Comets and asteroids : orbits

Comets & asteroids are particularly interesting because of their resemblance to planetesimals : the building blocks of the Solar System

Asteroids are rocky, most are found between Mars & Jupiter

Comets contain mostly ice ; outer Solar System objects with elliptical orbits

Q Do you think it is a coincidence that rocky asteroids are found near the rocky planets, icy comets near gas giants?

A

If asteroids & comets were formed where they spend most of their time (inner solar system for asteroids, outer for comets) we would expect them to reflect conditions there.

Inner solar system too hot for ices to be solid, so asteroids rocky.

Q However, the split between comets & asteroids is less absolute than the terrestrial planet / gas giant division. What else might be going on? Should we toss out the condensation vs. temperature theory we talked about last week?

A We dont need to toss it out, but should recognise that it describes conditions in the <u>early Solar System.</u>

Anything that modifies orbits afterward will mess up these correlations. Resonances with Jupiter have cleared out regions in the asteroid belts because the asteroids there get an extra gravitational kick from Jupiter over & over again.

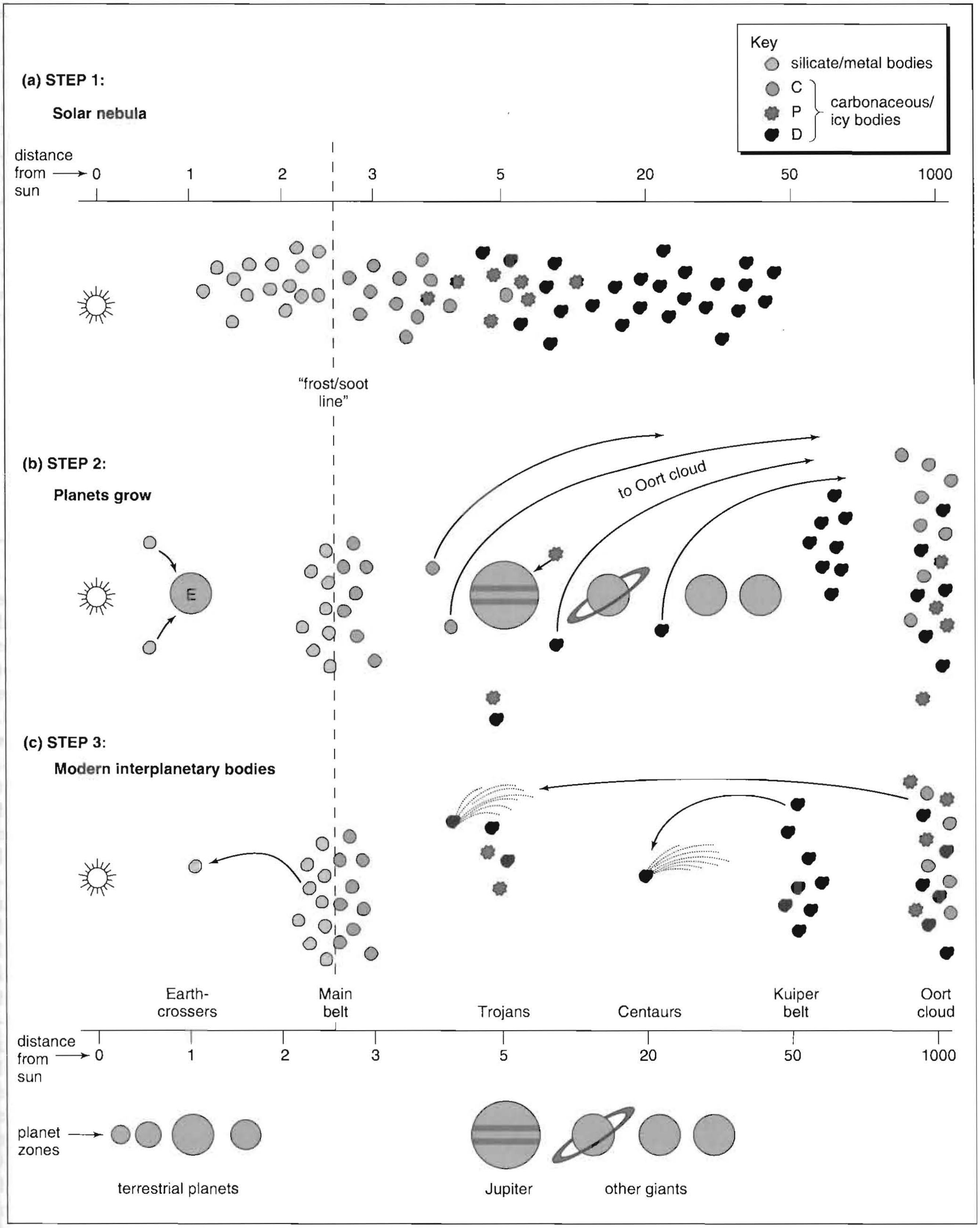

Figure 7-4. Schematic history of interplanetary bodies and distribution of taxonomic classes (not to scale). (**a**) Initial composition zones among planetesimals. (**b**) Perhaps 50 My later, planets are forming and the interplanetary bodies are being depleted by collisions with planets and ejection into the Oort cloud. The main asteroid belt and Kuiper belt are left stranded. (**c**) In the present system, a population of Earth-crossers, Centaurs, and active comets is maintained by processes of perturbation.

$\boxed{Q}$ What distinguishes asteroids from comets ?

Comets

Have eccentric orbits — spend most of their time in outer Solar system

When far from the Sun, they are balls of ice & dust 1-10 km across.

As orbit nears the Sun, around 3 AU, heat from Sun evaporates some of comet, forming the 'coma'.

This becomes the 2 tails, which point in different directions
- One is ion tail, ions like CO^+, N_2^+, CO_2^+
- Dust Tail is smoother.

Ion tail interacts with solar magnetic field

Dust Tail is repelled from Sun by radiation pressure.

Q Why do periodic comets often seem fainter on progressive returns to the inner Solar system?

A On each perihelion passage, the comet loses more volatiles to its coma & tail. Some of these will remain strung out along the comet's orbit. After several passages there will be less volatiles available to contribute to the coma & tail so the comet appears fainter.

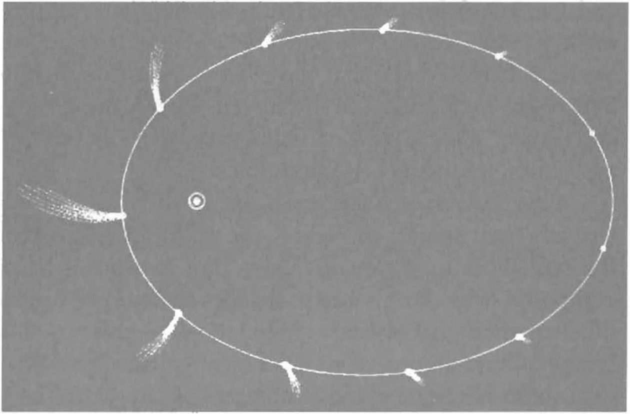

Figure 7-9. Orbit of a typical comet, showing development of the tail as the comet approaches and recedes from the sun.

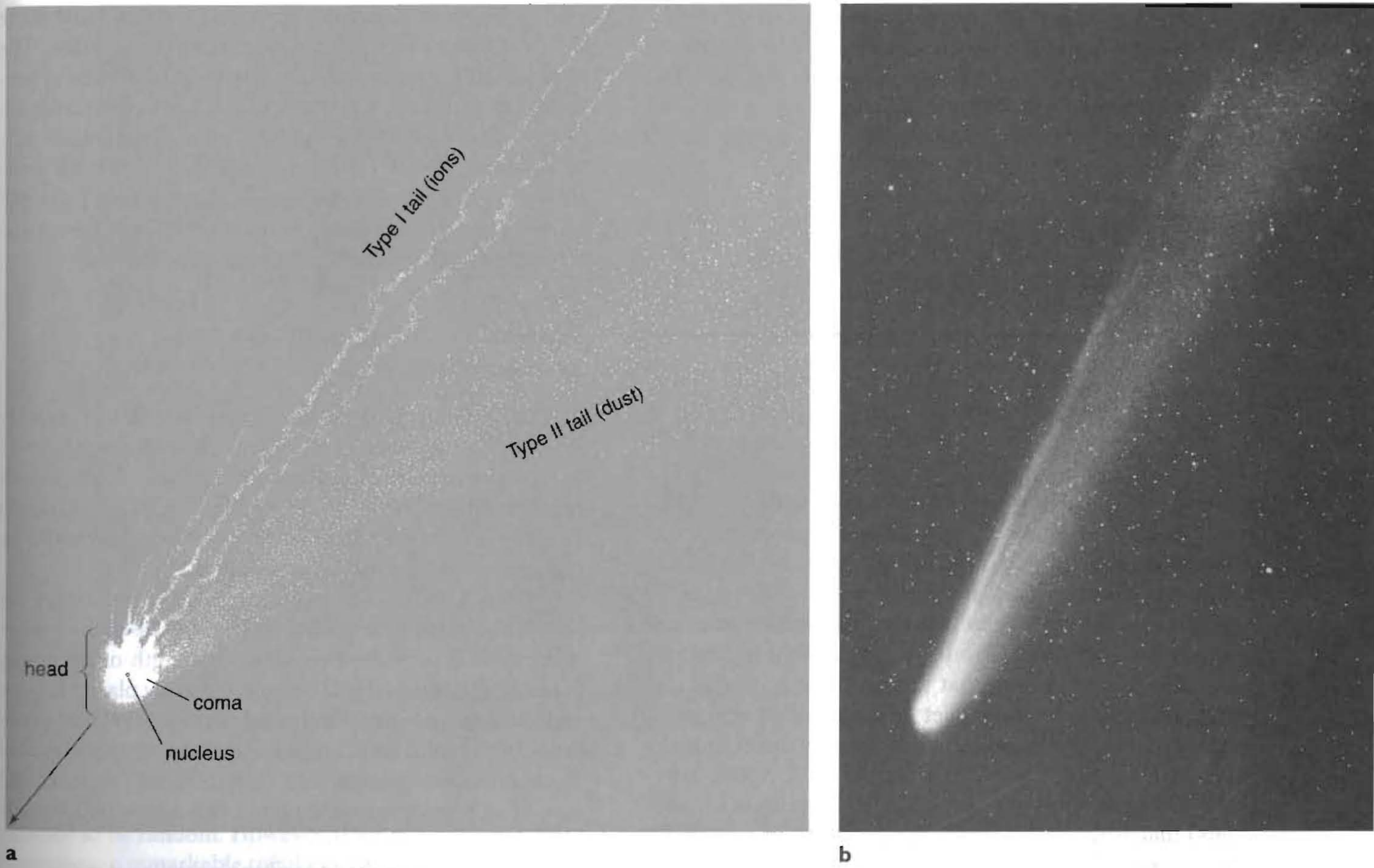

Figure 7-10. (**a**) Nomenclature of a comet. (**b**) Comet Kohoutek, showing the same features, with minimal separation of Type I and Type II tails. (NASA, Lunar and Planetary Laboratory, University of Arizona)

Q The movie shows observations of Halley's comet's <u>nucleus</u> by the Giotto spacecraft.

Giotto didnt hit the nucleus; why did the photos stop?

Q Comet orbits are not completely predictable, so we speak of 'recovering' a periodic comet when it is first confirmed to return. What might cause this erratic behavior?

A Perturbations from planets
Jets of gas from interior thru crust.

Cometary dust

- spreads out along orbit of comet
  - gegenschein (reflection of sunlight back towards Earth)
  - zodiacal light (close to Sun)

  - meteor showers

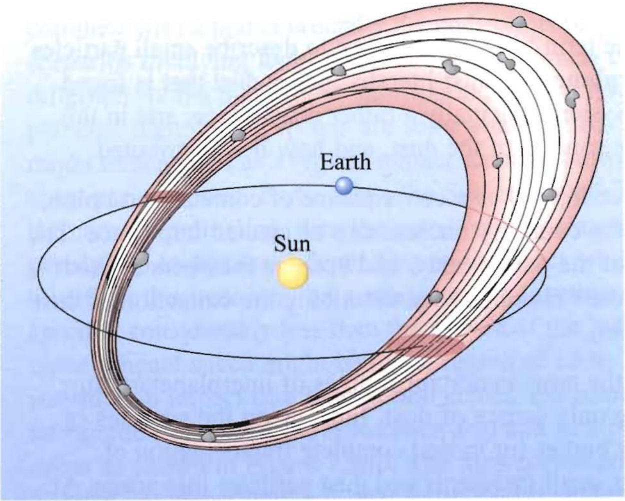

Figure 7.39 A meteoroid stream produced by the ejection of dust particles from a comet. The orbits of the dust particles are reasonably similar to the parent comet, producing a tube of dust in space, which is thickest at the aphelion region.

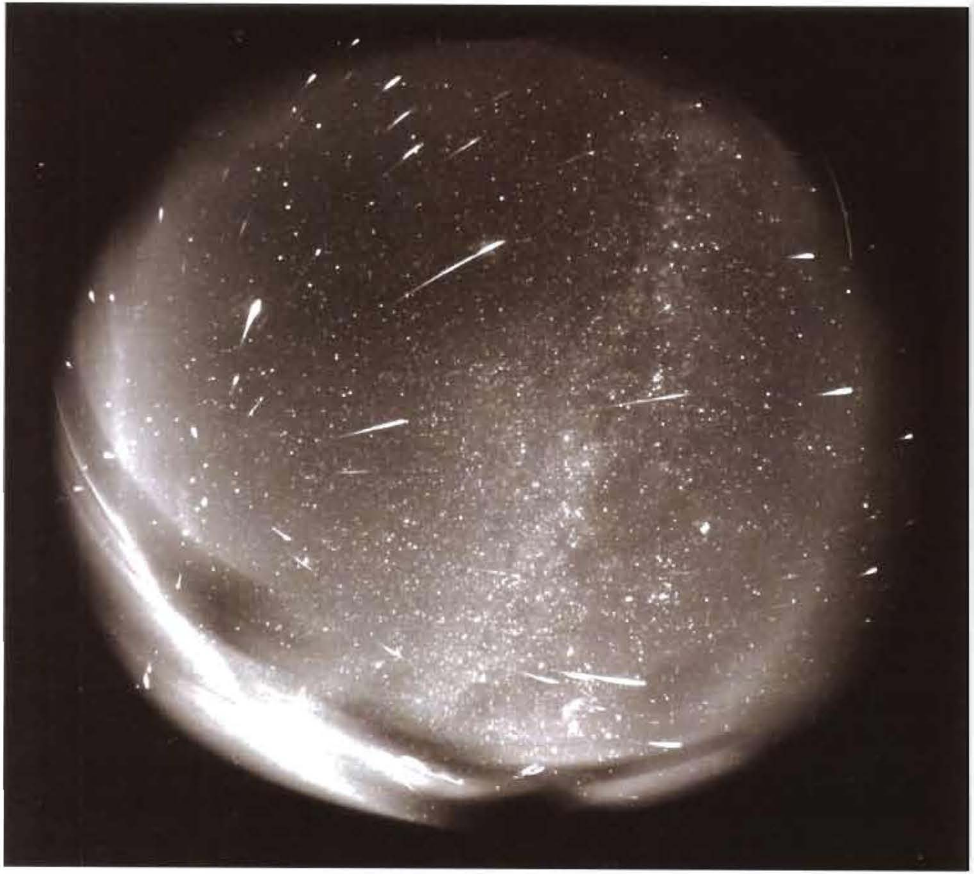

Figure 7.40 An all-sky image taken during the 1998 Leonid meteor shower, when the peak rate of meteors reached several hundred per hour. (Juraj Toth, Modra Observatory)

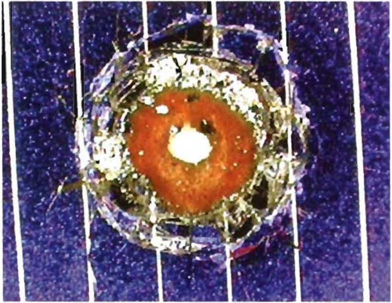

Figure 7.41 An impact crater found on the solar arrays of an Earth-orbiting satellite. The vertical lines are about 1 mm apart. The crater could have been made by a particle just 100 μm across.

m the asteroid belt, whereas a 1 cm object

Figure 7.43 A photograph, taken after sunset in 1997, of the zodiacal light (which extends up from the centre horizon) which is due to sunlight being scattered from the dust particles in the interplanetary dust cloud. Also seen in the photograph is comet Hale–Bopp. (J. C. Casado)

Radiation pressure

Dust grains feel momentum carried by solar photons.

(radiation pressure very important for massive stars)

momentum of photon $p = \frac{E}{c}$

Calculate radiation pressure at distance r from Sun:

consider a shell radius r

force on shell $F = \frac{dp}{dt}$

pressure $= \frac{\text{force}}{\text{area}} = \frac{dp}{dt} \Big/ 4\pi r^2$

$$\frac{dp}{dt} = \frac{1}{c} \frac{dE}{dt}$$

$\frac{dE}{dt}$ is energy given off by Sun every second — solar luminosity $L_\odot$

$$\frac{dp}{dt} = \frac{L_\odot}{c}$$

So radiation pressure at radius r is

$$\frac{L_\odot}{4\pi r^2 c}$$

For $r = 1$ AU, pressure is 5×10^{-11} atm.

$\boxed{\text{Ex}}$ For grains of density $1 g/cm^3$, find the grain size for which gravity & radiation pressure are equal.

Let d be the radius of the grain.

Then mass of grain $= 1 \cdot \frac{4}{3}\pi d^3 \cdot = m$

$$\text{Gravitational force} = \frac{G M_\odot m}{r^2}$$

$$= G M_\odot \cdot \frac{4}{3}\pi d^3 \cdot \frac{1}{r^2} \cdot$$

area of grain (cross-sectional) $= \pi d^2$

So radiation pressure force $= \frac{L_\odot}{4\pi r^2 c} \cdot \pi d^2$

Gravity & radiation pressure equal :

$$G M_\odot \cdot \frac{4}{3}\pi d^3 \cdot \frac{1}{r^2} = \frac{L_\odot}{4\pi r^2 c}\,\pi d^2$$

Independent of distance from Sun

$$G M_\odot \,\frac{4}{3}\cancel{\pi}\, d = \frac{L_\odot}{4\pi c}$$

$$\text{So} \quad d = \frac{L_\odot}{4\pi c} \cdot \frac{3}{4} \cdot \frac{1}{G M_\odot}$$

$$= \frac{3.8 \times 10^{33}}{4 . \pi . 3 \times 10^{10}} \cdot \frac{3}{4} \cdot \frac{1}{6.7 \times 10^{-8} . 2 \times 10^{33}}$$

$$= 5.7 \times 10^{-5} \text{ cm}$$

$$= .57 \text{ microns}$$

$F_{rad} \propto d^2 \quad F_{grav} \propto d^3 \quad$ so $\frac{F_{rad}}{F_{grav}} \propto \frac{1}{d}$

For $d < 0.5$ microns, radiation pressure dominates

ORIGIN (& HOME) OF COMETS

- short-period comets (< 200 years)
- long-period comets (> 200 years)

Approximately!

Most short-period comets have $P = 5-20$ yrs
low inclination orbits, prograde

Long-period comets : orbits are highly eccentric ellipses, appear nearly parabolic close to planets.

- Bound to solar system
- inclinations of all sizes
- ~~aphelions~~ semi-major axes $10^4 - 5 \times 10^4$ AU

(Pluto is ~40 AU)

(nearest star at 2.7×10^5 AU)

$\boxed{\text{Magnitude}}$: how astronomers measure apparent brightness

Used since ancient times, based on (logarithmic) response of eye

Objects with brightness B_1, B_2 have magnitudes m_1, m_2:

$$m_1 - m_2 = -2.5 \log_{10}\left(B_1/B_2\right)$$

- Sirius has magnitude ~ 0
- Factor of 100 in brightness is 5 magnitudes
- Dark site + naked eye can see to ~ 6

Kuiper belt

Home of short-period comets

Kuiper ('51) suggested : flattened ring of cometary nuclei outside Neptune's orbit

Leftovers from original solar system : where it petered out.

First Kuiper belt objects detected in 1992

Largest ones : size 100 - 200 km

Magnitude 24-25 (night sky ~ 20)

Now [illegible] many known with orbits that place them in Kuiper Belt

HST observations, [illegible], have shown the existence of objects the size of a typical comet nucleus (~10km) in the Kuiper belt.

Mass of Kuiper belt is very small ..... current estimate is less than mass of Earth

Pluto is thought by many (but not all) astronomers to be a rather large Kuiper belt object rather than a true planet

- eccentric orbit e = 0.25
- inclination to ecliptic 17°

Comets lose material on each successive perihelion passage .... we need a source of new comets as well

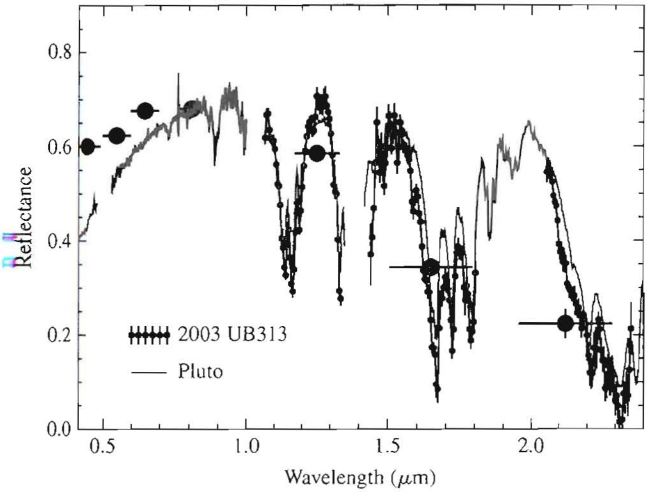

FIGURE 22.10 The reflection spectrum of 2003 UB313 (individual points) compared to the spe trum of Pluto (gray line). Absorption features of methane dominate the spectrum. The large poin are data from *BVRIJHK* photometry. [Courtesy of Mike Brown (Caltech), Chad Trujillo (Gemi Observatory), and David Rabinowitz (Yale University).]

Oort cloud : home of long-period ("new") comets

Spherical shell at $\sim 10^4 - 10^5$ AU

Comet nuclei spend billions of years there on average

Orbital perturbations can send a comet into inner solar system

- passing star
- Galaxy's tidal field
- Giant molecular clouds

Evidence for existence comes from comet orbits only, no nuclei directly observed in Oort cloud

Total mass tiny : estimated as ~10-100 Earth masses

Problem

Pluto orbits at ~ 40 AU and is so faint it was not discovered until 1930. (14th mag.) If something like Pluto was located in the Oort Cloud at 10,000 AU from the Sun, how much fainter would it appear from Earth?

Kuiper belt comet nuclei thought to be leftovers from edge of early Solar system

Chemical differences between long-period and short-period comets suggest short-period comets formed furthest from Sun

Oort cloud comets were probably originally formed near Jupiter & asteroid belt, perturbed out by giant planets ....

Q

How can you get Oort cloud comets originating from closer ~~into~~ in, nearer the Sun, than Kuiper belt comets ?

belt, planetary perturbations would have excited most of the icy planetesimals onto planet-crossing orbits in ten million years or less.

The long-period comets are thought to derive from a small fraction of the planetesimals that became planet-crossing. The first stage in placing a comet in the cloud is that planetary perturbations pumped up the orbital energy (i.e., semi-major axis, denoted a) of a planetesimal, while its perihelion distance remained nearly constant. If the planets had been the only perturbers, this process would have continued, in general, until the planetesimal became unbound from the solar system, and thereafter wandered interstellar space. However, the very reason that a comet's orbit becomes unbound at large distances – the presence of stars and other matter in the solar neighborhood that exert a gravitational force comparable to that from the Sun – provides a possible stabilizing mechanism. Once a comet's orbit becomes large enough, passing stars affect it. In fractional terms, stars change cometary perihelion distances much more than they change the overall size of the orbit. If passing stars can lift a comet's perihelion out of the planetary region before the planets can eject it from the solar system, the comet will attain an orbit in the Oort cloud. The size of the Oort cloud is set by the condition that the timescale for changes in the cometary semi-major axis is comparable to the timescale for changes in perihelion distance due to passing stars. In essence, the comet must attain an orbit large enough that it is significantly perturbed by passing stars, but not so large that the orbit is too weakly bound to the solar system and the comet escapes. This condition yields a cloud of comets with semi-major axes of order 10,000 to 100,000 AU (Heisler & Tremaine 1986, Duncan et al. 1987, Tremaine 1993). The trajectories of the stars are randomly oriented in space, so stellar perturbations eventually cause the comets to attain a nearly isotropic velocity distribution, with a median inclination to the ecliptic of 90° and a median eccentricity of $1/\sqrt{2} \sim 0.7$. Subsequently, passing stars reduce the perihelion distances of a small fraction of these comets so that they re-enter the planetary region and potentially become observable.

The above description is similar to Oort's vision of the comet cloud. However, less than half of the local galactic mass density is provided by stars, the rest being in gas, brown dwarfs, and possibly a small amount of "dark matter." We thus now recognize that the smooth long-term effect of the total amount of nearby galactic matter, i.e. the "galactic tide," perturbs comets somewhat more strongly than do passing stars. The galactic tide causes cometary perihelion distances to cycle outward from the planetary region and back inward again on timescales as long as billions of years (Heisler & Tremaine 1986). In addition, rare, but large, perturbers such as molecular clouds may affect the long-term stability of the Oort cloud.

2.2. Observed Orbital Distribution

When the orbits of long-period comets are integrated backward in time to well before the comets entered the planetary system, yielding the "original" orbits, about one-third of the comets are found to occupy a "spike" at near-zero but bound energies, representing orbits with $a > 10^4$ AU. It was, of course, this spike that led Oort to postulate the existence of the comet cloud. A few of the orbits are apparently slightly hyperbolic, due in most or all cases to imperfect modeling of nongravitational jetting forces (Królikowska 2001). The remaining two-thirds of long-period comets revolve on smaller, more tightly bound orbits.

Oort suggested that most new comets have semi-major axes of 25,000 to 75,000 AU. More recent determinations give values about one-half as large; Marsden et al. (1978) suggest that the peak, corrected for non-gravitational forces, is at 22,000 AU. Simulations by Heisler (1990) predict a peak closer to 30,000 AU. This discrepancy could result from errors in orbit determination, contamination of the "new" comet population with dynamically old comets with $a > 10^4$ AU, or, as Heisler proposed, could indicate that

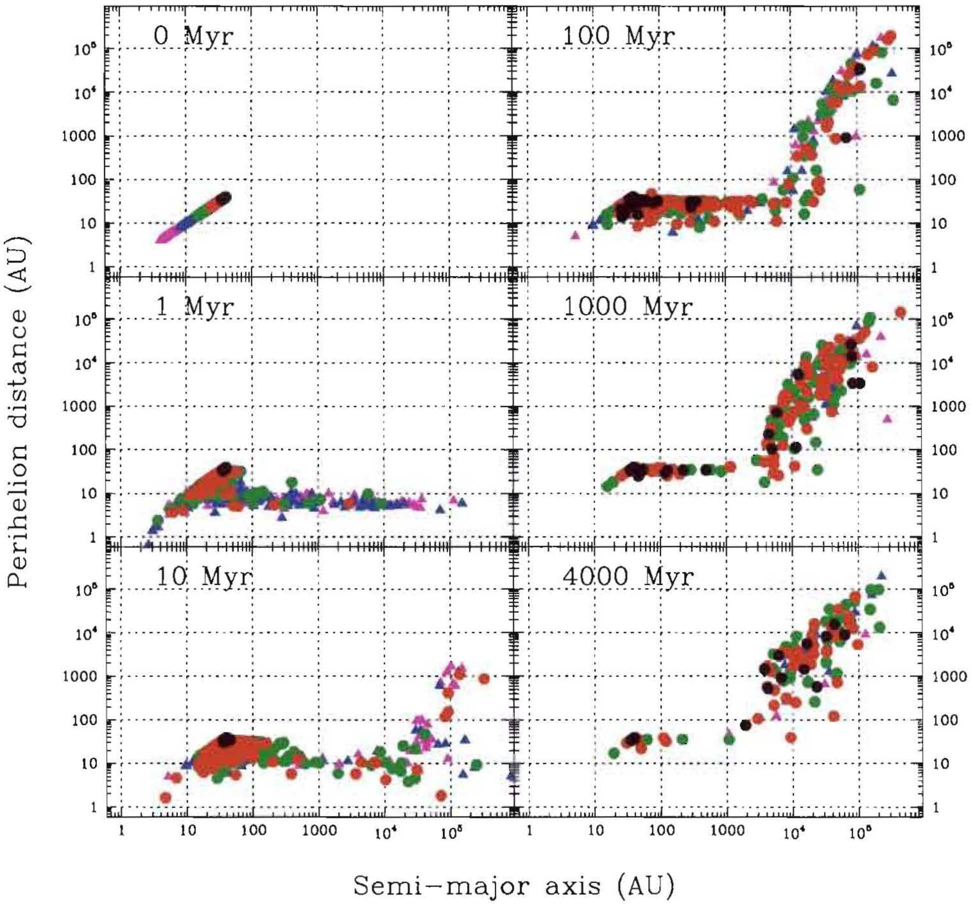

Figure 1. Scatter plot of osculating barycentric pericenter distance (q) vs. osculating barycentric semi-major axis (a) at various times in the DLDW "cold" simulation of the formation of the Oort cloud. This simulation included 2,000 test particles with initially small eccentricities and inclinations. The points in Figures 1 and 2 are color-coded by their formation location a_0: Jupiter region comets (a_0 between 4 and 8 AU) are magenta triangles; Saturn region comets (8–15 AU) are blue triangles; Uranus region comets (15–24 AU) are green circles; Neptune region comets (24–35 AU) are red circles; Kuiper belt comets (35–40 AU) are black circles. Panel (a): Initial conditions for the simulation [0 Myr]. Panel (b): 1 Myr into the simulation. Panel (c): 10 Myr into the simulation. Panel (d): 100 Myr into the simulation. Panel (e): 1 Gyr into the simulation. Panel (f): Final results for the simulation, at 4 Gyr, i. e., roughly the present time. Note that in panel (f), there is a nearly empty gap for semi-major axes between about 200 and 3,000 AU. Objects with a in this range and q in the planetary region evolve rapidly in a at nearly constant q, thereby depleting this region, as discussed by DQT87.

Meteorites are either asteroids or dust particles which become scattered around a comet's orbit. (meteoroid if it doesnt survive)

Well-known meteor showers occur when the Earth's orbit intersects a comet's orbit

Q Are the comets in question likely to be short-period (Kuiper belt) or long-period (Oort cloud) objects? Why?

these

A Comets are more likely to belong to Kuiper belt because it has a similar plane to the ecliptic, so the comet's whole orbit is close to the ecliptic and there is a good chance the Earth will intersect it.

If it were an Oort cloud comet its inclination could be high since Oort cloud is spherical. So most of these comets' orbits are outside the ecliptic & the Earth will never intersect them.

TABLE 13.1

Meteor Showers and Comets

Shower	*Comet*	*Occurrence*	*Meteors/h*
Quadrantids	1491 I	Jan. 1–4	80
Lyrids	Thatcher	Apr. 19–24	35
Aquarids	Halley	May 1–8	40
β Taurids	Encke	June 24–July 6	—
Perseids	Swift-Tuttle	Aug. 9–17	40
Orionids	Halley	Oct. 15–25	45
Taurids	Encke	Oct.–Nov.	5
Leonids	Temple-1	Nov. 15–20	40
Geminids	Phaethon	Dec. 7–15	60
Ursids	Tuttle	Dec. 17–24	5

Note: Showers are named for the constellation from which they appear to radiate. A comet is a candidate source of the meteor shower if its orbital elements are close to the meteors' orbital elements.