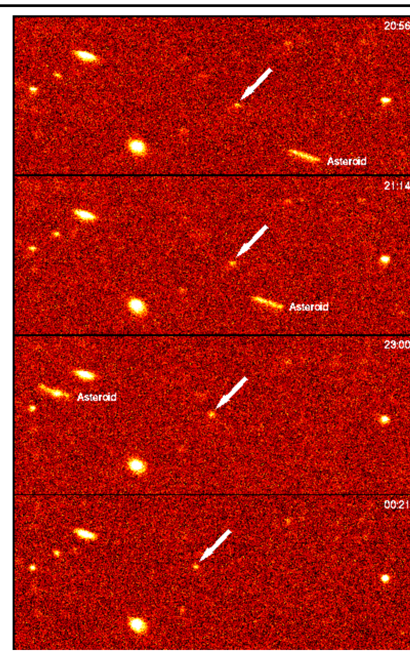
The Oort Cloud & the Kuiper Belt

- No comets have orbits coming from interstellar space.
- Strong tendency for aphelia at ~ 50,000 AU
- No preferential direction from which comets come

- Best current model: The Oort Comet Cloud
  - 10^{11} - 10^{12} comets in loosely bound solar orbits at 50,000AU
  - Gravitational perturbations occasionally deflect one in.
  - Guesstimate: 10 trillion (10^{13}) comets total
    x 10^{-10} earth-masses/comet = 10^{3} earth masses total.

Second source of comets: The Kuiper Belt

- At 30-100 AU,
  - just beyond Pluto.
- 60 faint objects spotted so far.
- 40% have 2:3 orbital resonances with Neptune, similar to Pluto's.
- Pluto/Charon probably in this class.



Second source of comets: The Kuiper Belt

CNN: Oct. 7, 2002

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  - just beyond Pluto.
- 60 faint objects spotted so far.
- 40% have 2:3 orbital resonances with Neptune, similar to Pluto's.
- Pluto/Charon probably in this class.

Biggest object since Pluto found in solar system

By Richard Stenger (CNN)
Monday, October 7, 2002 Posted: 12:54 PM EDT (1654 GMT)

(CNN) -- A newly discovered body in the outer reaches of the solar system is larger than all the objects in the asteroid belt combined, astronomers announced Monday.

Artist's concept of Quaoar

The spherical planetoid, half the size of Pluto, is the biggest found in the solar system since astronomers detected the ninth planet in 1930.

It orbits the sun from a distance of about 4 billion miles (6.4 billion kilometers) in a nether region known as the Kuiper Belt, a ring of thousands of primordial icy, rocky chunks beyond the planets that date back to the origins of the solar system.

The object, dubbed Quaoar, further strengthens the theory that Pluto is not a conventional planet but rather a Kuiper Belt object.

Story Tools
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PRINT THIS MOST POPULAR

REACHING QUAOAR
-- At walking speed, it would take 100,000 years.
-- In the space shuttle, about 25 years.
-- For sunlight, the trip takes five hours.

The death of comets

- Nucleus looses material on each passage
  - e.g. Halley's low brightness last time around.
- Comets run into things

- Comet Shoemaker-Levy 9 was broken up into a string of comets by Jupiter's gravitational pull, then impacted Jupiter (in 1994).

Comet Animation

Meteors

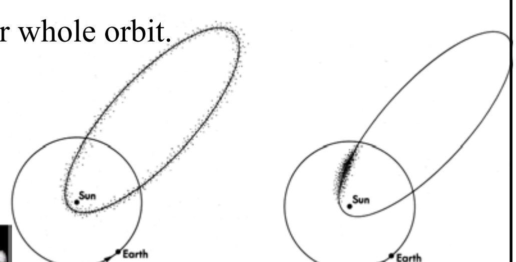
- Small particles burning up in Earth's atmosphere.
  - Typical meteor = 1 gram (size of a pea)
  - Bright fireballs = golf-ball sized particle.
  - Bowling balls would make it to Earth's surface.

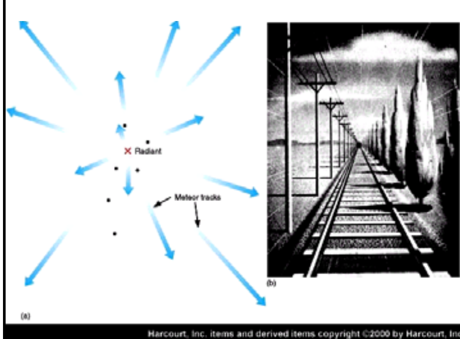
Meteorites

- Particles that make it to the Earth's surface.

Meteor showers

- Result of Earth passing through trail of debris from an old comet.
  - Some trails spread out over whole orbit.
  - Others are clumped up.

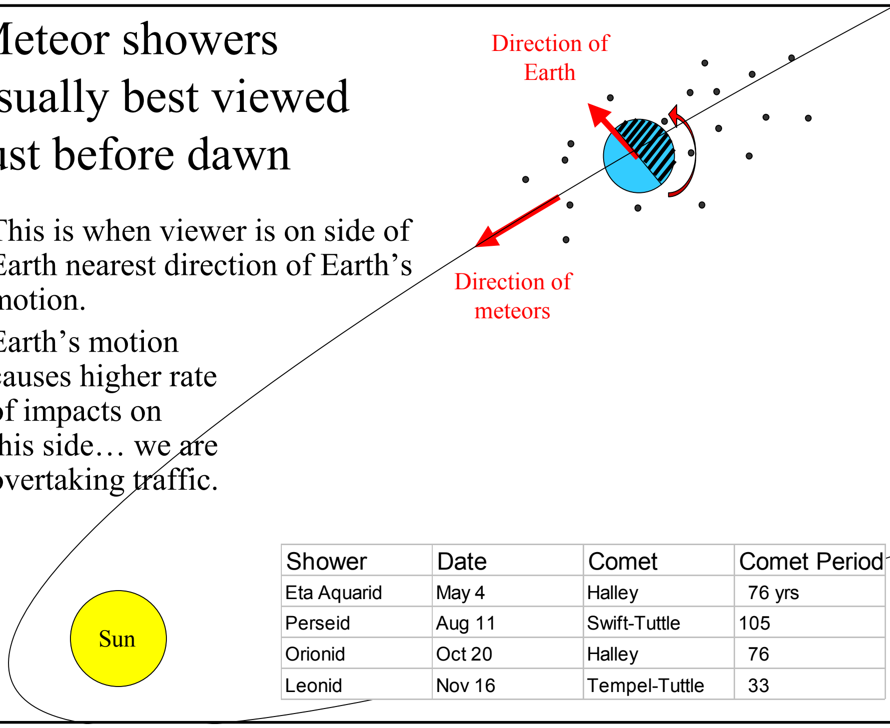




Radiant
- The direction from which the meteors appear to come.
- Determined by combination of motion of meteors and motion of Earth.

Meteor showers usually best viewed just before dawn

- This is when viewer is on side of Earth nearest direction of Earth's motion.
- Earth's motion causes higher rate of impacts on this side… we are overtaking traffic.



Shower	Date	Comet	Comet Period
Eta Aquarid	May 4	Halley	76 yrs
Perseid	Aug 11	Swift-Tuttle	105
Orionid	Oct 20	Halley	76
Leonid	Nov 16	Tempel-Tuttle	33

Meteorites

- The particles that make it to the Earth's surface.
  - Allende meteorite (Mexico): 2 tons of fragments recovered after airburst.
- Rocky pieces of asteroids, not of comets.
- Invaluable samples of early solar system.
  - Irons = Nickel/Iron
  - Stones= silicate or rocky material
  - Stony-irons
- A better classification:
  - Differentiated
    - irons, stony-irons, a few stony meteorites.
  - Primitive
    - – Gray silicates
    - – Carbonaceous meteorites
    - 92% of stony meteorites, 88% of all meteorites.

Chemical composition of Primitive Meteorites ➔ Relative proportions of heavy elements in early solar system.

- H, He, C, N, O, Ne, Ar under-abundant relative to atmosphere of Sun.
  - The lightest elements… boiled away in solar nebula.
- More lithium than in sun ➔ sun has destroyed some of its lithium.
- 16 amino acids in Murchison carbonaceous meteorite
  - Equal numbers of right, left-handed.
  - Life on Earth uses only left-handed.
  - Shows that amino acids in Murchison meteorite are extra-terrestrial in origin.

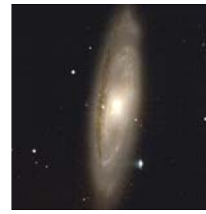
Ages of Primitive Meteorites➔ date of formation of Solar System.

- Determined from radioactive dating.
- Primitive asteroids have very narrow range in ages:
  - 4.48-4.56 billion yrs.
- Average=4.54 billion yrs.

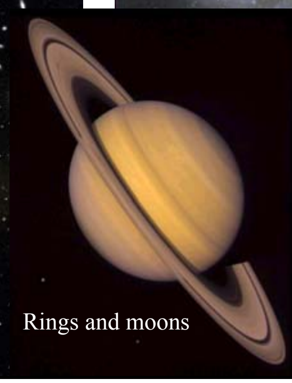
Formation of the Solar System

Spinning Disks

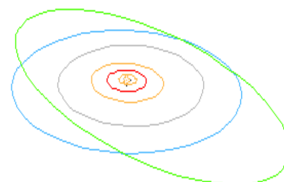
Accretion disks



Spiral galaxies

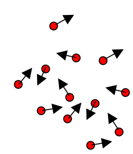


Rings and moons



The Solar System

How gas works

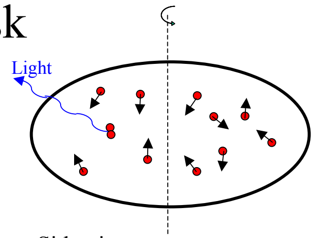


- Atoms/molecules fly around in all directions
  - Constantly bump into one another.
  - Directions of motion are randomized
- Average kinetic energy ($\frac{mv^2}{2}$) determines *temperature*.
- Transfer of momentum in collisions is called *pressure* (force per unit area)
  - Depends on both number and velocity of atoms.
  - Causes gas to fill available volume.
  - Pushes on any containing vessel.
- Very different situation if same material is consolidated into just a few planets, rocks, etc.
  - collisions very infrequent
  - planets continue on same orbit as when they were created.

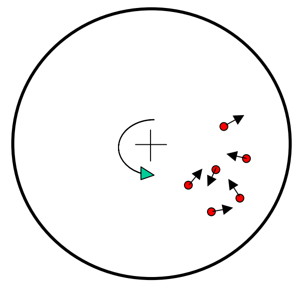
Why a collapsing gas cloud forms a spinning disk

- Collisions convert kinetic energy to light
  - Light carries away energy.
  - Nebula gets cooler
  - Contracts because of gravity.

- But angular momentum
  ➔ cannot collapse in direction perpendicular to spin axis
  ➔ disk.

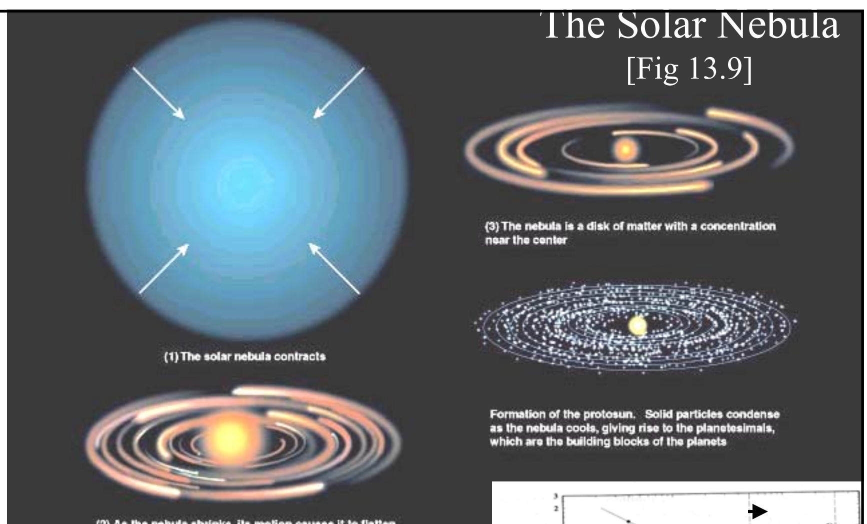


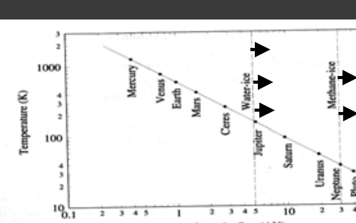
Side view -- as many atoms move up as move down.



Top view -- net rotation superimposed on random motions.

The Solar Nebula
[Fig 13.9]

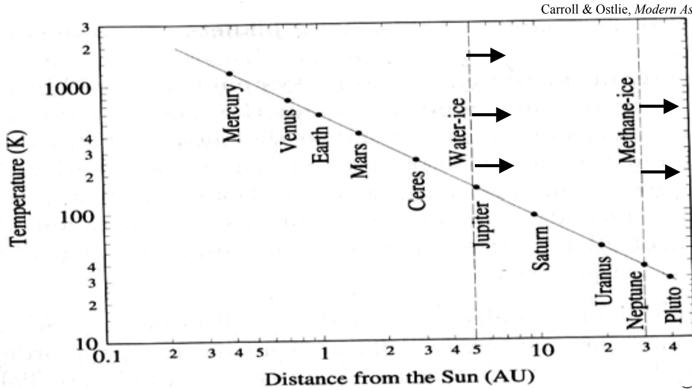


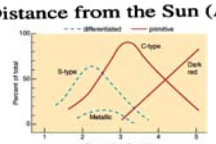


- Solar nebula collapses to disk
- Gas ➔ dust, small particles
  ➔ planetesimals ➔ coalesce into protoplanets
  - Cores of giant planets = ice + rock ➔attracts H, He.
  - Terrestrial planets = just rock ➔ gravity too weak to hold H, He.

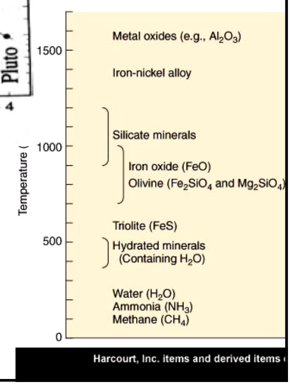
Thermal history of the Solar System

Carroll & Ostlie, *Modern Astrophysics*



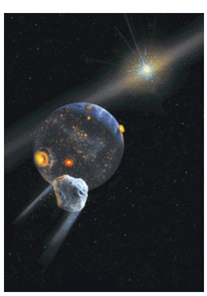


Asteroid types

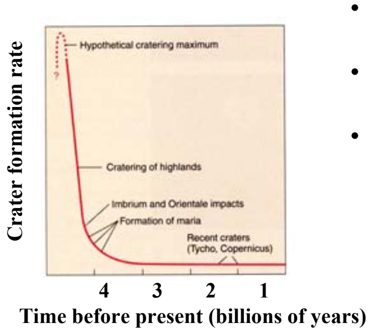


- Terrestrial vs. Giant Planets
- Asteroids vs. comets

Progressive Buildup of the Planets



- Before the Sun starts to produce its own energy:
  - Small (mm-sized) “dust” grains condense from nebula.
  - Condense into *planetesimals* 10’s of km in diameter (comets and asteroids).
  - Run away growth into *protoplanets*
    - larger bodies have sufficient gravitational attraction to collect lots of smaller bodies.
    - ➔ a few Mercury/Mars-sized objects which rapidly accrete further planetesimals.
    - Impacts produce considerable heating of interior of growing planet.
      - Leads to differentiation in molten interiors.



Giants vs. Terrestrials

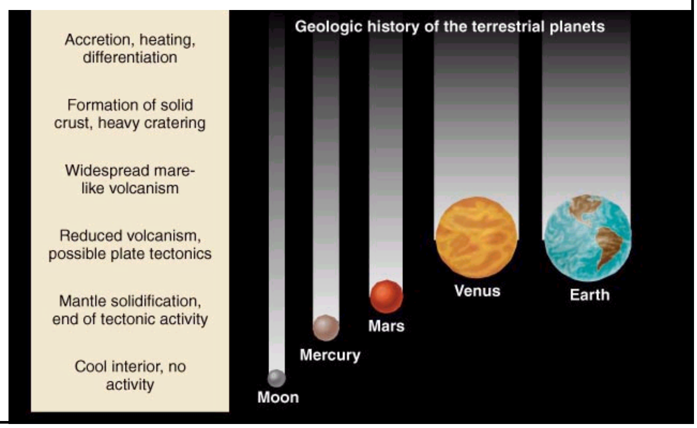
- In inner solar system.
  - Lighter elements evaporated away.
  - Planetesimals contained only heavy elements.
  - Growth stopped at Earth-sized planets.
  - But continuing impacts with planetesimals altered the planets
    - Earth's moon
    - Reversal of Venus' rotation, etc.
    - Dumped much of atmospheres onto planets
- In outer solar system.
  - Ices as well as silicates available for solid bodies.
  - Larger protoplanets resulted.
  - These cores able to attract surrounding H, He gas in order to build giant planets.
  - Gravitational field of giant planets perturbed orbits of remaining planetesimals.
    - Most comets ejected into Oort Cloud
    - Somehow governs existence of asteroid belt.

The End Game

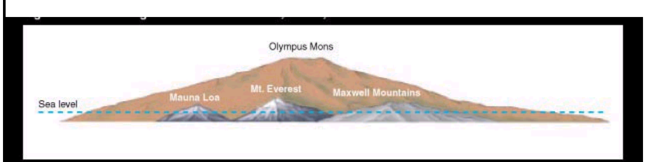
- The Sun becomes a star
  - *Solar wind* = high velocity particles streaming outwards from Sun.
  - Blows away the remaining H, He gas.
  - Leaves just protoplanets + remaining planetesimals to finish up their interactions.
  - Timescale to this point: only ~ 10 million years.

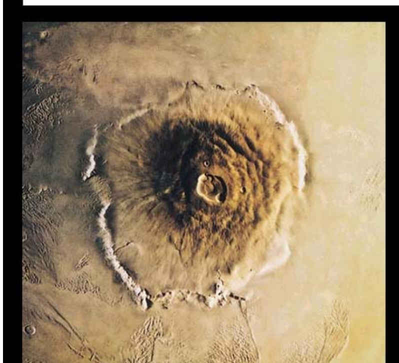
Evolution of the terrestrial planets

- Differentiation
- Geological activity
  - hot interior drives surface activity
- Gravity
- Atmospheres



Highest mountains





- Moon, Mercury
  - mountains mostly due to impacts
- Venus, Earth, Mars
  - mountains mostly due to geological activity
  - volcanoes, uplifting, plate tectonics
- Olympus Mons (on Mars) is much larger than mountains of Venus, Earth
  - Plates do not slide on Mars… Olympus Mons is stationary over a hot spot.
  - Lower gravity of Mars.