Oort cloud and Scattered Disc formation during a late episode of giant planet migration

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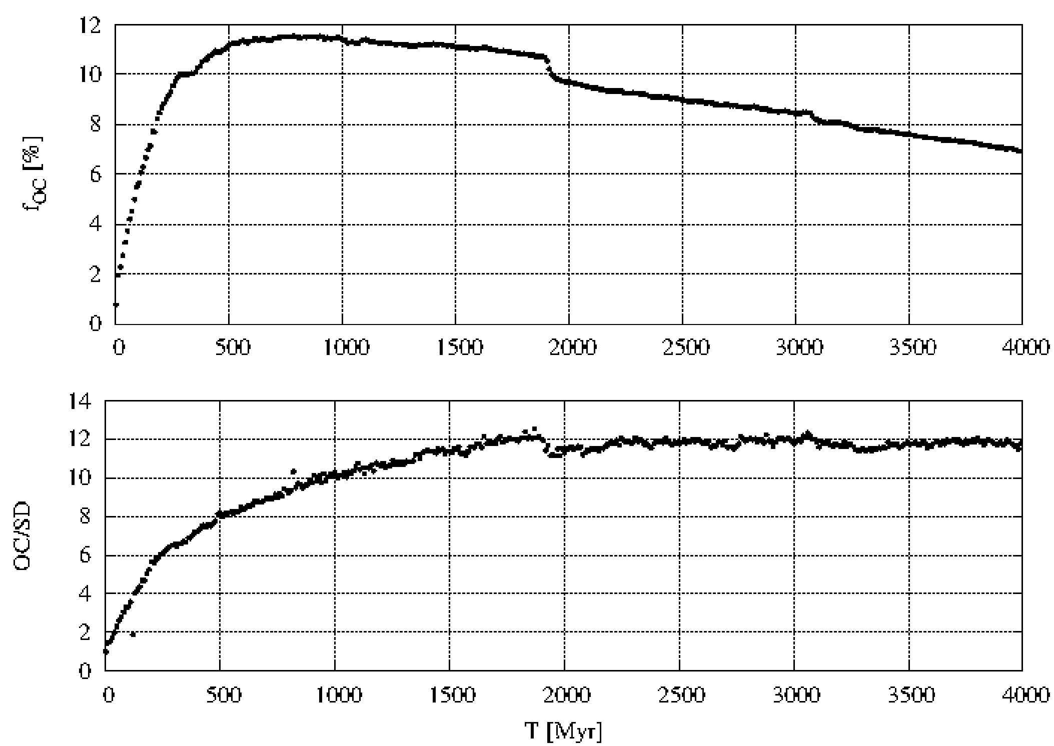
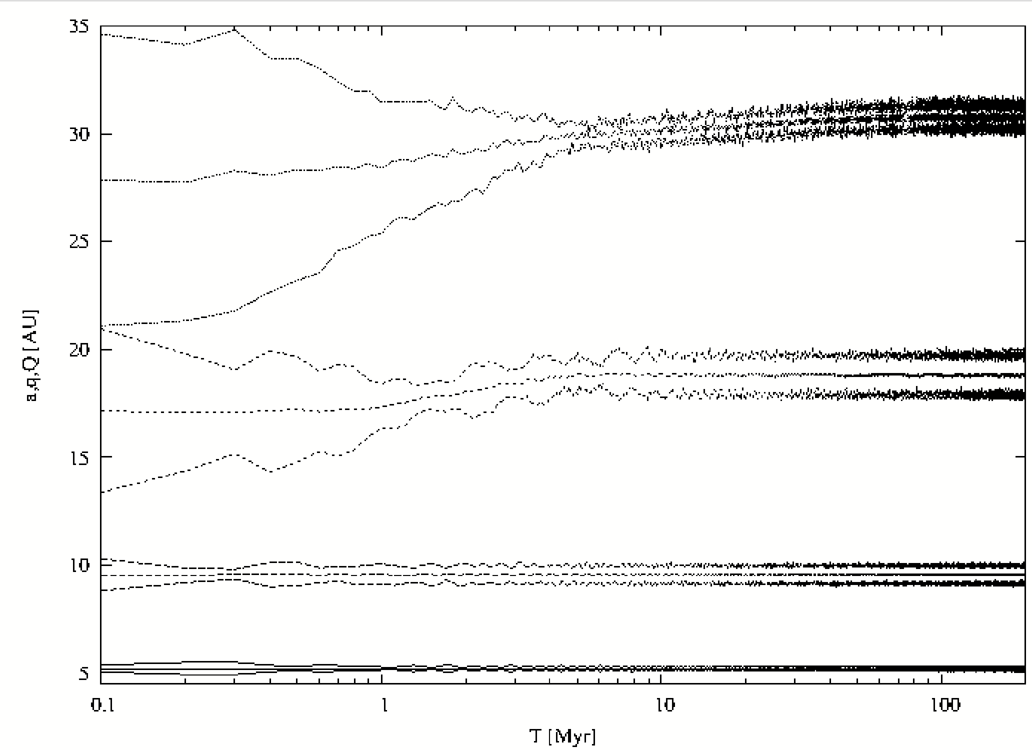
Overview

- Numerical evolution of OC and SD formation
- A new estimate of the flux of Long-Period Comets in the inner solar system
- The size and number of JFCs with absolute magnitude $H<6.5$.
- Updated estimate of visible JFCs.
- Size distribution of Jupiter-Family Comets
- A new estimate of the OC to SD population ratio.
- A few words about Halley-type comets.

A visualisation

OC and SD formation with planet migration





Duncan & Levison 97 did not include planetary migration, which could potentially change structure of SD. We do that here.

Use planetary evolution of Levison+2008.

Flux of JFCs and number SDOs depends on relative decay rate of SD: (df/dt)/f.

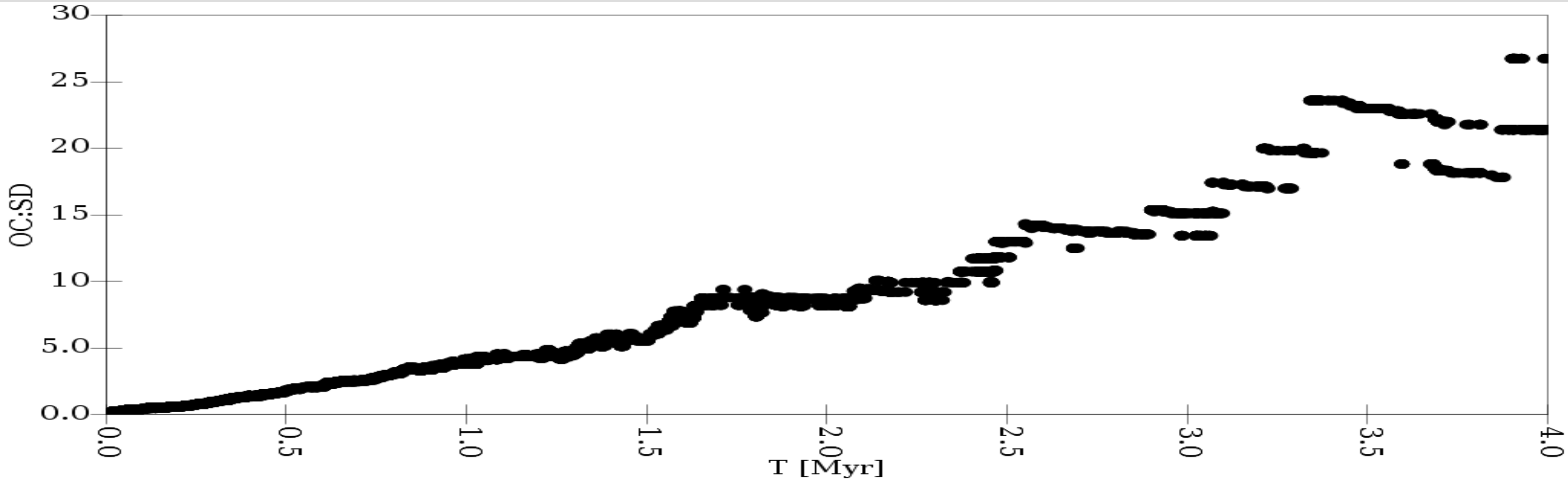
DL97: (df/dt)/f = -2.0×10^{-10} /yr. BM13 migration: -1.66×10^{-10} /yr.

Rodney Gomes with migration: -2.5×10^{-10} /yr. → Migration yields the same results.

OC formation efficiency: ~7%. OC:SD~10 → SD~0.7% efficiency

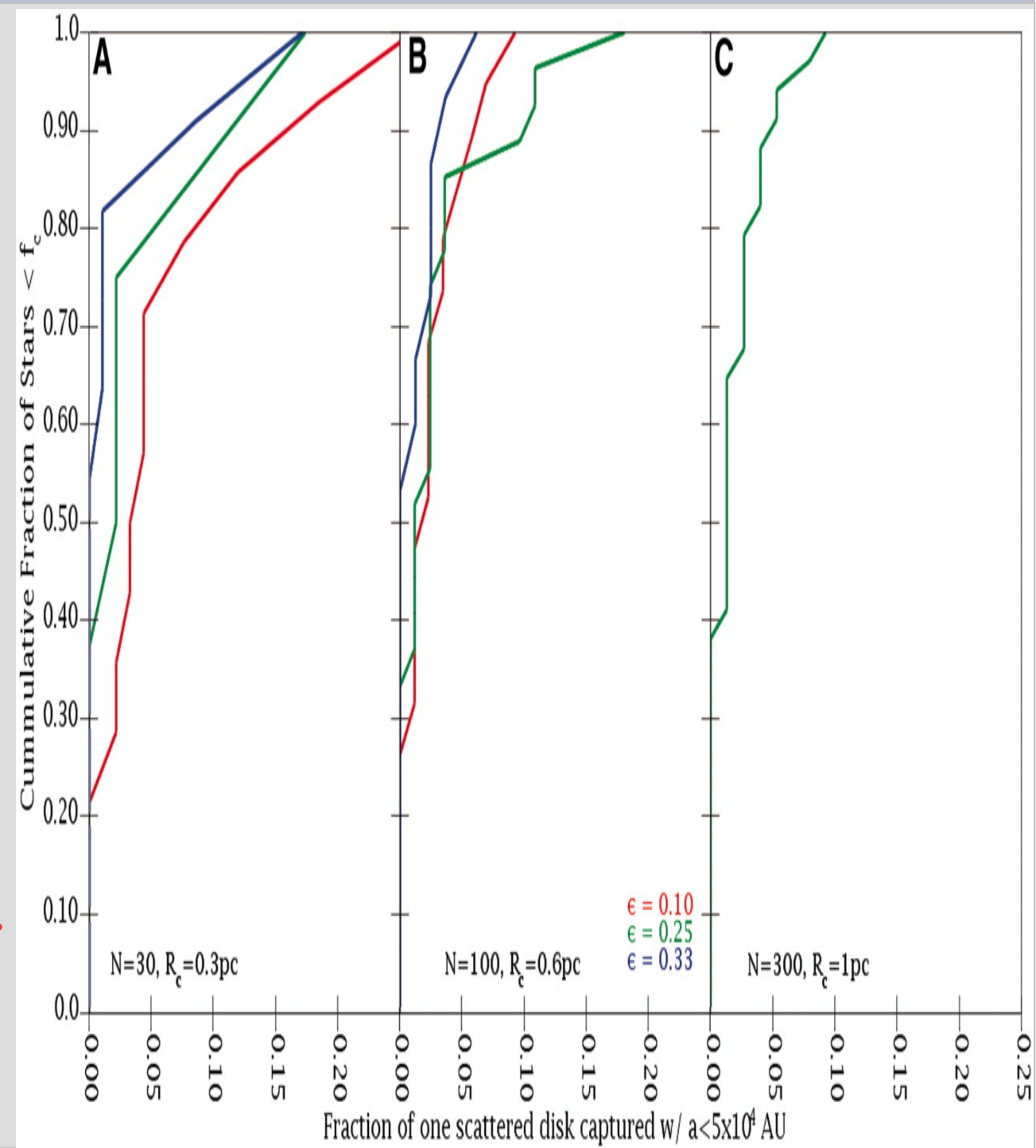
Classical population estimates

- The population of the Oort cloud is inferred from the flux of new comets that enter the inner solar system ($q < 4$ AU). Estimates range from 10^{11} to 10^{12} comets with total absolute magnitude $H<11$ (e.g. Weissman, 1996; Wiegert & Tremaine, 1999; Francis, 2005; Kaib & Quinn, 2009).
- The population of the Scattered Disc (SD) is inferred from the flux of Jupiter-family comets (JFCs). Duncan & Levison (1997) find SDO : JFC is $1.3 \times 10^6 : 1$. Using total number of JFCs with total absolute magnitude $H<9$ total SDO population is 6×10^8.
- Observationally-inferred ratio OC:SD ~ 100:1 to 1000:1.
- Simulations yield a ratio of ~ 20:1 to 10:1 (e.g. Dones et al., 2004; Kaib & Quinn, 2008; Brasser & Morbidelli 2013).
- How do we reconcile these differences?

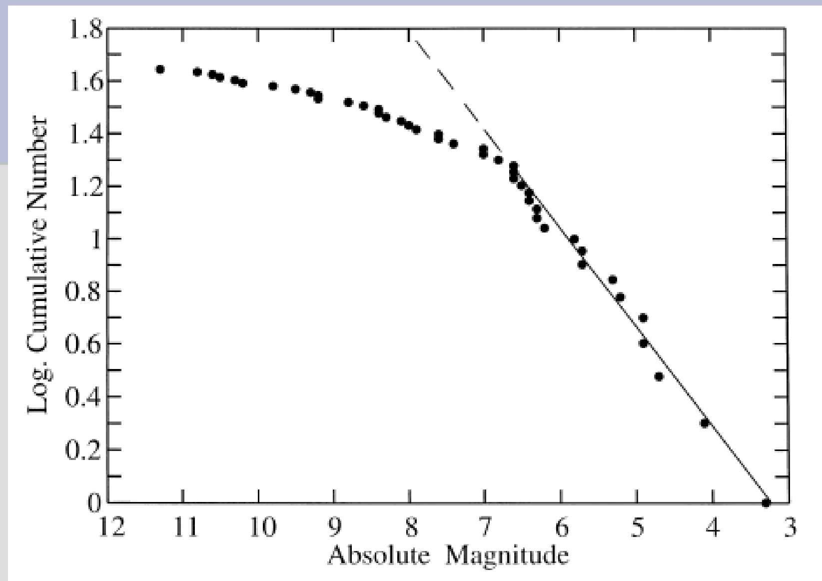


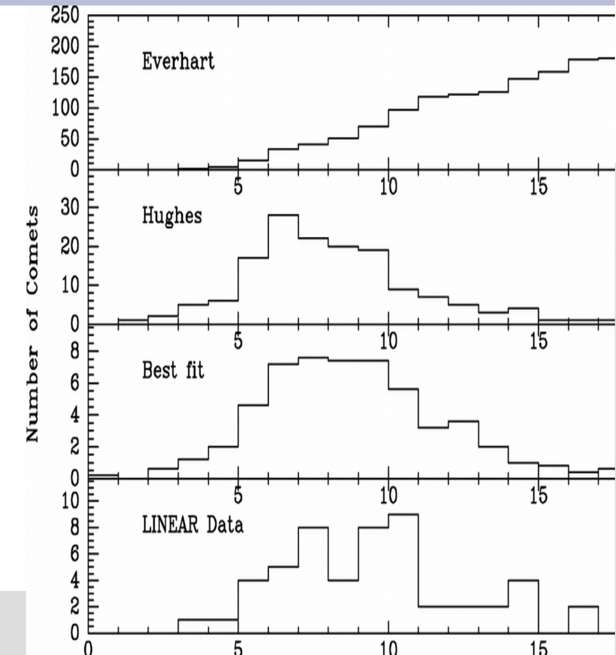
Proposed solutions to population discrepancy

- 1) The majority of comets were captured by the Sun as it exited its birth cluster (Levison et al., 10). → This gives the right amount of comets in the OC.
- 2) There is a size discrepancy between new and long-period comets (LPCs) and JFCs with the same absolute magnitude. We examine this solution here.



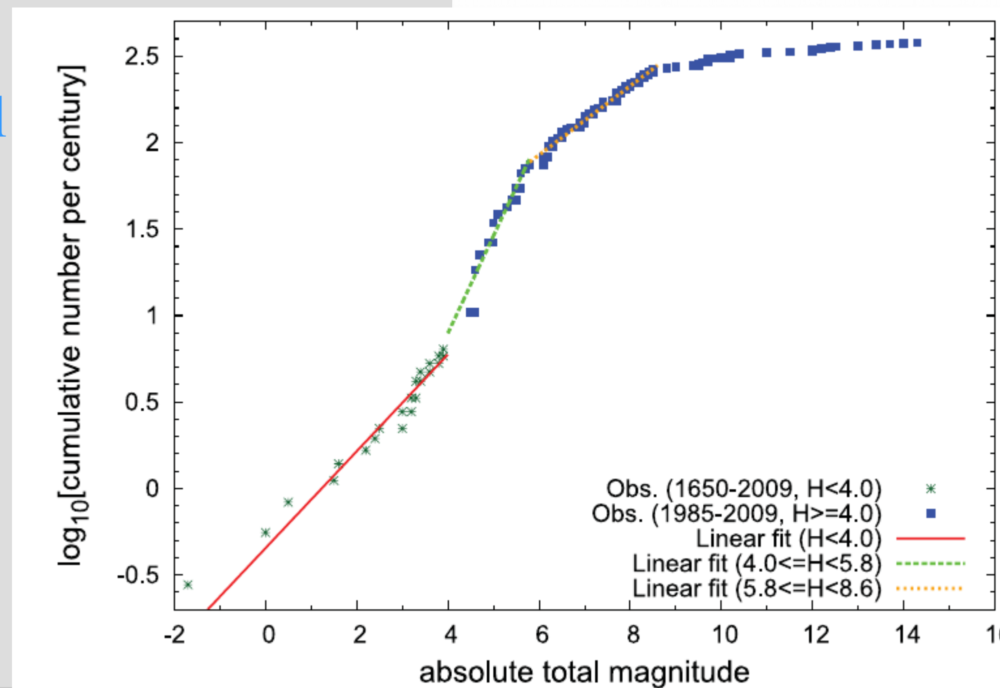
The flux of LPCs I: Raw data





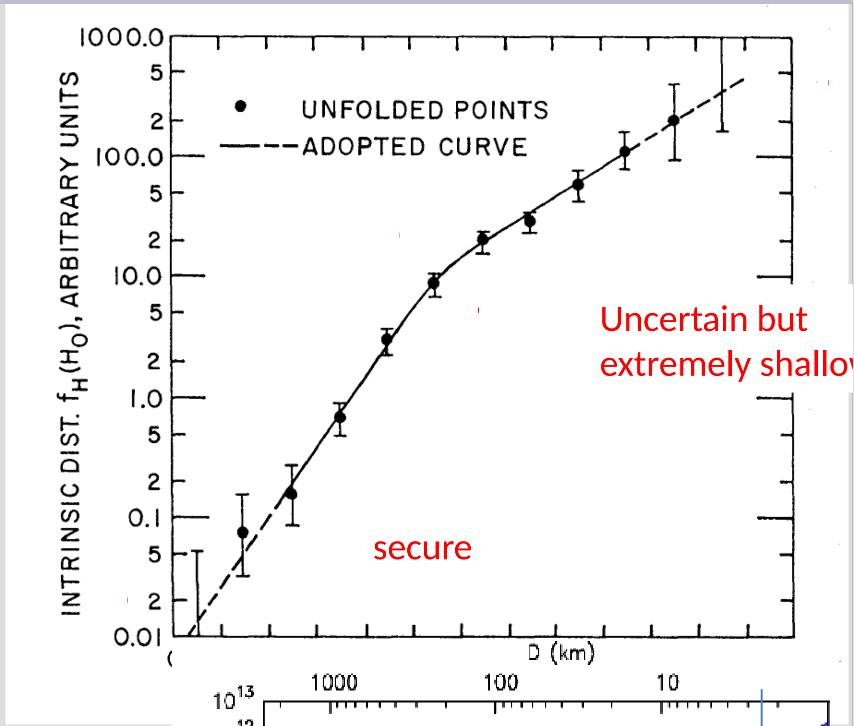
- Three main sources: Everhart 1967, Hughes 2001 and Francis 2005.
- Everhart: 60/yr with q<4 and H<11.
- Hughes: 0.5/yr with q<4 and H<6.5.
- Francis: 3/yr with q<4 and H<11.
- WHAT A MESS!!
- There is a catch: slope of absolute magnitude distribution shallow above H>6.5. Probably observationally incomplete. Need to redo for H<6.5.

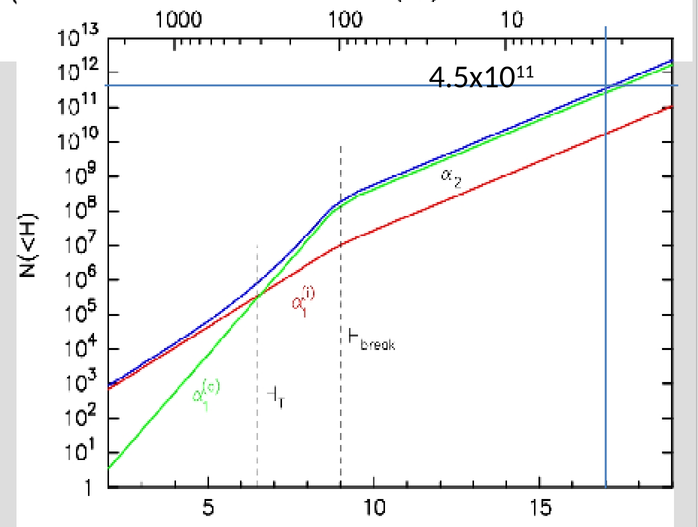
Also: the actual rate may be higher (Krolikowska's talk earlier today).



The flux of LPCs II: New determination

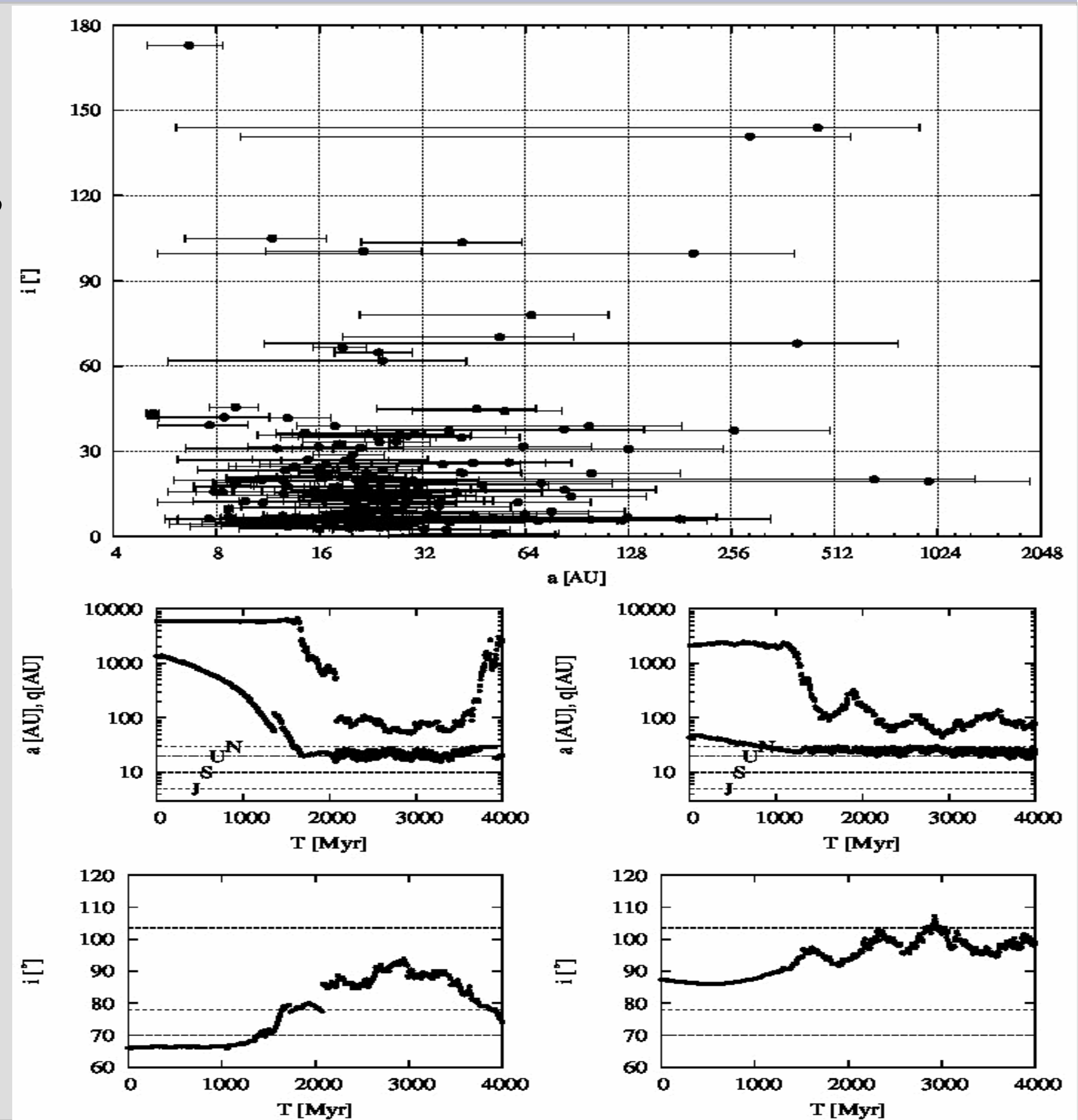
- Everhart: 60/yr with H<11 and q<4. Ratio between H=11 and H=6.5: 12. Restrict to q<2.5 and accounting for new comets → 1.1/yr with H<6.5 and q<2.5.
- Hughes: 0.44/yr H<6.5, q<2.5.
- Francis: 0.73/yr with H<6.5 and q<2.5.
- Average flux: 0.8/yr with H<6.5 and q<2.5.
- Kaib & Quinn (2009): probability of OC comet to be visible ~10^{-11}.
- Thus total OC population of comets with H<6.5: 0.8 x 10^{11}. NOTE: similar to, but on the low end of, earlier estimates for H<11.
- Population order of magnitude lower than Wiegert & Tremaine (1999).
- With our efficiency, ~ 1.5×10^{12} objects in the disc.
- What is the number of objects in the SD?





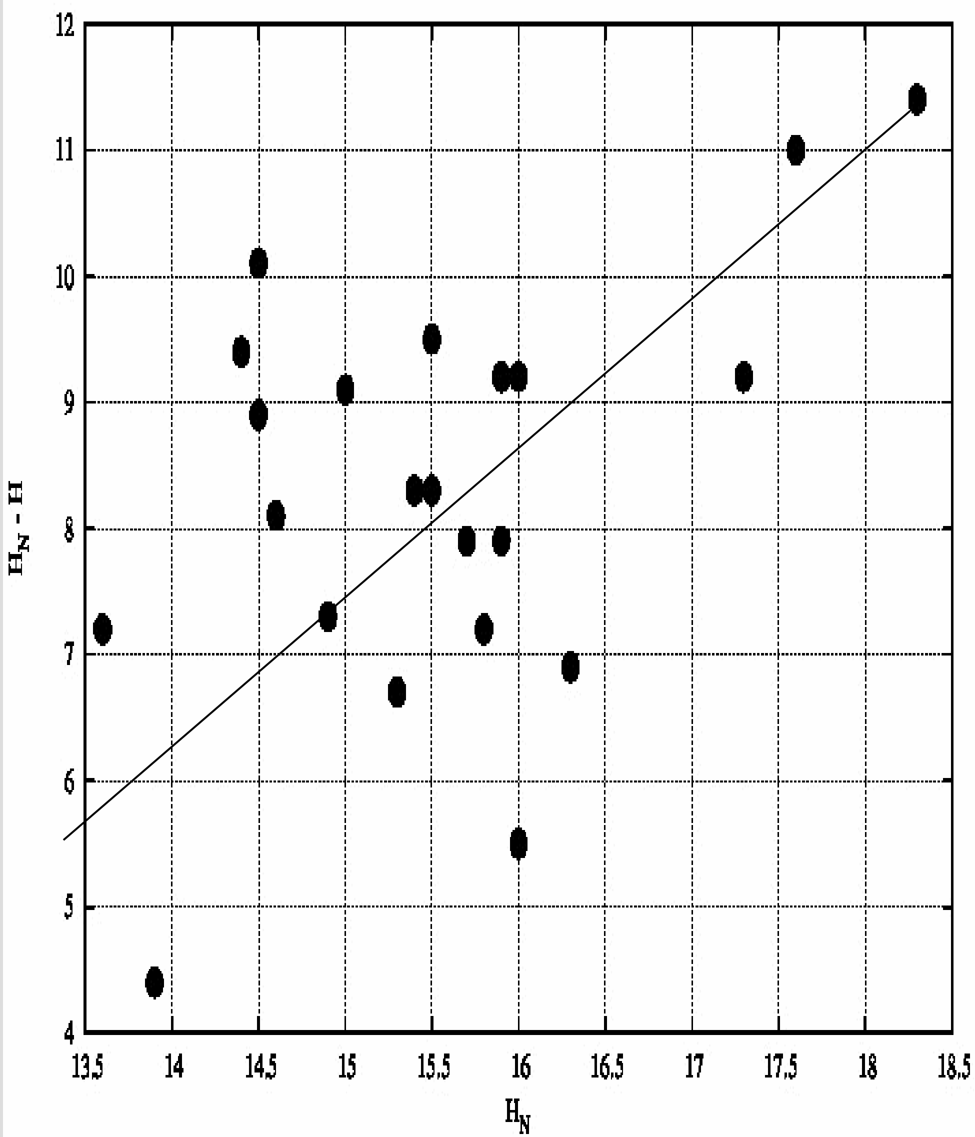
A second estimate of the number of Oort cloud objects: The high-perihelion high-inclination Centaurs

- Observed number of Centaurs with i>60 deg is much larger than predicted from KBO and SD inclination distribution → Additional source of Centaurs. Oort cloud?
- Three of these i>70, q>15, a<100. Pulled in from OC by Uranus and Neptune. Called HIHQ Centaurs.
- Probability of OC object being HIHQ: 10^{-5} (Brasser+2012).
- Estimated number of HIHQ with H_N<8: ~ 100.
- Number of OC objects with H_N<8: ~10^7
- Estimated number of OC objects with D>2.3 km (H_N<17): ~10^{11} if α ~ 0.4.



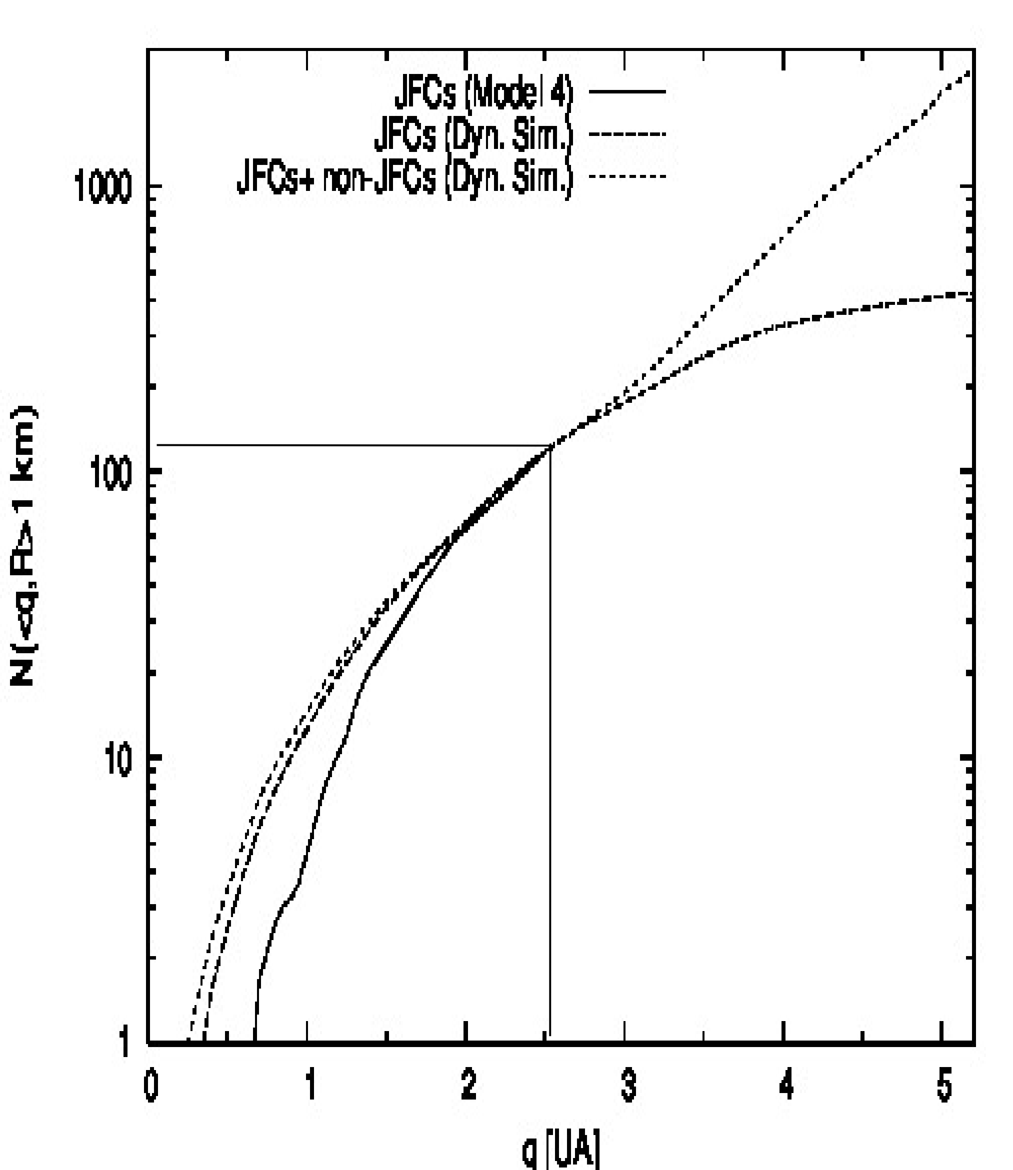
The sizes of LPCs and JFCs with H = 6.5

- LPCs. Use diameter-absolute magnitude relation from Sosa & Fernandez (2011): $\log(D) = 1.2 - 0.13H$. $H = 6.5 \rightarrow$ D = 2.3 km.
- JFCs: no clear relation exists because coma hides nucleus. No relation between H and diameter size, D → Use absolute magnitude of nucleus, H_N.
- Average value of $H_N - H$ for JFCs ~ 8.5 (Kresak & Kresakova 1989, 1994; Fernandez et al 1999) → JFC with $H = 6.5$ has $H_N \sim 15$. Assuming albedo 4% → D = 6.7 km.
- Thus LPC and JFC with same total absolute magnitude *HAVE A DIFFERENT SIZE!!!*
- We need to do the analysis for both LPCs and JFCs with diameter 2.3 km.



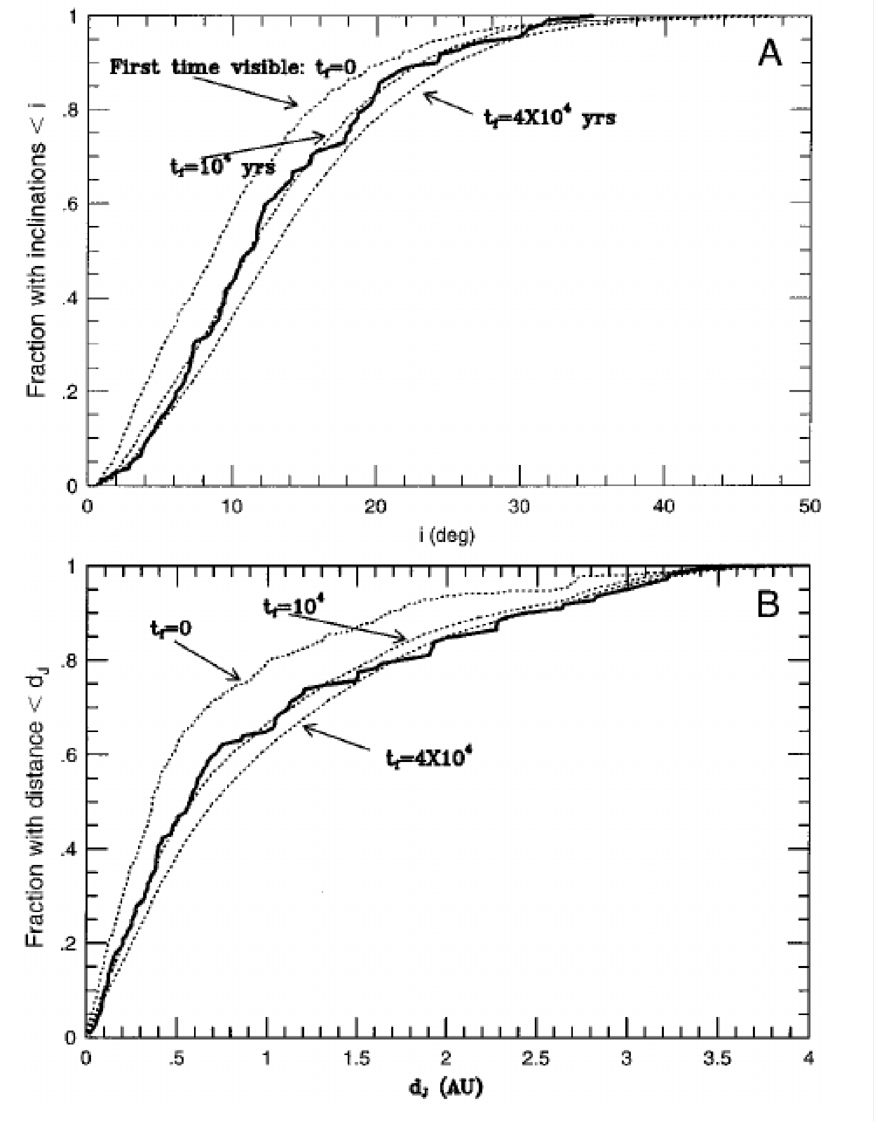
The number of JFCs with D > 2.3 km

- Di Sisto+09: 100 active JFCs with D > 2 km and q < 2.5 AU.
- Duncan & Levison (1997) find 108.
- Need to account for inactive comets because they fade.

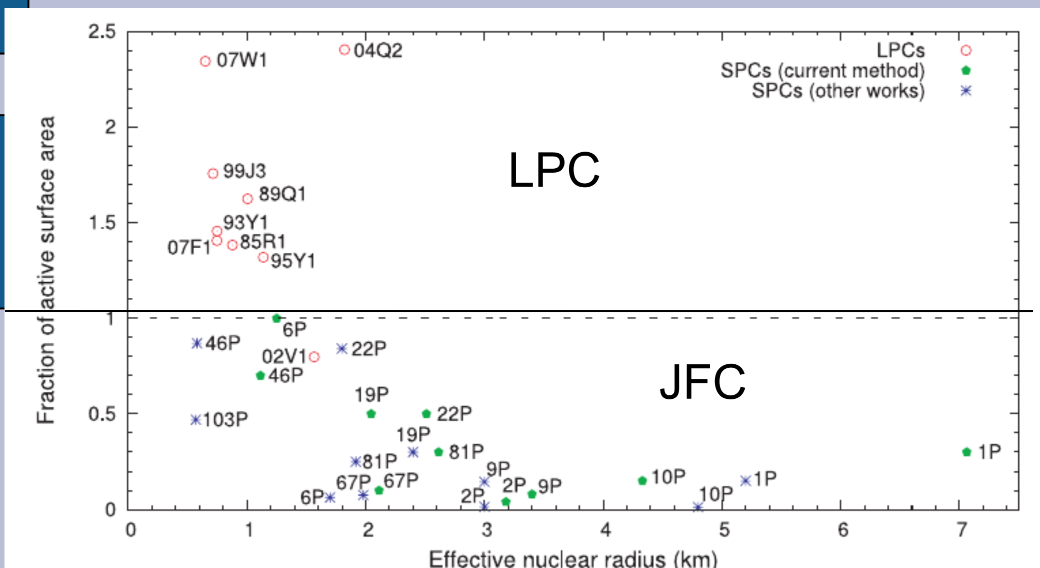


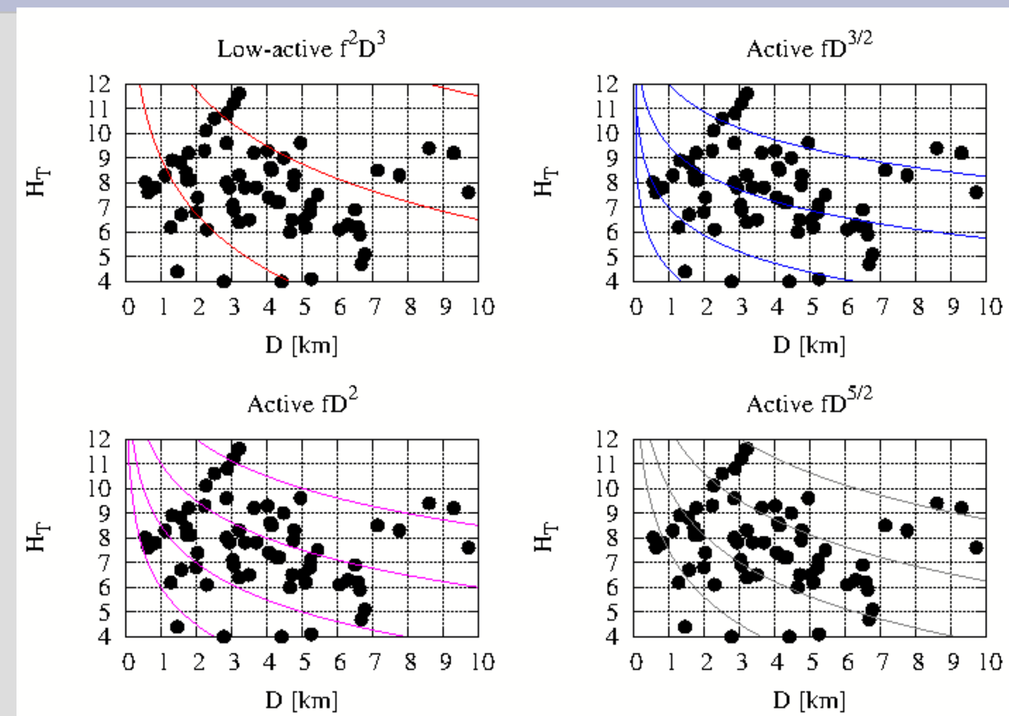
Fading of JFCs I

- Levison & Duncan (1997): Fading necessary to explain observed orbital distribution.
- Assumed comets 'switched off' after some visible time t_v.
- They found $t_v \sim 12$ kyr.
- But comets fade gradually...



Fading of JFCs II





LPC have active fraction f ~ 1.

JFCs <log f > = -1.73 ± 0.83.

JFCs are far less active than LPCs!

Relation between active fraction, diameter and H is complicated. Assume fD^2 = const →

H = C – 5log(D) – 2.5log(f) (JFC)

H=9.3 – 7.7log(D) (LPC) → C=8.31.

Fading changes absolute magnitude via ΔH ~ -2.5log(f) → ΔH ~ 4.3 magnitudes when <log f> = -1.73.

A JFC is typically 4.3 magnitudes fainter than an LPC of the same size!! (Brasser & Wang, 2015)

Fading of JFCs III: Monte Carlo experiments

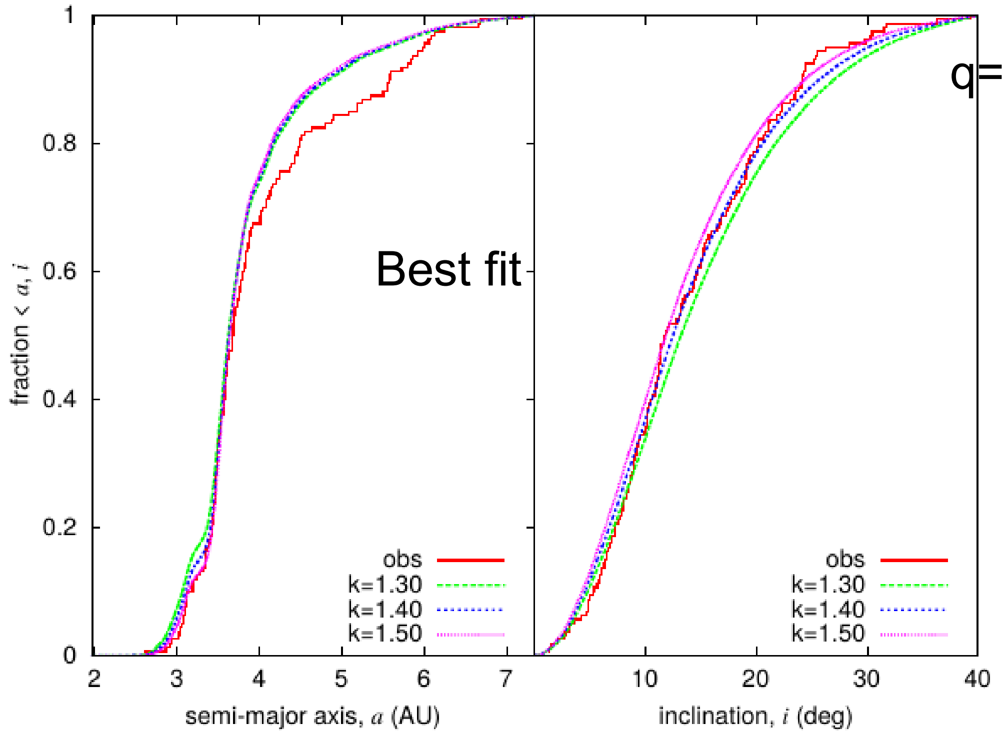


Fig. 6. The inclination and semi-major axis distributions from observation and simulation for JFCs that gave the best match from the delayed power law of Fig. 5.

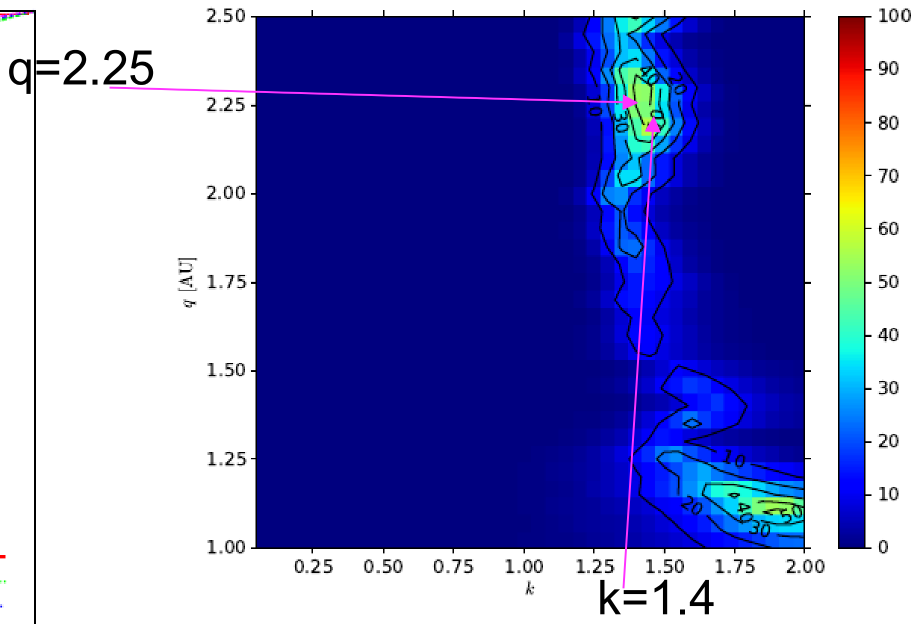


Fig. 5. Contour plots of the combined inclination and semi-major axis K-S probability as a function of the fading parameter and maximum perihelion distance for the delayed power law. Here log $M = 1.6$. The parameters that best fit both distributions are $k = 1.4$ and $q_m = 2.30$ AU.

The typical maximum number of perihelion passages with q<2.5 before ejection by Jupiter is <log n> = 2.62 ± 0.85 or <n> ~ 430 from dynamical simulations.

Need a fading law that produces ΔH=4.3 after 400 revs. Monte Carlo experiments results in approximate power law with $f \sim (40+m)^{-(k/2)}$ and k~1.4. Half-life 52 revs (Brasser & Wang, 2015).

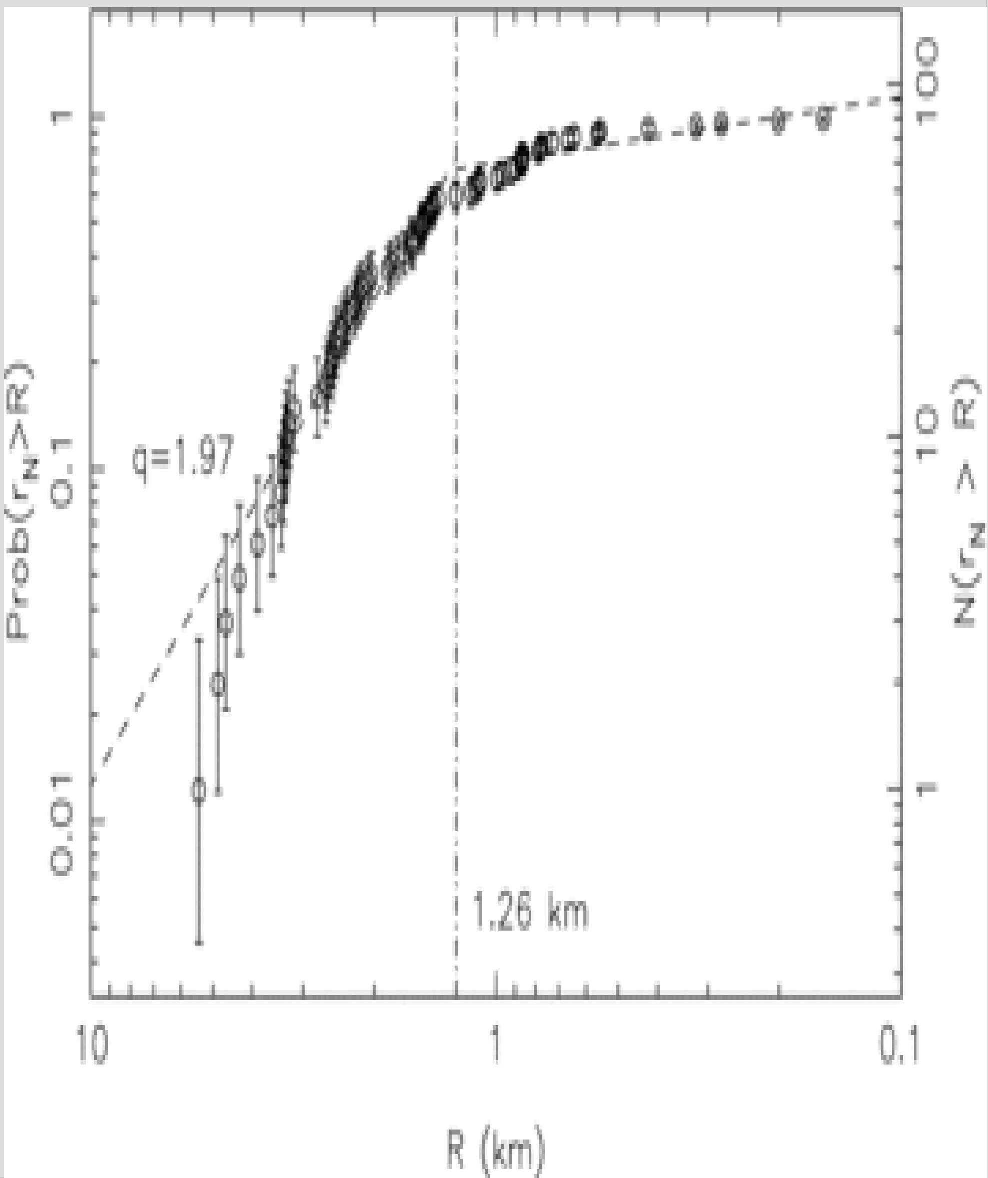
Fading law fits semi-major axis and inclination distributions. Observationally complete to q~2.3 AU.

The total active JFC population

- Fernandez & Morbidelli (2006): 8 (now 10) JFCs $q<1.3$, $H<9$.
- Brasser & Wang (2015): 18% of visible JFCs have $q<1.3 \rightarrow$ 56 comets total with $H<9$.
- JFC of same size as LPC is 4.3 magnitudes fainter.
- Need JFC population with $H<10.8 \rightarrow$ Size-frequency distribution of nuclei.

Size distribution of JFCs

- The cumulative size distribution of cometary nuclei follows N(>D) ~ $D^{-\gamma}$. In terms of absolute magnitude this becomes N(>H) ~ $10^{-\alpha H}$.
- Most studies find $\gamma = 1.9 \pm 0.1$ ($\alpha = 0.38 \pm 0.02$) (Meech+04; Weissman & Lowry; Lamy+04; Snodgrass+11).
- Exception: Tancredi+07: γ ~ 2.6.
- Some studies predict paucity of very small objects (D < 2.5 km). Probably true and no selection effects.
- If JFCs and OC objects share same source, then SFD or absolute magnitude distribution of OC objects should be same as JFCs.



The SD population of comets with D > 2.3 km

Using SFD: N_{JFC} ~300 with H<10.8 or D>2.3 km (56*10$^{[0.38*(10.8-9)]}$)
More than Di Sisto et al. (2009) by a factor of 3.

The total number of SDOs is then: $$N_{\mathrm{SDO}} = \frac{N_{\mathrm{vJFC}}}{\tau_{\mathrm{vJFC}} | r_{\mathrm{SD}} | f_{\mathrm{vJFC}}},$$

The active lifetime: $$\tau = \langle P \rangle \langle n_r \rangle,$$

The weighted (fading) mean period is: $$\langle P \rangle = \frac{\sum_{i=1}^{N_T} P_i w_i}{\sum_{i=1}^{N_T} w_i},$$

The fraction of SDOs that become JFCs ~ 15% (Brasser & Morbidelli, 2013).

The active lifetime is ~2000 yr (Brasser & Wang, 2015).

Total SDOs ~ 6 billion (Brasser & Wang, 2013).

OC to SD population ratio

OC: 0.8×10^{11}.

SD: 0.06×10^{11}.

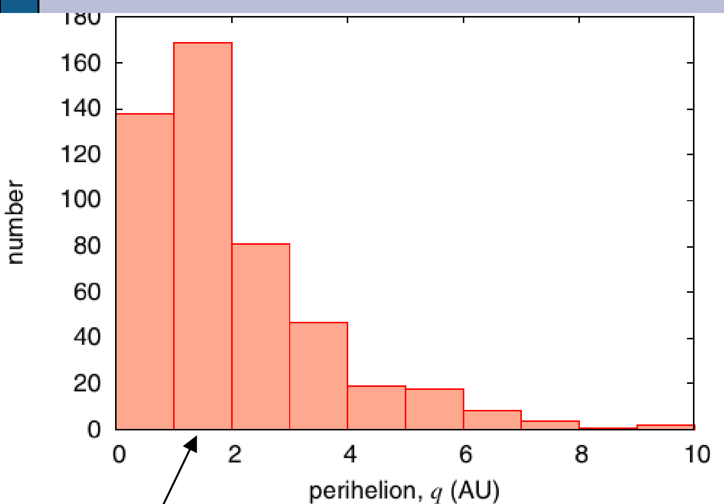
Ratio: 13, with large error bars.

Simulations and observations are consistent! (But only for the size I considered).

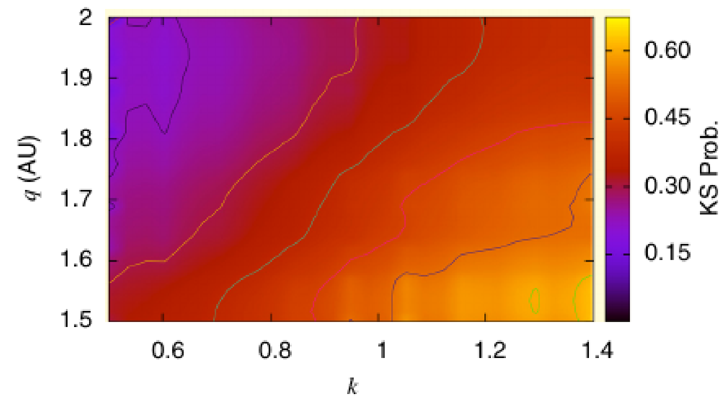
We don't need an extreneous source for comets, and the innermost Oort cloud (Sedna region) makes no relevant contribution to the JFC and LPC flux.

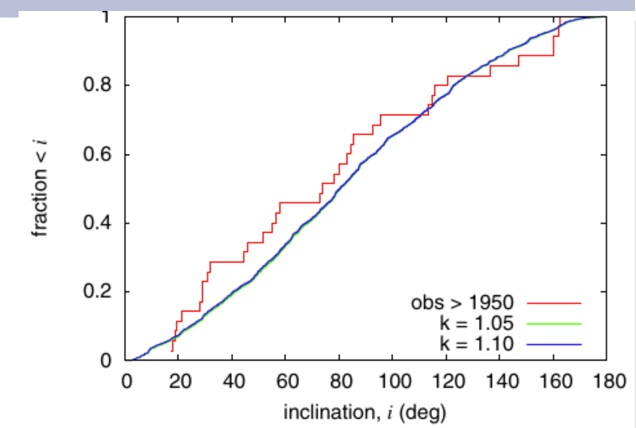
Case closed.

Implication: The Halley-type comets

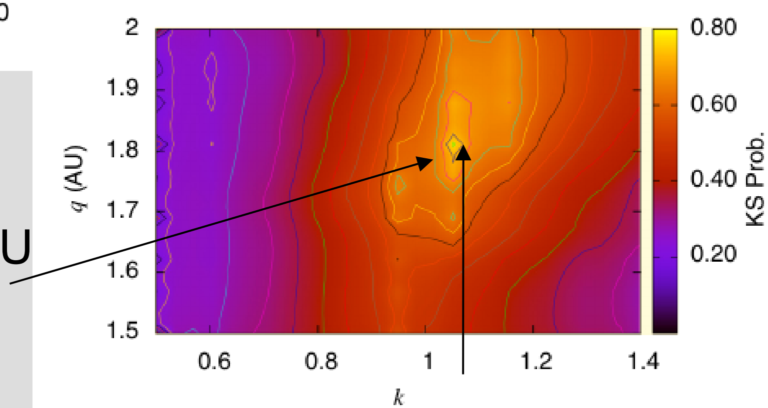


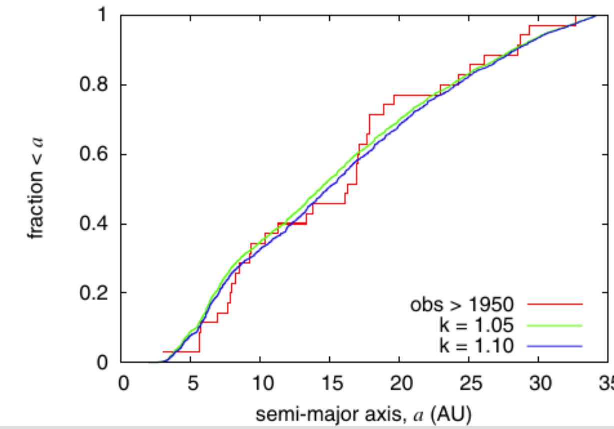
LPC perihelion distribution.





Max at q=1.77 AU





Applying fading to HTCs and assuming an OC origin, Wang & Brasser (2014) suggest there are ~100 HTCs with D>2.3 km and q<1.8 AU. Again, large error bars. We can reproduce semi-major axis and inclination distribution with an OC source.