Debris & Formation

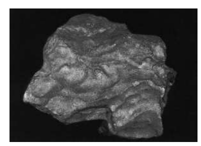
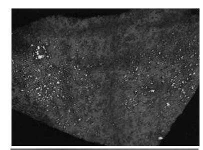
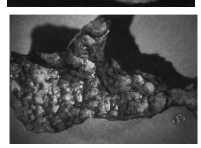
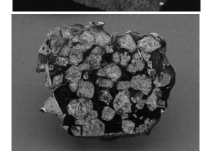
Meteors: Some Definitions

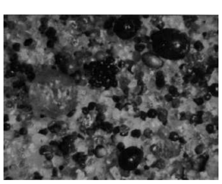
- ***Meteor*** - a bright streak of light observed when a piece of interplanetary debris enters a planetary atmosphere (also known as a 'shooting [or falling] star'
- ***Meteoroid*** - the aforementioned debris
- ***Meteorite*** - any surviving debris that reaches the planetary surface

Interplanetary Debris

- Meteoroids/meteorites fall into two categories
  - ***Stony*** - silicate (rock) composition
  - ***Iron*** - iron/nickel composition
  - ***Composite*** - mixtures of silicate/metals
- Origin
  - Fragments of larger bodies
  - Size/age of parent bodies determined by crystalization patterns in rock/iron

Meteorite/Meteoroid Types

What's Inside

- Widmanstatten - metal 'grains' that are a result of heating
- Chondrites/Chondrules
  - Spherical bits of materials -never been heated

Process

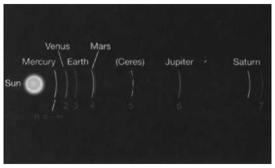
- Bits of debris (with $v > v_{esc}$) passes too close to Earth's atmosphere
- Atmospheric resistance (aerobraking) slows debris to below v_{esc}
- Debris falls into atmosphere. Resistance elevates temperature -> fireball

1766 – Titius-Bode Law

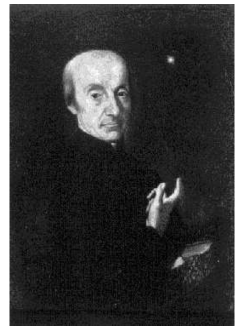
- Numeric sequence to determine planet location

  $$a_n = \left(0.4 + 0.3 \cdot 2^{n-2}\right) AU$$

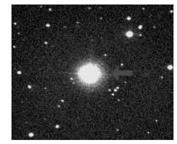
- Start with 0.4 AU (distance to Mercury)
  - 0.3 (to Venus) = 0.7 AU
  - 0.3 (Terra) = 1.0 AU
  - 0.6 (Mars) = 1.6 AU
  - 1.2 (?) = 2.8 AU
  - 2.4 (Jupiter) = 5.2 AU
  - 4.8 (Saturn) = 10.0 AU
  - 9.6 (Uranus) = 19.6 AU



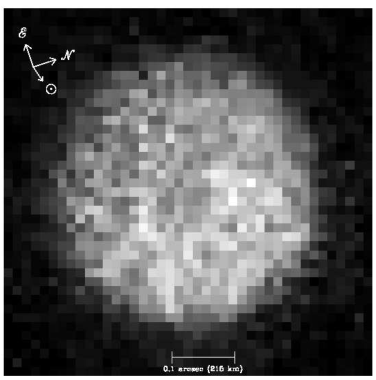
1801: Discovery of Ceres



- Jan 1 - Guiseppe Piazzi (1746-1826), in an attempt to verify Titius-Bode, finds the 'fifth planet' between Mars and Jupiter



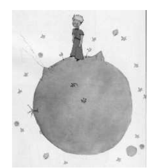
Ceres



- D = 910km
- a = 2.77 AU
- P = 4.61 years

Asteroids/Minor Planets

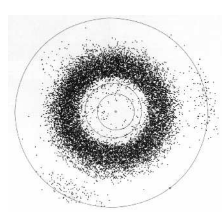
- Silicate/metallic, ~1-1000km diameter
- Stable orbits around Sol
- Most located in belt between 2.1-3.3 AU
- Many located further out/closer in
  - Near Earth asteroids
    - highly elliptical orbits
  - Trojan asteroids
    - Lagrange/libration points



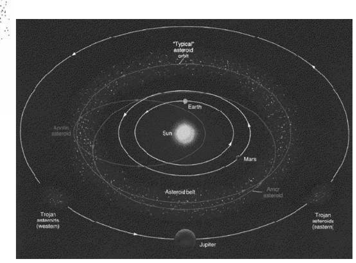
Asteroid Composition

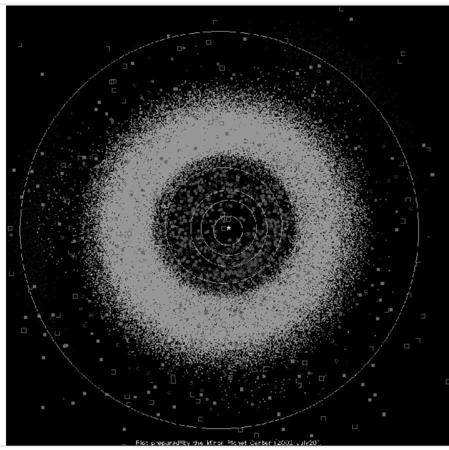
- ***C-type*** - dark, low albedo
- ***S-type*** - silicates, olivine
- ***M-type*** - metallic iron/nickel
- ***V-type*** - silicates, basalts

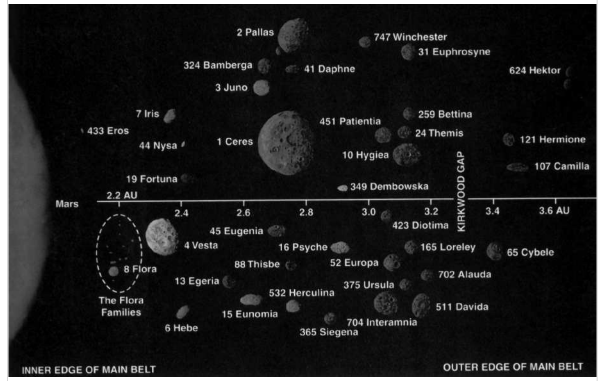
Asteroid Orbits



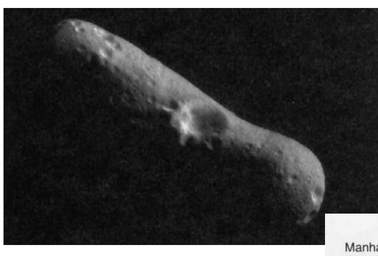
- Apollo - Earth crossing
  - Perihelion > 1AU
- Aten - Earth crossing
  - Perihelion < 1 AU
- Amor - Mars crossing
- Trojan - Jupiter lagrange

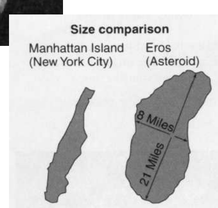






Eros

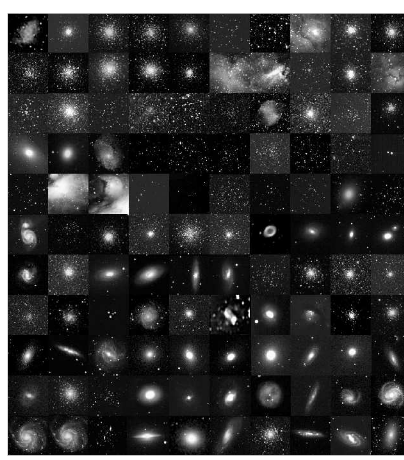




Comets

- Edmund Halley (1705) predicted that the orbits of comets observed in 1531, 1607, 1682 were the same -and 76 years apart. He predicted a return of the comet in 1758.
  - Comet was observed Christmas night of that year, 16 years after Halley's death.

Hale-Bopp

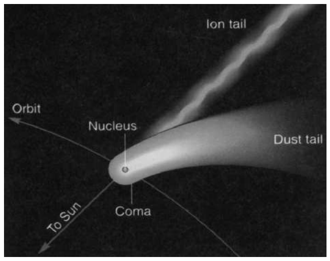


Not Comets.

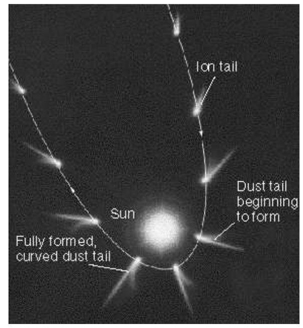
- Charles Messier (1730-1817) -comet hunter.
- Made a list of 101 things that were *not* comets.

Comet Structure

- Nucleus < 10 km
  - H_2O, CO, CO_2, Formaldehyde
- Coma ~10^6 km
- Tails ~ 10^8 km
  - ion (charged)
  - dust (uncharged)

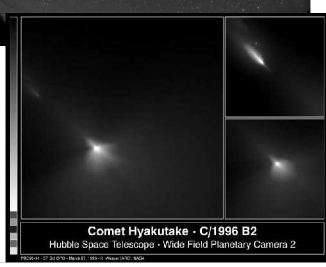


Tail Formation

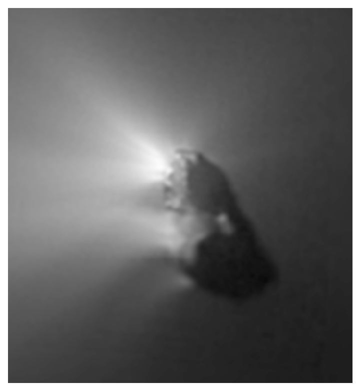


- ***Dust tail***
  - uncharged
  - white/yellow
- ***Plasma tail***
  - ionized CO
  - blue

Comet Hyakatuke



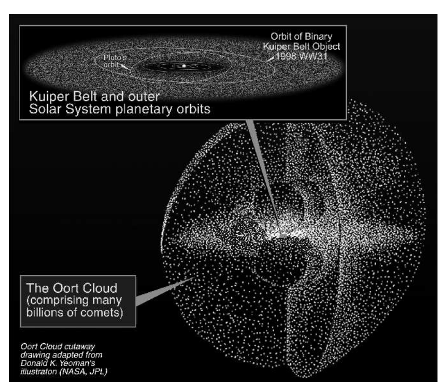
Halley's Nucleus



- Jets on sunlit side
- Surface of fragmented material
- Interior ~200K
- Surface ~350K

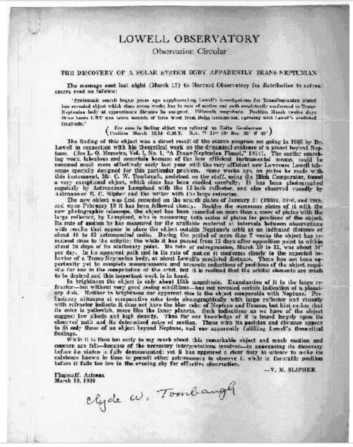
Cometary differences & Sources

- *SHORT PERIOD –*
  - *$i \leq 30^o$*
  - *P < 500 yrs*
- ***Edgeworth-Kuiper Belt*** - flattened disk of icy bodies at 30 to 50 AU
  - Comets would be dislodged by gas giants' gravity - comets with periods of 70-1000 years
- *LONG PERIOD –*
  - *$0 \leq i \leq 180^o$*
  - *P > 500 yrs*
- ***Oort cloud*** - spherical swarm of icy bodies at 10,000 to 75,000 AU
  - Comets formed when gravitational influence knocks snowball out of cloud



Planet P vs. Planet X

Pluto



LOWELL OBSERVATORY
Observation Circular

THE DISCOVERY OF A SOLAR SYSTEM BODY APPARENTLY TRANS-NEPTUNIAN

The message sent last night (March 12) to Harvard Observatory for distribution to astronomers read as follows:

"Systematic search begun years ago supplementing Lowell's investigations for Trans-Neptunian planet has revealed object which since seven weeks has in rate of motion and path consistently conformed to Trans-Neptunian body at approximate distance he assigned. Fifteenth magnitude. Position March twelve days three hours GMT was seven seconds of time West from Delta Geminorum, agreeing with Lowell's predicted longitude."

(For ease in finding object was referred to Delta Geminorum. Position March 12.14 G.M.T. R.A. 7h 15m 50s Dec. 22° 6' 49")

The finding of this object was a direct result of the search program set going in 1905 by Dr. Lowell in connection with his theoretical work on the dynamical evidence of a planet beyond Neptune. (See L. O. Memoirs, Vol. I, No. 1, "A Trans-Neptunian Planet," 1914). The earlier searching work, laborious and uncertain because of the less efficient instrumental means, could be resumed much more effectively early last year with the very efficient new Lawrence Lowell telescope specially designed for this particular problem. Some weeks ago, on plates he made with this instrument, Mr. C. W. Tombaugh, assistant on the staff, using the Blink Comparator, found a very exceptional object, which since has been studied carefully. It has been photographed regularly by Astronomer Lampland with the 42-inch reflector, and also observed visually by Astronomer E. C. Slipher and the writer with the large refractor.

The new object was first recorded on the search plates of January 21 (1930), 23rd, and 29th, and since February 19 it has been followed closely. Besides the numerous plates of it with the new photographic telescope, the object has been recorded on more than a score of plates with the large reflector, by Lampland, who is measuring both series of plates for positions of the object. Its rate of motion he has measured for the available material at intervals between observations with results that appear to place the object outside Neptune's orbit at an indicated distance of about 40 to 43 astronomical units. During the period of more than 7 weeks the object has remained close to the ecliptic; the while it has passed from 12 days after opposition point to within about 20 days of its stationary point. Its rate of retrogression, March 10 to 11, was about 30" per day. In its apparent path and in its rate of motion it conforms closely to the expected behavior of a Trans-Neptunian body, at about Lowell's predicted distance. There has not been opportunity yet to complete measurements and accurate reductions of positions of the object requisite for use in the computation of the orbit, but it is realized that the orbital elements are much to be desired and this important work is in hand.

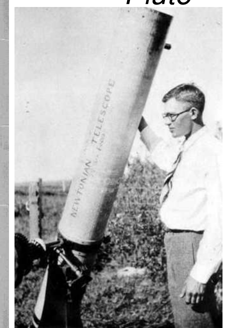
In brightness the object is only about 15th magnitude. Examination of it in the large refractor—but without very good seeing conditions—has not revealed certain indication of a planetary disk. Neither in brightness nor apparent size is the object comparable with Neptune. Preliminary attempts at comparative color tests photographically with large reflector and visually with refractor indicate it does not have the blue color of Neptune and Uranus, but hint rather that its color is yellowish, more like the inner planets. Such indications as we have of the object suggest low albedo and high density. Thus far our knowledge of it is based largely upon its observed path and its determined rates of motion. These with its position and distance appear to fit only those of an object beyond Neptune, and one apparently fulfilling Lowell's theoretical findings.

While it is thus too early to say much about this remarkable object and much caution and concern are felt—because of the necessary interpretations involved—in announcing its discovery before its status is fully demonstrated; yet it has appeared a clear duty to science to make its existence known in time to permit other astronomers to observe it while in favorable position before it falls too low in the evening sky for effective observation.

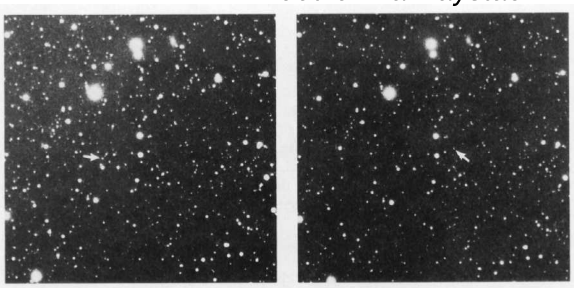
—V. M. SLIPHER.

Flagstaff, Arizona
March 13, 1930

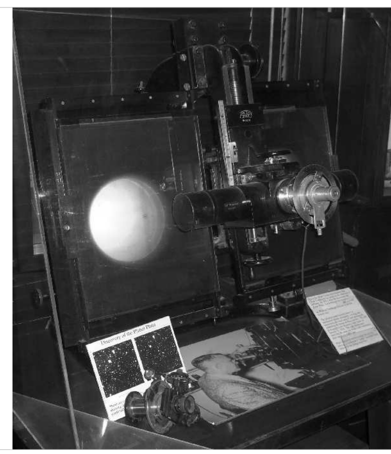
Clyde W. Tombaugh



Needle in a Haystack



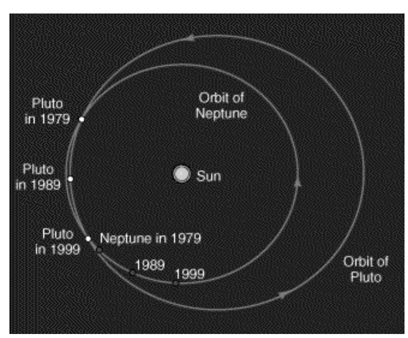
- L exposure - 01/23/30, R exposure 01/29/30
- Field ~ 6'38" x 6'38", displacement ~ 84"

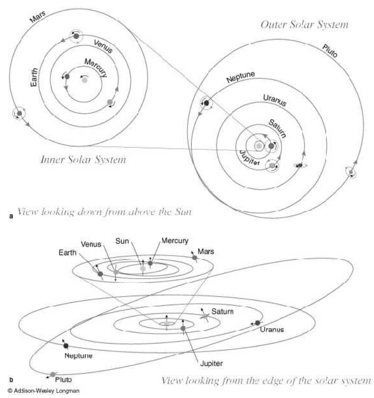


1930/03/13: Pluto Discovered

- Semimajor axis: 39.5 AU
- Sidereal year: 248.5 years
- $0.0022M_\oplus$, $0.18R_\oplus$, ρ~2000 kg/m^3
- Rotation period: 6.4 mean solar days
- Axial tilt: 122°
- Orbital eccentricity: 0.248
- Inclination of orbit to ecliptic: 17°

Pluto's Eccentric Orbit





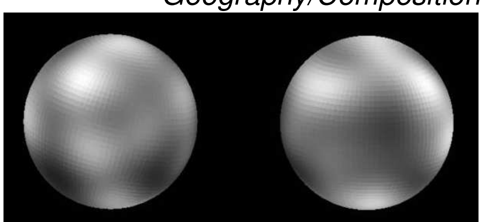
Orbital Anomalies

- Elliptical orbit (ϵ=0.25, crosses Neptune)
- Inclined orbit (17°)
- Mercury's orbit is elliptical (ϵ=0.21) & inclined (17°)

Pluto's Shortcomings

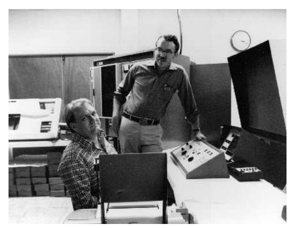
- While Pluto seems to be where Lowell predicted (more or less), there are problems.
  - Mass and size are too small (by a factor of 5 at least)
  - Highly elliptical orbit (crosses Neptune's)
  - Highly inclined orbit
  - Out of place for a terrestrial planet
  - Obviously not a jovian planet

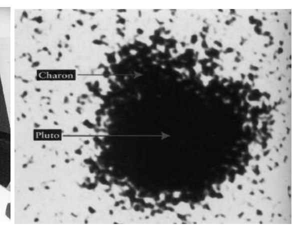
Geography/Composition



- Photographs show albedo features
  - Impact basins/craters? Polar caps?
- Plutonian ice ⇨ frozen nitrogen
- Atmosphere: methane at 10^{-5} $P_\oplus$

New Moon

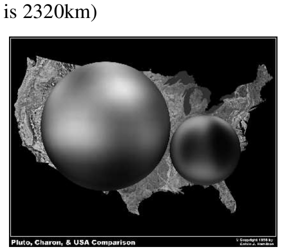


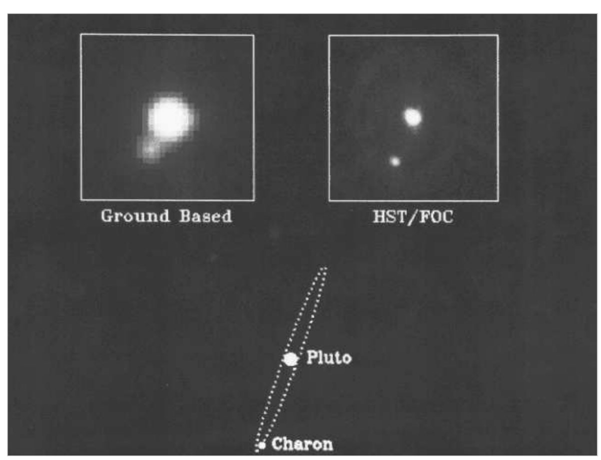


- James Christy (June 22, 1978) USNO
  - Lumpy Pluto - period of $6^d 9.3^h$

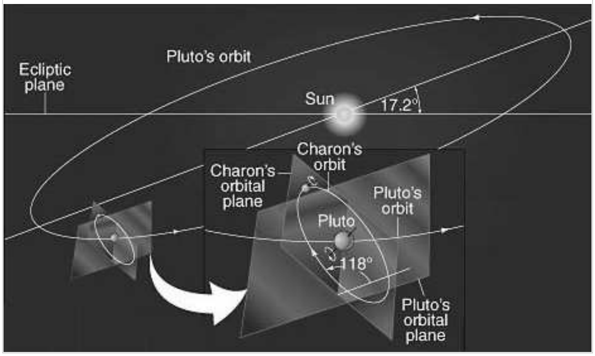
Pluto/Charon Binary System

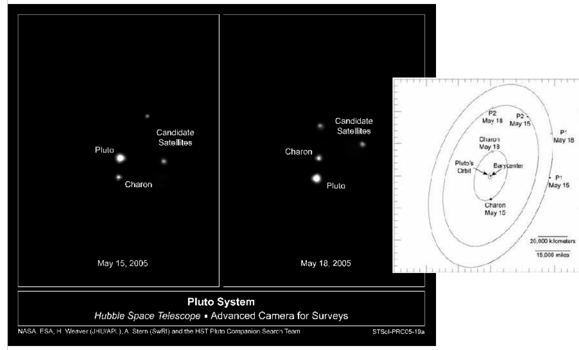
- Distance from Pluto ~1/20 distance between Terra & Luna
- Diameter - 1270km (Pluto is 2320km)
- Mass - 1/10th $M_{♇}$
- Charon allowed determination of Pluto's mass
- Synchronous rotation (6.4 days)





Orbit Detail



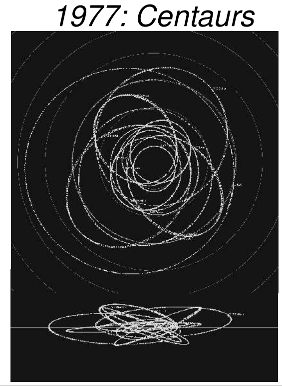


Pluto's Shortcomings

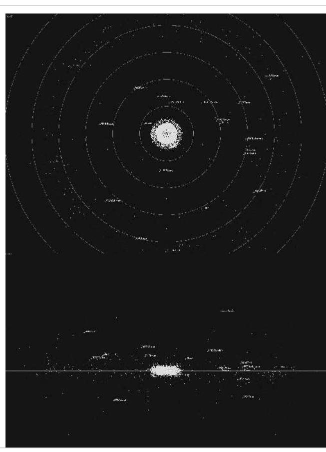
- Pluto's moon is too big for her
- Obviously not a jovian planet
- Neither very rocky or metallic for a terrestrial planet
- Orbit is highly inclined to the ecliptic
- **No answer for these...**

1977: Centaurs

- Charles Kowal (Palomar) → Chiron
  - '10th planet', asteroid
  - Developed 'tail'
- Centaurs:
  - Carbonaceous chondrites
  - Ices
  - Diameters ~30-300km
  - Highly elliptical, inclined orbits

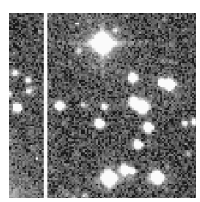


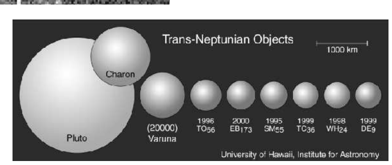
1992 QB_1



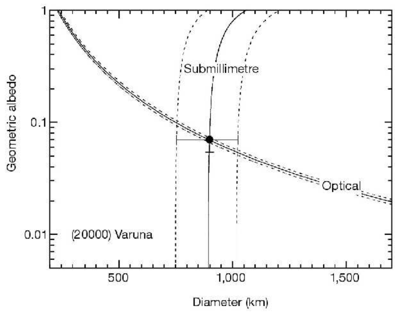
- Cubewanos
- Plutinos
- KBOs
- TNOs
- SDOs

($2000\ WR_{106}$)
20000 Varuna

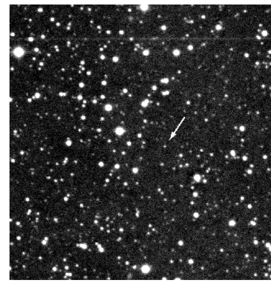




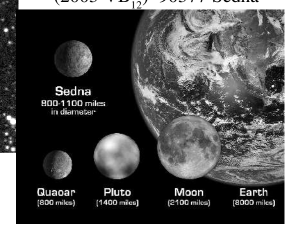
Determination of Size

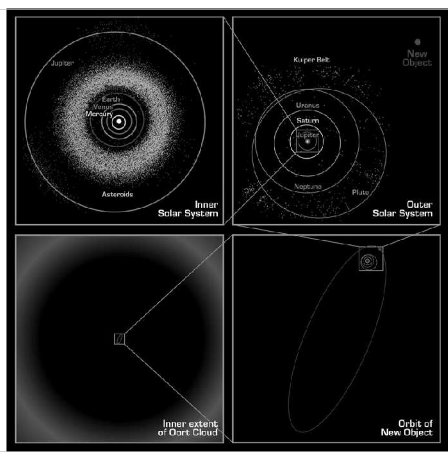


Challengers

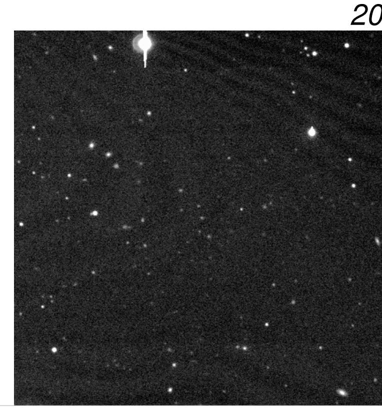


- (2001 KX_{76}) 28978 Ixion
- (2002 LM_{60}) 50000 Quaoar
- (2003 VB_{12}) 90377 Sedna

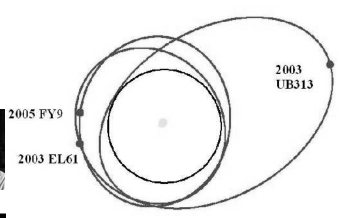


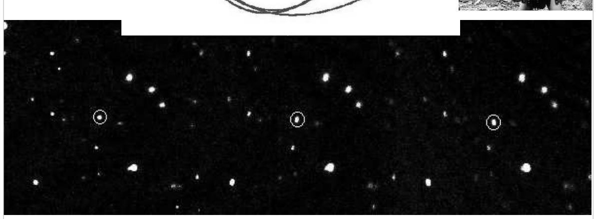


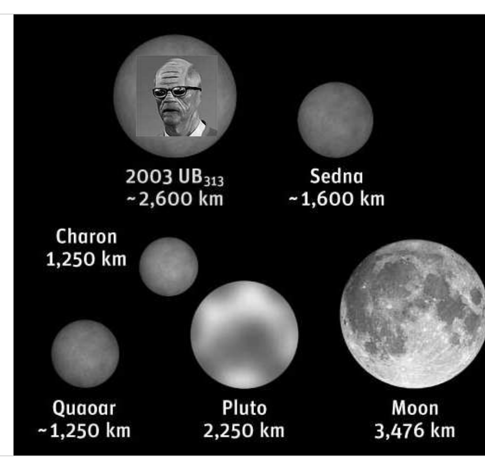
2003 UB_{313} (Xena)



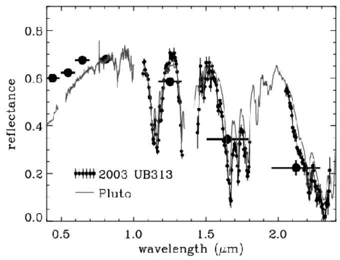
Xena



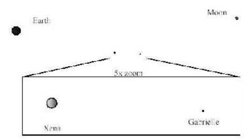


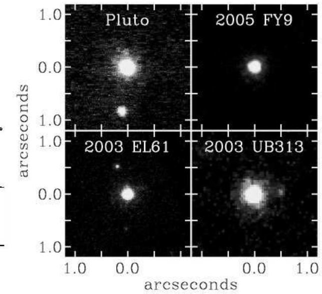


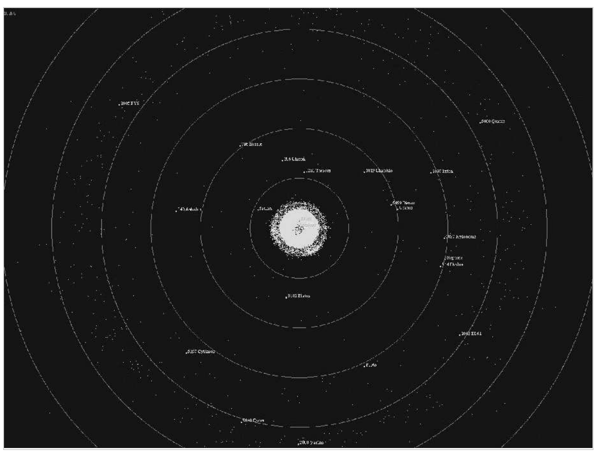
Composition

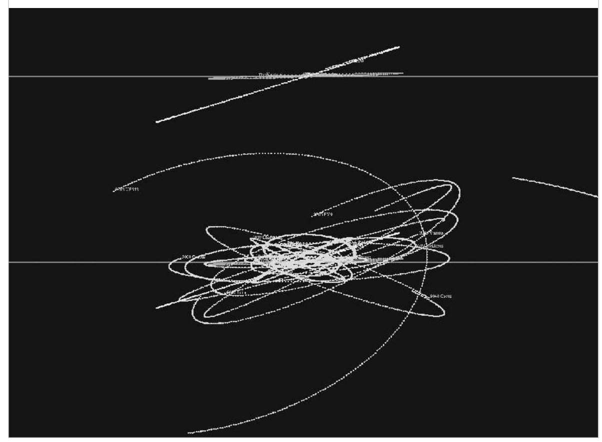


S/2005 (2003 UB_{313})$_1$

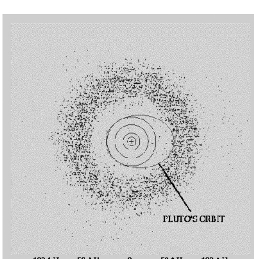


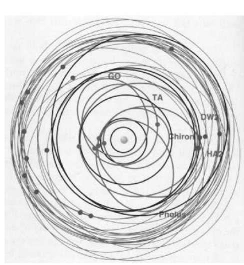






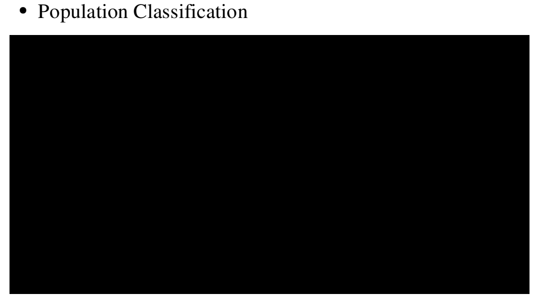
Pluto, Centaurs, & the Kuiper Belt





What is a Planet?

- Population Classification



Remember our Planetary System Model Criteria?

- Each planet is relatively isolated in space
- Orbits of planets are nearly circular
- Orbits of planets lie in the same plane
- Direction of orbits is same as Sol's rotation
- Planetary rotation is in the same direction as Sol's rotation

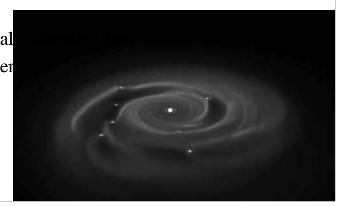
- Most moons revolve in the same direction as planetary axial rotation
- Planetary system is highly differentiated
- Asteroids are very old and share properties unlike terrestrial or jovian planets
- Comets are icy, primitive fragments that do not orbit in ecliptic and reside far from the Sun

The Solar Nebula

- Est. 4.6 billion years ago
- 10-100 million years to form planets
  - isotope abundances
- mass < 0.1 $M_{\oplus}$
  - most mass blown away by stellar wind
  - $\rho_{avg} \sim 10^{-7}\, \rho_{air,\oplus}$

Condensation

- Heat produced by Kelvin-Helmholtz contraction
  - Temps from several thousand K near core to 100K at 10 AU (Saturn)
- Particles condense from cooling gas
- ***Differentiation***
  - stable materials (metal
  - hydrogen, helium later



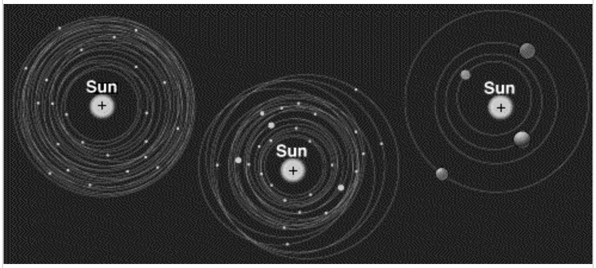
Planetesimal Formation

- Condensed matter (grains) slowly stuck together
- ***Accretion*** - as pieces stuck together, gravitational force increased and attracted more pieces
- ***Planetesimals*** - larger accumulations of matter, from 10^{-3} to 10^{5} m (asteroids)
- Planetesimals likely aided condensation process

Terrestrial Planet Formation

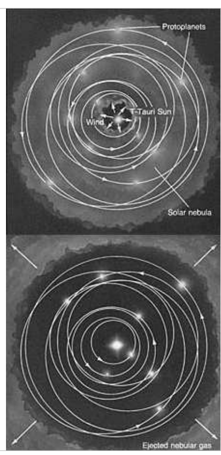
- Formation began near 1600K
  - metals, silicates, very little water/gases
- Surfaces of Mercury, Mars highly suggestive of planetesimal collisions
- *Underrepresented* in light material
  - Temperatures so warm that gases condense
  - Surface gravities too small to retain
  - Gases likely 'blown away' by protostellar winds

Planetesimal Aggregation



Jovian Planet Formation

- Formation began almost immediately
  - Cooler temperatures in outreaches allowed immediate condensation of gases
  - Lighter gases condensed around cooler bits of iron/silicates
  - As cooler planetesimals swept through nebular gas, warmer gas condensed on the planetesimals



Cleanup

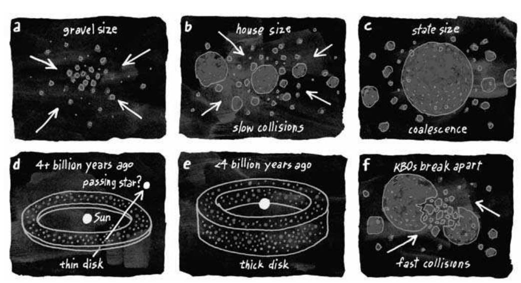
- Light, ice-based planetesimals probably ejected outward to form Oort Cloud, Kuiper Belt
- Non-aggregate nebular gas blown away from solar system

Cleanup

- As planets form, the original elliptical orbits of the planetesimals 'average' out to nearly circular orbits.
- Eventually, most of the material near the newly-formed planets is 'swept' up.
  - several of the terrestrial planets still bear the scars of the last impacts?

Residue

- In areas, some of the proto-matter remains - never accreted into a larger body.
  - Asteroids
  - Kuiper Belt/Scattered Disk
  - Oort Cloud
- These objects generally have more elliptical/inclined orbits



Review

- Condensation theory accounts for all of our observations.
  - Planets' orbits are circular, in same plane, and in same direction as Sol's rotation due to nebula's shape and rotation.
  - Rotation of planets and moon systems due to tendency of small eddies to inherit overall rotation of nebular disk
  - Growth of planetesimals results in widely-spaced orbits
  - Heating of nebula, solar ignition result in differentiation
  - Debris from accretion-fragmentation account for asteroids/comets

Catastrophism: Exceptions Explained

- Mercury's large nickel-iron core
- Venus' low rotation rate
- Luna's orbit, size
- Mars' asymmetry/lack of atmosphere
- Uranus' axial tilt
- Uranus' moon Miranda
- Triton's retrograde motion
- Pluto-Charon system