

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?



(a)



(b)

Figure 7.31 Halley's Comet.
(a) The image shows what was observed from Earth in 1986, whereas, (b) shows the nucleus ($15 \text{ km} \times 7 \text{ km}$), imaged by the European Space Agency's Giotto spacecraft in 1986. ((a) NASA; (b) European Space Agency)

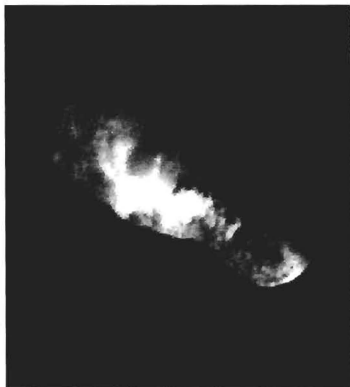
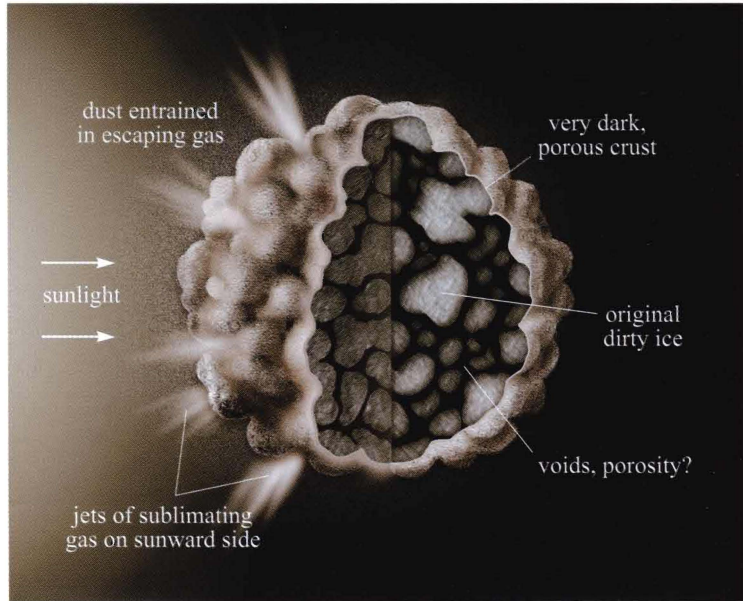


Figure 7.32 Comet Borelly ($8\text{ km} \times 3\text{ km}$). The image was obtained in 2001, by NASA's Deep Space 1 spacecraft. It shows a nucleus similar to that seen for Halley's Comet. (NASA)

Figure 7.33 The expected structure of a cometary nucleus. The 'dirty snowball' of the nucleus is almost certainly very porous and low density, with a structure probably more akin to a rubble pile rather than a homogeneous body. (Copyright Don Davis)





(a)

Figure 7.37 The impact of comet Shoemaker–Levy 9 with Jupiter. (a) The comet, imaged by the Hubble Space Telescope, is seen to have split into fragments which spread out along the comet’s orbit. (b) The ‘scars’ in Jupiter’s atmosphere left after the impact of several of the comet fragments. (NASA)



(b)

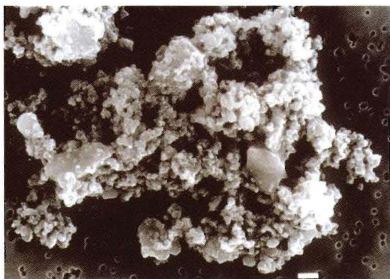


Figure 7.38 An interplanetary dust particle, thought to be from a comet. This sample was collected in the stratosphere by a high-altitude aircraft, and is shown in this electron microscope image. The dust particle is very porous. When in the comet, the voids probably would have had ices in them, but these will have sublimated when heated by the Sun. (NASA)

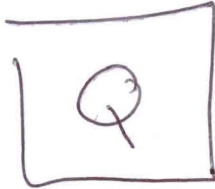
ORIGIN (& HOME) OF COMETS

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

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
- ~~apertures~~ semi-major axes $10^4 - 5 \times 10^4$ AU
(Pluto is ~ 40 AU)
(nearest star at 2.7×10^5 AU)



Why do you think
astronomers used 200 years
as the dividing period
between short & long-period comets?

Kuiper belt

Home of short-period comets

Kuiper (1951) 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 29 known with orbits that
place them in Kuiper Belt

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

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 :

$$m_1 - m_2 = -2.5 \log(B_1/B_2)$$

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

These have magnitude 28-29 — very difficult to detect, even with HST.

Telling comet nuclei apart from cosmic rays very difficult

Predicted orbits of Kuiper belt objects, both prograde (expected) & retrograde (not)

Looked for objects that moved in these orbits about 1 arcsec/hr

34 ^{10-min} ~~10-min~~ observations, covered 30 hours

Significantly more prograde (53 candidates) than retrograde (24 candidates)

All excess have orbits with low inclination ($< 12^\circ$)

The Kuiper belt really exists!

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

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 $\sim 10 - 100$
Earth masses

Problem

Pluto orbits at ~ 40 AU and is so faint it was not discovered until 1930. (14^{th} 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 ^{asteroid belt} Jupiter, perturbed out
by giant planets



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

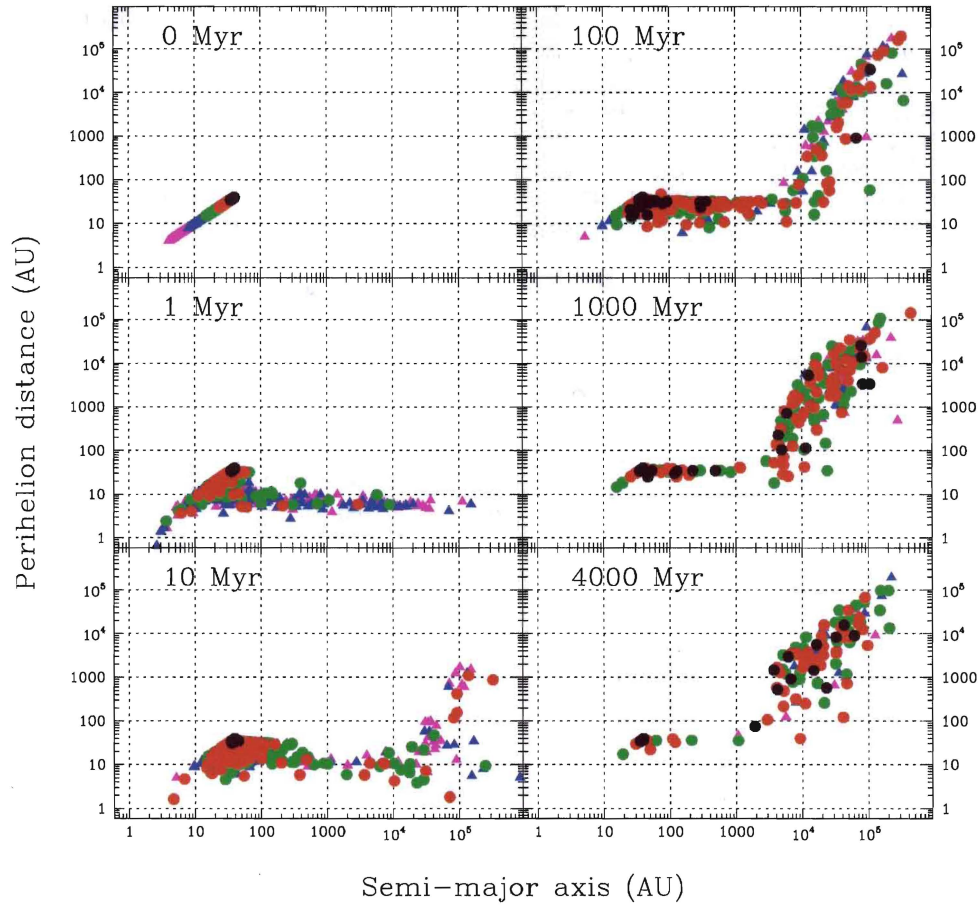


Figure 1. Scatter plot of osculating barycentric pericenter distance (q) vs. osculating barycentric semi-major axis (a) at various times in the DLDW “cold” simulation of the formation of the Oort cloud. This simulation included 2,000 test particles with initially small eccentricities and inclinations. 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.

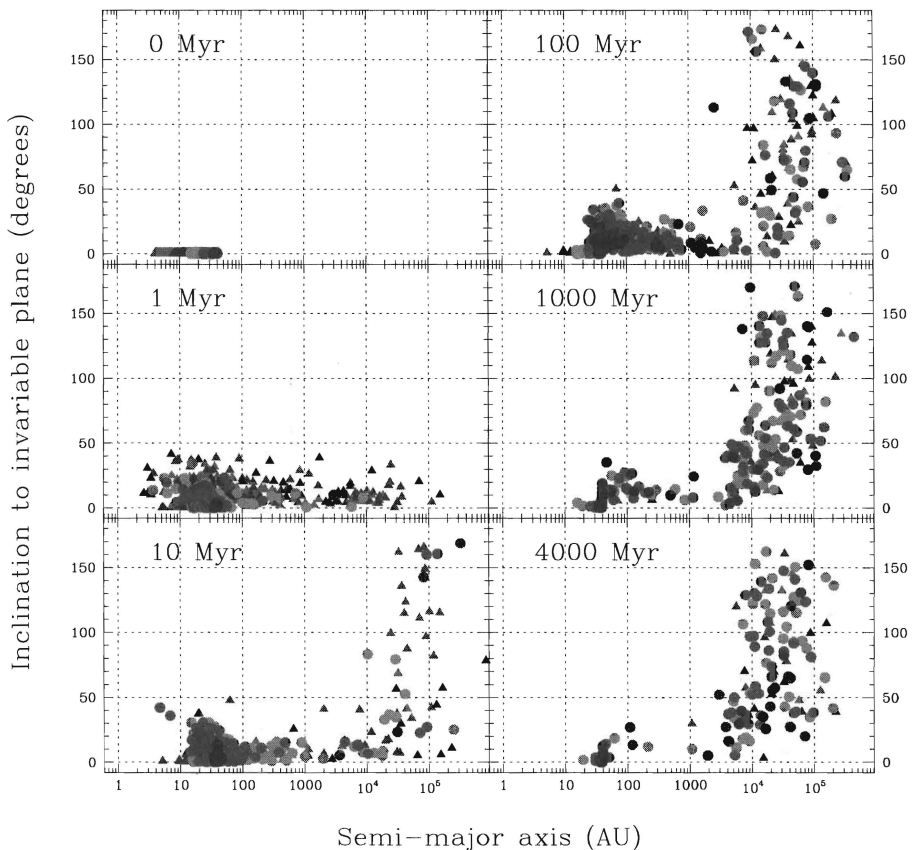


Figure 2. Scatter plot of osculating inclination to the invariable plane vs. semi-major axis at various times in the DLDW “cold” simulation of the formation of the Oort cloud. Panel (a): Initial conditions for the simulation [0 Myr]. Panel (b): 1 Myr. Panel (c): 10 Myr. Panel (d): 100 Myr. Panel (e): 1 Gyr. Panel (f): Final results for the simulation, at 4 Gyr. The region in which each comet originated is labeled as in Figure 1. By the end of the calculation, the inclination distribution is nearly isotropic, even in most of the inner Oort cloud.