March 2004 KITP Conference on Planet Formation

Cometary Reservoirs as Clues to Planet Formation

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Goals:

- Use dynamics of observed comets as clues to reservoir properties
- Use properties of reservoirs as clues to planet formation processes

*Collaboration with Hal Levison (SWRI). Some portions also in collaboration with Luke Dones (SWRI), Brett Gladman (UBC), Ian Lepage (Queen's) & Paul Weissman (JPL).

The Story so far…

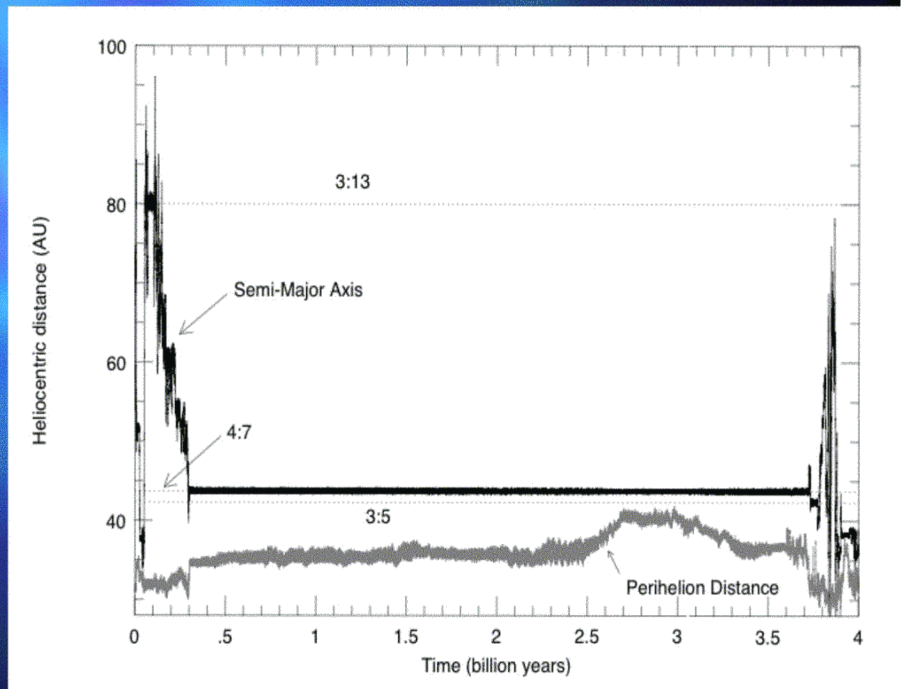
- Recall **Tisserand parameter** T is an approximation of the Jacobi constant (conserved 'energy' for test particle in rotating frame of restricted 3-body problem) . In current context T with respect to Jupiter is important.
- **'Short-period comets'** are those with periods < 200 years.
  - *Jupiter-family comets (JFCs)*: short-period comets with $2 < T < 3$.
  - *Halley-type comets (HTCs)*: short-period comets with $T < 2$.
- Simulations (eg Levison & Duncan 1997: LD97) showed that a flattened population of Neptune-encountering bodies 'hands-off' an armada of comets in excellent agreement with observed JFCs and Centaurs but produces very few HTCs. (However LD97 stopped integrating comets when semimajor axes exceeded 1000 AU – see below)
- Duncan & Levison (1997: DL97) extended LD97 integrations to 4 Gyr to obtain remnant structure of primordial planetesimal population scattered during outer planet formation in early solar system.

Origin of JFCs: The Scattered Disk

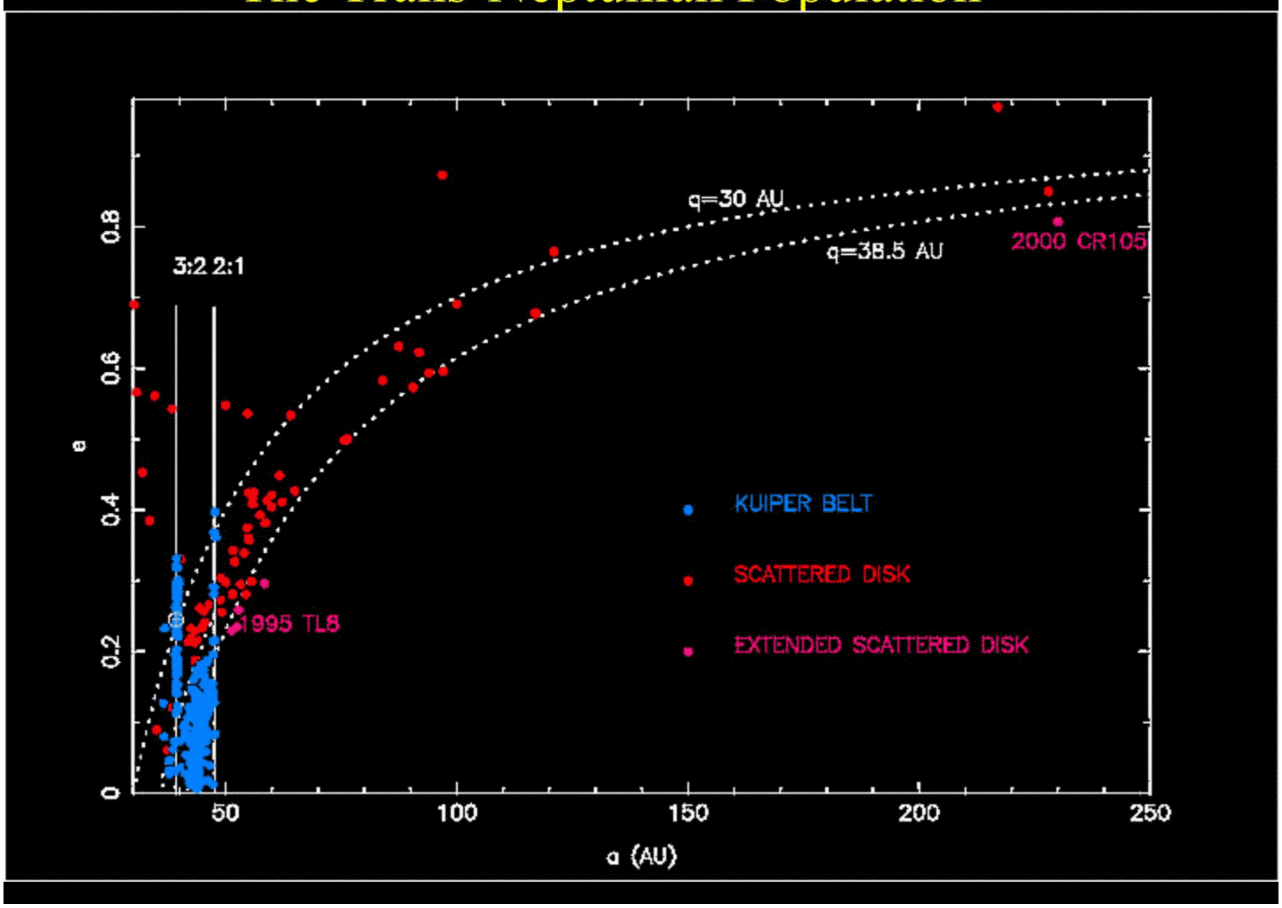
- About 1% of particles survive for 4 Gyr in DL97 calculations ⇒ some planetesimals originally in Uranus/Neptune zone and/or the inner Kuiper belt could have been trapped in the Scattered Disk (SD) for 4 Gyr and be currently leaking inward to make the JFCs.

- Trapping occurs in part because Neptune's mean motion resonances are sticky - they can increase the perihelion distance (q) and typically leave ~32 AU < q < ~ 40AU.

- Makes enough JFCs if there are **now** ~ 10^9 objects with D > 1 km in SD, corresponding to ~10-20 Earth Masses originally scattered by Neptune.

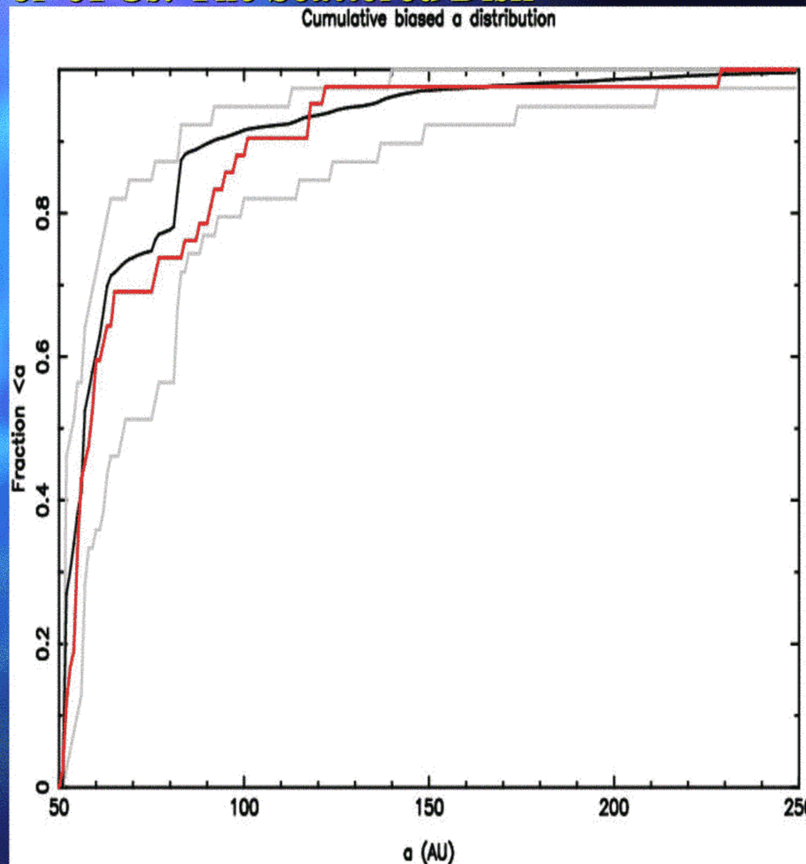


The Trans-Neptunian Population



Origin of JFCs: The Scattered Disk

- Morbidelli, Emel'yanenko & Levison (2004) incorporate observational biases via generalization of M. Brown's method.
- They show semimajor axis distribution of SD objects in DL97 consistent with observations when observational biases included.
- However, DL97 doesn't explain 'extended' SD (Gladman et al 2002) of objects with pericentres larger than ~38.5 AU.



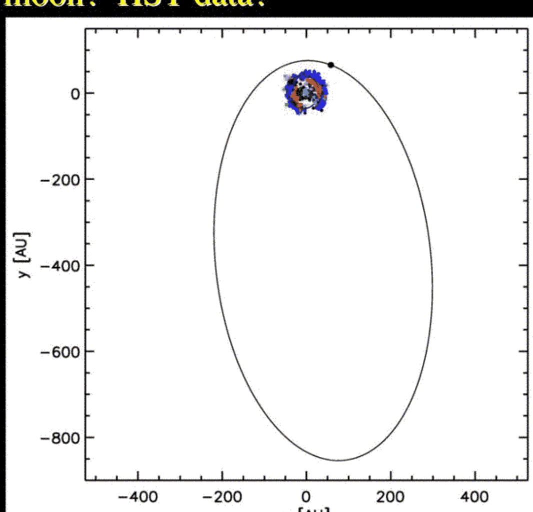
2003 VB12: "SEDNA" (Brown, Trujillo & Rabinowitz)

R magnitude: 20.5, H=1.7

Extremely red

Not detected in IR by Spitzer or IRAM ->
D < 1800 km, so it's smaller than Pluto. Probably bigger than Quaoar (D = 1250 km).

Rotation period: 40 days. -- > despun by a moon? HST data?



a = 532 AU (3 oppositions)

q = 75.796 AU !!

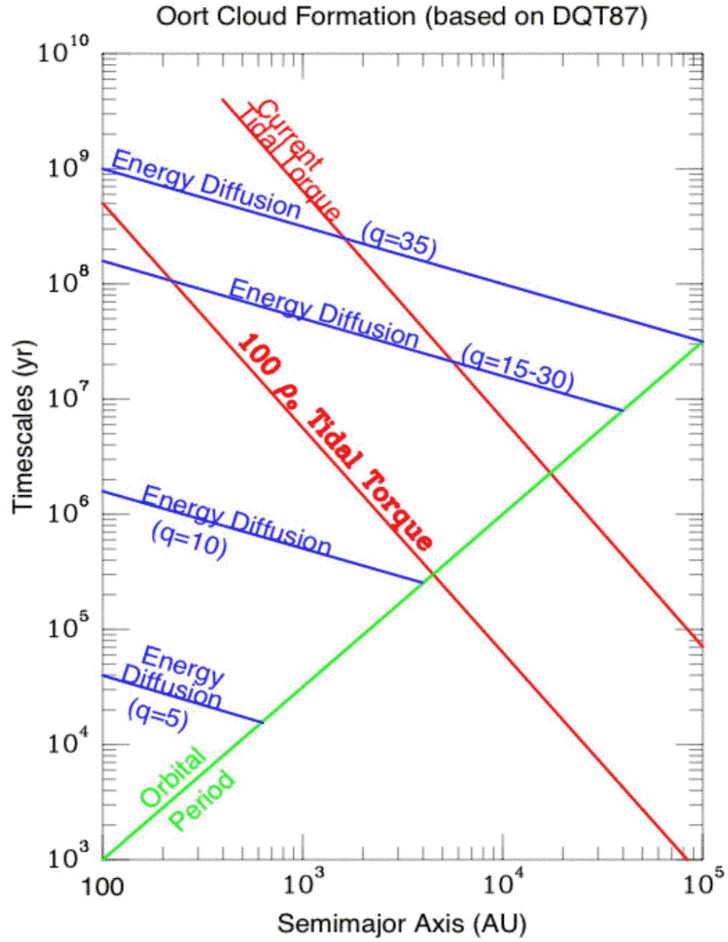
i = 11.9 degrees

Now at 90 AU --> will reach perihelion in 2076!)

Origin? (cf. Preprint by Morbidelli & Levison)

Galactic vs Planetary Perturbations

- The upper red curve shows the timescale for the Galactic tidal field to change the perihelion distance 'q' by 10 AU of a comet orbiting the Sun with q0 = 25 AU (IN THE ABSENCE OF PLANETARY PERTS).



Origin of Halley-type Comets: Isotropic Inner Oort Cloud ?

Levison, Dones & Duncan(2001) integrated the orbits of 27,700 test particles.

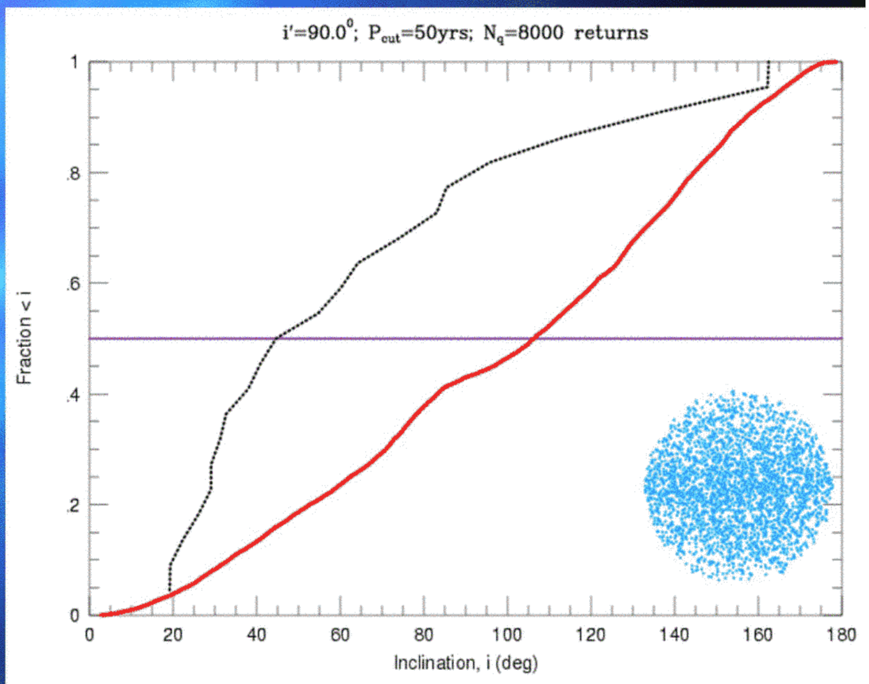
o Initial orbits:

uniform in a between 5000 & 50,000AU

uniform in q between qmin(a) and 34AU (reproduce Jupiter Barrier)

uniform in cos(i).

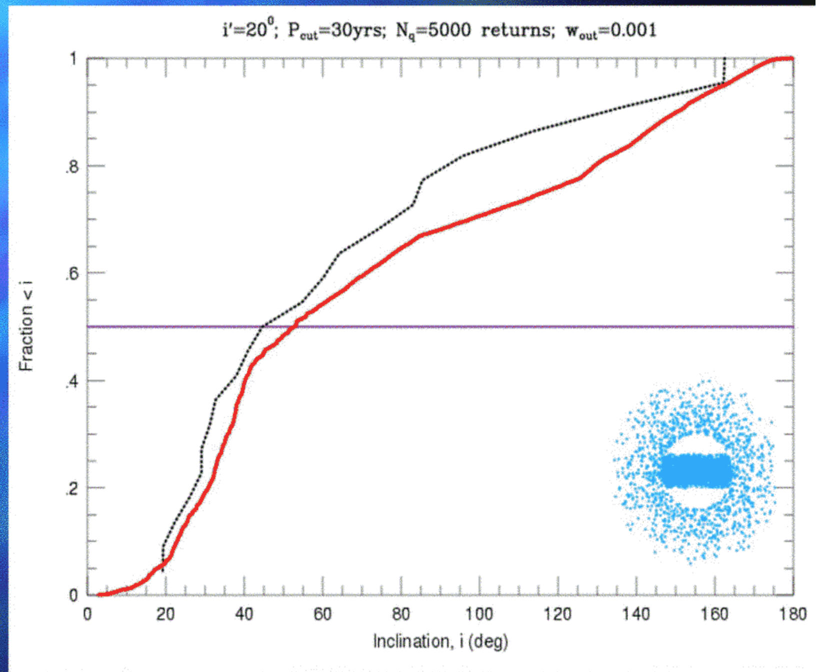
o Forces included Sun and 4 giant planets, Galactic tides & passing stars.



Isotropic model does not reproduce the observed HTC inclination distribution

Origin of Halley-type Comets: Flattened Inner Oort Cloud?

- 2-Component models
- Include an isotropic outer (a>20,000AU) and flattened inner cloud (a<20,000AU): varied mean inc. (i') in inner cloud
- Varied the inner/outer mass ratio.
- 4 free parameters.
- Find 10 degrees < i' < 50 degrees required.
- Median inclination of entire cloud ~ 50 degs.

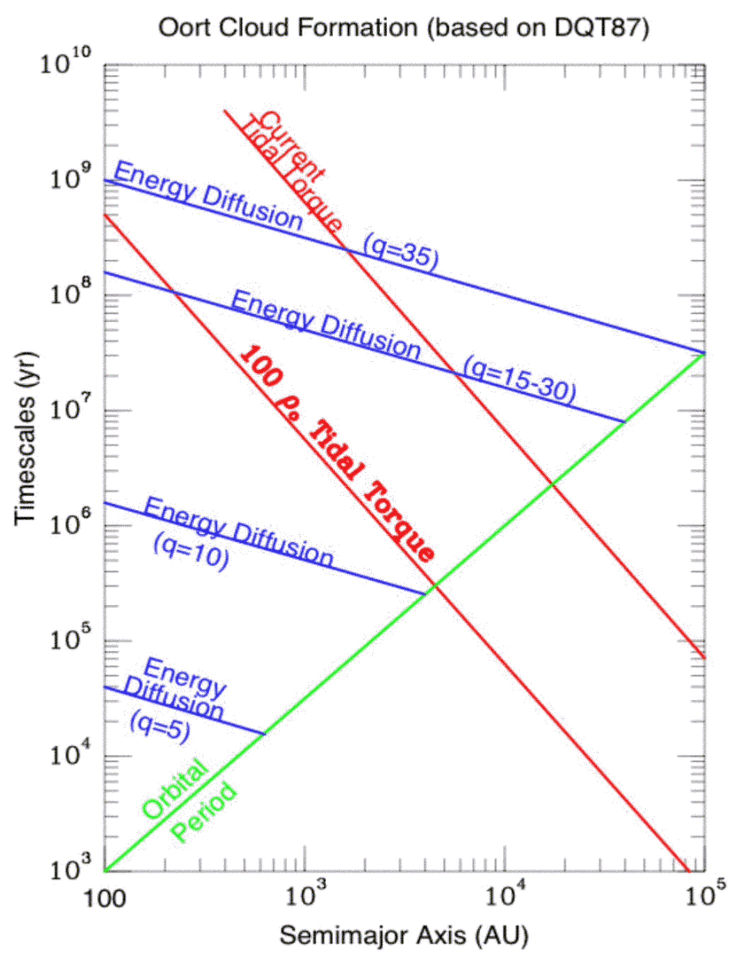


Requires a massive flattened inner Oort cloud but extremely difficult to simultaneously
1) have tides weak enough not to isotropize orbits and
2) strong enough to drive peri of comets past Neptune before Neptune ejects it.

Evolution of SD:

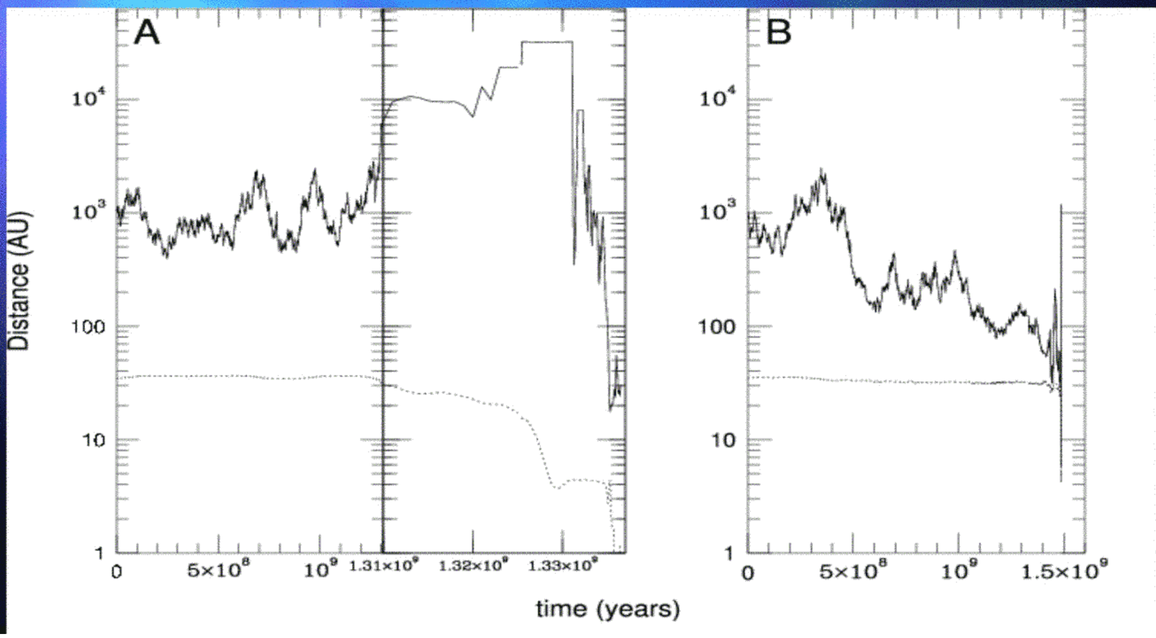
Eccentric orbits with peris just beyond Nep diffuse in semimajor axis (upper left blue curve).

If comets go beyond ~ 2000 AU, Galactic tidal field can torque them enough to change peri by ~10 AU (top red curve) before they diffuse much further in 'a'.



Origin of Halley-type Comets: The Scattered Disk?

- Levison, Duncan, Dones & Gladman (2004 - LDDG04) resumed integration of 28 objects (plus 20 clones each) in LD97/DL97 which had q > 25 AU and were stopped after at least 1 Gyr because a > 1000 AU.
- Included Sun, 4 Giant planets, Galactic tidal field and passing stars. Made 999 clones for comets first reaching q = 18 AU. Used 100 processors as necessary.
- RESULTS: Comets reaching small enough q to be visible typically followed 2 paths:
- Panel A: Nep drives a out until tides + J&S produce HTC-like orbit. Panel B: produces JFCs

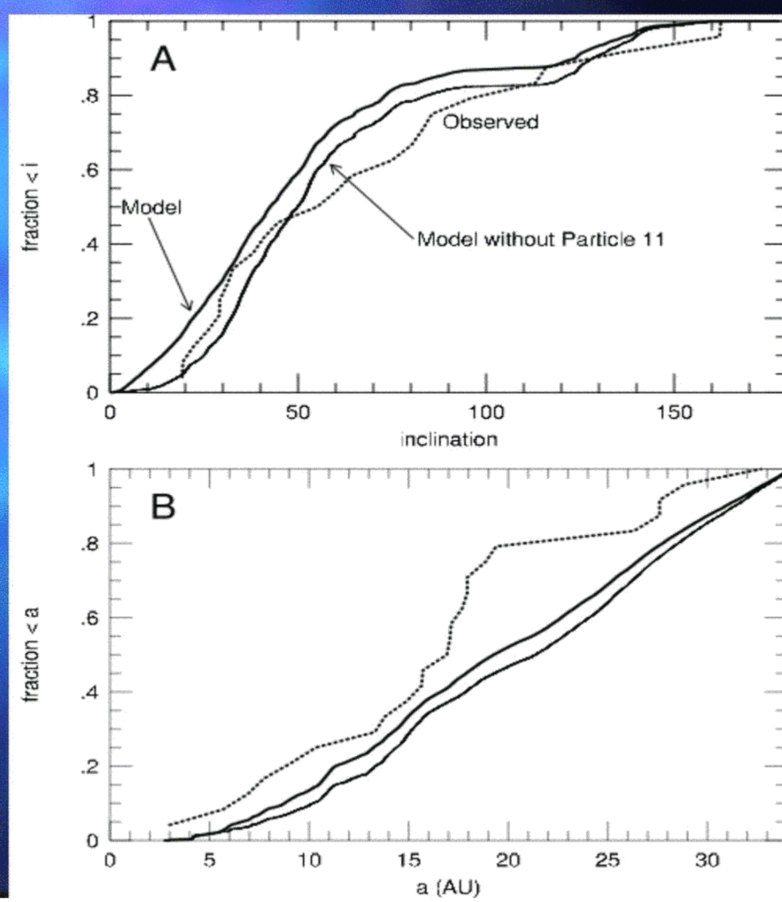


Origin of Halley-type Comets: The Scattered Disk?

LDDG04 RESULTS

1) KS test shows good agreement considering small # of HTCs and likely observational incompleteness for large semimajor axis.

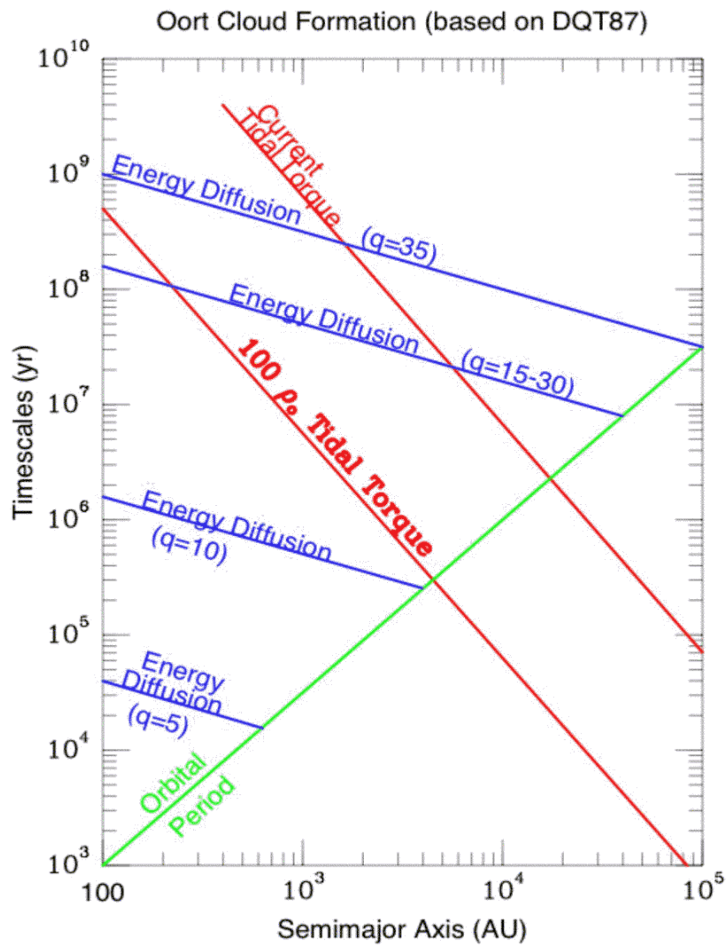
2) Approx. 0.01% of objects evolve to HTC-like comets. A Scattered Disk like DL97 containing ~ 5 billion comet-sized bodies could supply all the observed HTCs.



Oort Cloud Dynamics

In current Galactic environment (upper red curve) Jup & Sat (lower 2 blue curves) tend to eject comets with peris in their vicinities.

Comets with peris in Ura - Nep zone and beyond (top 2 blue curves) can have peris lifted by tides before ejection.

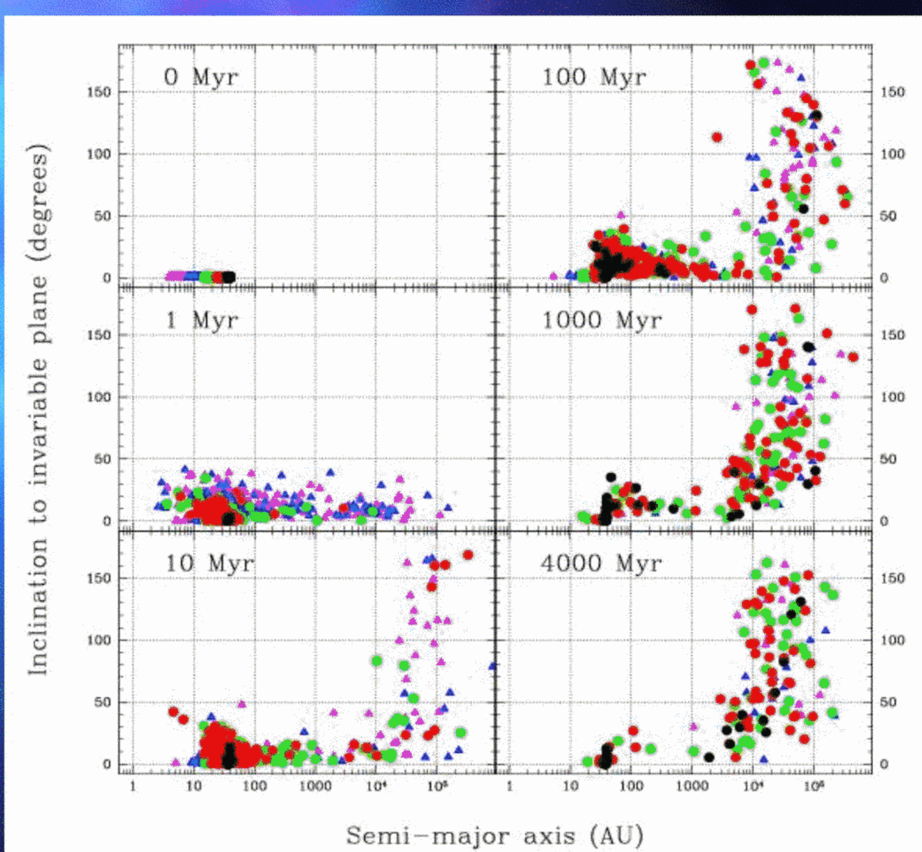


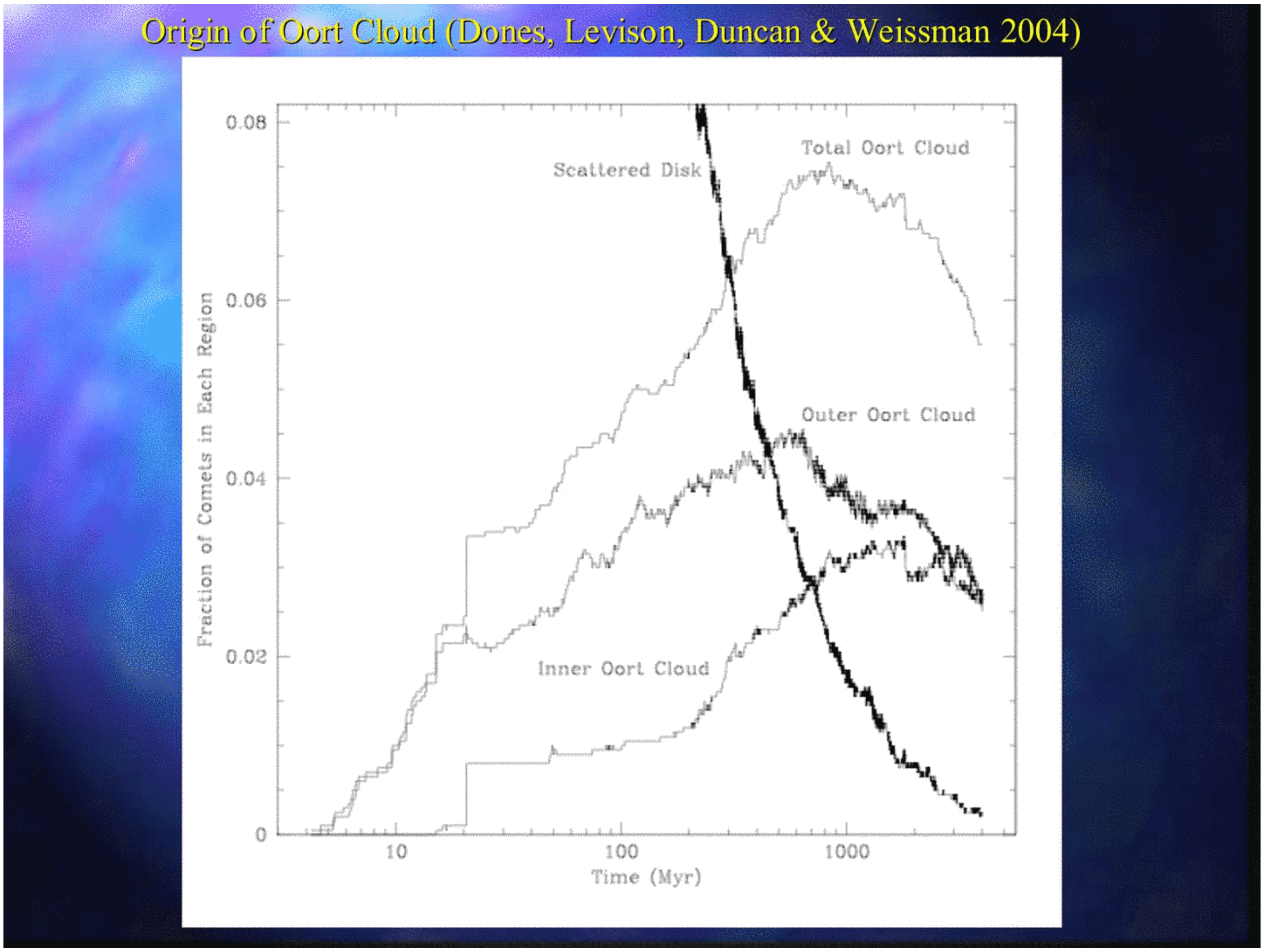
Origin of The Oort Cloud

Dones, Levison, Duncan & Weissman 2004 integrated the orbits of several thousand test particles.

Initial orbits were uniform in semimajor axis between 4 &40 AU with **small** eccentricities & inclinations (unlike DQT87)

Forces included Sun and 4 giant planets, Galactic tides (both disk and radial components) & passing stars.





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Summary

- Our simulations show that dynamical transport of bodies from a relatively low inclination trans-Neptunian disk successfully reproduces the Jupiter Family comet population and the Centaurs.
- Roughly 1% of objects encountering Neptune survive for the age of the solar system. A scattered disk of ~10^9 comets left over from planet formation could supply all observed Jupiter Family Comets and is consistent with observations of the scattered disk except for the extended component (q > 40 AU).
- Our simulations of capture from the Oort cloud into Halley-type orbits are inconsistent with an isotropic source. Simulations suggest a dominant flattened component must be the main source. The scattered disk of DL97 containing ~ 5 x 10^9 comets can naturally produce the observed HTCs.
- Planetesimal clearing using existing planetary orbits and Galactic tidal field is very inefficient (~2.5%) at creating the outer Oort Cloud and produces a total [scattered disk / Oort cloud] mass ratio much larger than inferred from observations. Preliminary results incorporating simple migration models give similar results. Next steps include growth of planetary masses, damping by gas and collisions, denser Galactic environment and/or cumulative effects of encounters with Giant Molecular Clouds.