Small bodies of the solar system

Lecture by Klaus Jockers, Göttingen, winter term 2004/2005

# Comets4

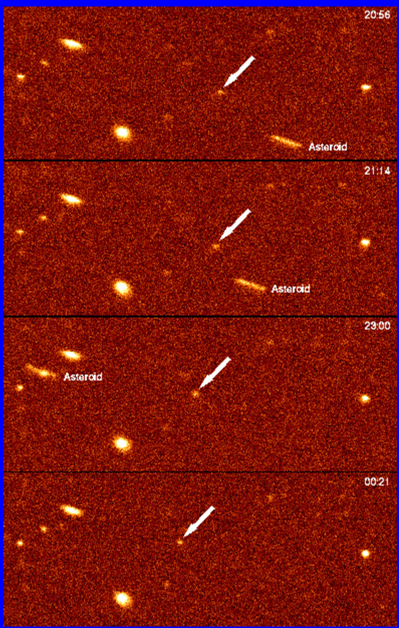
## Dynamics of comets

- Kuiper belt
- Orbits of comets
- Oort cloud
- Non-gravitational forces (jet action)

1992 QB1 the first Kuiper belt object.

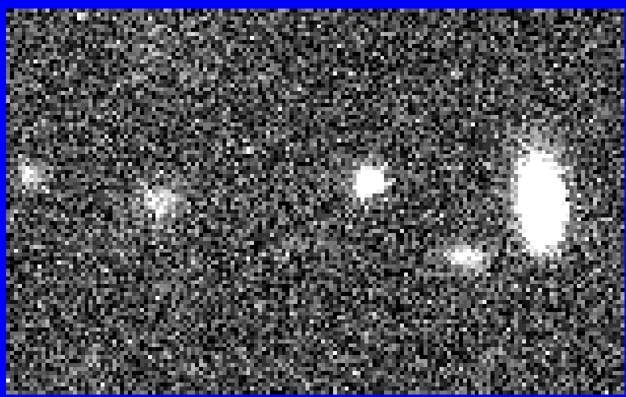
It was discovered by David Jewitt and his coworkers at the University of Hawaii.

See Jewitt DC and JX Luu, Protostars and Planets IV, 1201-1229.




From DC Jewitt's Kuiper belt website

Kuiper Belt Object 1999 KR16 imaged with the University of Hawaii 2.2 meter telescope on Mauna Kea in Hawaii in April 2000. These images had an integration time of 400 seconds and were taken over a 4 hour period. Movie compiled by Scott Sheppard



From DC Jewitt's Kuiper belt website

## Orbital elements of a solar system body (comet)

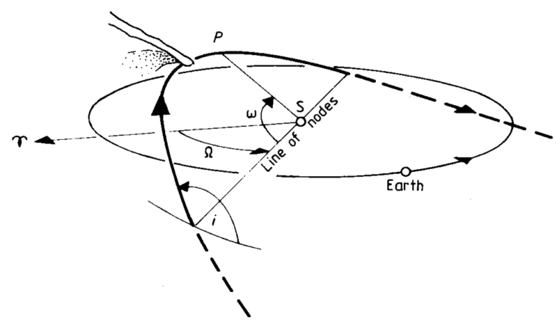


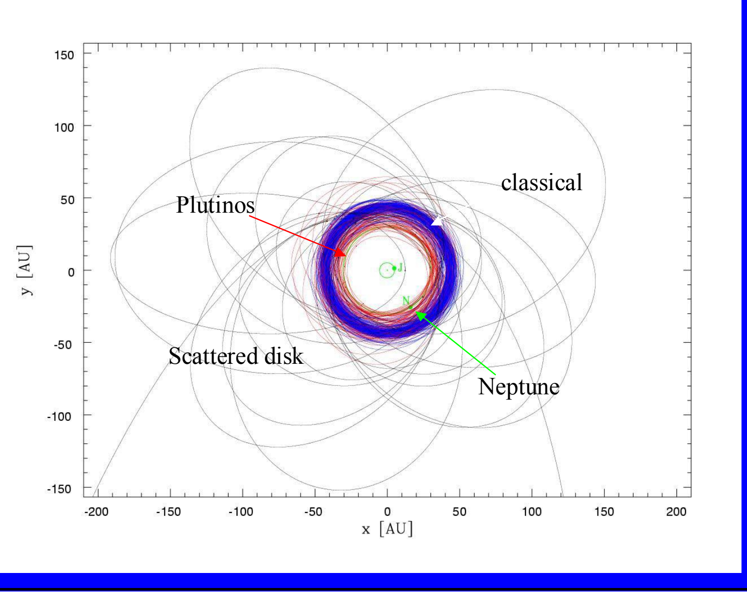

**Figure 2.** Main features of a comet moving on a typical very eccentric orbit. The symbols stand for: perihelion ($P$), inclination of the orbit with respect to the ecliptic plane ($i$), argument of perihelion ($\omega$) and longitude of the ascending node ($\Omega$) measured with reference to the vernal equinox (♈). Note that in this case the comet moves on a retrograde orbit with respect to the orbital motion of the Earth. Comet Halley moves on an orbit similar to the one represented here.

q: perihelion distance, e: excentricity (=1 parabola), a: semimajor axis

**Classical Kuiper belt objects (KBOs):**
These are about 2/3 of the well observed objects. a ≥ 42 AU, q > 35 AU. Orbits stable during 4.5 GYears, the age of the solar system. Have modest excentricities, but inclinations as large as $32^0$.
**Plutinos:**
1/3 of KBOs are near the 3:2 mean motion resonance with Neptune at 39.4 AU. When corrected for observational bias, Plutinos may represent 10% of KBOs. Orbits are stable with respect to Neptune.
**Scattered objects:**
Chaotic swarm of bodies scattered outward by Neptune during the early stages of the solar system.

The Kuiper belt, a vast population of small bodies orbiting the Sun beyond Neptune.

From DC Jewitt's Kuiper belt website



Jewitt DC and JX Luu, Protostars and Planets IV, 1201-1229

Orbit parameters:
a: semimajor axis
q: perihelion distance
e: excentricity
i: inclination
Note: 1/a ~ the total energy of an orbit.



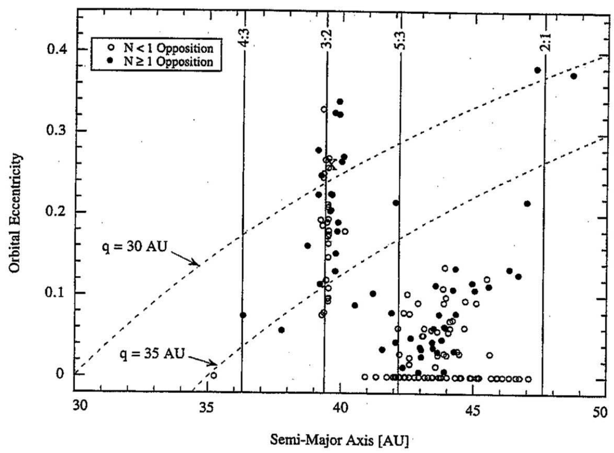



Figure 2. Semimajor axis eccentricity for Kuiper Belt objects. Filled circles denote multiopposition orbits. Open circles denote orbits computed from astrometry taken within a single opposition. Pluto is marked by X. Neptune is at $(a,e)$ = (30,0). The dashed lines mark $q$ = 30 AU and $q$ = 35 AU. Objects above the upper line are Neptune-crossers. Scattered Kuiper Belt object 1996 $TL_{66}$ ($a,e$ = 85 AU, 0.59) is off scale and not plotted. Vertical lines mark the locations of mean-motion resonances.

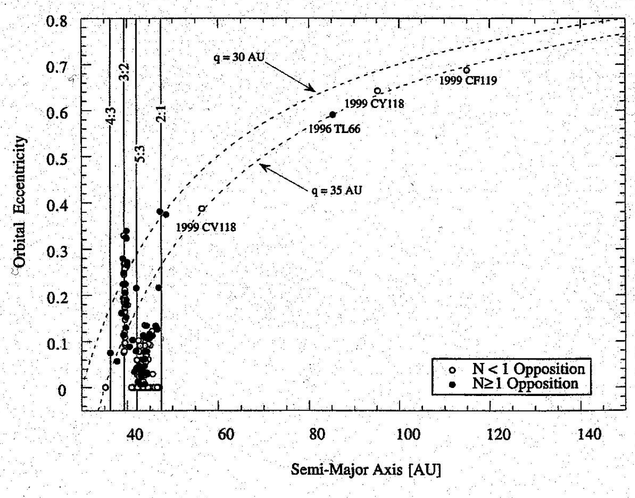
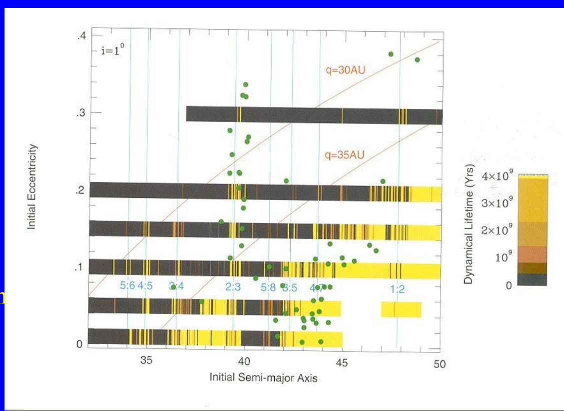



Figure 3. Same as Figure 2 but on a larger scale to show the scattered Kuiper Belt objects. All four scattered KBOs fall along the perihelion distance $q$ = 35 AU line.

There is the suggestion (Fernandez and Ip, Malhotra et al.) that in the early solar system scattering of planetesimals by the giant planets led to an asymmetry which drove Saturn, Uranus and Neptune away from the Sun, while Jupiter, the ultimate source of the angular momentum, moved closer to the Sun.
In this way resonances slowly swept through the Kuiper belt (and the asteroid belt as well) and in this way KBOs and asteroids may have been collected or removed from the resonance locations.

## The observed orbits of Kuiper belt objects are quite stable.




The dynamical lifetime for small particles in the Kuiper belt derived from 4 billion year integrations. Each particle is represented by a narrow vertical strip, the center of which is located at the particle's initial excentricity and semimajor axis (initial orbit inclination for all particles was 1°). The color of each strip represents the dynamical lifetime of the particle. The yellow strips represent objects that survive for the length of the integration, 4 x $10^9$ years. Dark regions are particularly unstable on these timescales. For reference, the locations of the important Neptune mean motion resonances are shown as blue vertical lines and two curves of constant perihelion distance, *q*, are indicated. The green dots show the orbits of the known Kuiper belt objects which have been observed at more than one opposition as of October 1999.

Duncan et al. 1995: The dynamical structure of the Kuiper belt. Astron. J. 110, 3073-3081

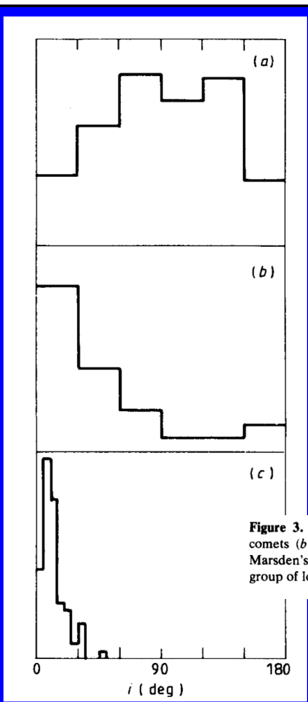
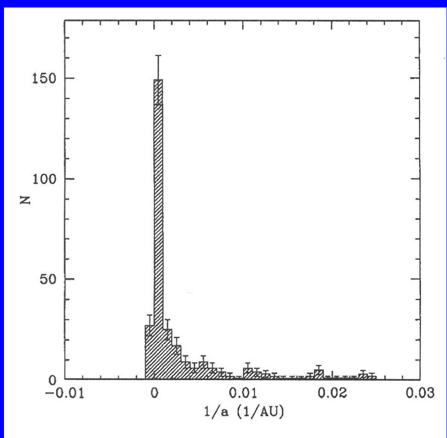
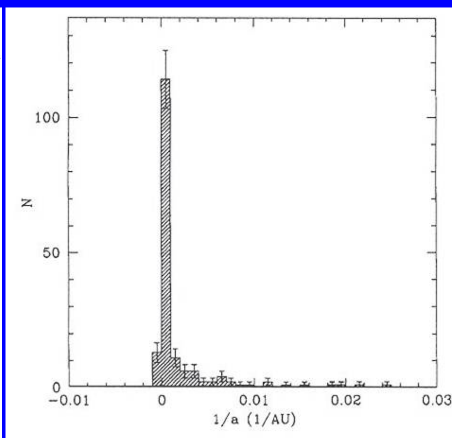



**Figure 3.** Inclination distributions of 538 long-period comets (*a*) ($P > 200$ yr), 25 intermediate-period comets (*b*) ($13 < P < 200$ yr) and 88 short-period comets (*c*) ($P < 13$ yr). All the comets appearing in Marsden's (1979) Catalogue of Cometary Orbits are represented, but the eight members of the Kreutz group of long-period comets with similar orbital elements are considered as a single comet.

## Histogram of 1/a for (left) 287 long-period comets and (right) for 170 comets with the most reliable orbits




Wiegert P, Tremaine S. 1999: The evolution of long-period comets, Icarus 137, 84-121.

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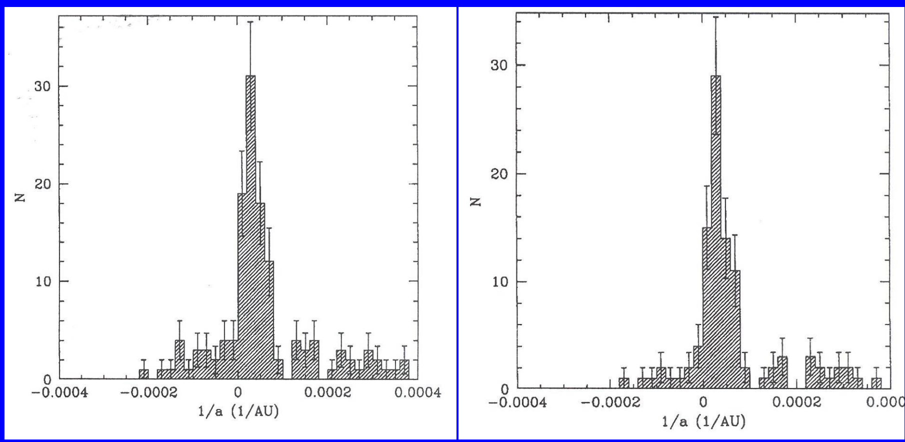


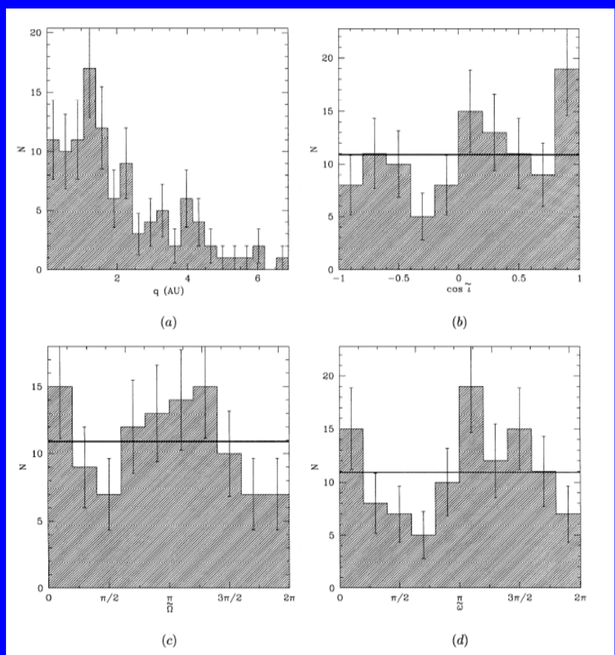

Note that the peak histogram element is distinctly positive.
1/0.000025 = 40000 AU = 0.2 parsec. Prox Cen is at 1.31 parsec.

Distribution of orbital elements for the 109 dynamically new comets ($1/a<10^{-4}$ AU$^{-1}$).

a: perihelion distance
b: inclination
c: longitude of ascending node
d: argument of perihelion

All angular elements are measured in the Galactic frame.

Wiegert P, Tremaine S. 1999: The evolution of long-period comets, Icarus 137, 84-121.



Gravitational forces acting on a comet:

Gravitation of Sun as main force
Gravitation of planets in the inner solar system
Gravitation of passing stars at large distance from the Sun
Gravitation of galactic bulge

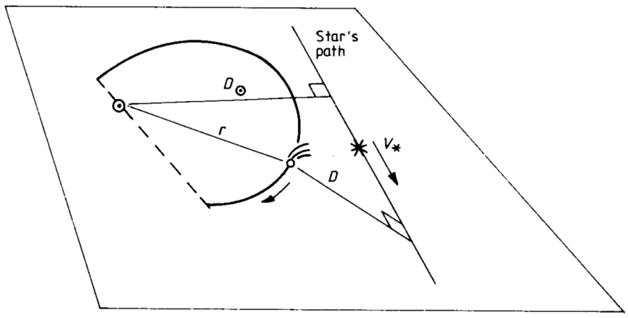



**Figure 13.** Geometry of a stellar encounter.

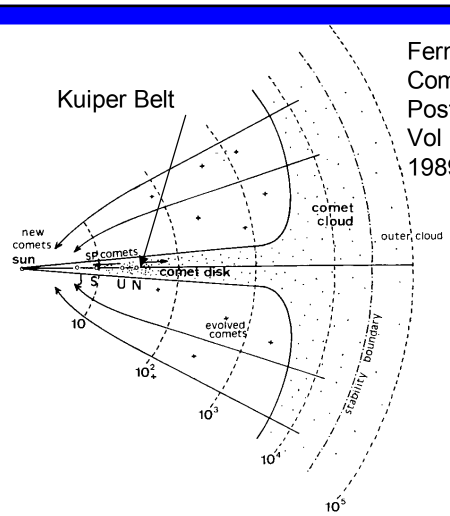
**The concept of the Oort cloud:**

Comets from the peak of the 1/a distribution < $10^{-4}$ $AU^{-1}$, when passing through the inner solar system, receive an energy kick $\Delta(1/a)$, which strongly depends on perihelion value (less on the inclination).
At $q \approx 6$ AU $\Delta(1/a) = 10^{-4}$ $AU^{-1}$,
at $q \approx 10$ AU $\Delta(1/a) = 10^{-5}$ $AU^{-1}$, so at q=1 AU, where most comets are observed, $\Delta(1/a)$ is much larger than the average kick. Therefore the comets from the peak of the 1/a distribution come to the inner solar system for the first time. Only 5% of these "dynamically new" comets with perihelion of 1 AU will leave the planetary system with a semimajor axis which again places it into the 1/a peak.

Problems with the concept of the Oort cloud come from its replenishment, i. e. it is not very clear, how the comets got there.

The comets in the Oort cloud may simply be left-overs from the origin of the solar system. But there is not enough mass available that far from the Sun, and the orbit inclinations should than be concentrated to the ecliptic.

It is easier to get them there from the Neptune region than from the Jupiter region, but this is not generally accepted. Nevertheless this was the strongest argument for postulating the existence of the Kuiper belt by Fernandez and Ip, 1983.

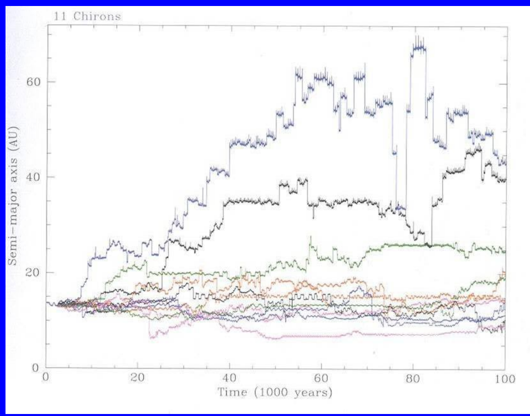



Fernandez and Ip, Comets in the Post-Halley era Vol I, 487-533, 1989

Fig. 15: A schematic picture of the current spatial distribution of comets around the solar system if they formed in the protoplanetary disk. A comet disk might still be present, stretching from the region of the outer planets to a few $10^3$ AU. Farther away, the action of external perturbers should have by now randomized the orbital planes of comets. New comets probably come from the Oort cloud, whereas most SP comets may come from the comet disk. The spherical volume a few $10^3$ AU in radius should contain evolved LP comets (crosses). The dashed circles indicate distances to the Sun in AU.

## Instability of Chiron's Orbit

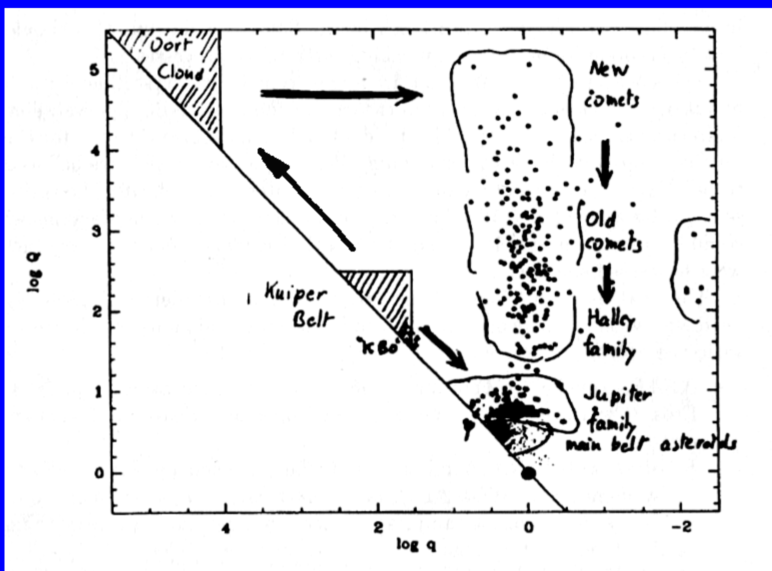
de Pater, J.J. Lissauer, Planetary Scienes, Cambridge 2001




Eleven simulations of the future orbital semimajorn axis of P/Chiron, which currently crosses the orbits of both, Saturn and Uranus. Initial orbital elements of the simulated bodies differed by about 1 part in $10^6$, which is smaller than observational uncertainties. Note that the orbit is highly chaotic, with gross divergence of trajectories in less than $10^4$ years. Courtesy: L. Dones; adapted from Lissauer 1999a.

## All observable comets have their origin in the Kuiper Belt

Plot of q (perihelion distance versus Q (aphelion distance). The arrows denote evolutionary pathways.




Adapted from Crovisier 1999, in Greenberg & Li (eds): Formation and Evolution of Solids in Space, Kluwer.

# Non-gravitational forces acting on comets (jet action)

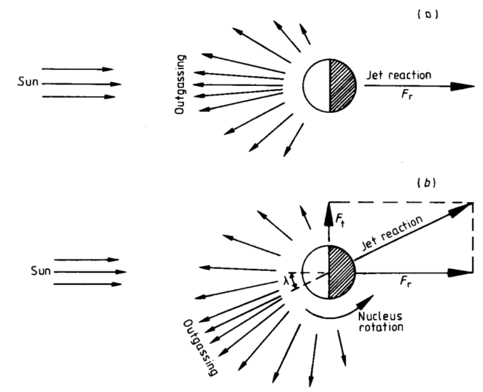



**Figure 4.** The action of non-gravitational forces on comets. The subliming gases from the nucleus give rise to a jet force in the opposite direction to that of maximum outgassing. A non-rotating nucleus will experience a radial non-gravitational force (*a*). On a rotating nucleus the zone of maximum outgassing will lag with respect to the subsolar point, giving rise also to a transverse component of the non-gravitational force (*b*).

Non-gravitational forces may be of importance to derive the mass of nucleus, if jet forces are known.