Comets and Asteroids: Orbits

Comets and asteroids are particularly interesting because of their resemblance to planetisimals: the building blocks of the Solar System.

Asteroids are rocky, and most are found between Mars and Jupiter.

Comets are outer solar system objects with elliptical orbits and contain mostly ice.

Question:

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

Answer:

Asteroids and comets are formed where they spend most of their time (inner solar system for asteroids, outer for comets). We would expect them to reflect the conditions there when they were formed.

The inner solar system was too hot for ices to be solid, so asteroids are rocky.

Question:

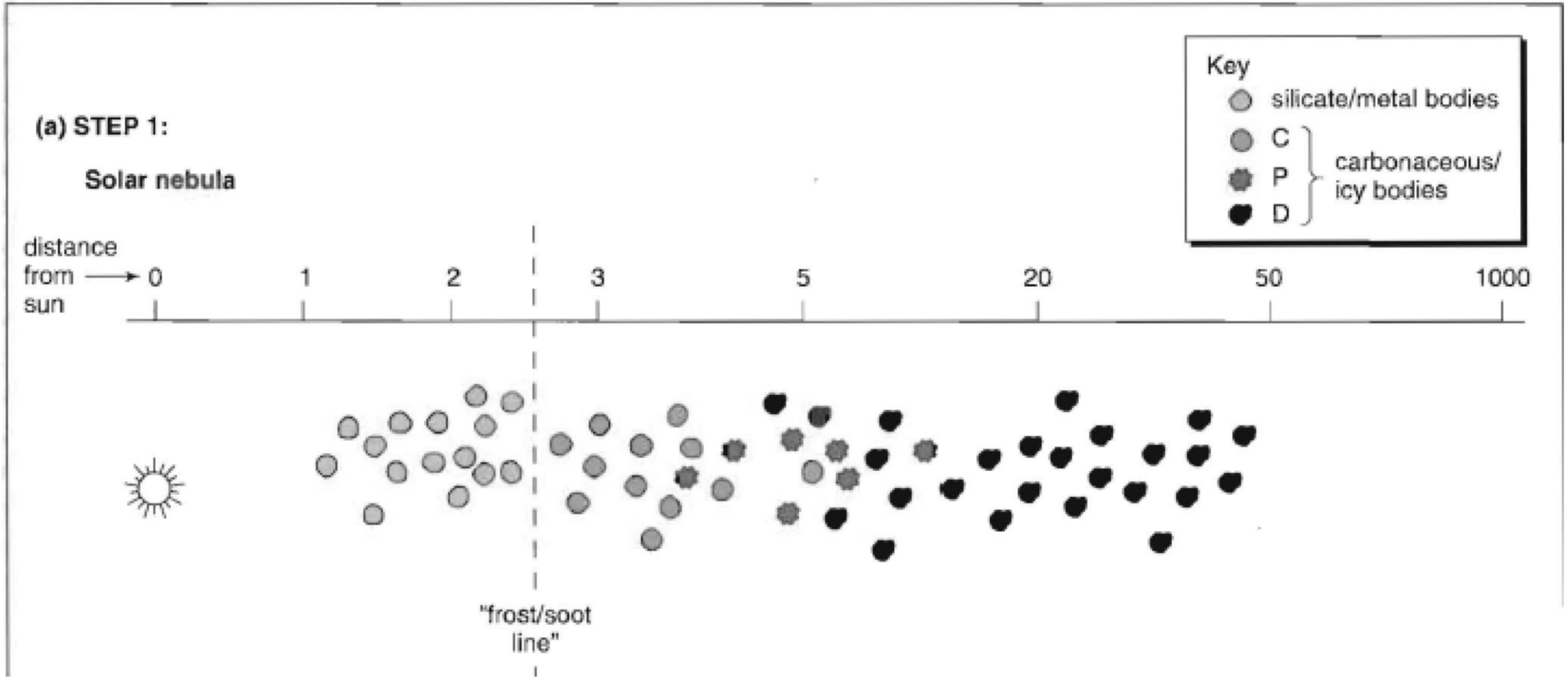
However, the split between comets and asteroids is less absolute than the terrestrial planet/gas giant division. What else might be going on? Should we disregard the condensation versus temperature theory we talked about last week?

Answer:

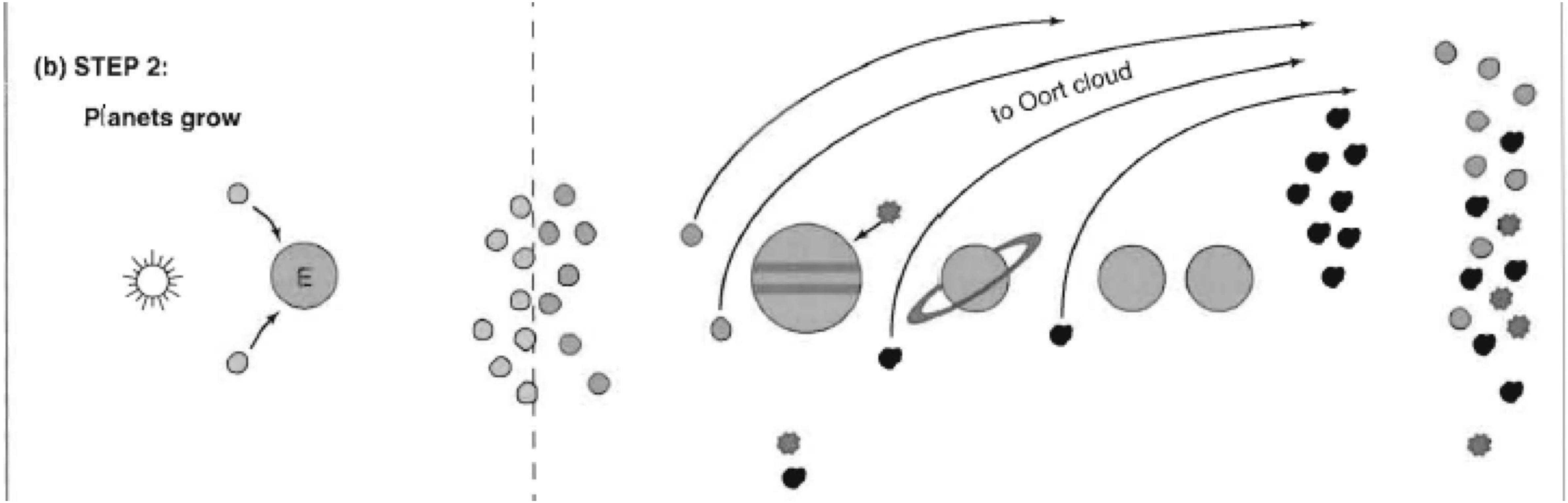
We don’t need to toss it out, but should recognize that the theory describes conditions in the early solar system.

Anything that modifies orbits afterwards will mess up these correlations. We have talked before about the Kirkwood gaps, where resonances with Jupiter have cleared out regions in the asteroid belt because objects there get an extra gravitational kick over and over again from Jupiter.

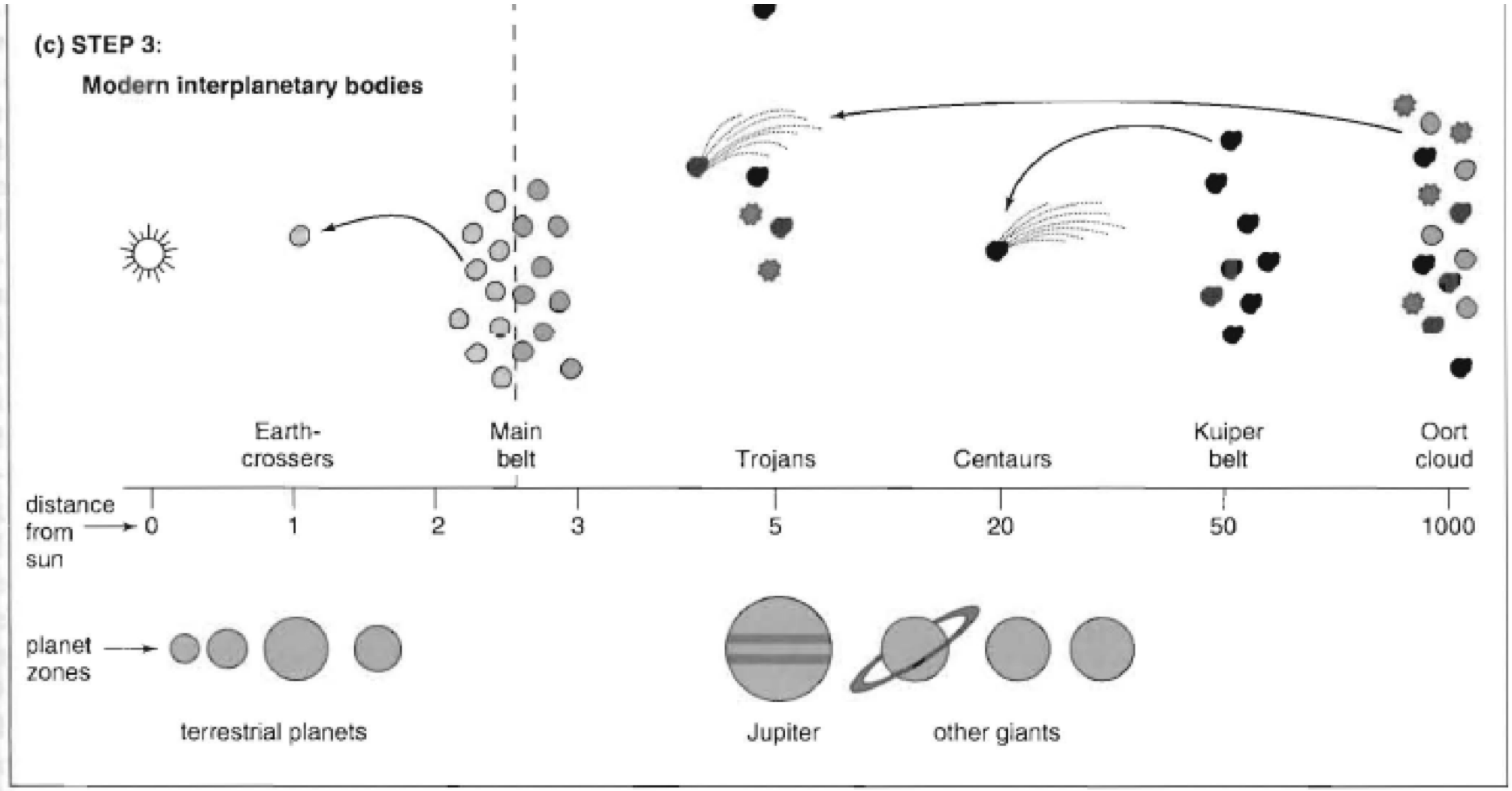
Timesteps in solar system formation/evolution:



Creation of Oort cloud via giant planet interactions



Solar system today



Comets

Comets have eccentric orbits and spend most of their time in the outer Solar System.

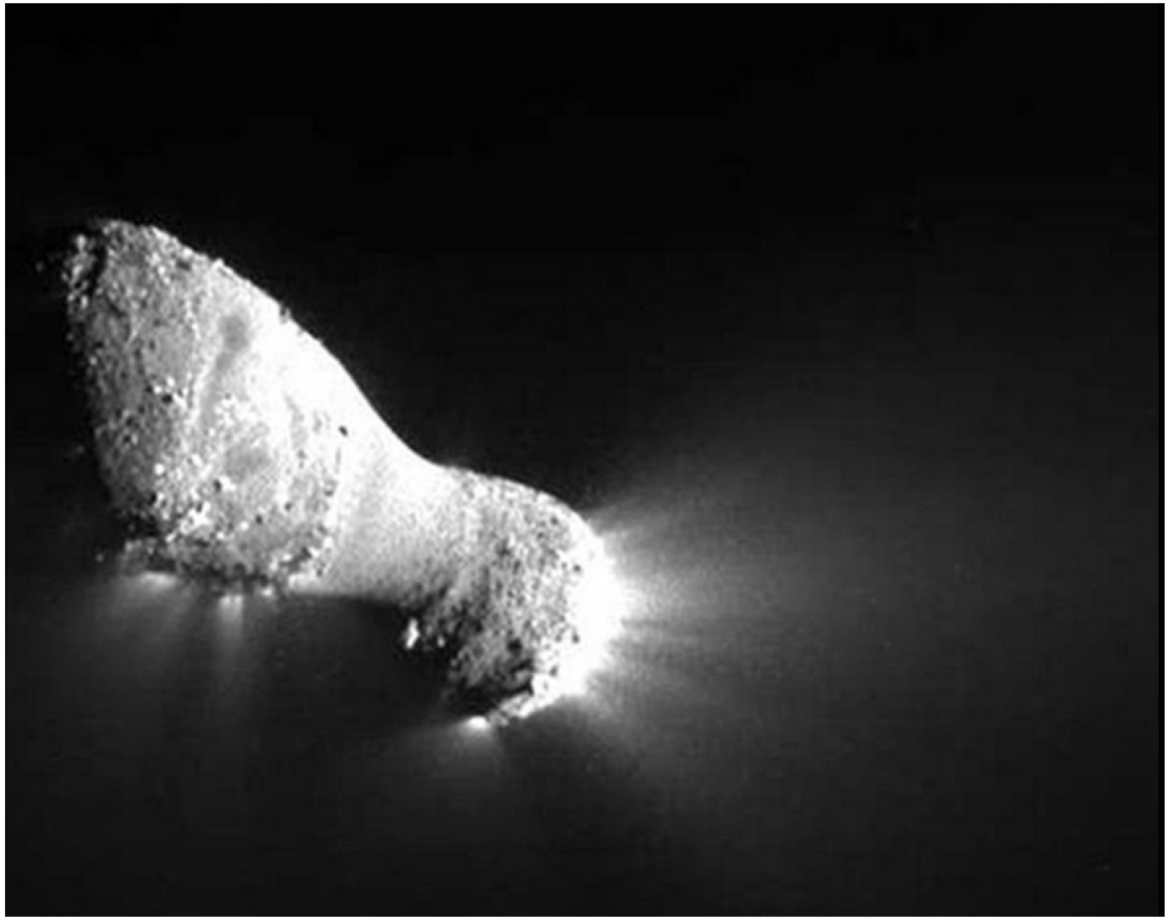
When far from the Sun, they are balls of ice and dust 1-10 km across.

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

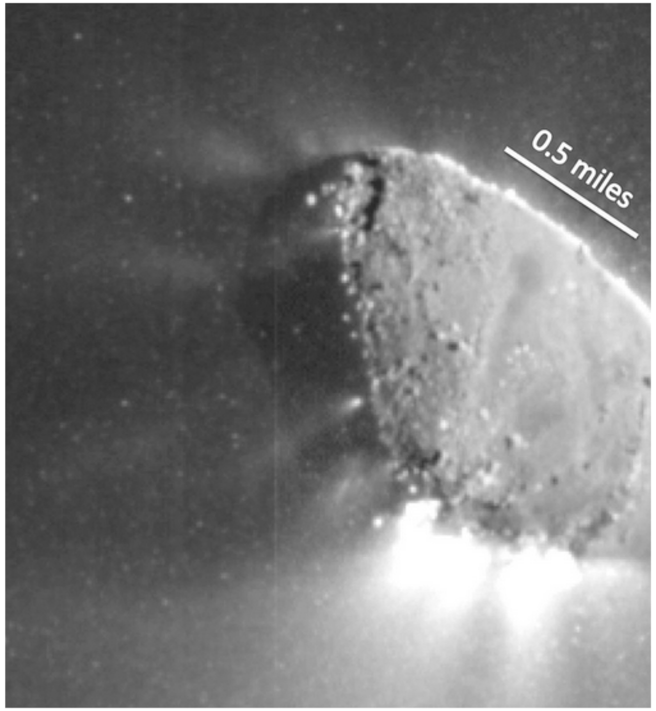
The coma becomes two tails, which point in different directions:

- One is an ion tail. For example: CO^+,N_2^+,CO_2^+.
  - The ion tail interacts with the solar magnetic field.
- The dust tail is smoother.
  - The dust tail is repelled from the Sun by radiation pressure and left behind along the comet's orbit.

Periodic comet 103P/Hartley



Comet is ~2 km long. Note similarity to Halley movie, and gas and snow jets below



Question:

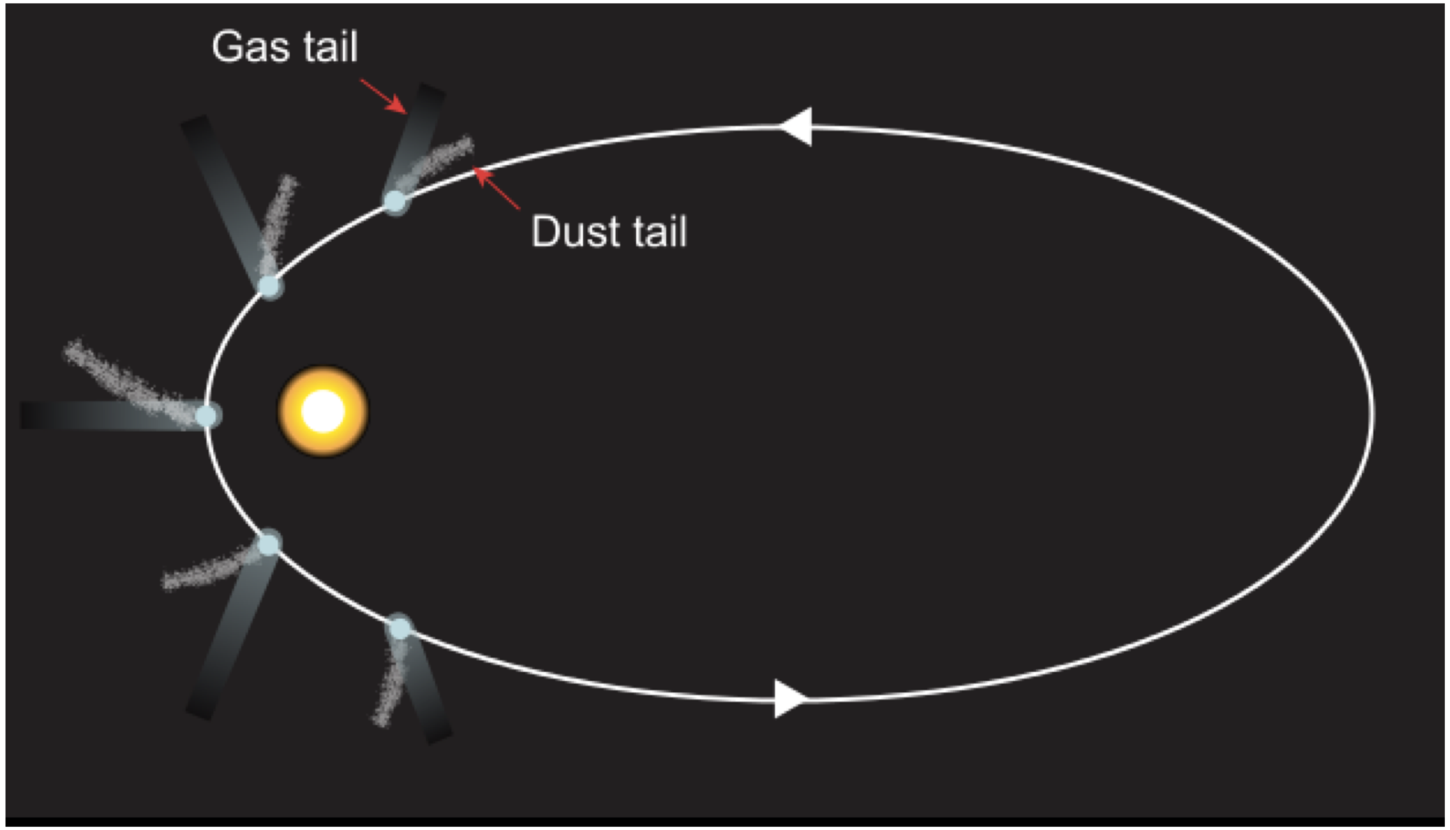
Why do periodic comets often seem fainter on progressive returns to the inner Solar System?

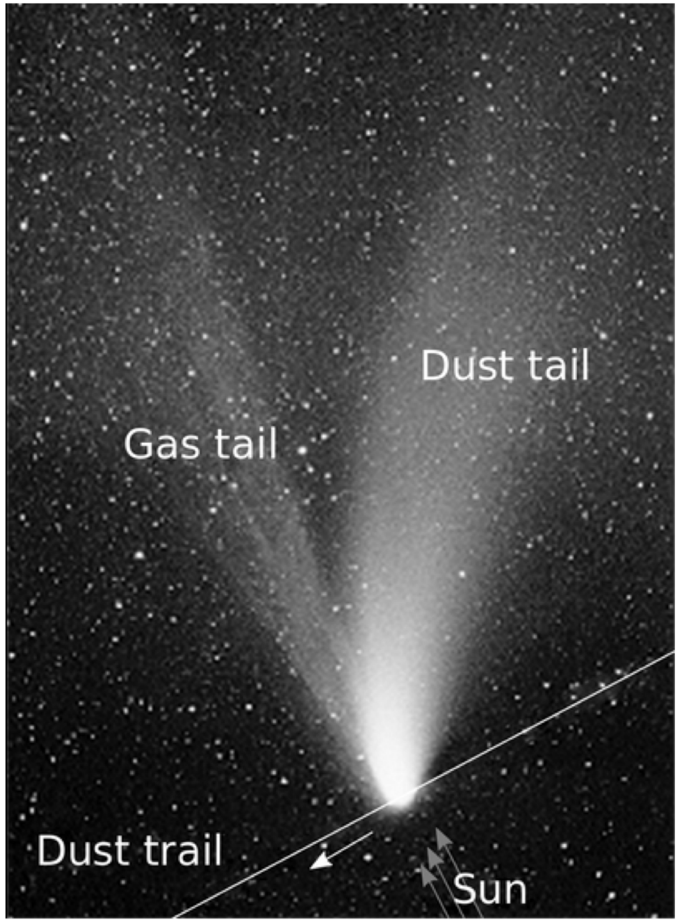
Answer:

On each perihelion passage, the comet loses more volatiles to its coma and 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 and tail. This causes the comet to appear fainter.

Comet tails: dust and gas





Question:

The movie shows observations of Halley's Comet's nucleus by the Giotto spacecraft. Giotto didn't hit the nucleus. Why did the photos stop?

Answer:

Near to a comet nucleus, when it is close to the Sun, is a hazardous environment for spacecraft, due to possible impacts from particles expelled by the comet

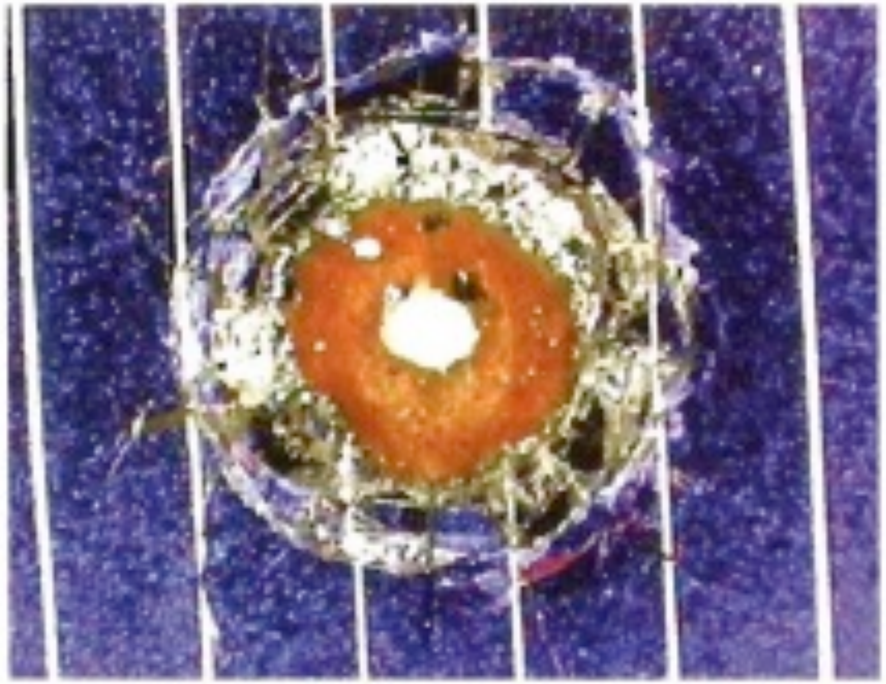


Figure 7.41 An impact crater found on the solar arrays of an Earth-orbiting satellite. The vertical lines are about 1 mm apart. The crater could have been made by a particle just 100 μm across.

Question:

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?

Answer:

(i) Perturbations from planets as the comet nucleus passes nearby.

(ii) Jets of gas from interior through crust can also alter orbit.

Cometary dust:

Spreads out along orbit of comet, observed as

- Gegenschein (reflection of sunlight back toward Earth)
- Zodiacal light (close to Sun)
- Meteor showers (see later)

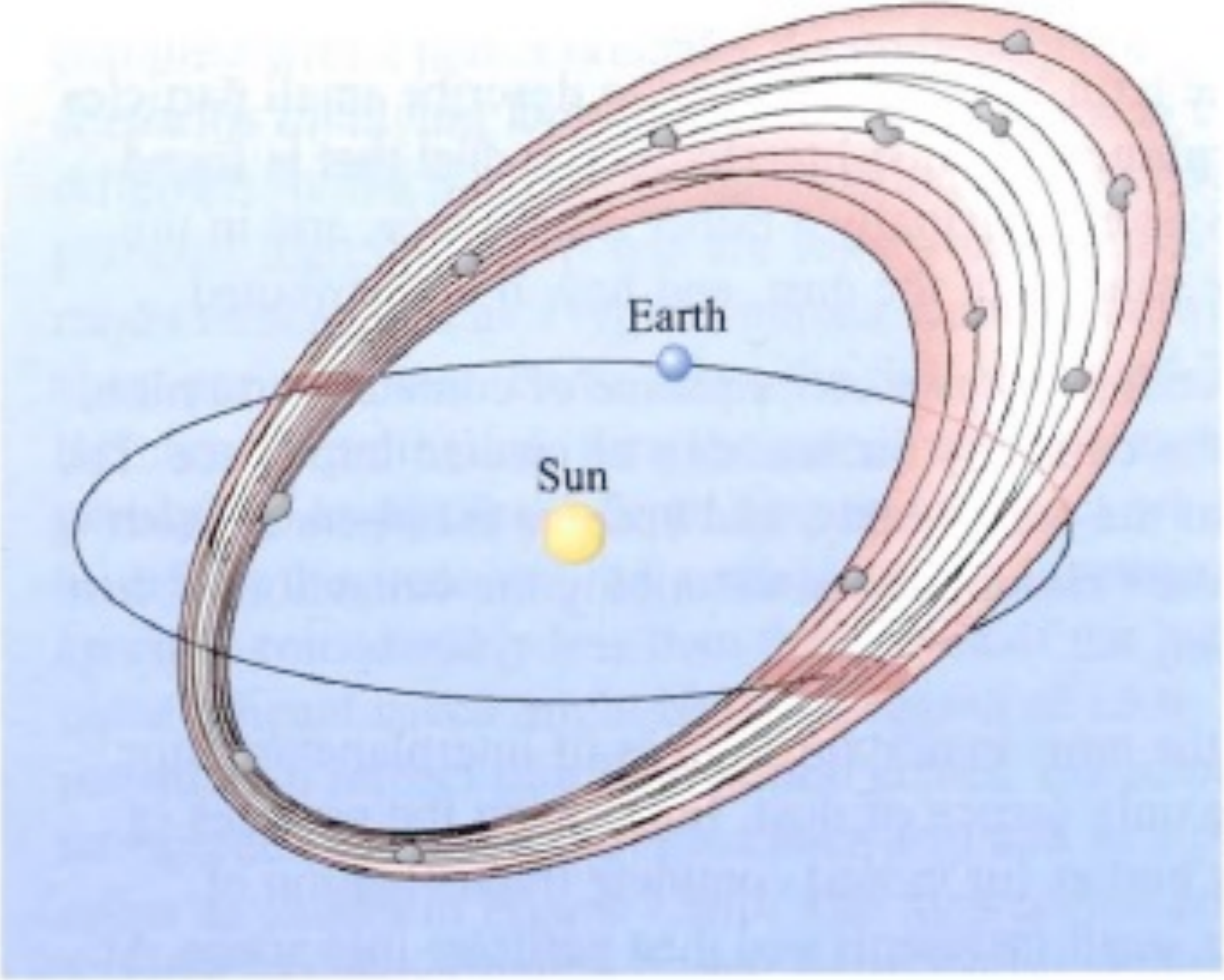


Figure 7.39 A meteoroid stream produced by the ejection of dust particles from a comet. The orbits of the dust particles are reasonably similar to the parent comet, producing a tube of dust in space, which is thickest at the aphelion region.

Zodiacal light

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)

Zodiacal light at Paranal

Paranal is the site of the four 8-m telescopes run by the European Southern Observatory. It is located in the Atacama desert in Chile

Leonid meteor shower

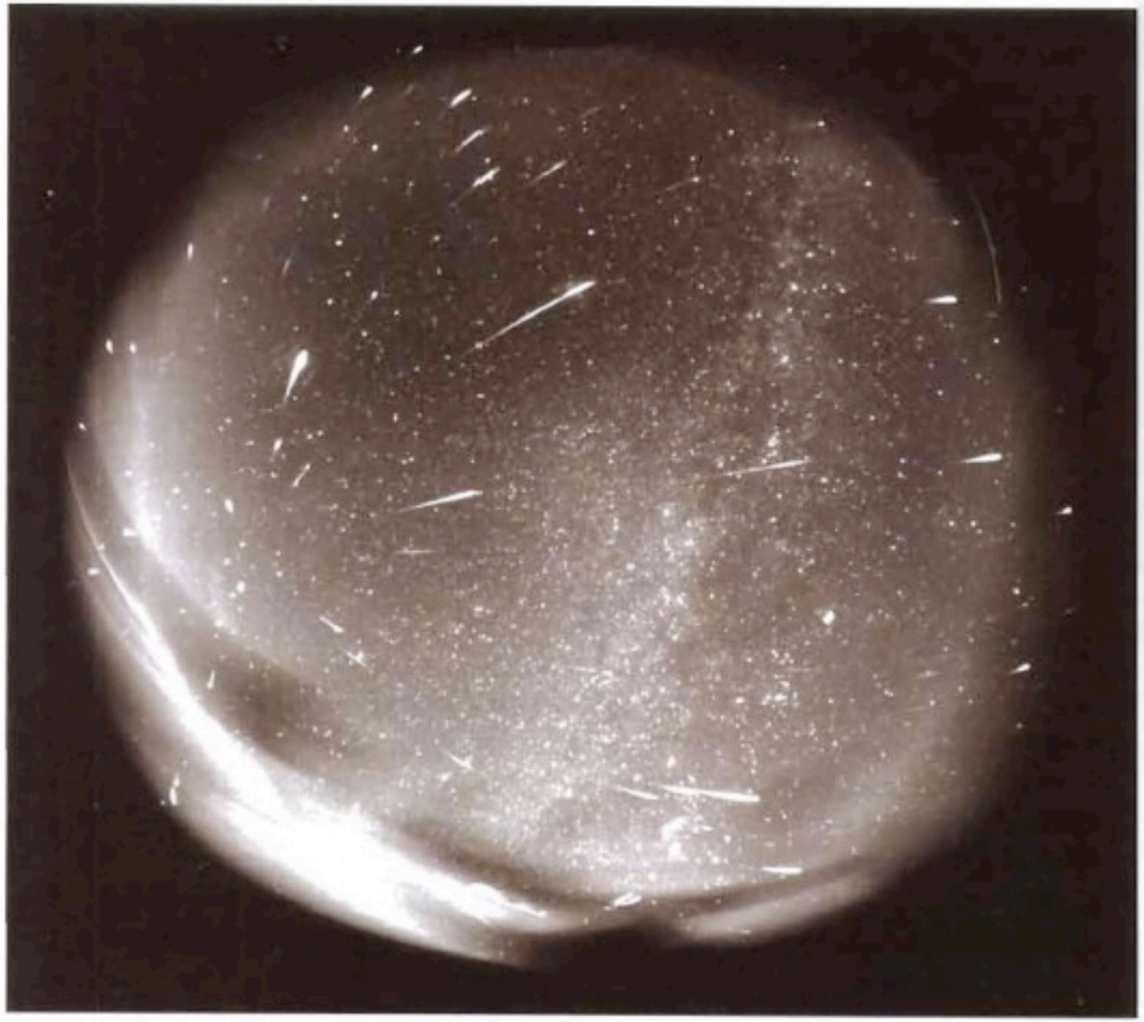


Figure 7.40 An all-sky image taken during the 1998 Leonid meteor shower, when the peak rate of meteors reached several hundred per hour. (Juraj Toth, Modra Observatory)

Radiation pressure

Dust grains feel momentum carried by solar photons.

(Radiation pressure is very important for massive stars and limits their maximum size)

Momentum of a photon: $p = \frac{E}{c}$

Calculate the radiation pressure at a distance r from the Sun:

Consider a shell of radius r. The force on the shell will be

$$F = \frac{dp}{dt}$$

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

Using the equation for the momentum of a photon:

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

Now $\frac{dE}{dt}$ is also the energy given off by the Sun every second, known as the solar luminosity $L_{\odot}$, so

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

So radiation pressure at radius r is $\dfrac{L_\odot}{4\pi r^2 c}$

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

Example:

For grains of density 1 g/cm^3, find the grain size for which gravity and radiation pressure are equal.

Let d be the radius of the grain.

Then the mass of the grain, m, is:

$$m = 1 \cdot \frac{4}{3}\pi d^3$$

1. Gravitational force $= \frac{GM_\odot m}{r^2}$

$$= GM_\odot \frac{4}{3}\pi d^3 \frac{1}{r^2}$$

2. Area of grain (cross-sectional) = πd^2

Question: why do we use cross-sectional area here, not surface area?

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

Since we are solving for the grain size for which gravity and radiation pressure are equal:

$$gM_\odot \frac{4}{3}\pi d^3 \frac{1}{r^2} = \frac{\mathrm{L}_\odot}{4\pi r^2 c} \cdot \pi d^2$$

Simplifying, we find that this is independent of distance from the Sun

Grain size $$\boxed{d = \frac{\mathrm{L}_\odot}{4\pi c} \cdot \frac{3}{4} \cdot \frac{1}{g\mathrm{M}_\odot}}$$

Calculation of actual grain size:

$$d = \frac{3.8\times10^{33}}{4\cdot\pi\cdot3\times10^{10}}\cdot\frac{3}{4}\cdot\frac{1}{6.7\times10^{-8}\cdot2\times10^{33}}$$

$$d = 5.7\times10^{-5}\,cm = 0.57\ microns$$

$$F_{radiation} \propto d^2$$
$$F_{gravitational} \propto d^3$$

$$\frac{F_{rad.}}{F_{grav.}} \propto \frac{1}{d}$$

For d < 0.5 microns, radiation pressure dominates.

Origin (& home) of comets:

Historically, comets have been divided into short-period (< about 200 years) and long-period comets (> 200 years approximately)

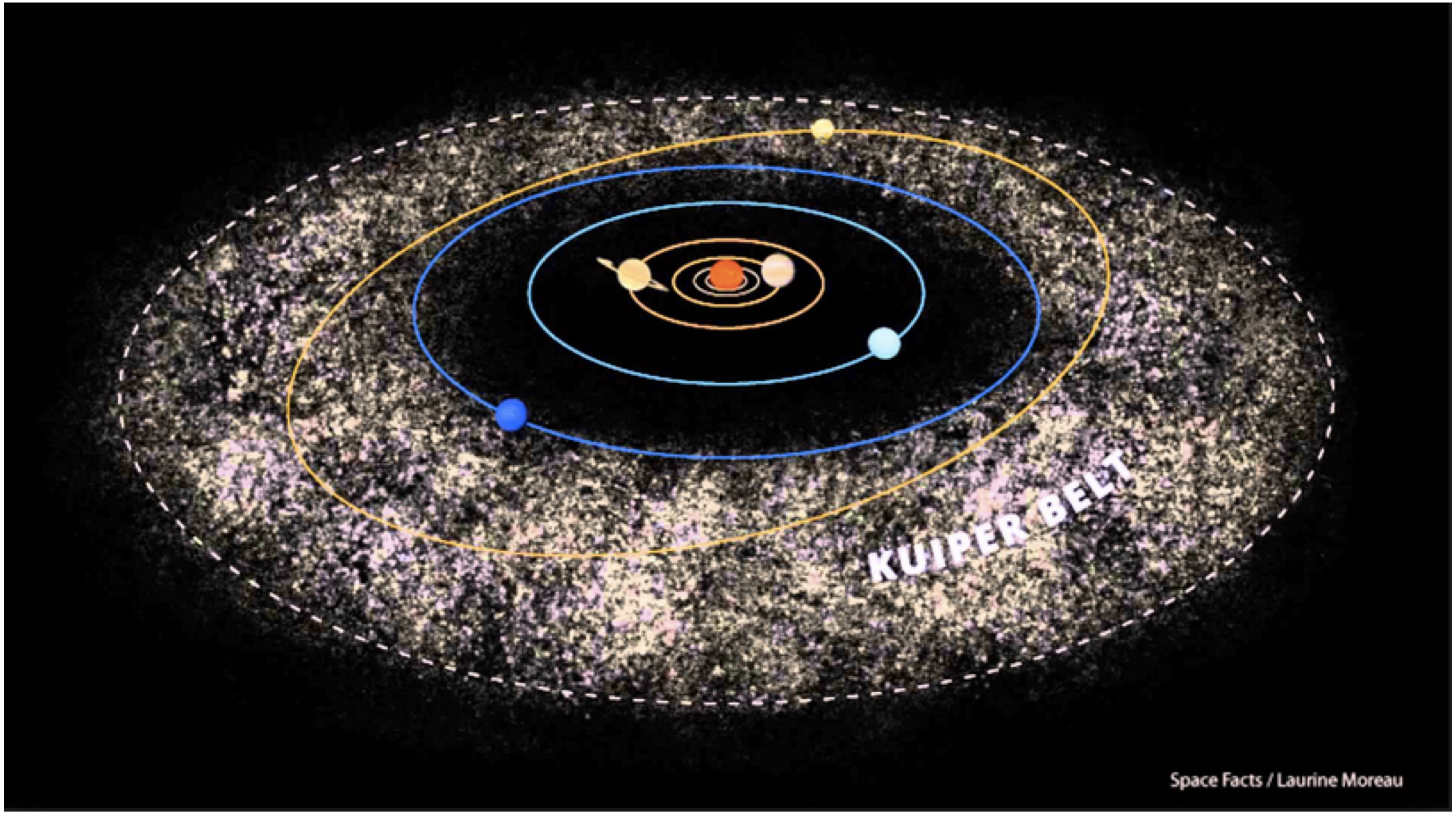
Most short-period comets:

- have P=5-20 years
- Have low inclination orbits
- Orbit in prograde direction

Long-period comets:

- Orbits are highly eccentric ellipses
- appear nearly parabolic close to planets, but are bound to the solar system
- inclinations of all sizes
- (Note that Pluto is at ~40 AU; the nearest star is 2.7×10^5 AU away

Kuiper belt



Kuiper Belt:

Home of short-period comets

Kuiper ('51) suggested that a flattened ring of cometary nuclei outside of Neptune's orbit were leftovers from the original solar system; where it petered out.

1992: The first Kuiper belt objects that were detected were the largest

- 100-200 km
- magnitude 24-25 (night sky~ 20 mag/sq arcsec)

There are now many objects known with orbits that place them in the Kuiper belt

Magnitudes:

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 respectively:

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

Sirius has magnitude ~ 0

A factor of 100 in brightness is 5 magnitudes

At a dark site with the naked eye you can see to ~ 6th mag.

Kuiper Belt:

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

Mass of the Kuiper belt is very small:

- the current estimate is less than the mass of Earth

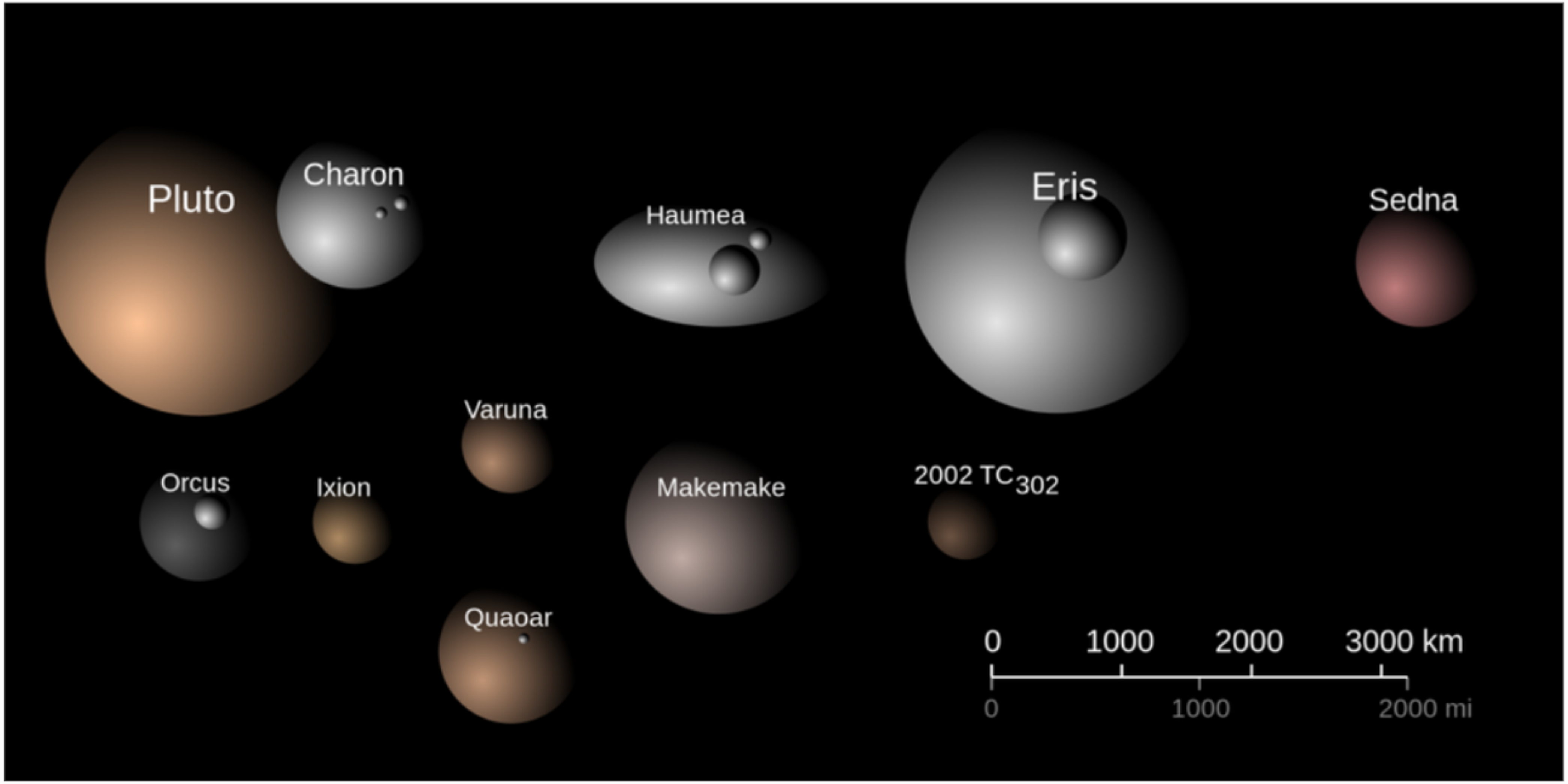
Pluto is a dwarf planet in the Kuiper belt

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

Comets lose material on each successive perihelion passage

…….we need a source of new comets as well

Illustration of relative sizes, colours and albedos of the large trans-Neptunian objects.



Another large Kuiper belt object: UB 313

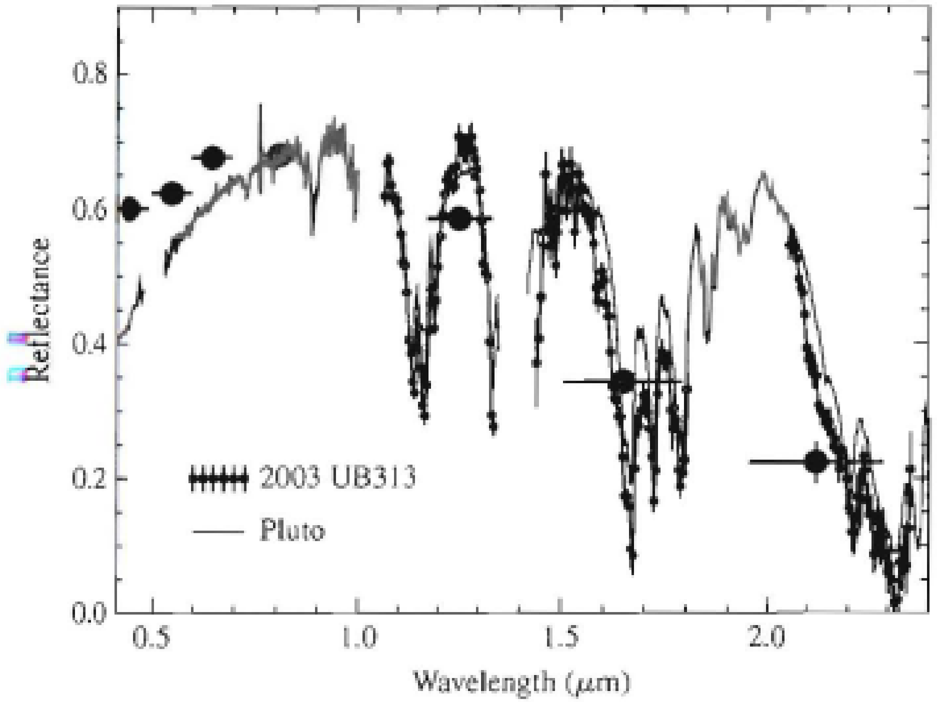
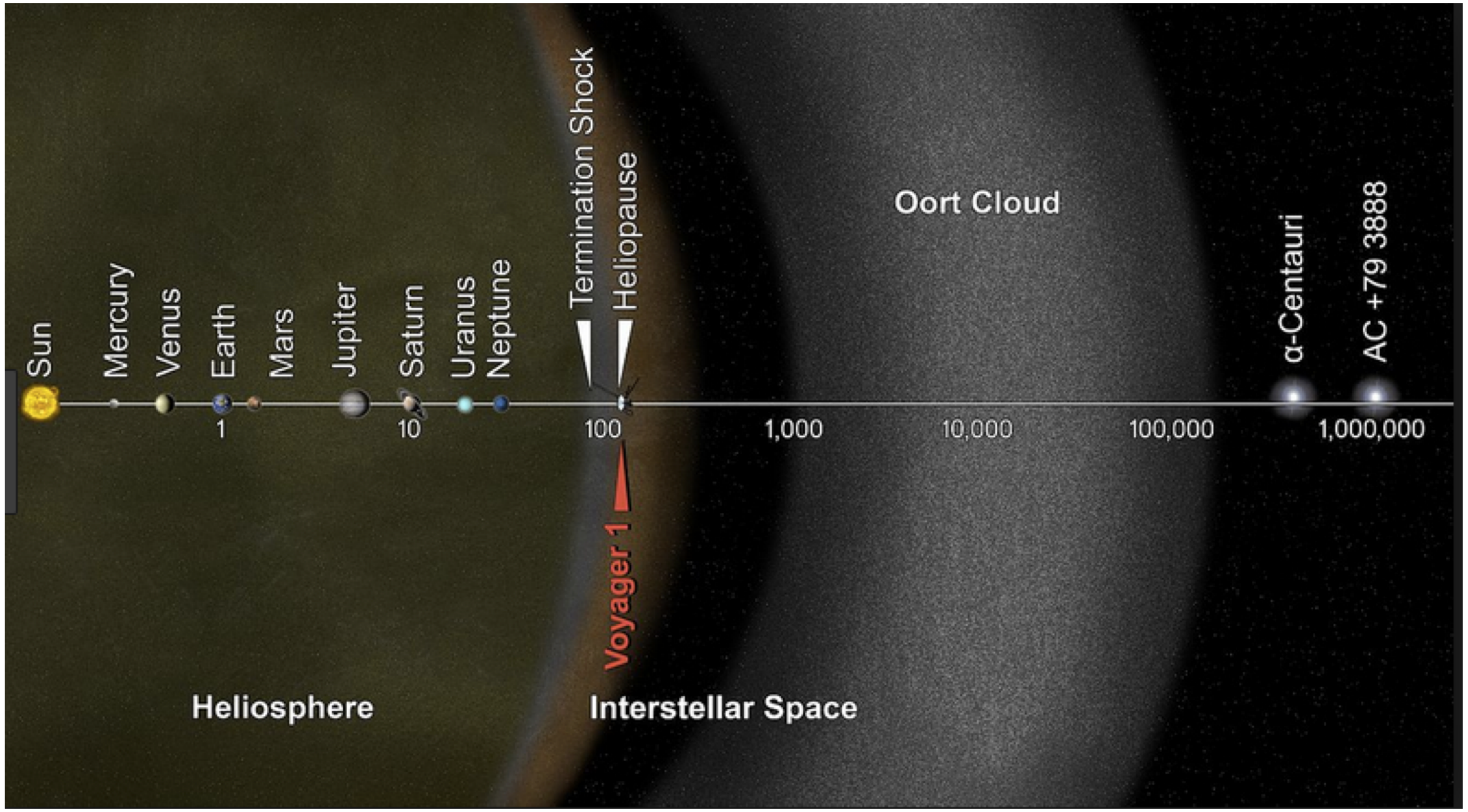


FIGURE 22.10 The reflection spectrum of 2003 UB313 (individual points) compared to the spe trum of Pluto (gray line). Absorption features of methane dominate the spectrum. The large poi are data from BVRIJHK photometry. [Courtesy of Mike Brown (Caltech), Chad Trujillo (Gemi Observatory), and David Rabinowitz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

Oort Cloud:

Home of long-period ("new") comets; Spherical shell at~10^4-10^5 AU

Comet nuclei spend billions of years there on average



Evidence for Oort Cloud's existence comes from comet orbits ONLY,

no comet nuclei directly observed out there

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

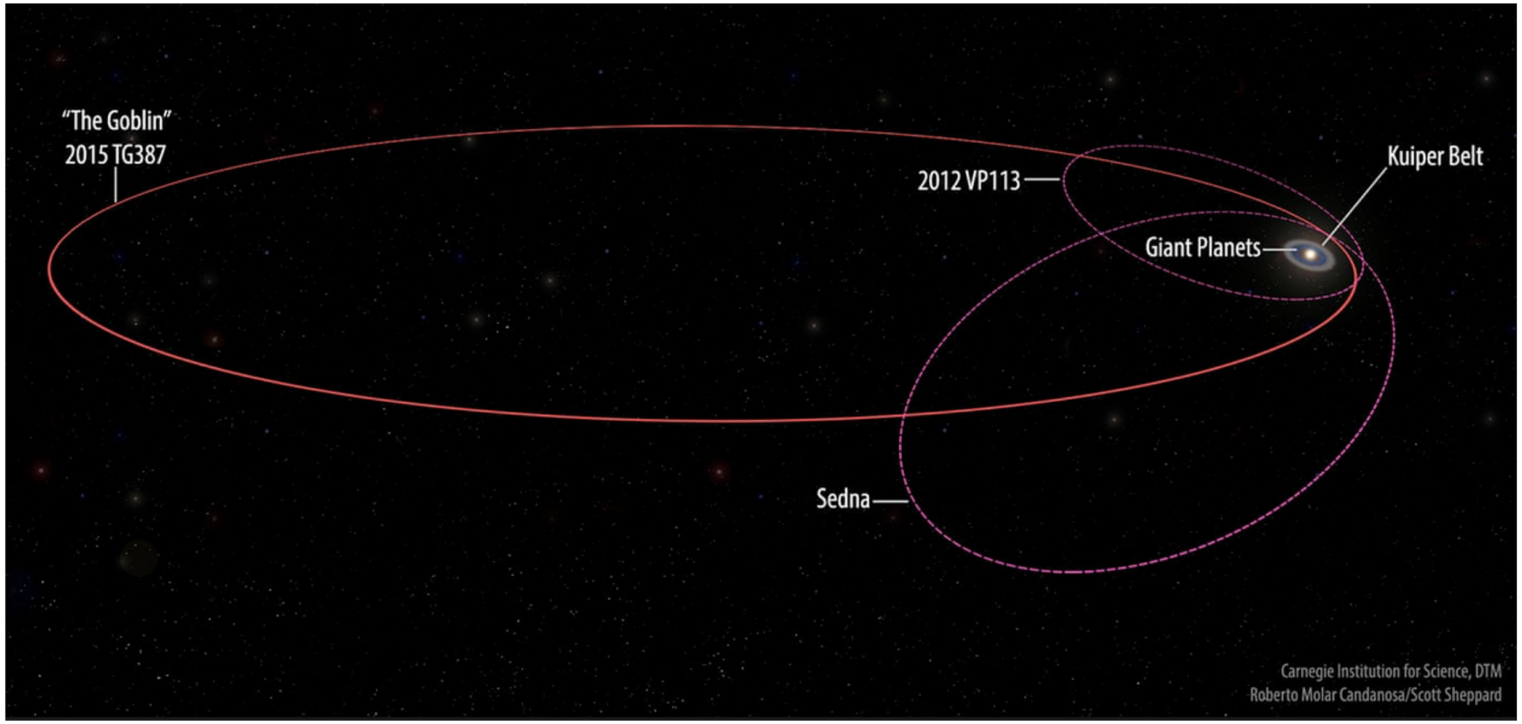
Why cant we observe things in Oort cloud?

Pluto orbits at~ 40AU and is so faint it was not discovered until 1930 (14th magnitude). 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?

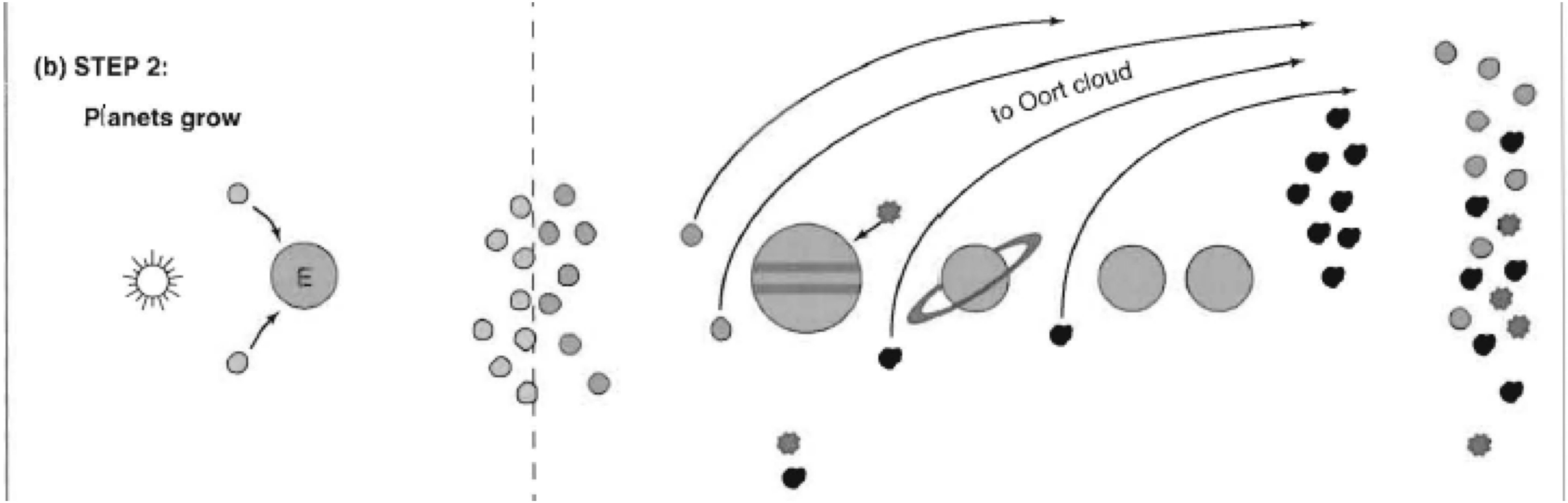
Orbital perturbations can send a comet into the inner Solar System. Perturbations can come

- From a passing star
- From the Galaxy's tidal field
- From giant molecular clouds

The Goblin: Oort cloud object after it was kicked into the Solar System proper



Creation of Oort cloud via giant planet interactions



- 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 further from the Sun!
- Oort cloud comets were probably originally formed near Jupiter and the asteroid belt and were then perturbed out by giant planets

Simulations of the formation of the Oort cloud

Dones et al 2004