Planet-Migration

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- planet–migration driven by a gas–disk: type I & type II
- planet–migration driven by a planetesimal disk
- Solar System & extra–solar planets: evidence for/against planet–migration?

Type I migration: follow the angular momentum

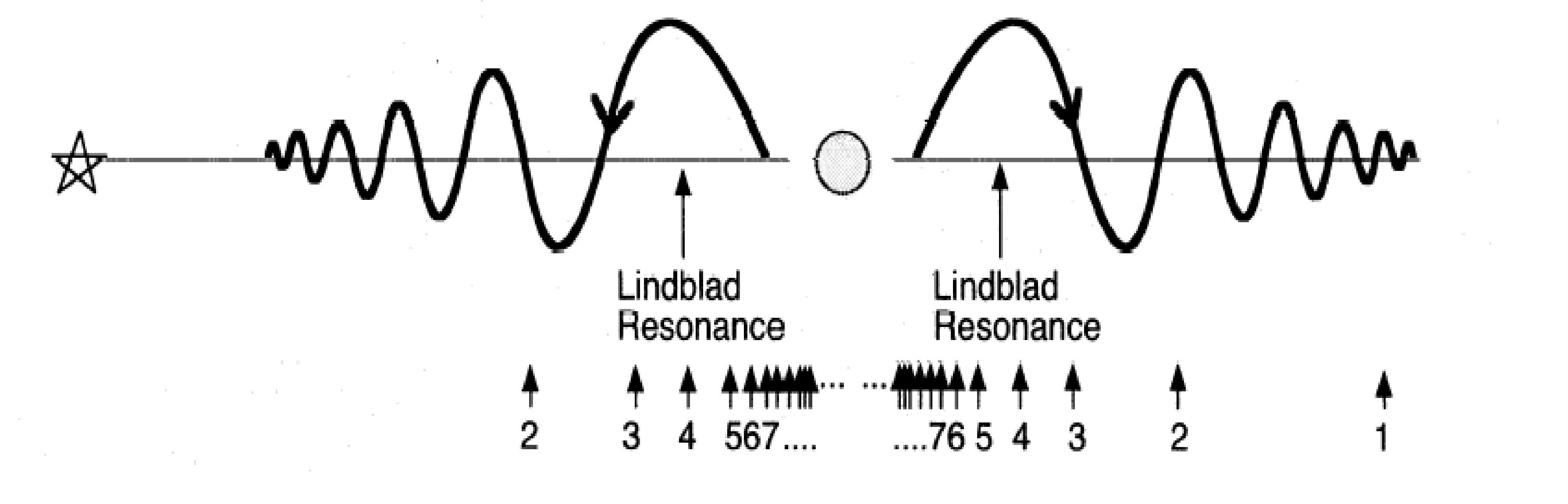


figure from Takeuchi *et al.* 1996.

Consider a planet embedded in a gas disk,
spiral density waves excited at Lindblad resonances,
interior waves transport negative **L** (planet gains **L** from inner disk),
exterior waves transport positive **L** (planet loses **L** to outer disk),
Note: no migration would imply a very delicate torque balance!

Differential Lindblad torques

Use spiral density wave theory to calculate torque on planet from m^{th} resonance:

$$T_m = \pm f_m \left(\frac{M_p}{M_\odot}\right)^2 \left(\frac{\pi\sigma r^2}{M_\odot}\right) \left(\frac{h}{r}\right)^{-3} M_\odot (r\Omega)^2$$

(G&T 1980, Ward 1993, 1997, Arty. 1993).

Strongest torques from $m \sim \frac{r}{h}$ at $\Delta r \sim \pm h$.

Differential torque is ~ 30–50%T_m.

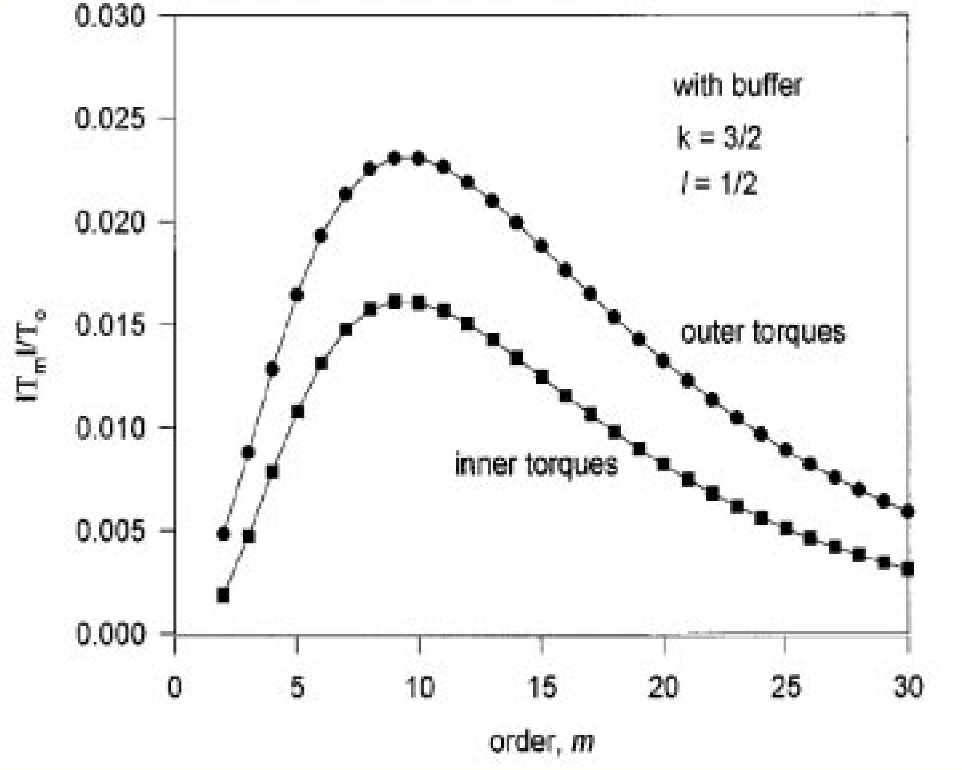


figure from Ward 1997.

Total Type I torque

$$
\begin{aligned}
T_{total} &= \sum T_m \\
&\simeq -C_{k,\ell} \left(\frac{M_p}{M_\odot}\right)^2 \left(\frac{\pi\sigma r^2}{M_\odot}\right) \left(\frac{h}{r}\right)^{-2} M_\odot (r\Omega)^2
\end{aligned}
$$

where $C_{k,\ell} = 1 + 0.06k + 1.2\ell$ with $\sigma \sim r^{-k}$ and Temp$\sim r^{-\ell}$.
$\Rightarrow$ inwards drift provided Temperature decreases with r.

orbit decay timescale $$\tau = \frac{L_p}{|2T_{total}|} \simeq \frac{1}{4\pi C_{k,\ell}} \left(\frac{M_p}{M_\odot}\right)^{-1} \left(\frac{\pi\sigma r^2}{M_\odot}\right)^{-1} \left(\frac{h}{r}\right)^2 P_{orb}$$

$$\sim 10^5 \left(\frac{M_p}{M_\oplus}\right)^{-1} \text{ orbits.}$$

These analytic torques were confirmed by 2D hydro models (Korycansky and Pollack 1993). However 3D models give $T_{3D} \simeq \frac{1}{3}T_{2D}$ so $\tau \to 3\tau$ (Tanaka, Takeuchi, and Ward 2000).

It is likely that Type I torques are not a *grave* concern for terrestrial planet formation since they probably formed in a gas–free environment:

$\tau_{growth} \sim 10^8$ years $> \tau_{nebula}$.

But type I migration *is* an issue for the formation of giant–planet cores since

$\tau_{migration} \sim 10^5$ years $< \tau_{growth} < \tau_{nebula}$.

Type I migration, scattering, and gas drag, all have effects on both the orbital & accretional histories of giant–planet cores.

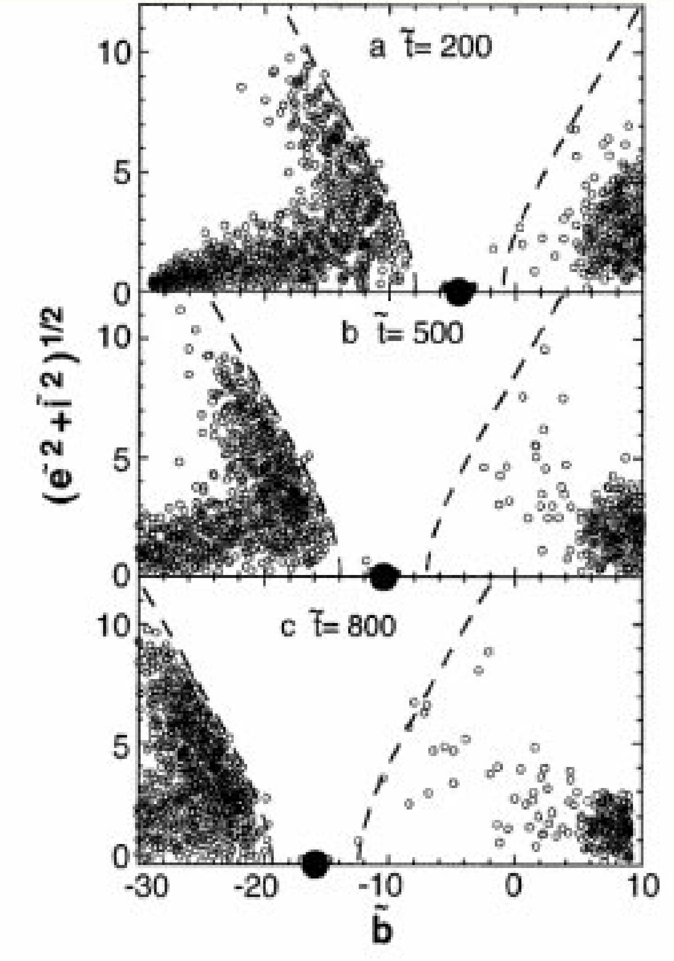


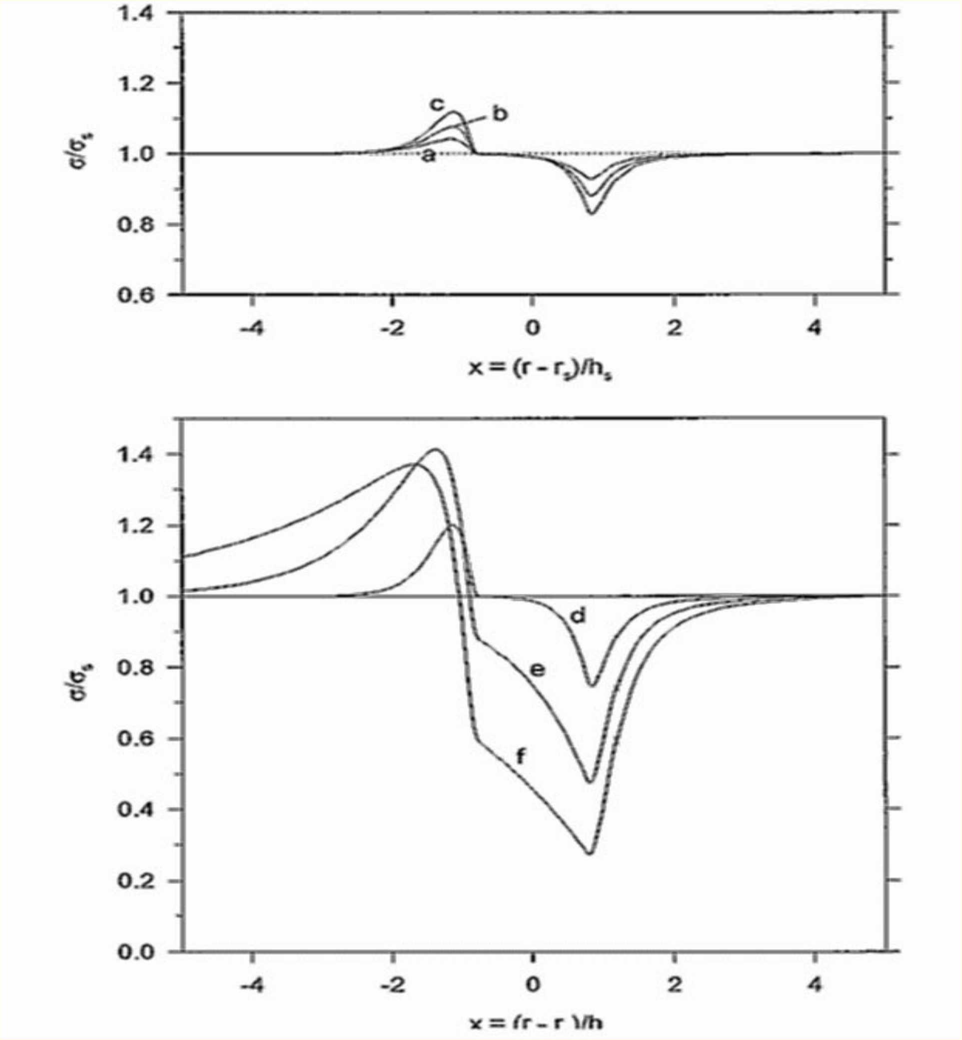
figure from Tanaka and Ida 1999.

Sculpting the Gas Disk

A kinematic wave co–evolves with the migrating protoplanet, slowing migration somewhat.

If the protoplanet achieves sufficient mass prior to falling into the Sun, then it opens a gap in the gas disk and shuts off type I migration.

figure from Ward 1997.



Gap Formation Criteria

Gap formation shuts off type I migration.

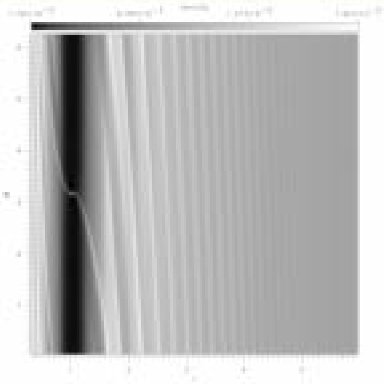
If waves damp locally (e.g., upon launch), then gap–formation requires $|T_{total}| > T_{viscous} \Rightarrow$ mass criterion:

$$M_p \gtrsim 3\sqrt{\frac{\nu}{r^2\Omega}}\left(\frac{h}{r}\right)^{3/2} M_\odot \sim 10\sqrt{\frac{\alpha}{10^{-4}}}M_\oplus.$$

with a gap width $\sim 2h$ (Hourigan and Ward 1984).

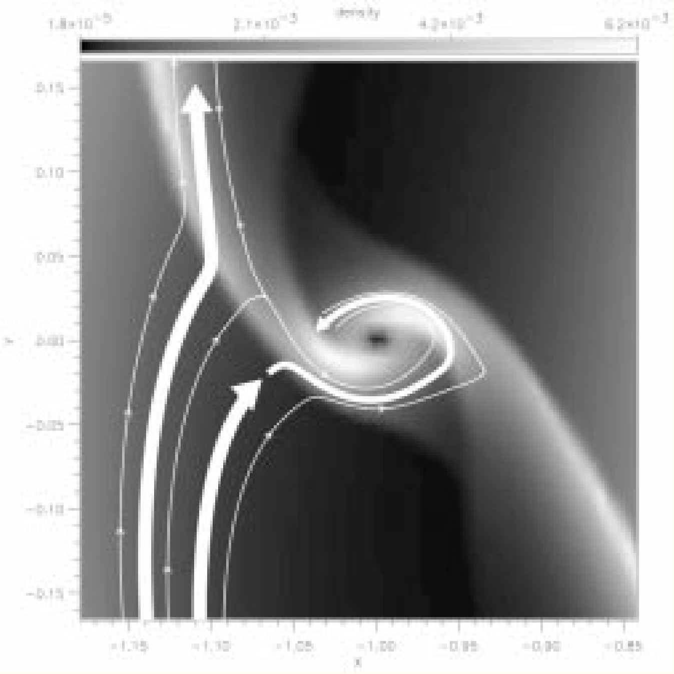
Waves might damp locally due to radiative damping (Cassen and Woolum 1996), 'channeling' to outer disk layers where they shock (Lubow and Ogilvie 1998), nonlinear shocks, viscous damping.

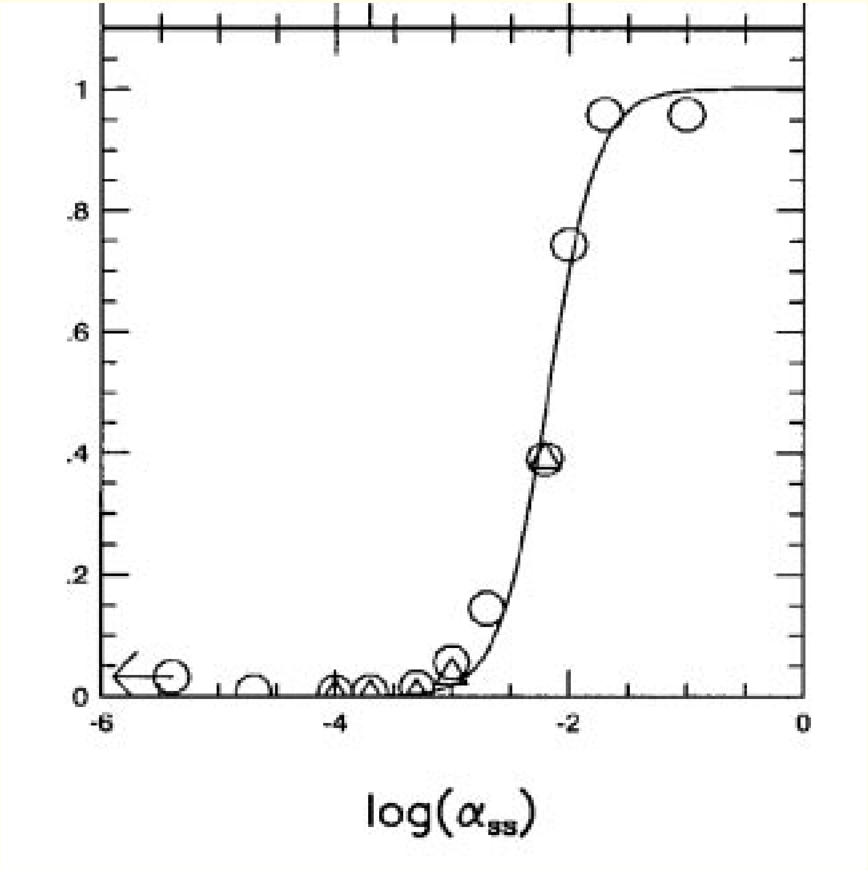
Note that if wave–damping is non–local (e.g., waves damp downstream of the resonance), then the mass–threshold is raised and the gap becomes wider.



Lubow *et al.* 1999.

Gap Formation & Accretion





Bryden *et al.* 1999.

Type II migration

Protoplanet’s gap is a mass–barrier that co–evolves with the disk on a viscous timescale

$$\begin{aligned}\tau_{mig} &\sim \frac{r^2}{\nu} \sim \frac{1}{2\pi\alpha}\left(\frac{h}{r}\right)^{-2} P_{orb} \\ &\sim 3\times10^5\left(\frac{\alpha}{10^{-4}}\right)^{-1} \text{ orbits}\end{aligned}$$

Note that high α disks can destroy their protoplanets!

This mechanism can drive both inwards & outwards migration.

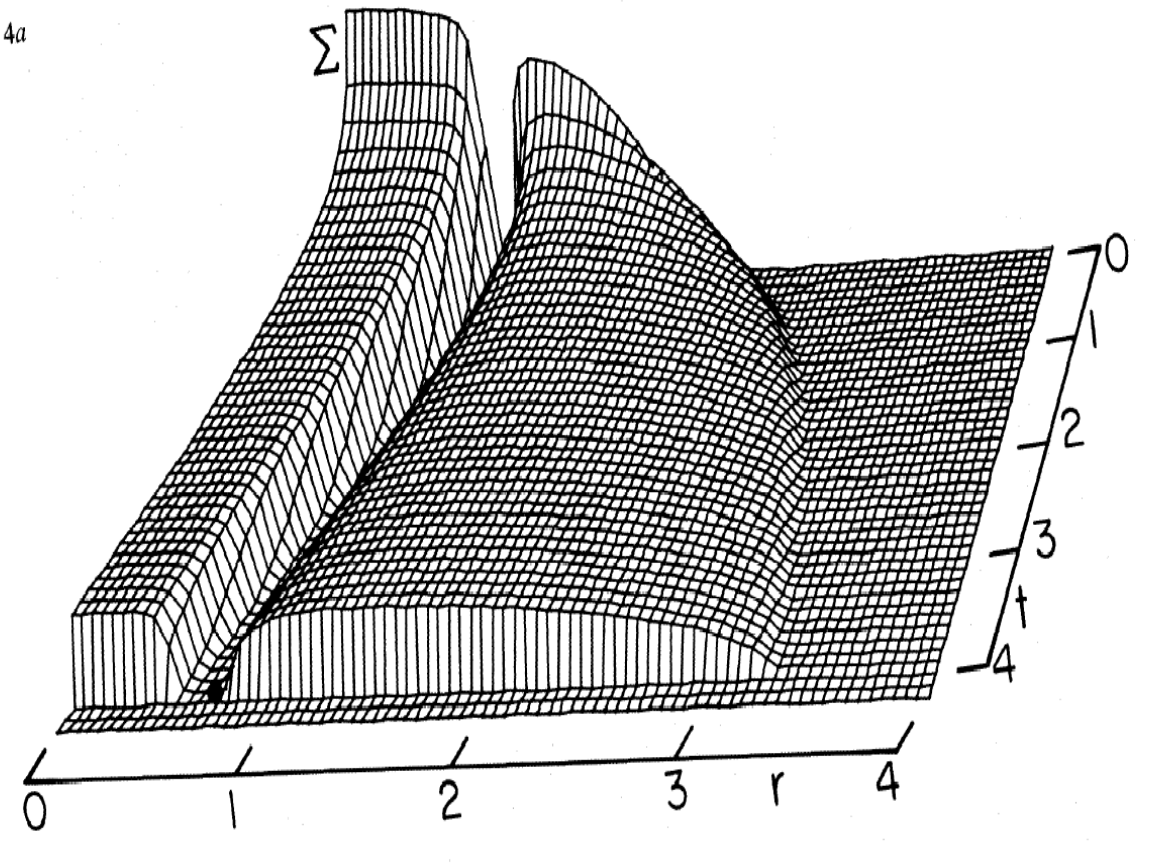


figure from Lin & Papaloizou 1986.

Forming Planets in a High α Disk

The observered accretion luminosity of young star/disk systems + disk evolutionary models suggest $\alpha \sim 10^{-3 \text{ to } -2} \Rightarrow$ giant–planet cores suffer type II migration over timescales $\tau_{mig} \sim 3 \times 10^{5 \text{ to } 4}$ years.

However cores could survive in Gammie's (1996) layered accretion scenario:

- the disk's outer 'active' layers are ionized by cosmic rays,
- these layers suffer the Balbus Hawley MHD instability which drives the disk with $\alpha \sim 10^{-2}$.
- giant planet cores could form in the dead zone where $\alpha \sim 0$.

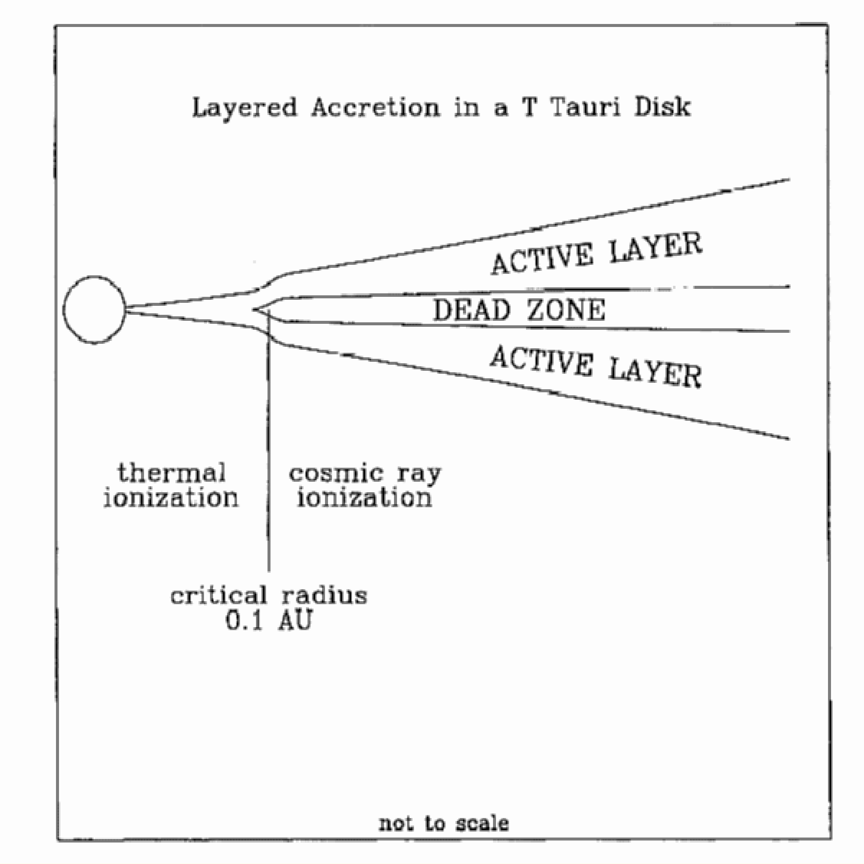


figure from Gammie 1996.

Type I⇒II transition

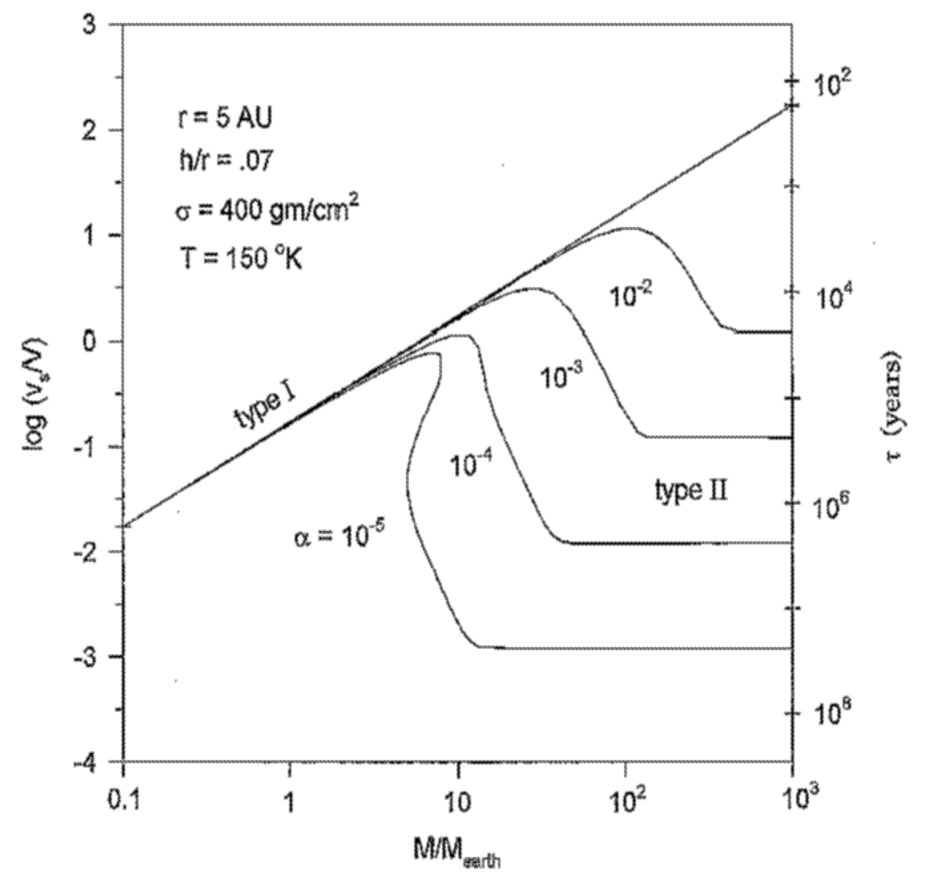
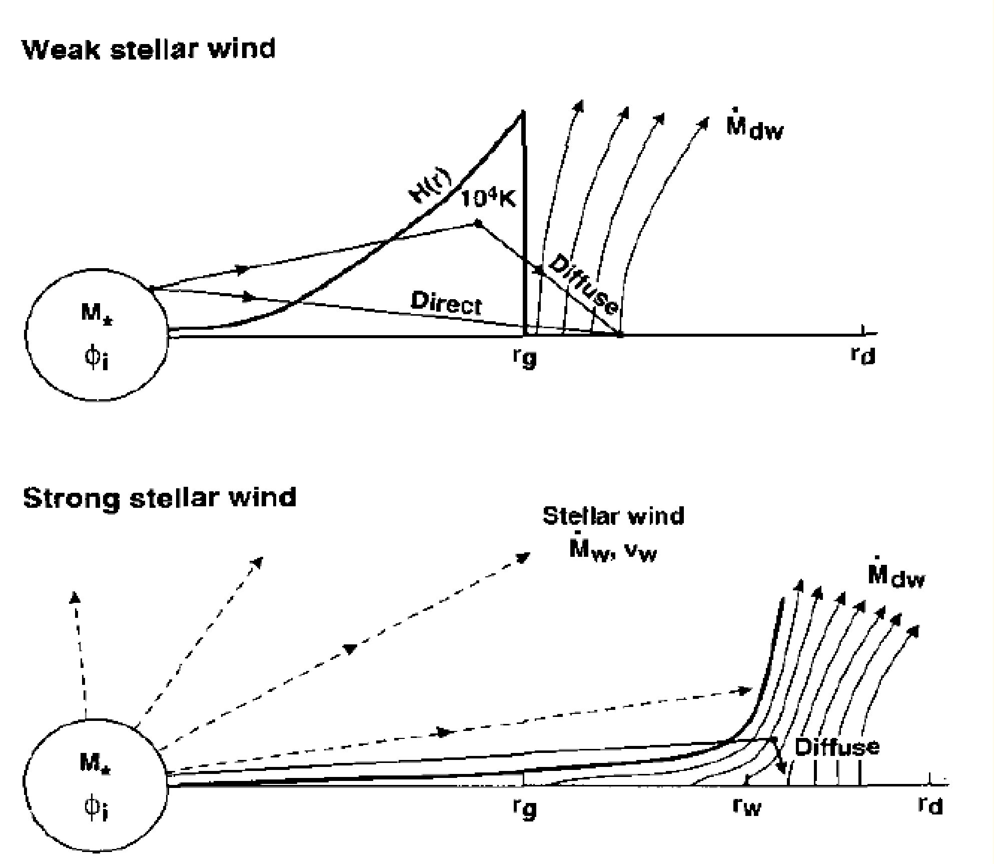


figure from Ward 1997.

Possible Interpretations

- giant–planets are rare or nonexistent.
- giant–planets survive only when a delicate balance exists: $\alpha \lesssim 10^{-4}$ and $\tau_{growth} < \tau_{dispersal} < \tau_{migrate}$.
- multiple generations of planets live & die in disks, and the the timing of nebular dispersal selects the surviving generation.

Nebula Dispersal



leading candidate process:

photoevaporation, which erodes the disk from its outer edge.

figure from Shu, Johnstone, and Hollenbach 1993.

Observational Constraints on Theories of Planet–Migration

- observations of circumstellar disks
- extra–solar planets
- Solar System structure → migration in a planetesimal disk?

Observations: Circumstellar Disks

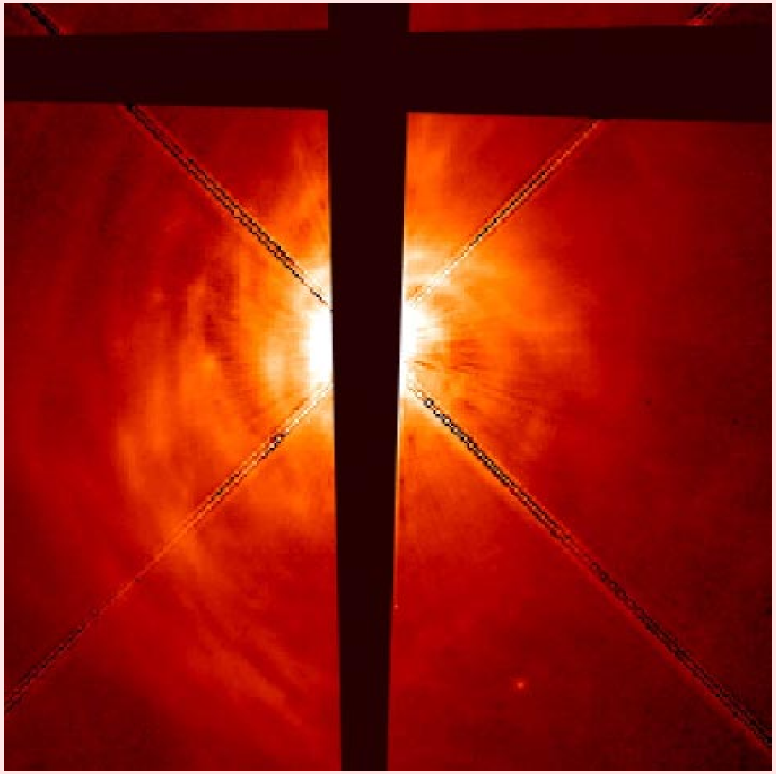
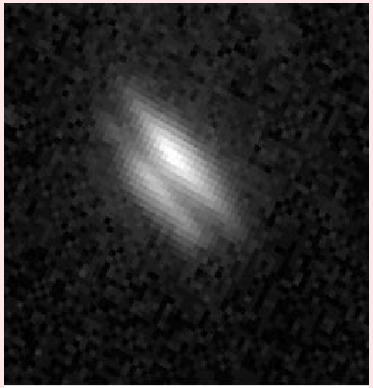


image of AB Aurigae by Grady *et al.* 1999

Star–subtracted images of circumstellar disks systems suggest annular gaps in disks at $r \sim 250$ AU in HD 141569 (Weinberger *et al.* 1999) and $r \sim 300$ AU at HD 163296 (Grady *et al.* 2000).

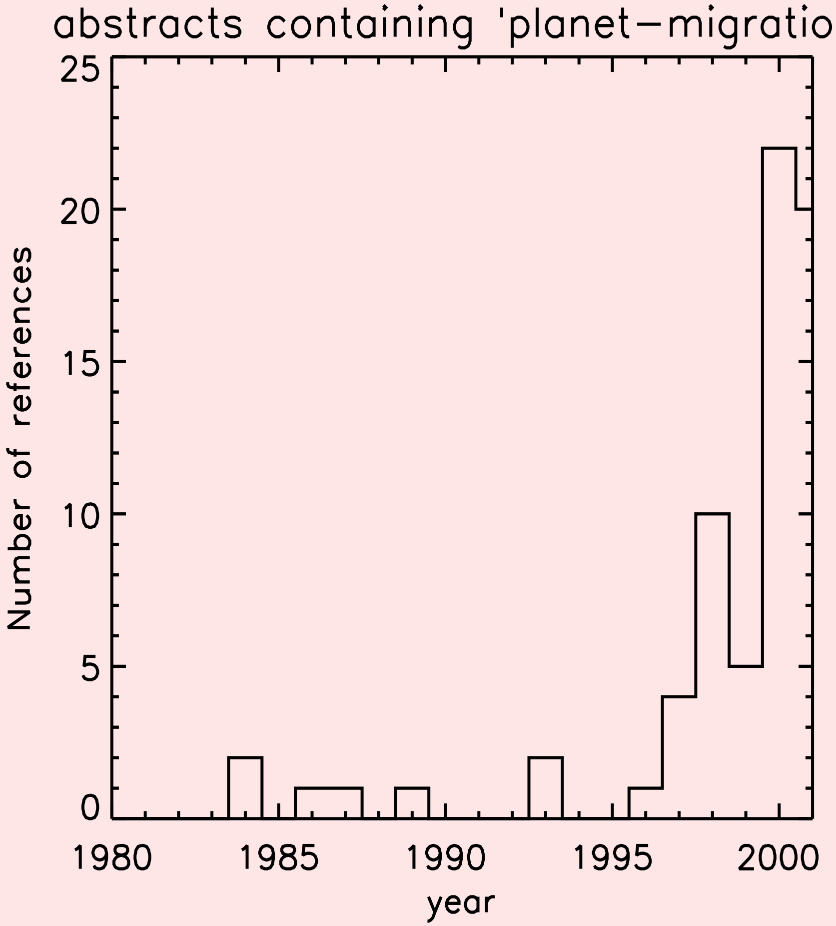
Are there faint stars or brown dwarfs living in those gaps (if real)? Such disk–companion systems could be used to test the prediction made by theories of type I & II migration and gap–formation.

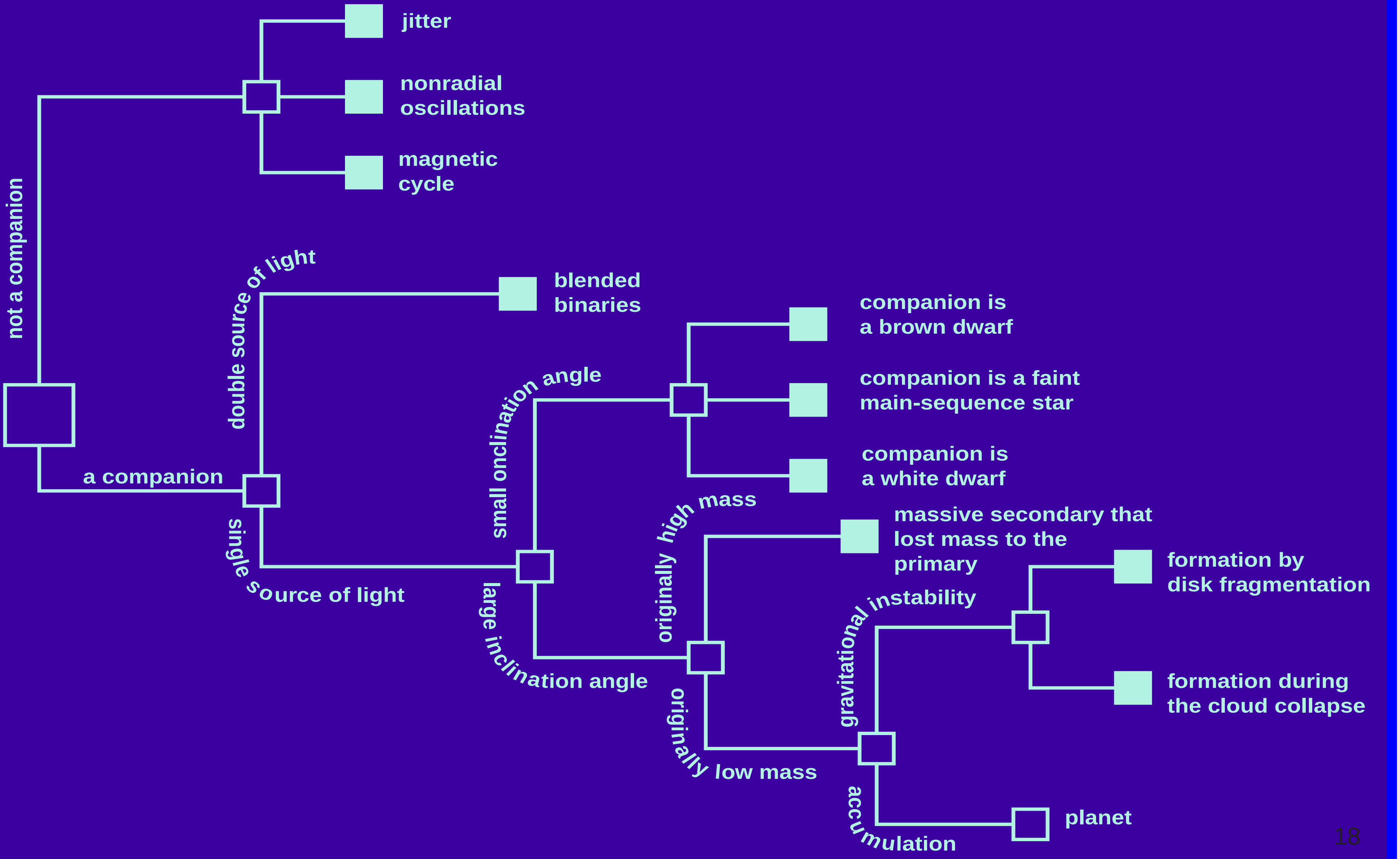


HK τ_C by Stapelfeldt *et al.* 1998

Observational Constraints on Planet–Migration: Extra Solar Planets

The discovery of 51 Peg b in 1995 was liberating ... planet–migration theorists could come out of the closet!





not a companion

jitter

nonradial oscillations

magnetic cycle

a companion

double source of light

blended binaries

single source of light

small onclination angle

companion is a brown dwarf

companion is a faint main-sequence star

companion is a white dwarf

large inclination angle

originally high mass

massive secondary that lost mass to the primary

originally low mass

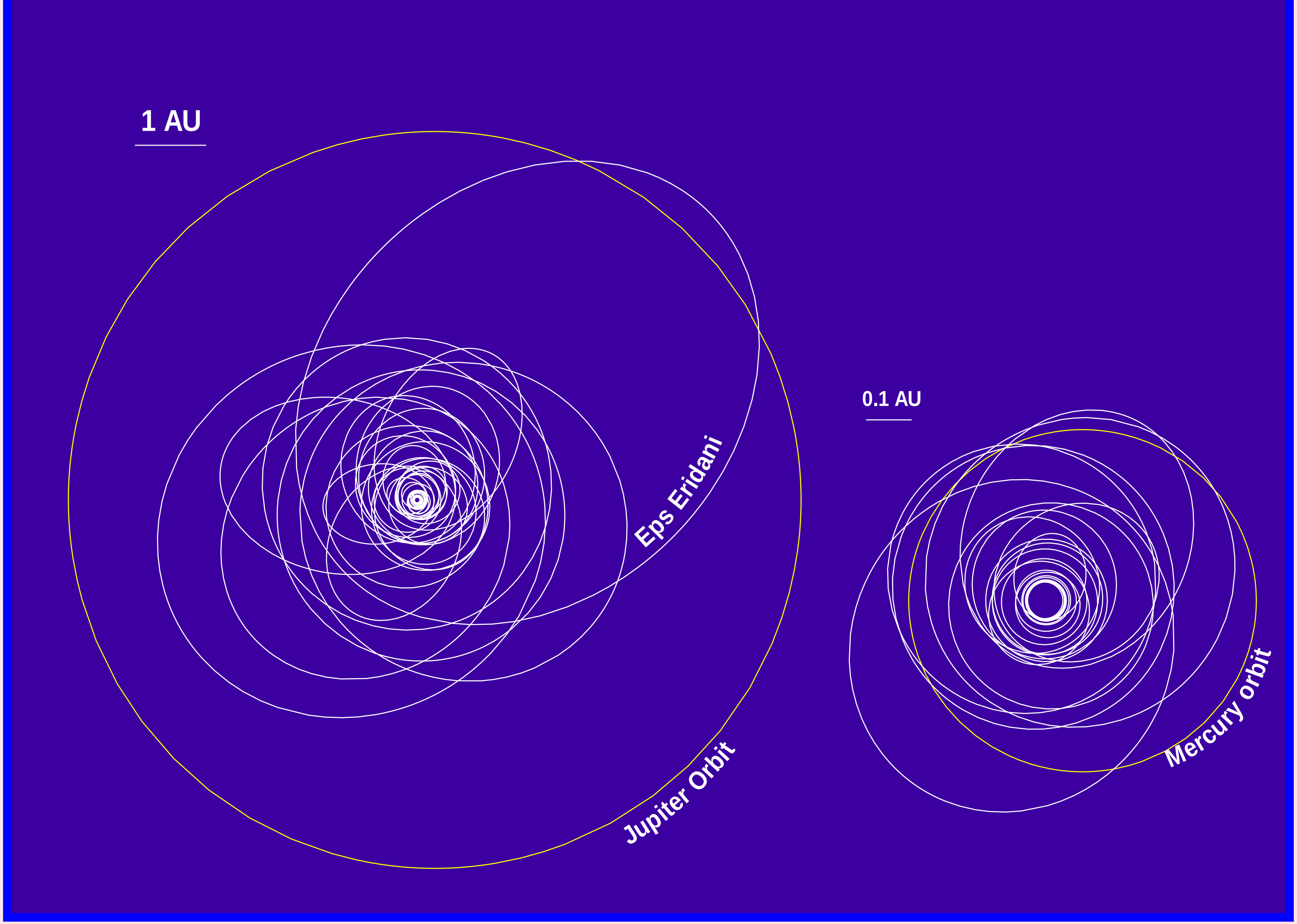
gravitational instability

formation by disk fragmentation

formation during the cloud collapse

accumulation

planet


1 AU
Eps Eridani
Jupiter Orbit
0.1 AU
Mercury orbit

Parking Planets at $a \sim 0.05$ AU

Migrating Planets can avoid a fiery death only if:

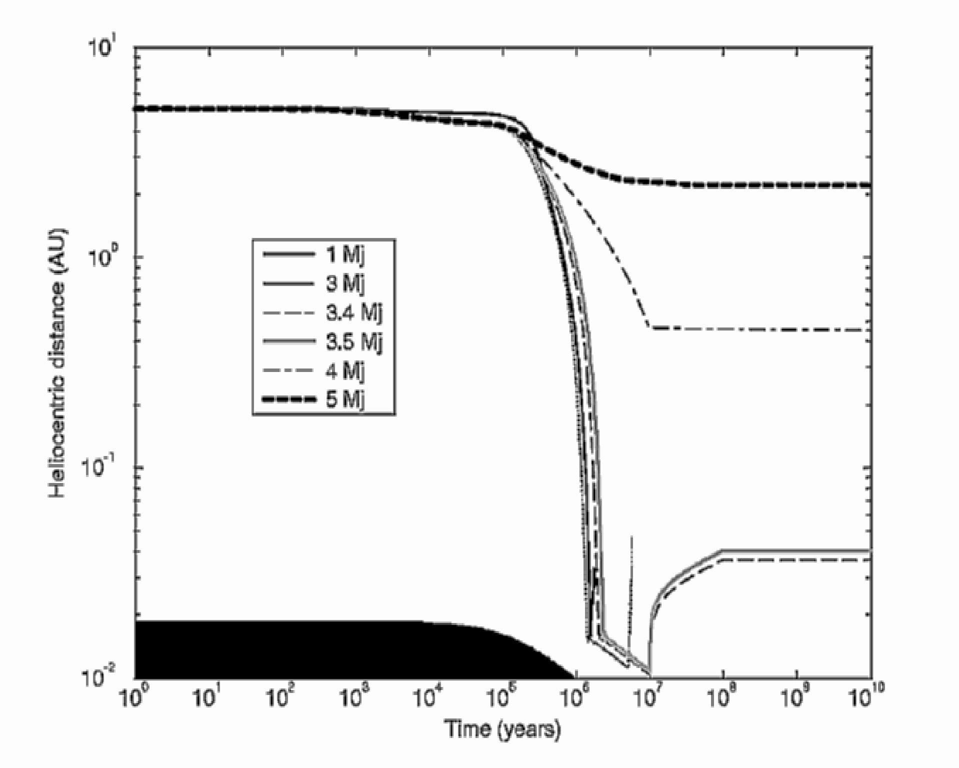
- an external torque counterbalances the disk torque.
  - Lin, Bodenheimer, & Richardson (1996) suggest stellar tide or clearing the inner disk with the stellar magnetosphere.
- good timing, e.g., $\tau_{dispersal}$ is almost $\tau_{migrate}$.
- disks produce multiple generations of planets.

Alternate scenario: Weidenschilling & Marzari(1996) and Rasio & Ford (1996) show that giant–planet scattering & tidal circularization can produce hot Jupiters.

A Matter of Good Timing?

Trilling *et al.* (1998) shows that stellar tides + Roche overflow can slow orbit decay while approaching a star.

In some instances this salvages the migrating planet provided the disk disperses in time, e.g, $\tau_{migrate} \lesssim (0.1 \text{ to } 1) \times \tau_{dispersal}$ and the planet is sufficiently massive.

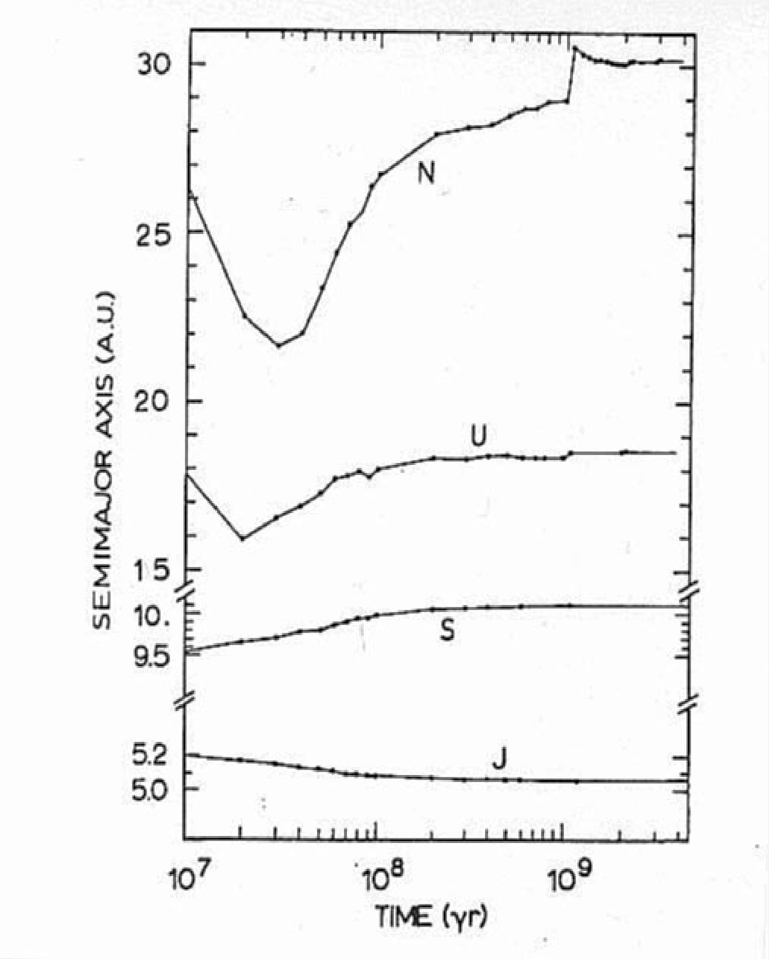


Constraints on Planet–Migration: the State of the Solar System

Migration in the Natal Planetesimal Disk?

Fernández and Ip (1984) used an Öpik integrator to model the accretion of Uranus & Neptune embedded in a $M_d \simeq 100$ $M_\oplus$ disk.

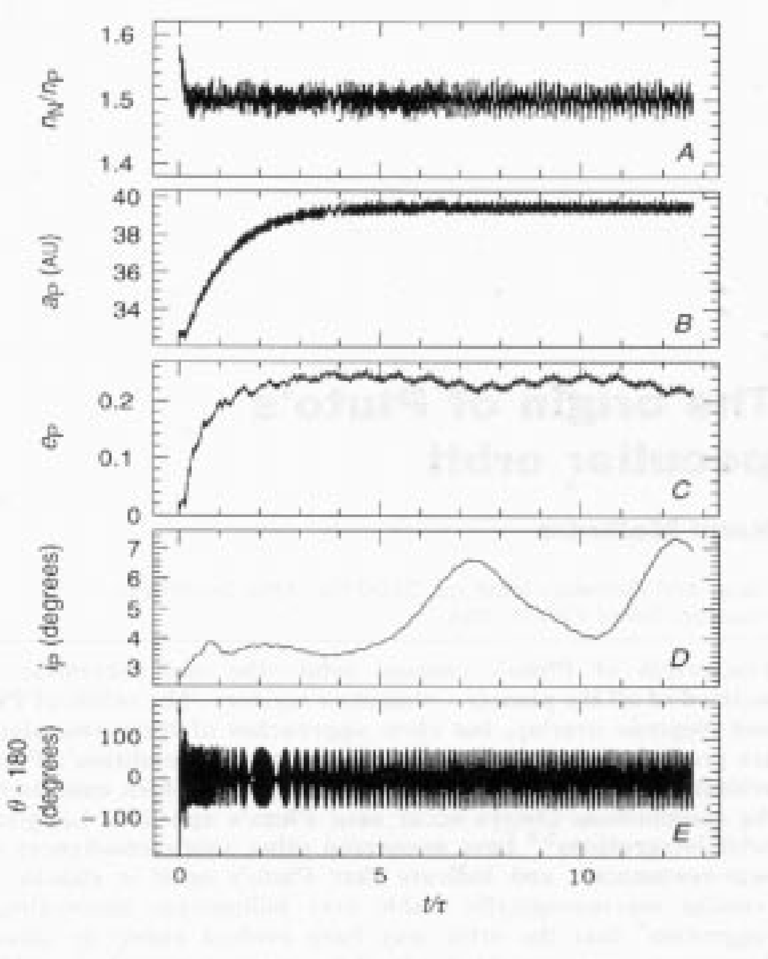
Uranus & Neptune acquire **L** (and migrate outwards) as they scatter bodies to smaller perihelia, while Jupiter's orbit shrinks slightly as it ejects that mass.



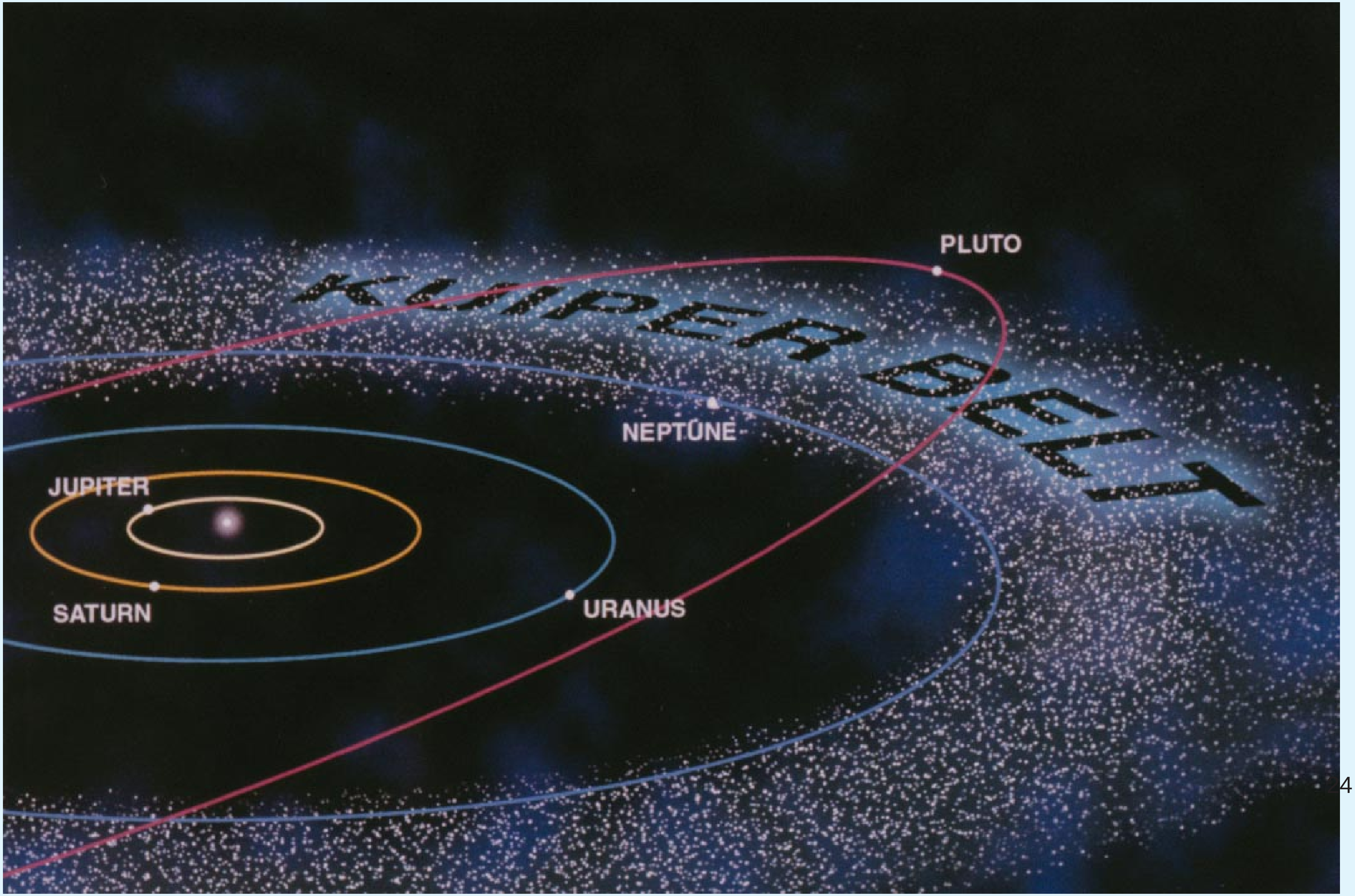
Initial Evidence: Pluto

Malhotra (1993) recognized that this early episode of migration could explain Pluto’s peculiar orbit: $e = 0.25$ and $a = 39$ AU at 3:2 resonance with Neptune.

Had Neptune’s orbit expanded by $\Delta a_N \geq 5$ AU, Pluto can get trapped in the advancing 3:2 resonance and have its e pumped up to 0.25.



Further Evidence: the Kuiper Belt



The Kuiper Belt Orbit Elements

Malhotra (1993) also showed that the observed e–excitation among KBOs at resonance depends on Neptune's Δa_N.

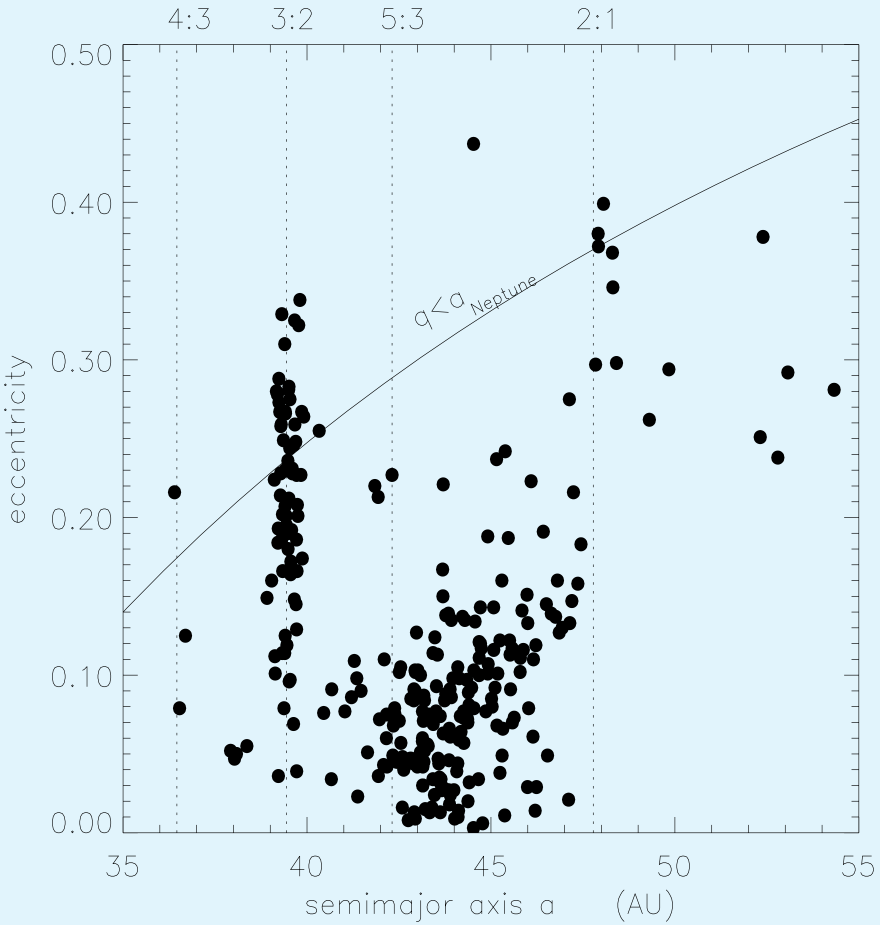
Yu & Tremaine (1999) show that a trapped particle has $\beta \equiv a(t)[(m+1)\sqrt{1-e(t)^2}-m]^2$ that is conserved while shepherded:

$$\frac{\Delta a}{a_f} = 1 - \left[(m+1)\sqrt{1-e_f^2}-m\right]^2 .$$

For $m = 2$, $a_f = 39.5$ AU, $e_f = 0.3$,

$$\begin{aligned} \Rightarrow \Delta a &= \text{10 AU and} \\ \Delta a_N &= (1+1/m)^{-2/3}\Delta a = 8 \text{ AU} \end{aligned}$$

The early planetary system expanded $\sim 35\%$.



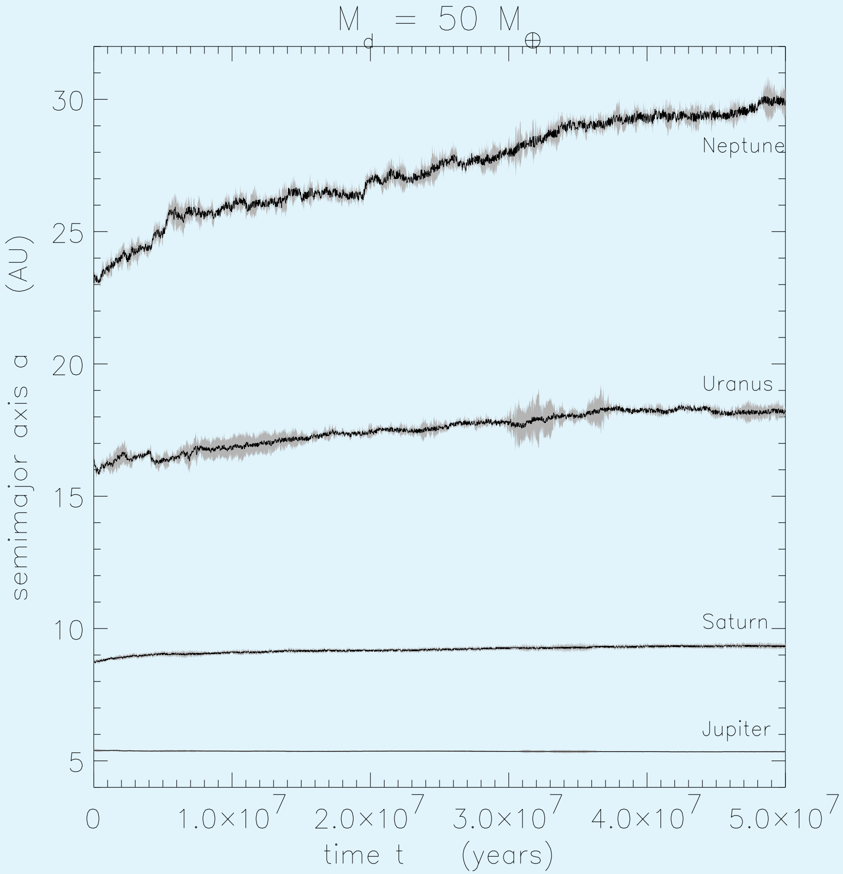
The Initial Mass of the Kuiper Belt

N–body simulations by Hahn and Malhotra (1999) show that giant–planets embedded in a sufficiently massive planetesimal disk do indeed migrate.

To get $\Delta_N \sim 8$ AU requires an initial KB mass of $M_d \sim 50$ M$_\oplus$ distributed over $10 < r < 50$ AU.

Remaining issues:

- N=1000, $m_p = 0.05$M$_\oplus$ $\Rightarrow$ the disk was poorly resolved.
- accretion & migration are likely concurrent, yet this model ignored accretion.
- back–torque on Neptune from outer disk can slow/stall migration.

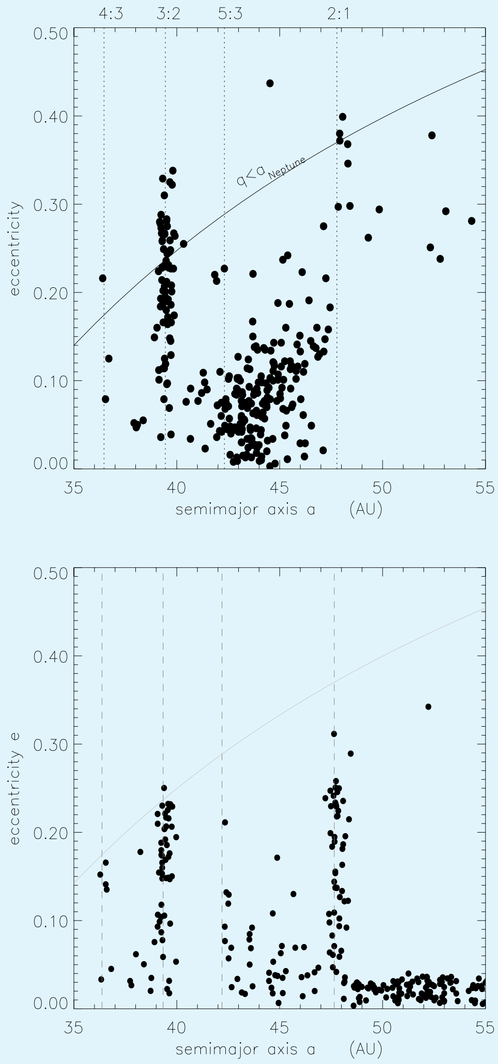


The ‘Planet–Migration’ Interpretation of the KBO orbit elements:

The high abundance of KBOs at the 3:2 resonance and (perhaps) the 2:1 suggests $\Delta a_N \sim 8$ AU.

Other issues:

- telescopic selection effects are important!
- there might be a steep size–gradient with r.
- where is the rest of the solar system at $r > 50$ AU?
- observed $i \sim 12^\circ$ whereas model $i \sim 3^\circ$.
- there are alternative explanations for Kuiper Belt structure...



Overview of Planet–Migration

Type I and II migration introduce ‘bottlenecks’ for giant–planet formation:

- shutting off type I torques via gap formation requires achieving $M_p \gtrsim 10\sqrt{\frac{\alpha}{10^{-4}}}$ $M_\oplus$; models of migration/accretion (e.g., Tanaka & Ida 1999) using ‘nominal’ disk parameters generally fail to halt orbit decay.

- avoiding type II orbit decay (e.g., $\tau_{II} > \tau_{dispersal}$) requires $\alpha \lesssim 10^{-4}$ in the Jupiter–Saturn–forming zone of the solar nebula.

- alternate scenario: several generations of giant–planets live & die in disks, and that the timing of nebula dispersal selects the surviving generation.
  - is this consistent with SS structure, eg., terrestrial planets and asteroid belt?

- what astronomical observations and techniques might better constrain planet–migration theories?

- Extra Solar Planets: invoking planet–migration does NOT explain the origin of ESPs, at least until the planet–parking problem is solved in a compelling way.
  - Also: why isn't Jupiter orbiting at 0.05 AU?

- Finally, there is evidence (preserved in the Kuiper Belt) for an early epoch of "modest" planetary migration that was driven by the natal planetesimal disk.