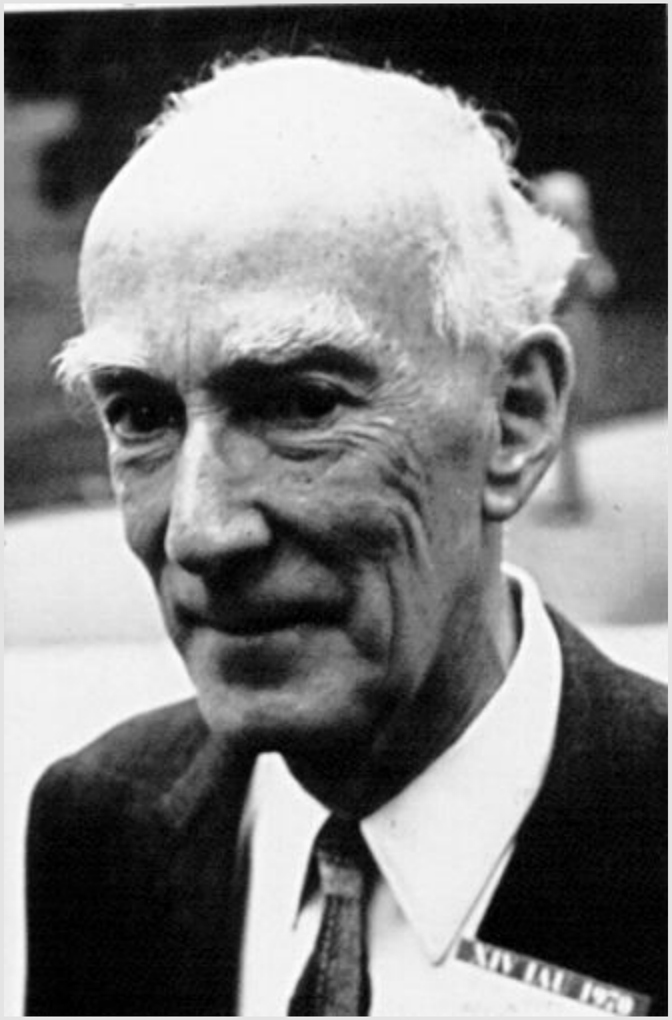
Planet formation mini-course. 3

Leiden University
June 2007



Jan Oort (1900-1992)

Director, Leiden
Observatory 1945-1970

Gerard Kuiper (1905-1973)

Ph.D., Leiden, 1933

Comets:

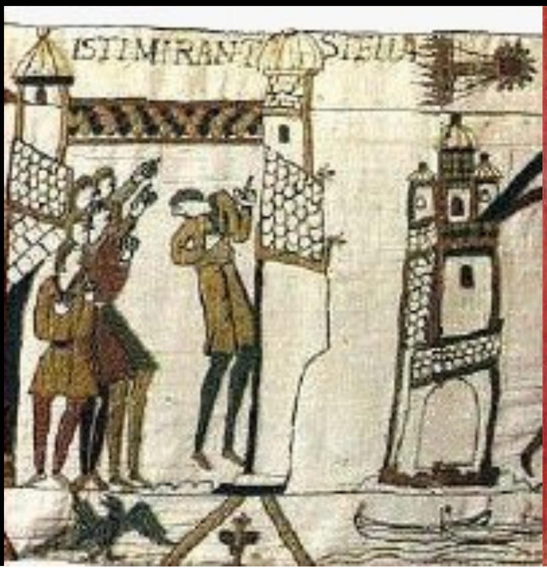
- chunks of ice and rock a few km across
- when within a few AU of the Sun, material begins to sublimate and produces a tail, so brightness increases dramatically
- two tails: gas and dust

Comets:

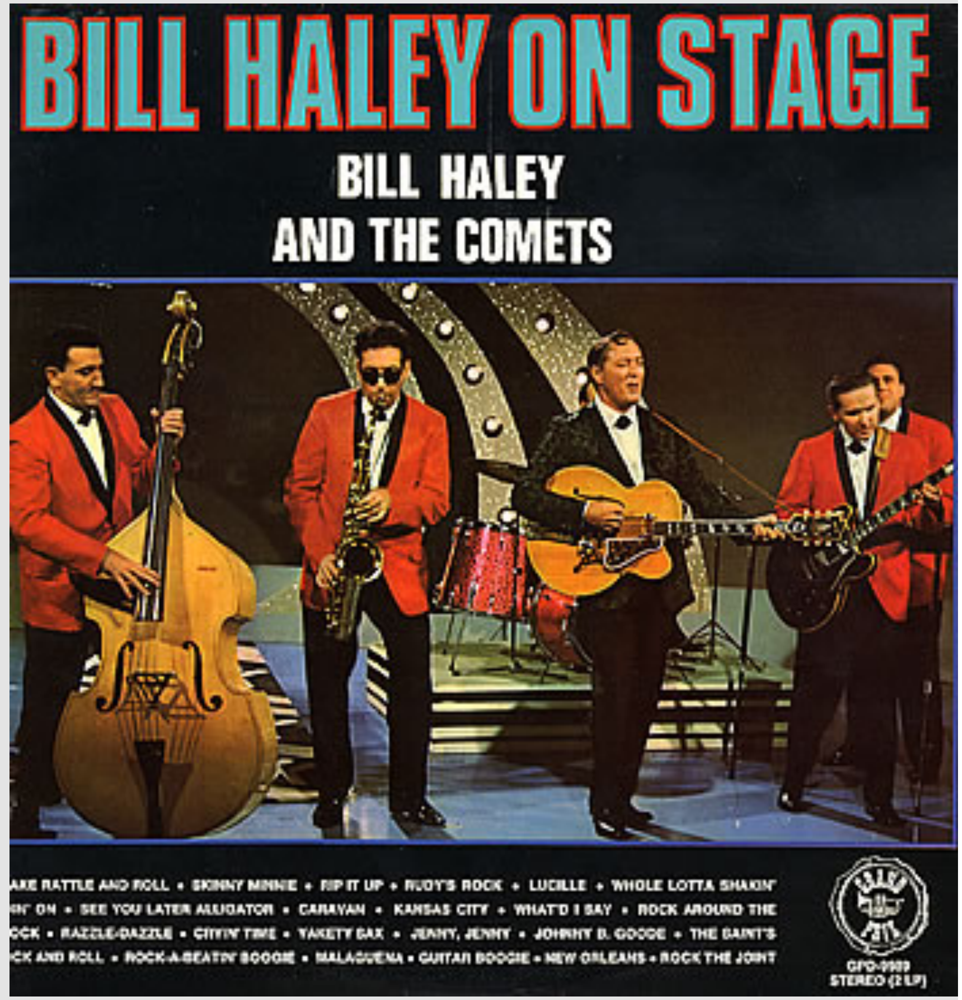
- image of Comet Tempel 1 from the Deep Impact flyby spacecraft
- size 7 X 5 km

Halley's comet:

- recorded since 250 BC
- P = 76 yr
- imaged by ESA's Giotto spacecraft in 1986, closest approach 600 km
- nucleus of 15 X 8 km, density 0.3 g/cm^3, mass 2 X 10^{17} g
- 50% ice, 50% rock and organic material



Edmund Halley



Bill Haley and the Comets

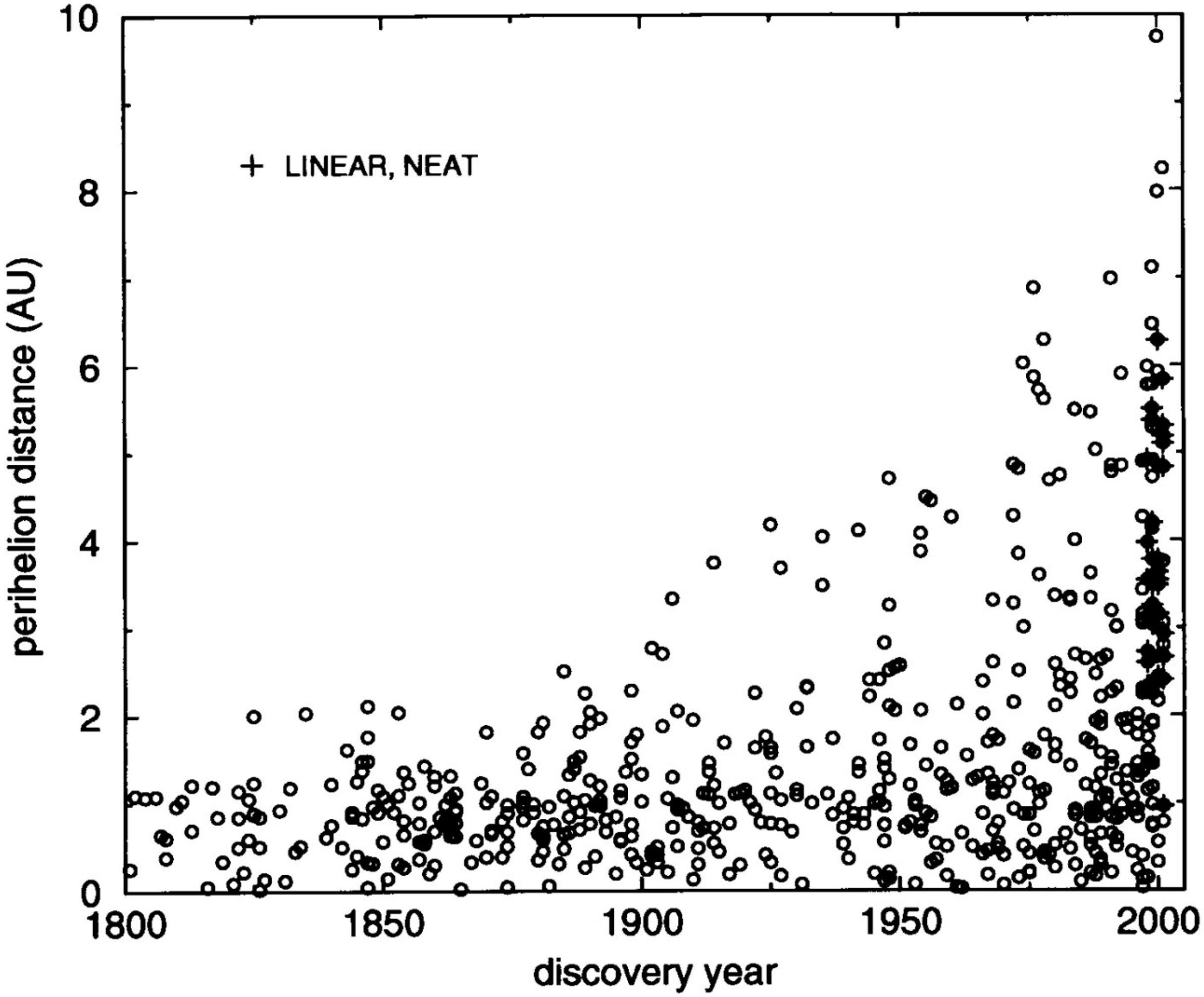


Figure 1. Perihelion distances of the observed long-period comets with orbital periods $P > 10^3$ yr versus discovery year. The sign plus is for LINEAR and NEAT discoveries.

brightness of comets is a very strong function of their distance from the Sun (Schmidt 1951)

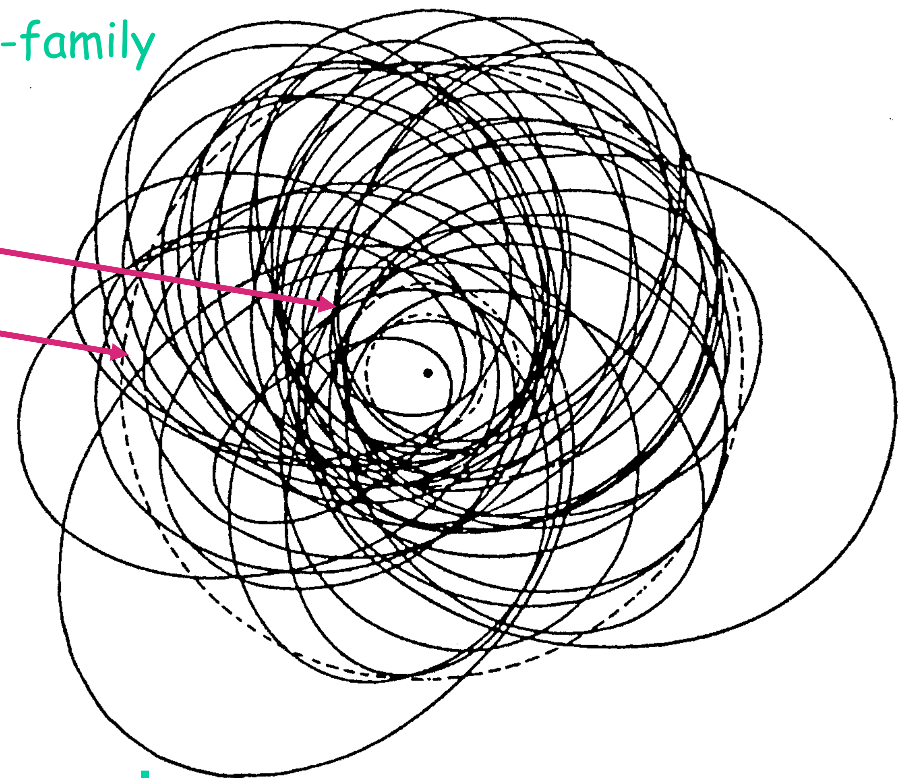
thus comets are typically only discovered when they come within a few AU of the Sun

Comets

orbits of the Jupiter-family comets

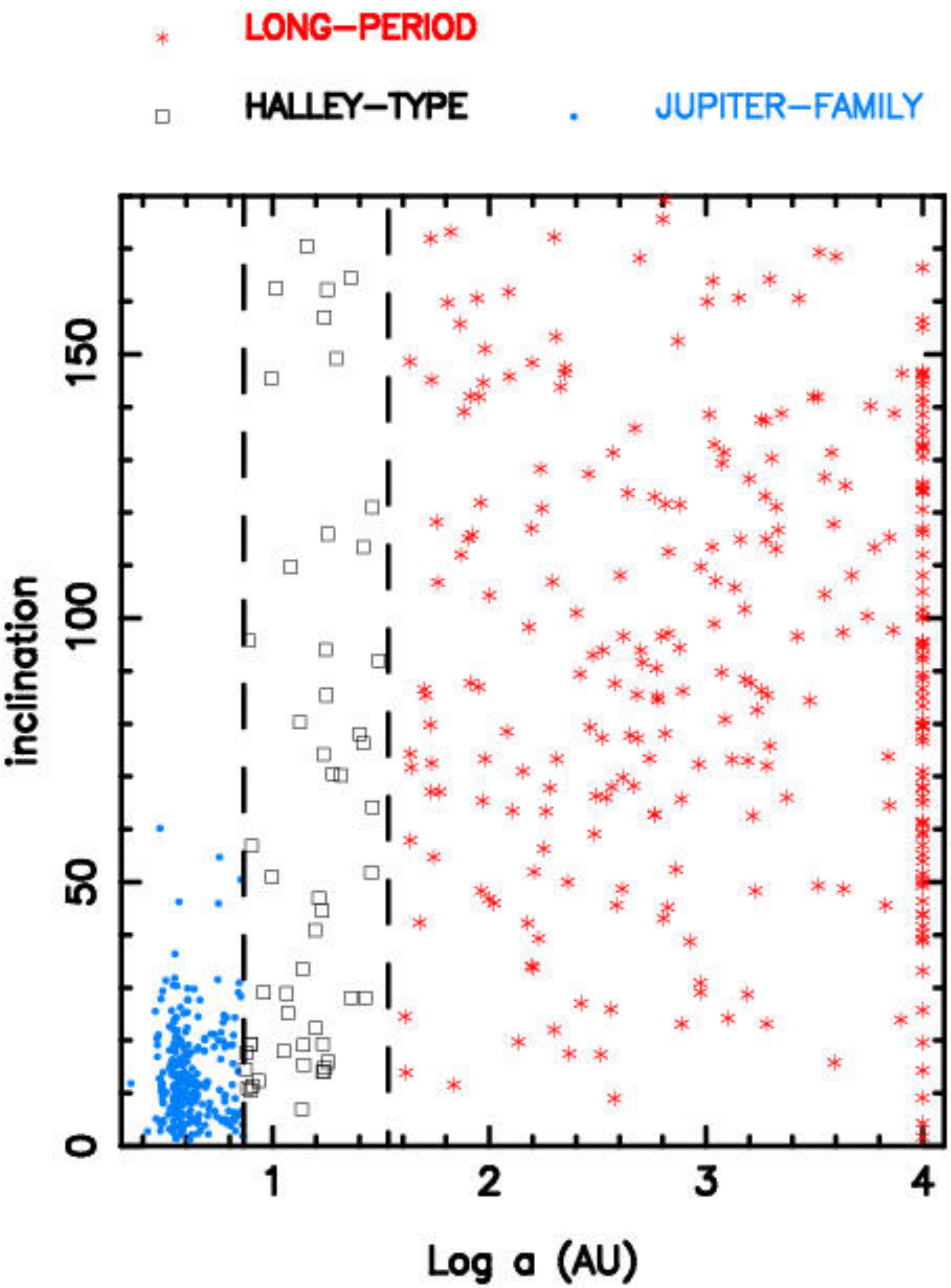
Mars

Jupiter



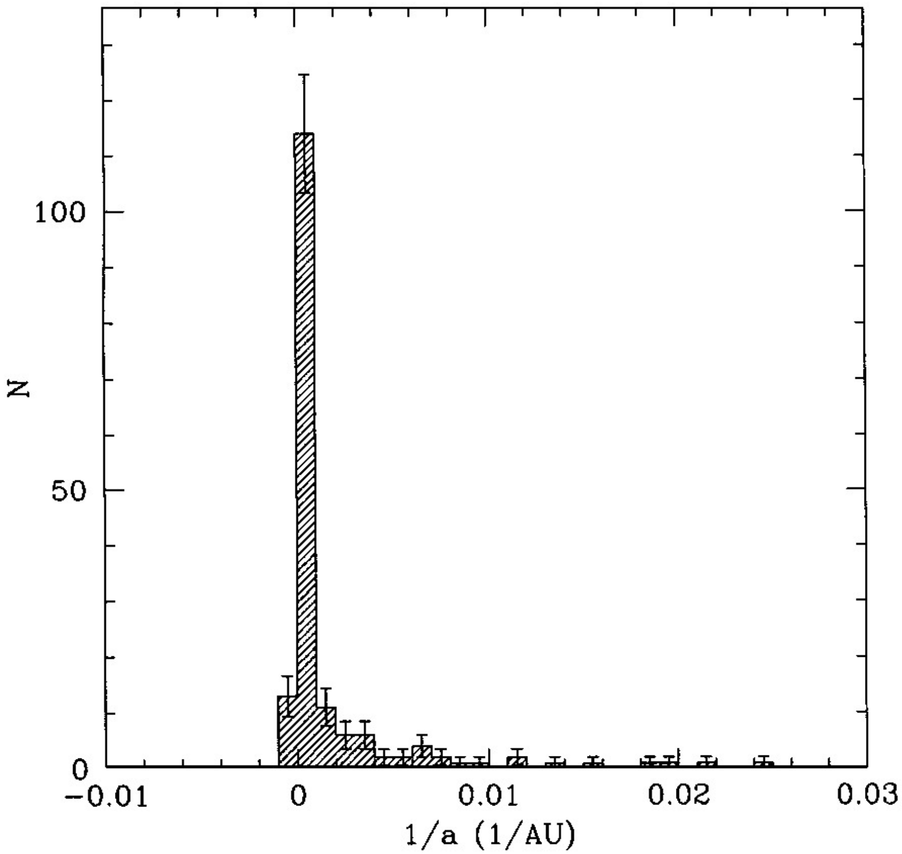
- wide range of orbital periods P:
- **P < 20 yr: Jupiter-family comets**
  - e.g. Tempel 1
  - low inclinations (remain close to plane of the planets)
- **20 yr < P < 200 yr: Halley-family comets**
  - e.g. Halley
  - typically more than one appearance
  - approximately isotropic
- **P > 200 yr: long-period comets**
  - approximately isotropic
  - many have ***very*** large semi-major axes, i.e., nearly parabolic

orbits are more and more eccentric since $q < 2$ AU



P^2 (years) = a^3 (AU)

- many long-period comets have very large semi-major axes so orbits nearly parabolic
- in this plot, orbits indistinguishable from parabolic are plotted at a=10^4 AU



- many long-period comets have very large semi-major axes so orbits nearly parabolic

- orbital energy $E=-GM_{\odot}/2a$ so use 1/a as "energy", and plot 1/a rather than a

- comets coming from outside the planetary system have already been perturbed by Jupiter, Saturn, etc. Yields random change $\Delta(1/a) \sim 10^{-3}\ AU^{-1}$

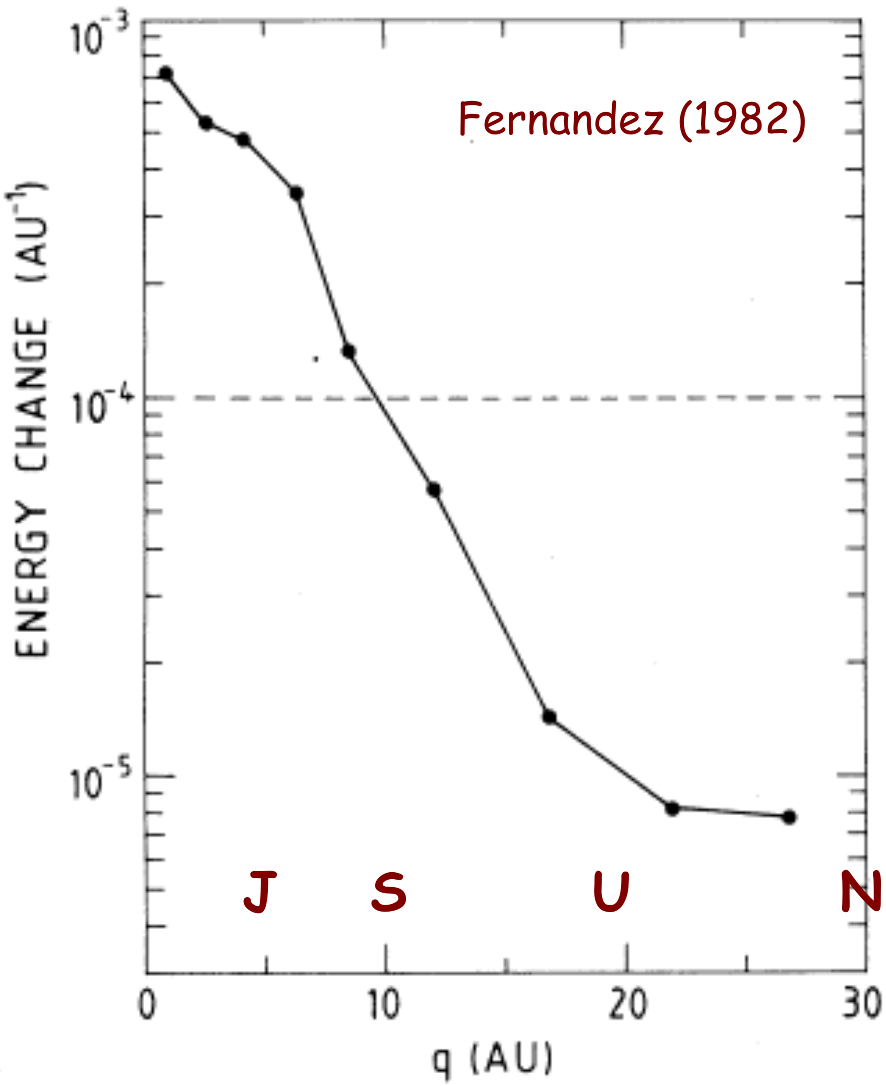
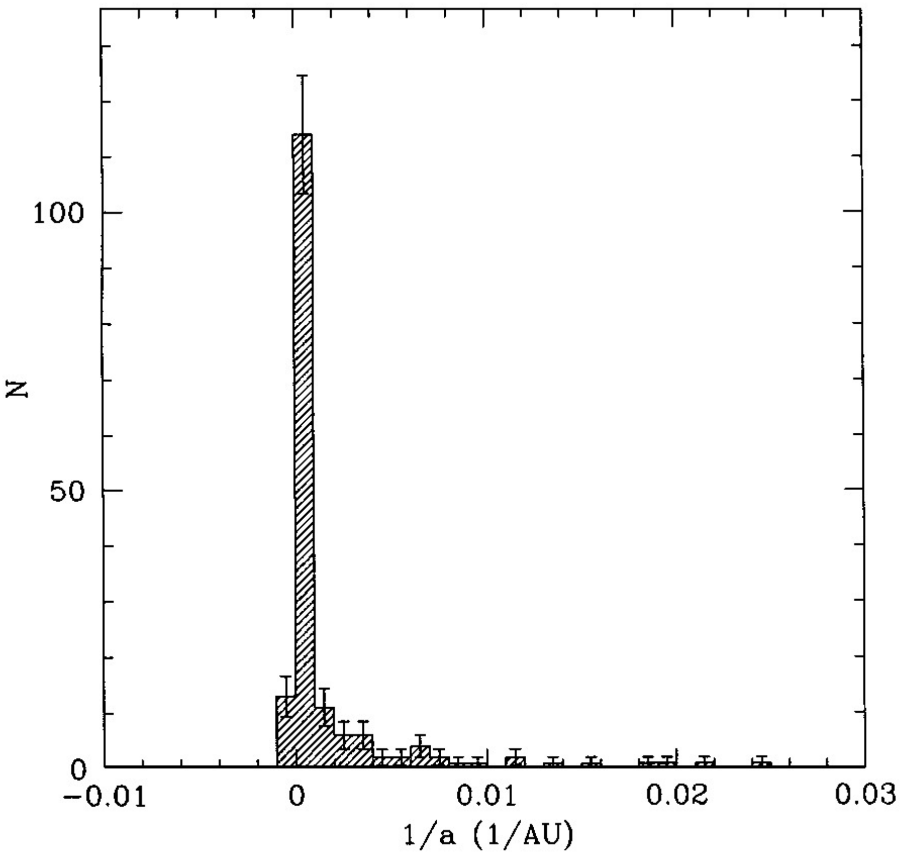


FIG. 7. Typical energy change per passage for a comet in near-parabolic orbit with a random orientation of its orbital plane as a function of its perihelion distance. The energy change is expressed as a change in the reciprocal semimajor axis.

- comets coming from outside the planetary system have already been perturbed by Jupiter, Saturn, etc. Yields random change $\Delta(1/a) \sim 10^{-3}$ AU^{-1}
- therefore useful to calculate "original" orbits, i.e. orbits that the comets had before they entered the solar system

$$\langle (\Delta x)^2 \rangle^{1/2} \approx \frac{10}{a_p} \frac{M_p}{M_\odot}$$



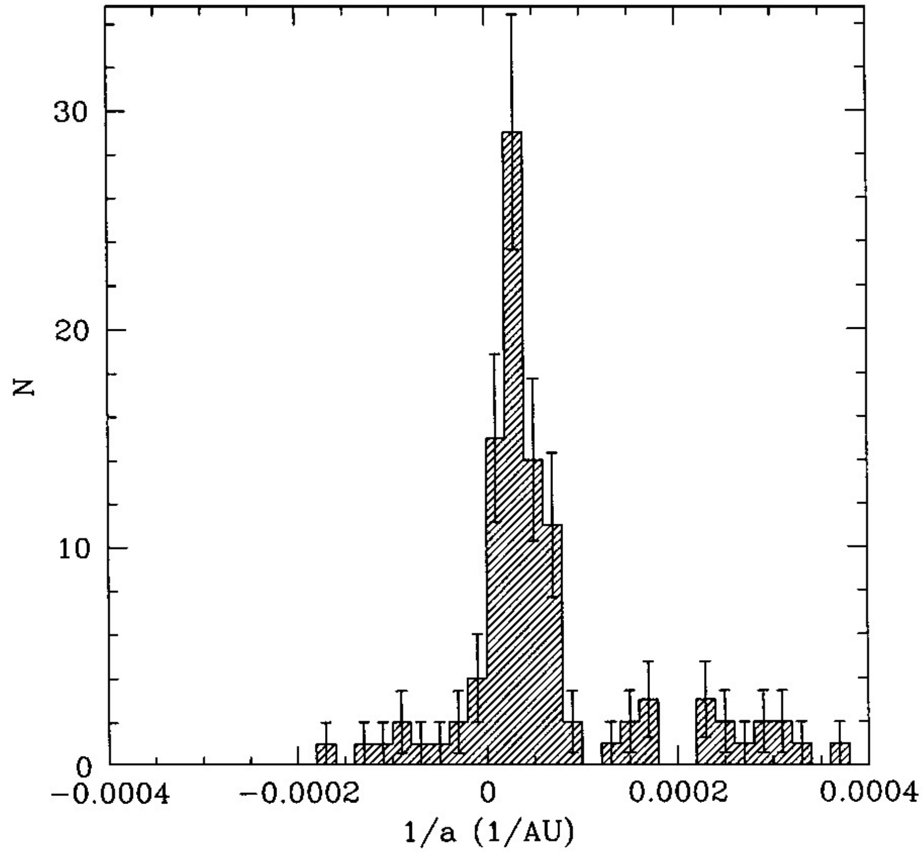
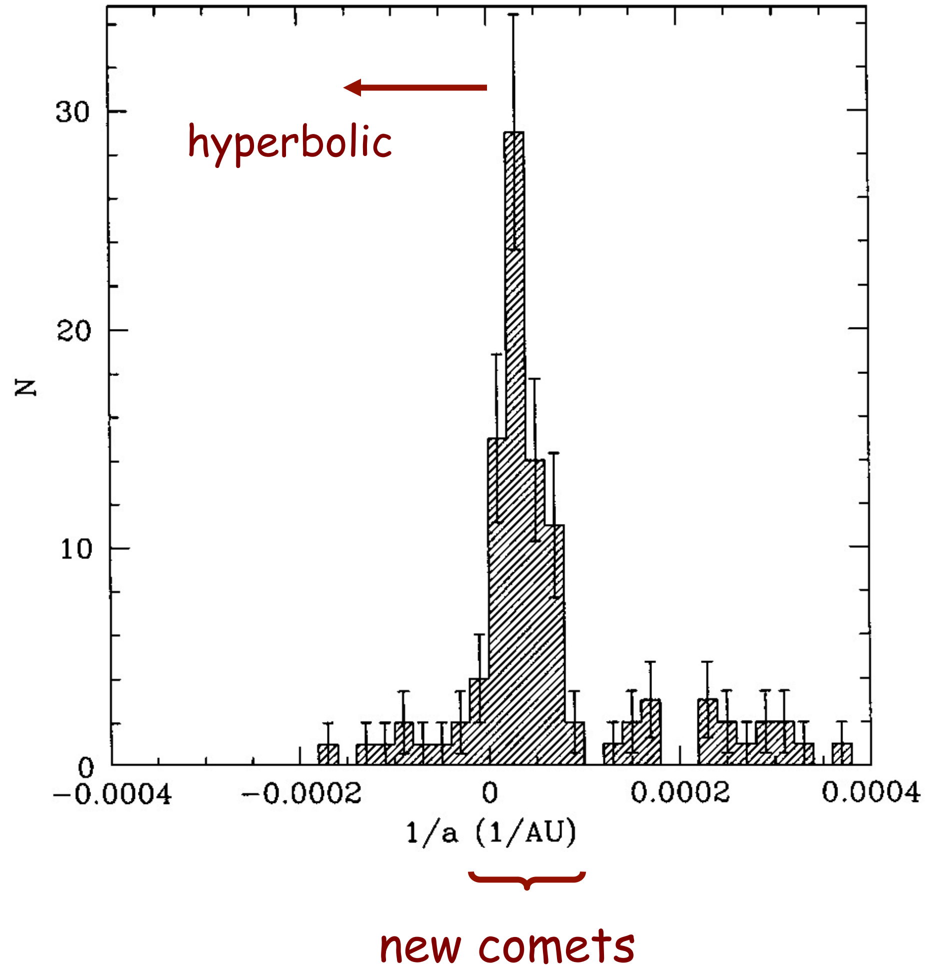


TABLE I
Distribution of original semi-major axes
(*a* in Astronomical Units)

1/*a*	*n*
< ·000 05	10
·000 05 – 10	4
10 15	1
15 20	1
20 25	1
25 50	1
·000 50 75	1
> ·000 75	0

Oort (1950)



- original orbits of long-period comets exhibit a strong peak at energy $1/a \sim 10^{-4}$ AU^{-1}
- peak is displaced to positive 1/a so most are bound, and there is no strong evidence for hyperbolic comets (interstellar comets would have $1/a \sim -1$ AU^{-1})
- comets in this peak are called "new" comets since this must be their first passage through the planetary system
- without planetary perturbations, all new comets would pass 1 AU with speed 42.122 km/s, within 0.001 km/s of escape speed

Formation of the Oort cloud

- assume comets can be identified with planetesimals (typical size of a few km coincides with size of planetesimals produced by Goldreich-Ward instability)
- planet formation not 100% efficient so some planetesimals will be left over
- orbits that approach too close to a planet are chaotic ⇒ eccentricity growth and eventual escape or collision with Sun
- at high eccentricity the evolution can be modeled as a diffusion process ("gambler's ruin" with bankruptcy = escape)

r.m.s. change in $x = 1/a$ per perihelion passage is

$$D = \langle(\Delta x)^2\rangle^{1/2} \sim (10/a_p)(M_p/M_\odot)$$

where a_p, M_p are planet's semi-major axis and mass

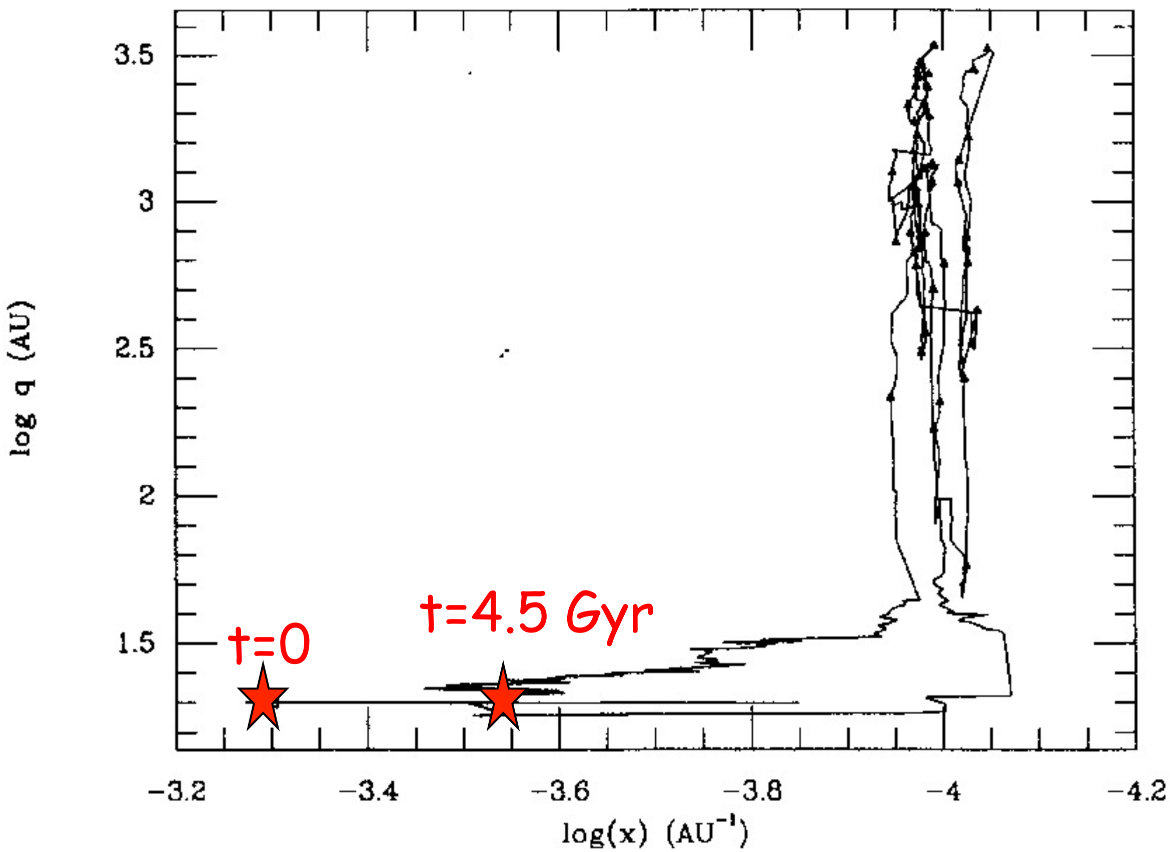
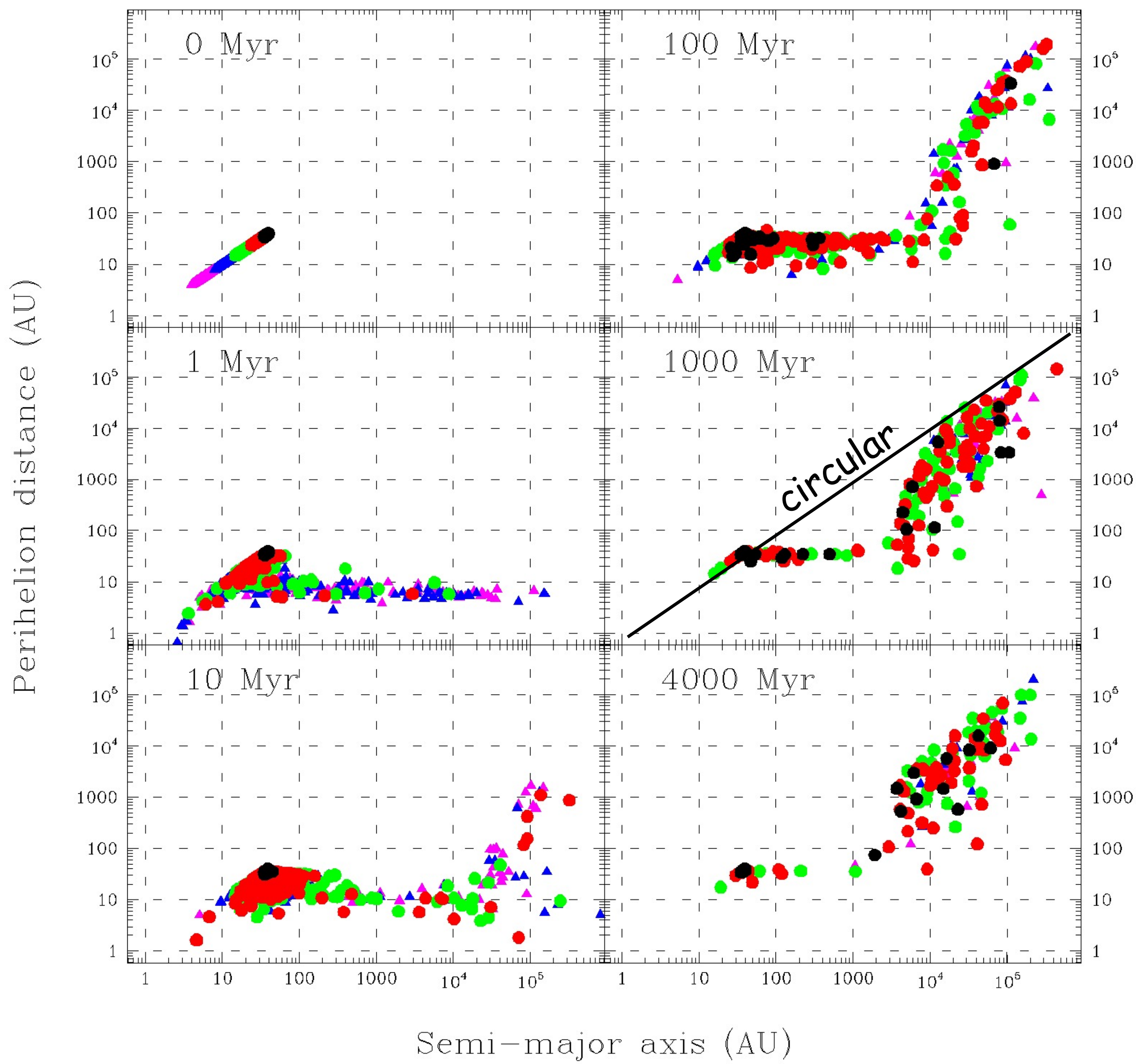


FIG. 3. The evolution in semimajor axis and perihelion is displayed for a typical comet. One data point is plotted per orbit. The comet started with a semimajor axis of 2000 AU and a perihelion of 20 AU (light square) and ended after 4.5×10^9 yr at the light circle. A triangle is plotted every 10^8 yr.

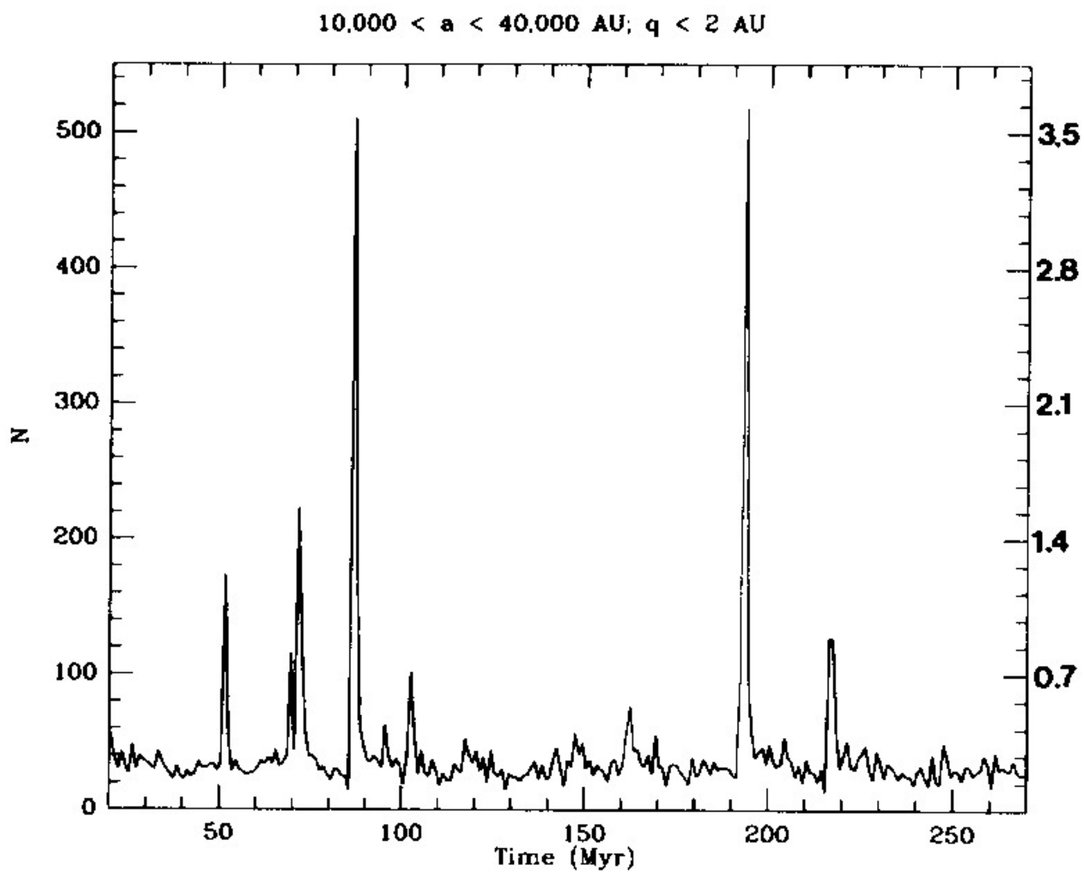


Jupiter region
Saturn region
Uranus region
Neptune region
outside Neptune

Dones et al. (2004)

the inner Oort cloud

- We only see "new" comets (comets with $x < 10^{-4}$ AU^{-1}) if they can jump the "Jupiter barrier" between $q > 20$ AU (small planetary perturbations at perihelion) to $q < 2$ AU (visible from Earth) in less than one orbit $\Rightarrow a \sim 30{,}000$ AU
- the Oort cloud could extend to much smaller semi-major axes and contain much more mass (Hills 1981) – anywhere from a factor 2 to a factor 1000
- inner cloud gives rise to rare "comet showers" during close stellar passages



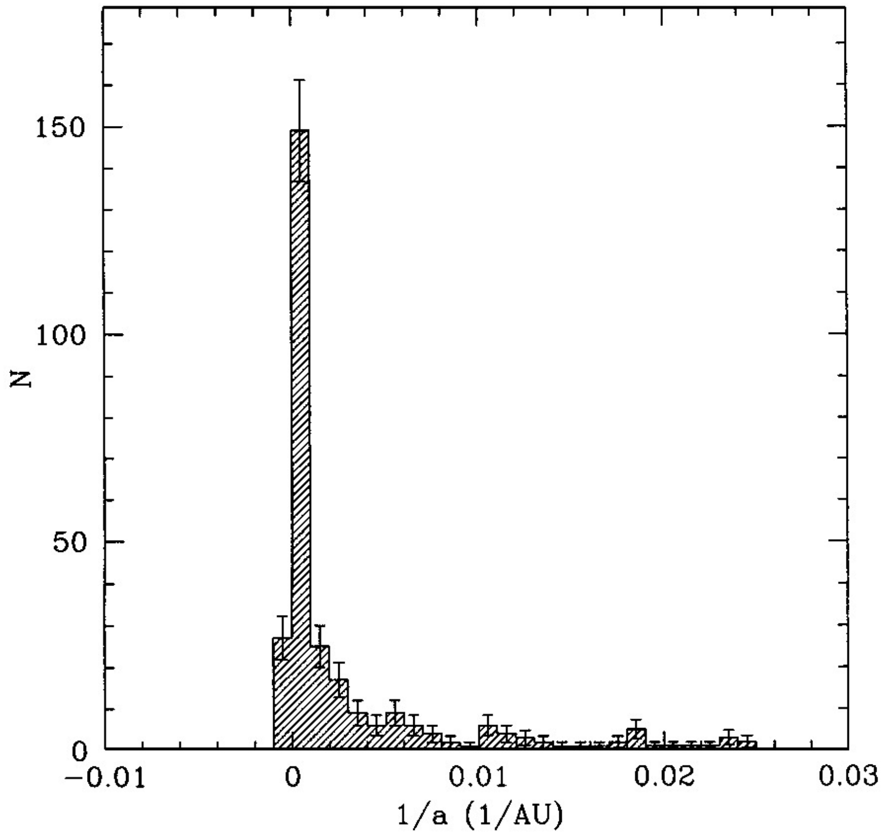
Heisler (1990)

the Oort cloud - successes

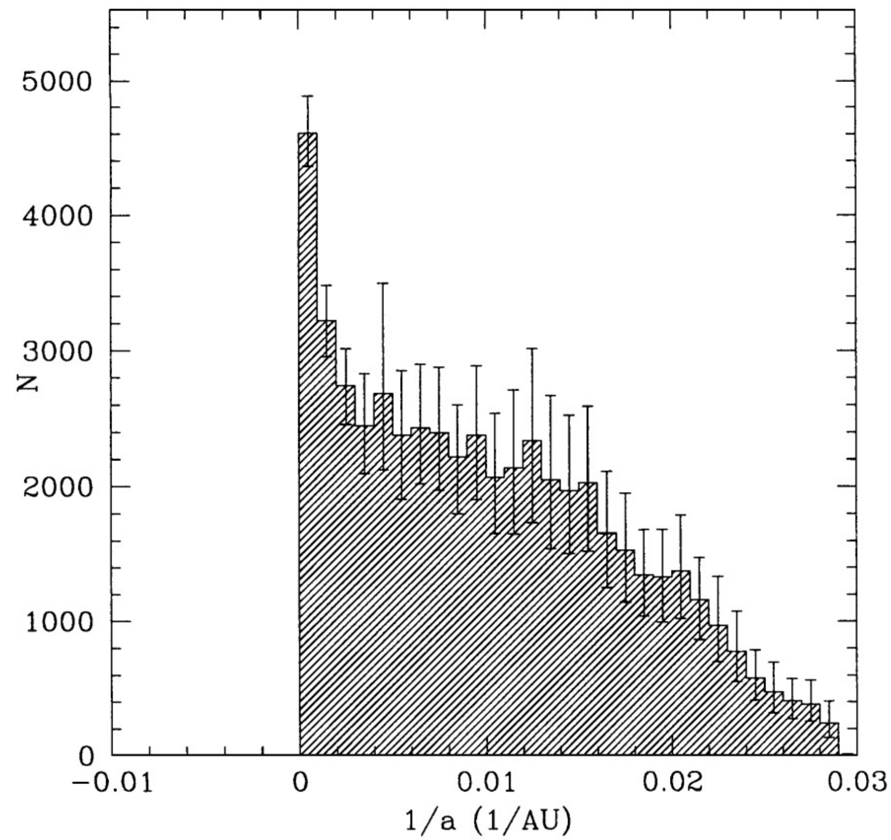
- the characteristic semi-major axis of Oort cloud comets, a ~ 30,000 AU, is a natural consequence of the requirement that the Galactic tide can change the perihelion from outside the planetary system to < 2 AU in one orbit
- the total population of comets in the Oort cloud is about 10^{11} based on an extrapolation from the discovery rate of new comets. Mass ~ $5M_{\oplus}$ but very uncertain
- the Oort cloud is formed naturally and inevitably from scattering of planetesimals in the Uranus-Neptune region; this process also produces an inner cloud that is only visible during comet showers or by detecting comets with perihelia > 20 AU
- simulations suggest that the masses of the inner and outer clouds are similar

the Oort cloud - problems

- the "fading problem": matching the actual distribution of long-period comets requires that most new comets are destroyed after their first passage
- formation efficiency is rather low – only about 3% for classical Oort cloud and another 3% in the inner cloud. Given current mass of about 5 $M_\oplus$ in the classical cloud, this requires 200$M_\oplus$ or more in residual planetesimals, far larger than the amount in the giant planets
- formation models predict far too many objects in the high-eccentricity component of the Kuiper belt
- influence of birth cluster



observed



simulated (no fading)

The Kuiper belt

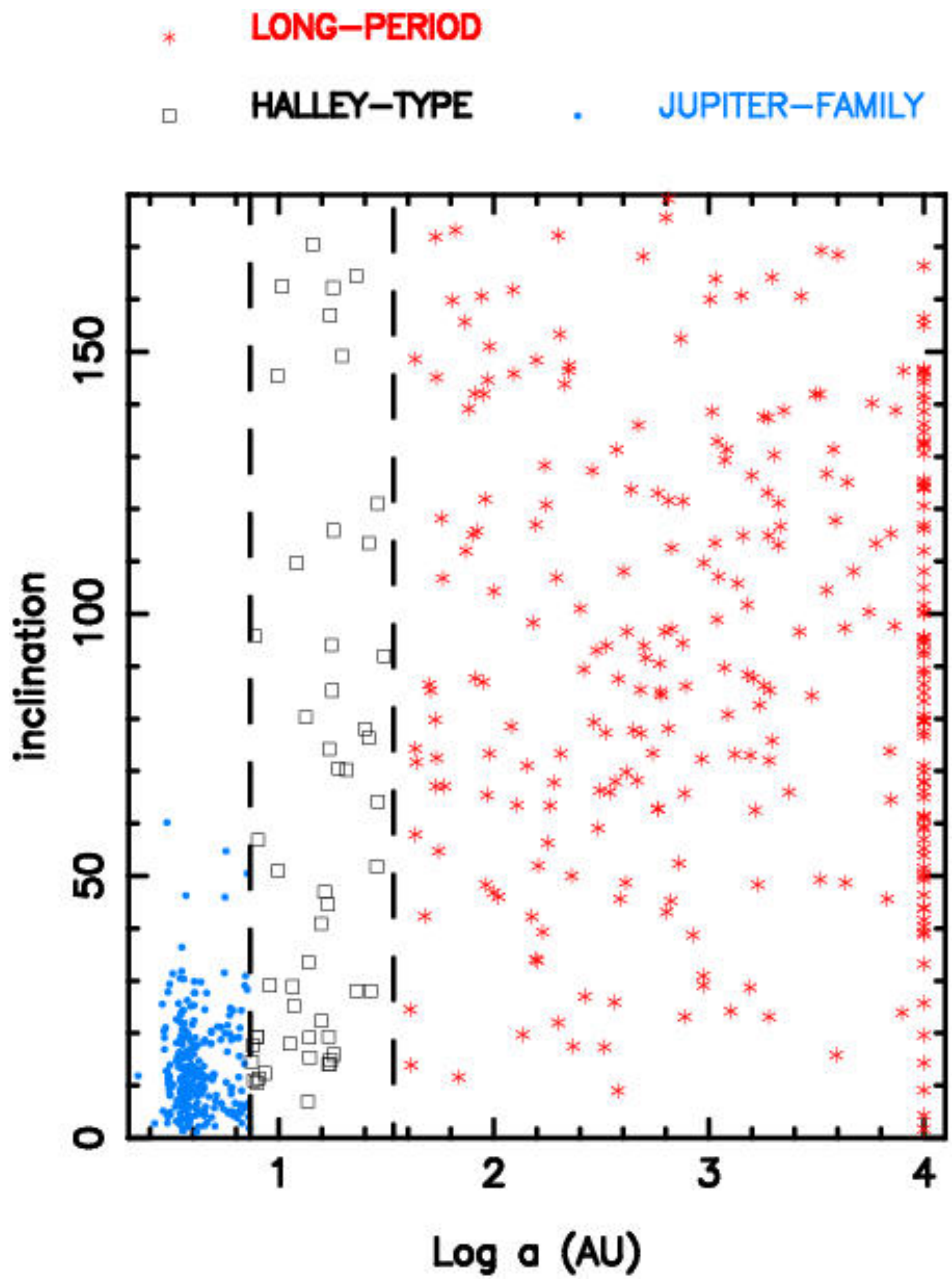
- first suggested by Edgeworth (1949) and Kuiper (1951)

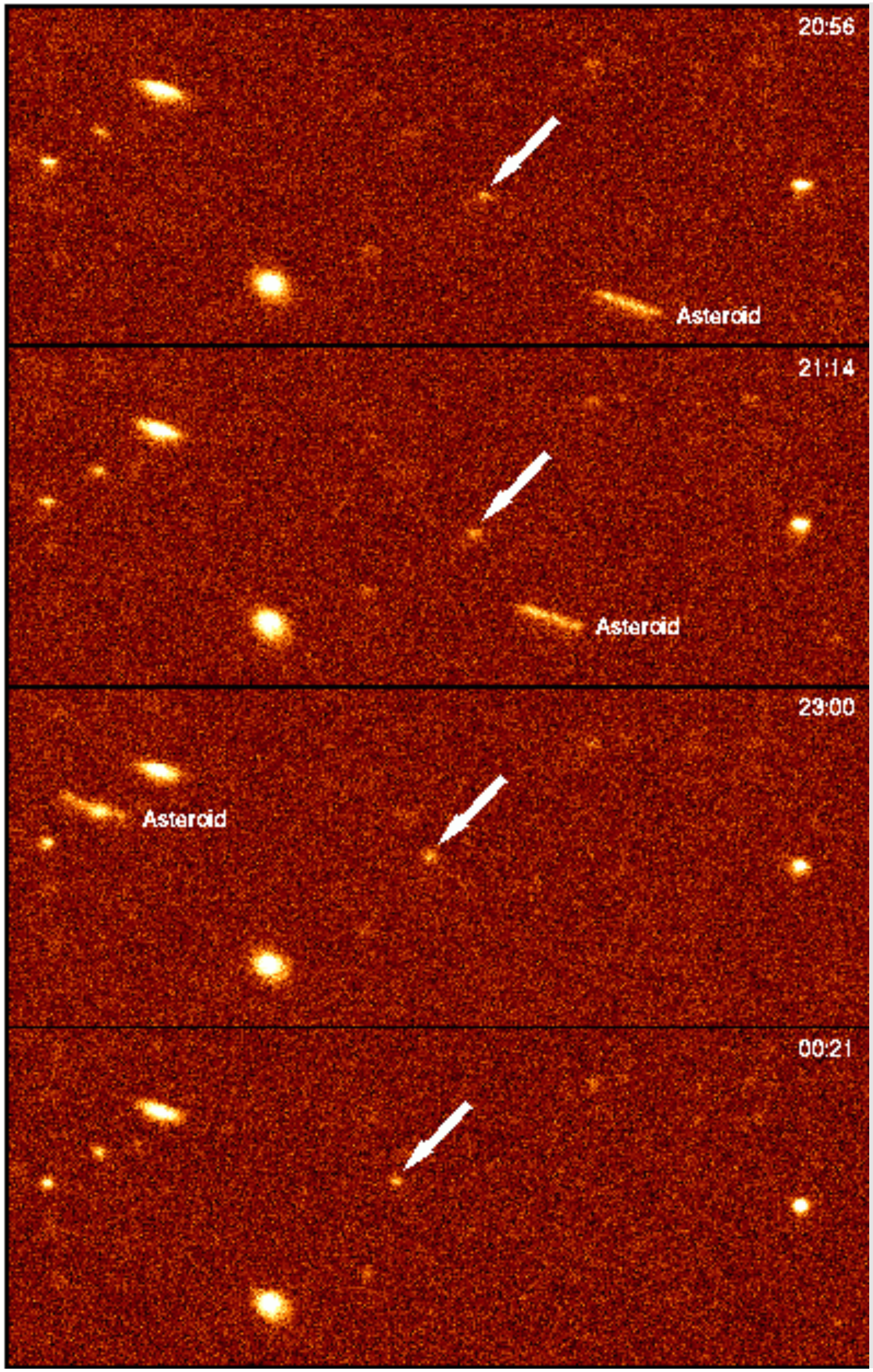
42. It would be unreasonable to suppose that the original rotating disk of scattered material came to an abrupt end outside the orbit of Neptune. There must have been a gradual thinning out of the material at the outer boundary. There is no definite evidence as to the opacity of this material except that it was insufficient to lead to the formation of a planet.

- originally only a hypothetical object, but the evidence was there all along

The Kuiper belt

- Jupiter-family comets (P < 20 yr) have low inclinations, therefore they cannot come from the spherical Oort cloud
- they must come from a flattened source, i.e. a disk outside Neptune
- requires ~ 0.1 $M_{\oplus}$, too small to be detected dynamically
- first Kuiper belt object found by Jewitt & Luu (1993)





1992 QB1

(Jewitt & Luu 1993)

THE OUTER SOLAR SYSTEM

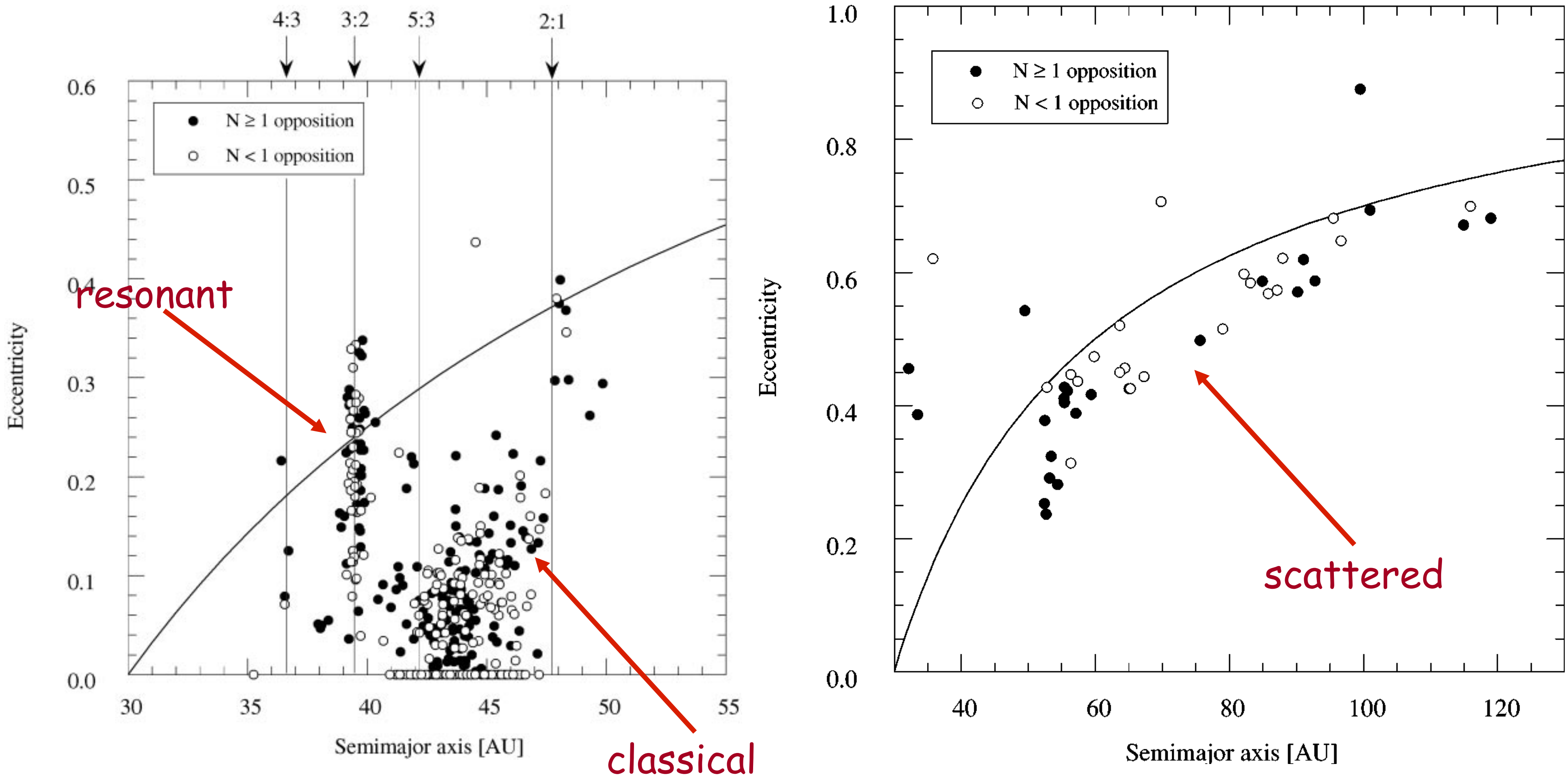
This animation shows the motion of the outer part of the solar system over a 100-year time period. The sun is at the center and the orbits of the planets Jupiter, Saturn Uranus and Neptune are shown in light blue (the locations of each planet are shown as large crossed circles).

Comets: blue squares (filled for numbered periodic comets, outline for other comets)
High-e objects: cyan triangles
Centaurs: orange triangles
Plutinos: white circles (Pluto itself is the large white crossed circle)
"Classical" TNOs: red circles
Scattered Disk Objects: magenta circles

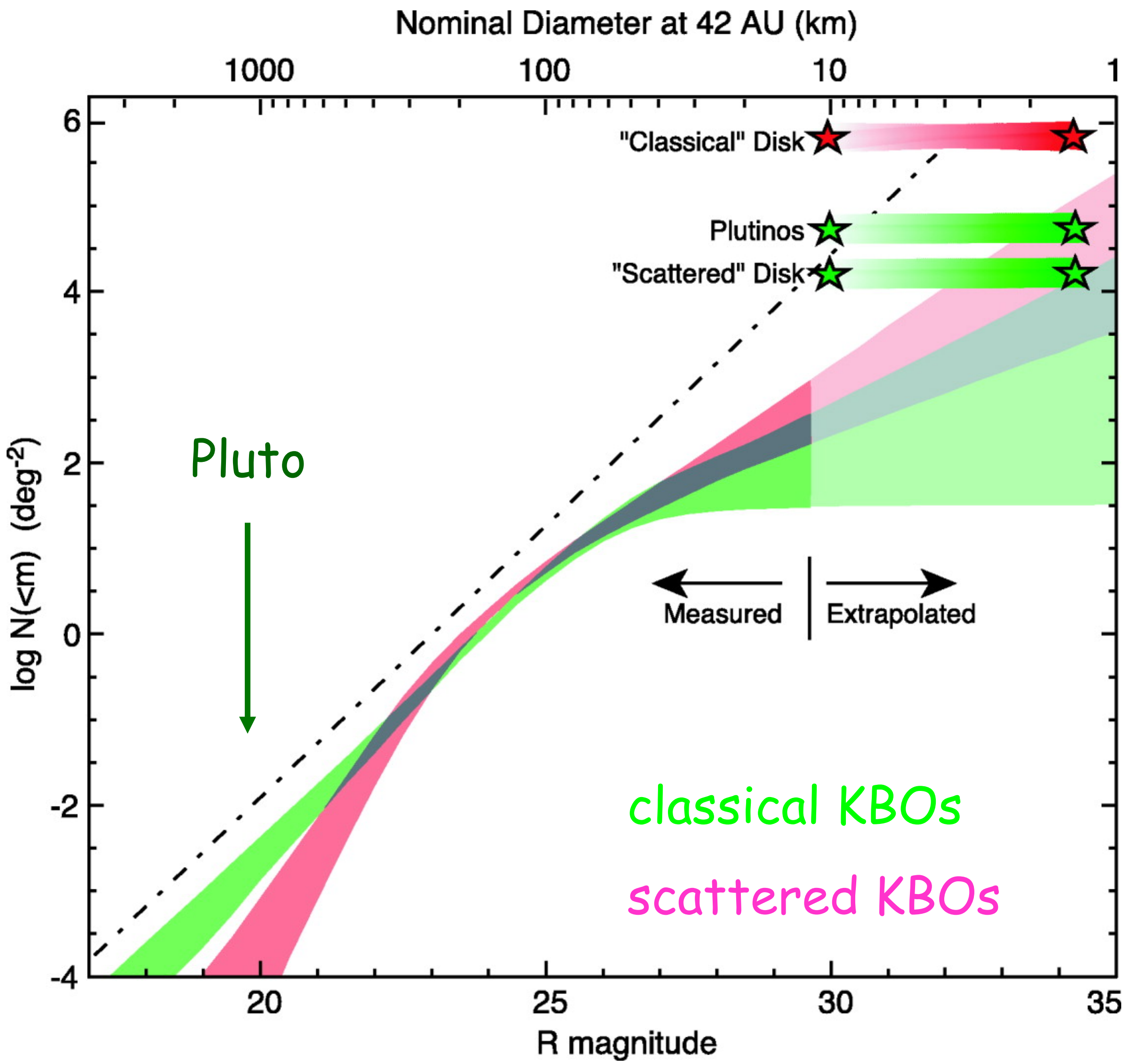
The individual frames were generated on an OpenVMS system, using the PGPLOT graphics library. The animation was put together on a RISC OS 4.03 system using !InterGif.

The Kuiper belt

- now over 1000 Kuiper-belt objects (KBOs)
- also over 100 Centaurs (objects orbiting between Jupiter and Neptune)
- three classes:
  - **classical KBOs (~40%)**
    - semi-major axes ~ 40-50 AU (sharp outer edge at 47 AU)
    - e ~ 0.1, i ~ 20o
    - rms velocity ~ 1 km/s
  - **resonant KBOs (~30%)**
    - in resonance with Neptune
    - mainly 3:2 resonance (Pluto and Plutinos), but also 2:1, 5:2, 1:1, etc.
    - produced by migration of Neptune
  - **scattered KBOs (~30%)**
    - high eccentricity and inclination (up to e ~ 0.8)
    - only visible because seen near perihelion
    - may be comets diffusing towards the Oort cloud



Luu & Jewitt (2004)



size distribution:

- most of mass concentrated near R = 50 km
- total mass of classical KBOs only ~ $0.01M_\oplus$
- scattered KBOs may have mass $0.1M_\oplus$
- there may not be enough mass for the Jupiter-family comets

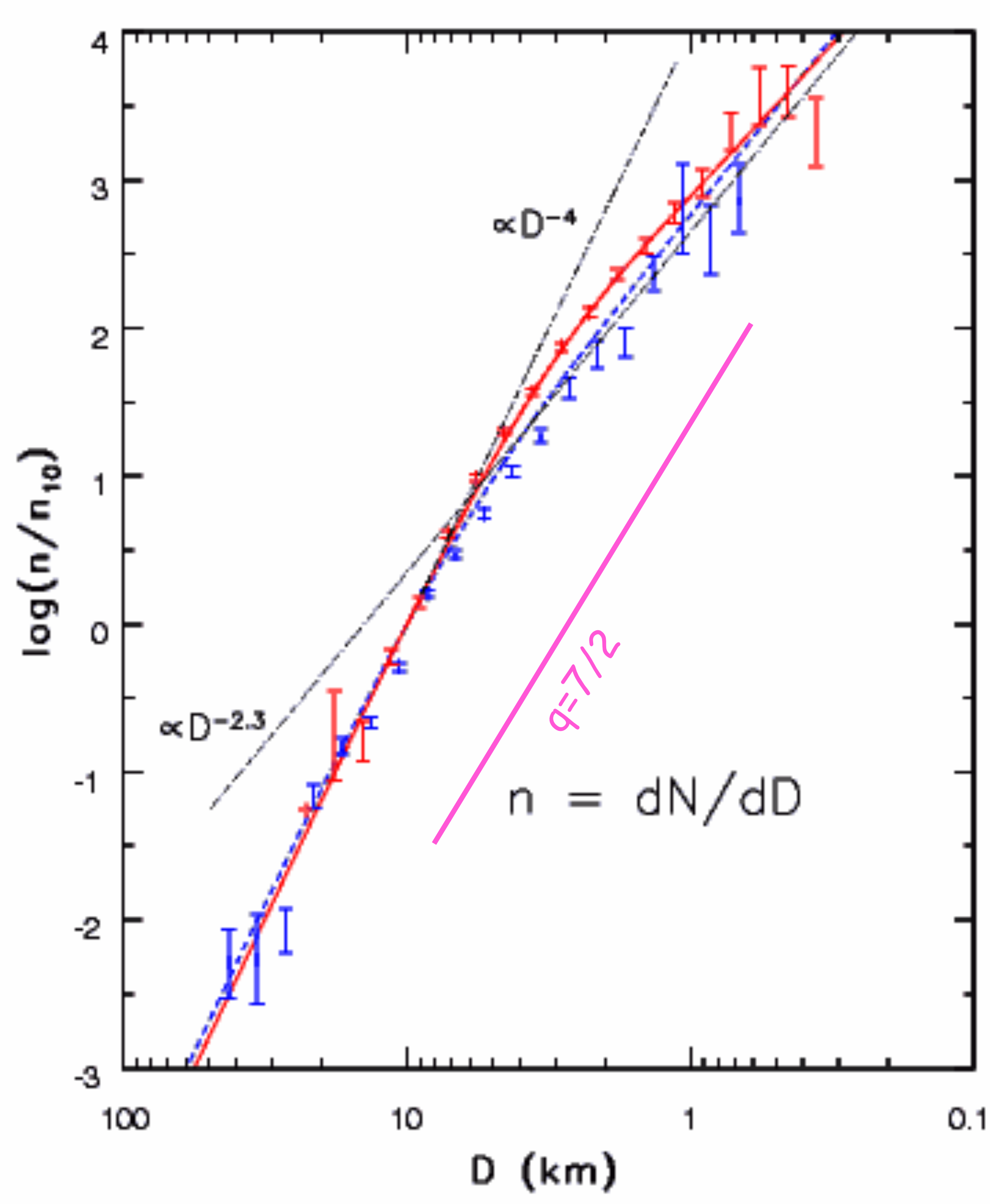
Bernstein et al. (2004)

Formation of the Kuiper belt

- Kuiper belt is a fossil planetesimal disk so offers unique insight into formation of the solar system
- **Puzzle 1:**
  - extrapolation of the minimum solar nebula yields $5M_\oplus$ between 40 AU and 50 AU compared to $0.1M_\oplus$ in the Kuiper belt – where did the mass go?
- **Puzzle 2:**
  - KBOs in the scattered disk were presumably excited to high inclination and eccentricity by the planets, in which case they should have $q < 30$ AU. How then to explain Sedna ($q = 76$ AU)?
- **Puzzle 3:**
  - icy bodies with $R \sim 50$ km have escape speed 0.3 km/s compared to current velocity dispersion of 1 km/s, so Safronov number $\Theta \sim 0.1$ $\Rightarrow$ no gravitational focusing $\Rightarrow dr/dt \sim \Sigma\Omega/\rho_p \Rightarrow r \sim 1$ km after 5 Gyr
  - collisions at 1 km/s break up icy bodies
  - so how did the KBOs form?

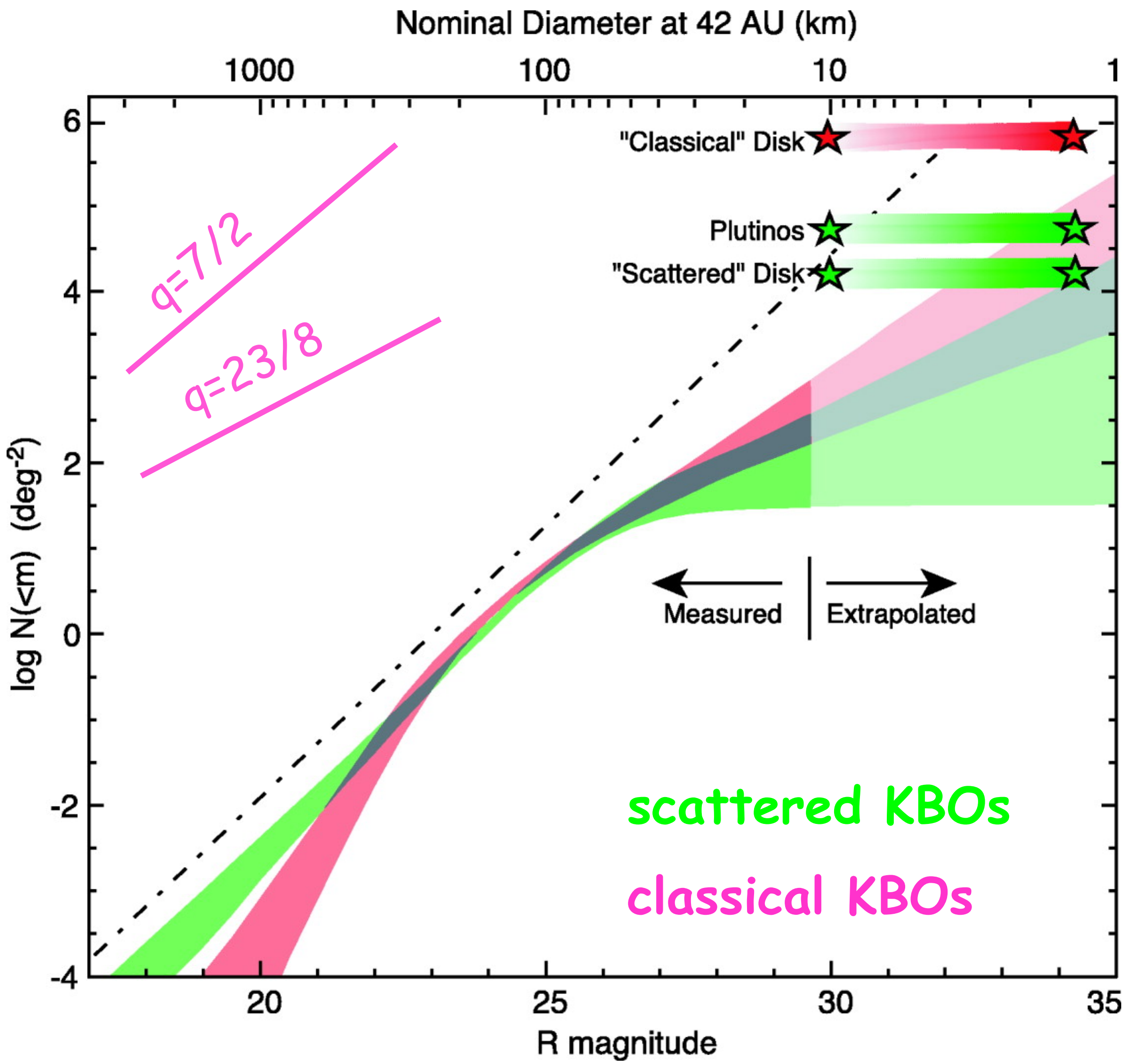
Formation of the Kuiper belt

- probably the Kuiper belt did start with about the surface density implied by the minimum solar nebula
- initial velocity dispersion was much lower so collisions were not erosive and gravitational focusing could occur
- runaway growth produced large bodies containing a few percent of the mass in the original belt
- then the disk was heated (by Neptune? by the largest bodies in the belt? by stars in the birth cluster which also pumped up Sedna's perihelion?) and the resulting high velocities ground up the small bodies



asteroid size distribution

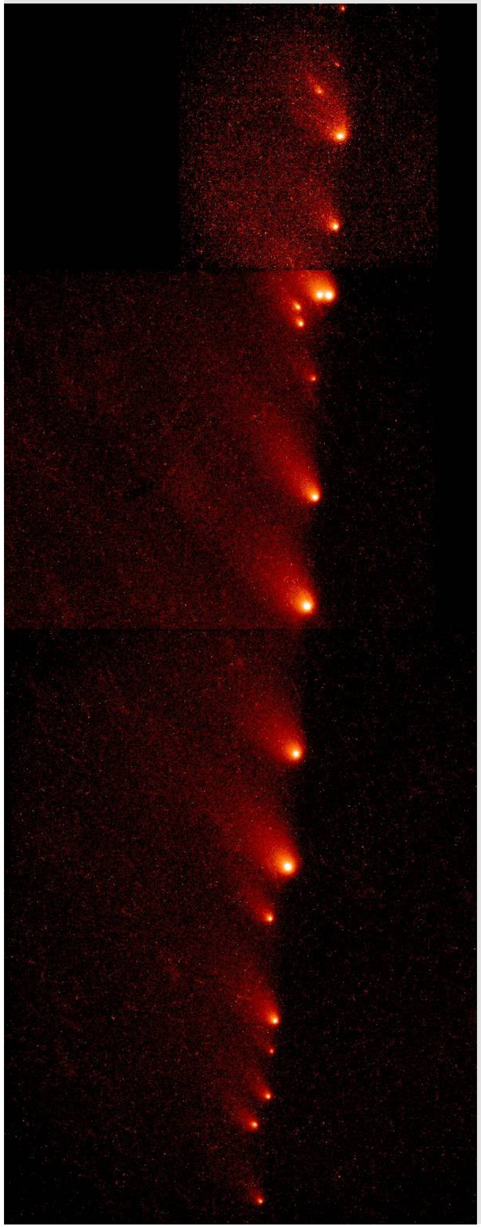
SDSS (Ivezic et al. 2001)



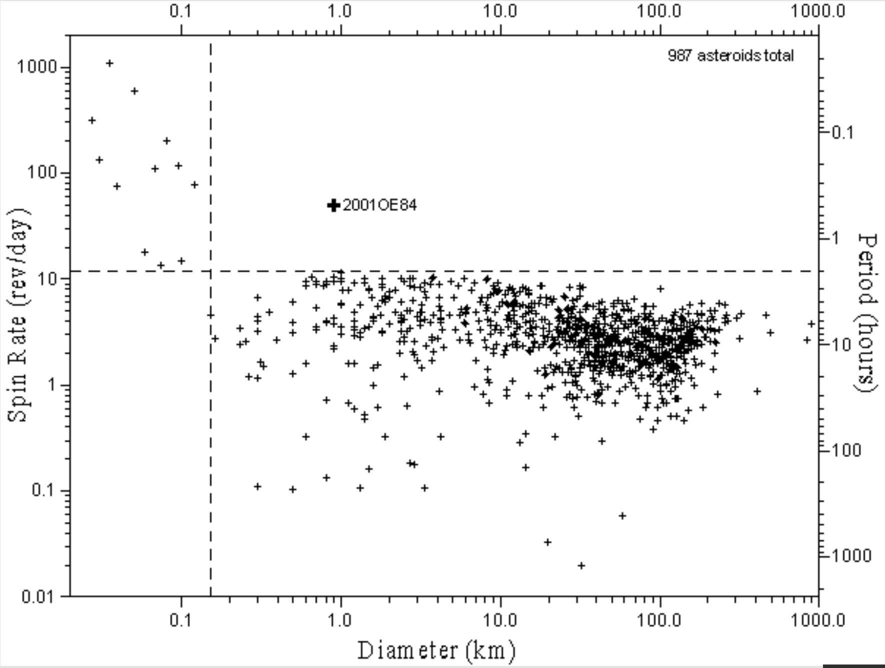
- above r ~ 50 km the KBOs have not suffered catastrophic collisions
- below r ~ 50 km the KBOs form a collisional cascade
- dn ~ $r^{-23/8}$ dr as expected for gravity-dominated cascade
- KBOs are "rubble piles" with negligible strength

evidence for rubble piles

1. breakup of Comet Shoemaker-Levy 9

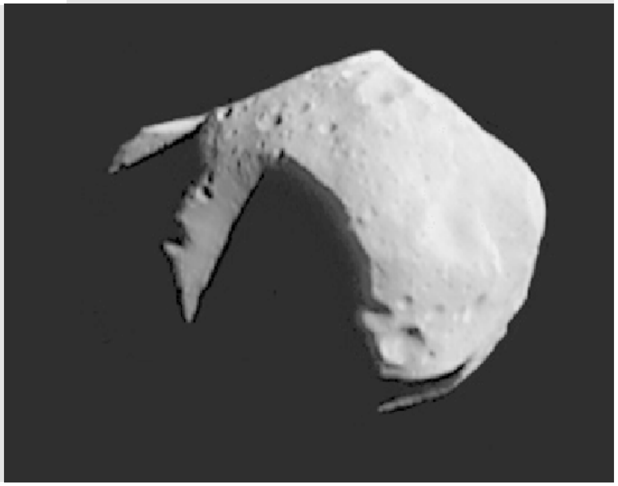


2. asteroid rotation rates



3. asteroid collisions tend to shatter but not disrupt the target

4. large craters and low densities (e.g., 253 Mathilde has ρ = 1.3 g/cm^3)



The future for studies of the Oort cloud and the Kuiper belt

- Taiwan-America Occultation Survey (TAOS) is looking for occultations in the Kuiper belt
- large time-domain surveys (Pan-STARRS, LSST):
  - dramatically increase the number of comets with well-determined orbits and provide complete, unbiased samples
  - deep surveys will see comets beyond the Jupiter barrier (10 X higher density)
  - hyperbolic comets