Dynamical Shake Up of Planetary Systems

KITP Conference on Planet Formation

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with

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Mar 19th, 2004

Basic Motivation

1 To provide a scenario for **rapid gas & ice giant formation**
2 To infer the **dynamical structure origin** in the Solar System
3 To extrapolate the existence of extrasolar Earth-type planets

Core Accretion Scenario: Relevant Processes

1. Planetesimals dynamics
2. Gas accretion onto cores
3. **Planet-disk interaction**
4. **Secular interaction between planets**

Main ingredients:

1. Gas, 2. Grain, 3) Planetesimals, 4) Embryos, 5) Cores
Slight departure from minimum mass nebula

Available planet building material

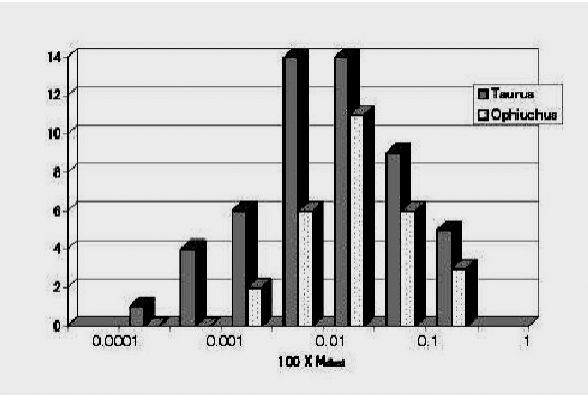
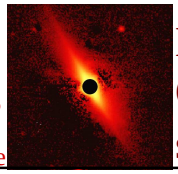


TABLE 5
SME MEAN ABUNDANCES FOR PLEIADES STARS

ELEMENT	MEAN log N/N$_H$ (SME)	log N/N$_H$ Solar	log N/N$_H$ Meteoritic
Li...	2.51 ± 0.513	1.16	3.31
Na...	6.23 ± 0.042	6.33	6.31
Si...	7.54 ± 0.054	7.55	7.55
Ca...	6.33 ± 0.025	6.36	6.34
Sc...	3.00 ± 0.094	3.10	3.09
Ti...	4.93 ± 0.044	4.99	4.93
V...	4.02 ± 0.038	4.00	4.02
Cr...	5.61 ± 0.037	5.67	5.68
Fe...	7.44 ± 0.021	7.54	7.51
Co...	4.81 ± 0.051	4.92	4.91
Ni...	6.13 ± 0.031	6.25	6.25

Mm dust (Beckwith and Sargent) Wilde

Minimum mass nebula 0.02 M_e

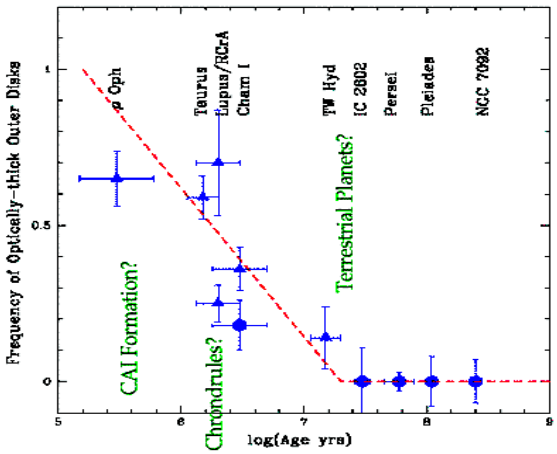


Homogenety ΔF_e<5%
G dwarfs in Pleiaides stars (100 Myr old).

Optically-thick Outer Disks (1-10 AU) vs. Age

IRAS data (▲) .
ISO data (●).

Meyer & Beckwith (2000)



Observational limit:
2 x minimum mass

Weak gas depletion time constraints: 10My

Formation of the first gas giant

Minimum mass nebula

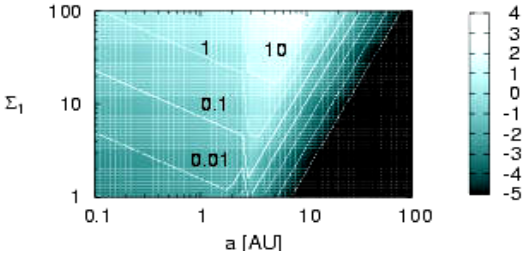
$\Sigma = 10\ (a/1AU)^{-1.5}$ g cm^{-2}

Embryo growth time scale:

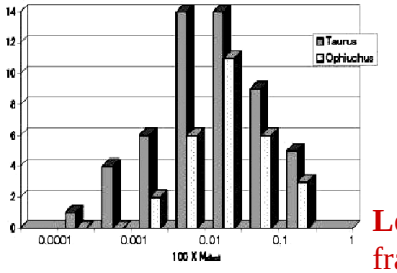
$$\dot{M}_c \sim \pi R_c^2 \rho_d \left(\frac{2GM_c}{R_c\sigma^2}\right)\sigma \sim 2\pi R_c^2 \Sigma_d \Omega_K \left(\frac{GM_c}{R_c\sigma^2}\right)$$

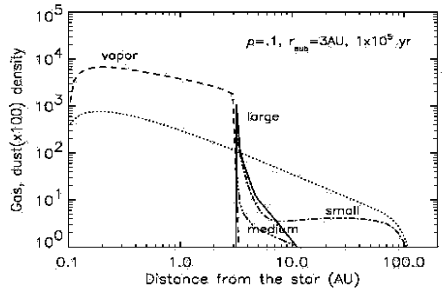
Extended isolation mass with gas damping: a few M_{earth}

$M_{isolation} \sim \Sigma^{1.5}\ a^3$ (Lissauer, Ida, Kokubo, Sari, etc)



Global enrichment

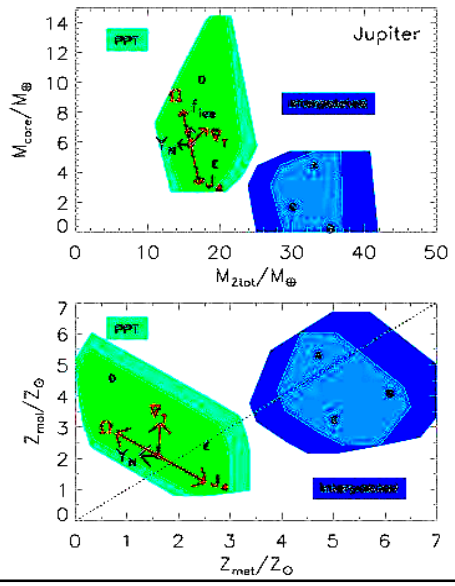


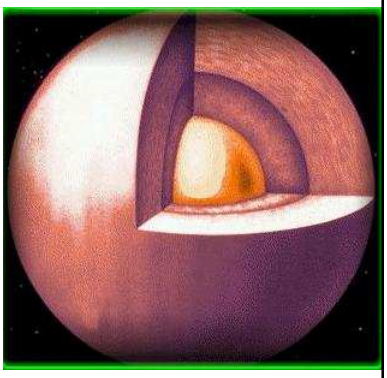


Local enrichment: elemental abundances fractionation (Stevenson,Takeuchi, Youdin)

Metal Enrichment in Gas Giants

T. Guillot et al.





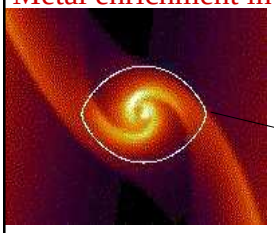
More heavy elements are accreted onto the envelope than the core

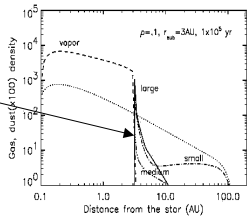
Requirements:)

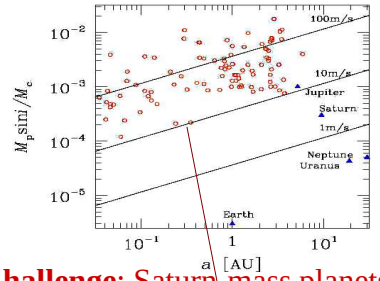
1) **Local enrichment or**
2) **Erosion of massive cores**

Limited Accretion onto Cores

Metal enrichment in the envelope

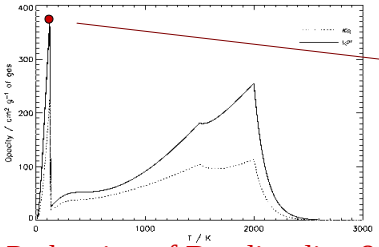


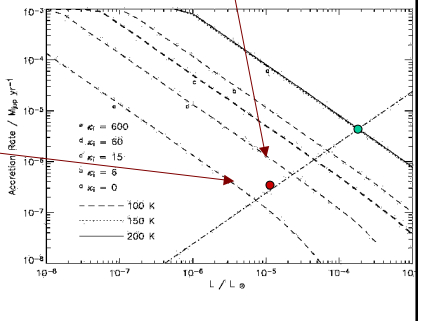




Challenge: Saturn-mass planets!

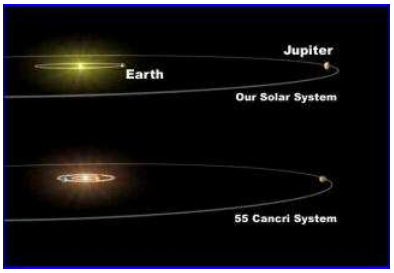
Kley, Ciecielag, Artymowicz …)

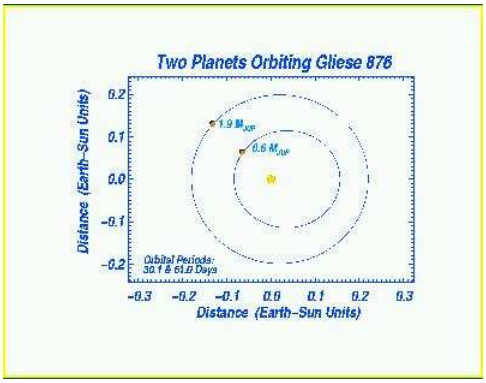




Preheating of Bondi radius & reduction of accretion rate (Edgar)

Gas giant formation timescale





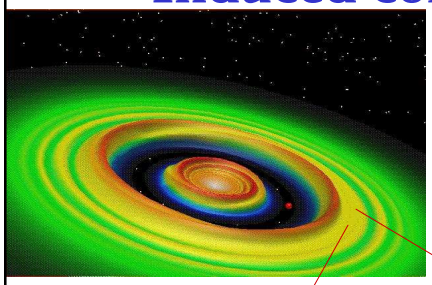
Three configurations:

1) Solar system
2) GJ 876 & 55 Can
3) Ups And

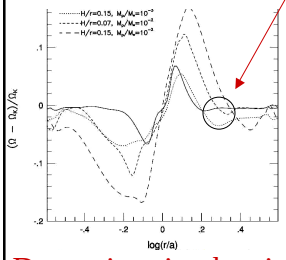
(Lee, Peale, Kley, Bryden)

Time interval between successive gas-giant formation is comparable to the migration time scale

Induced core formation



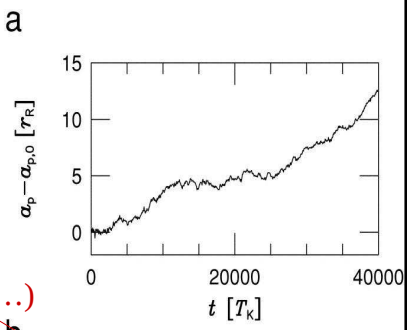
(Papaloizou, Kley, Nelson, Artymowicz …)

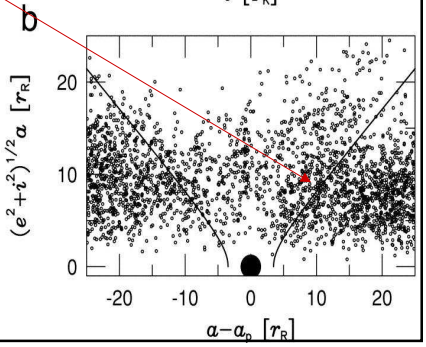


Dust migration barrier (Bryden, Rozczyska)

Protoplanet migration (Ida, Levison etc)

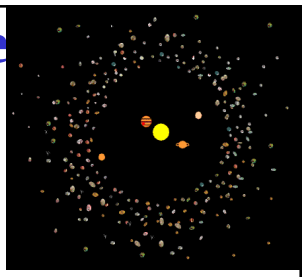
Modified type I migration of embryos (Ward)

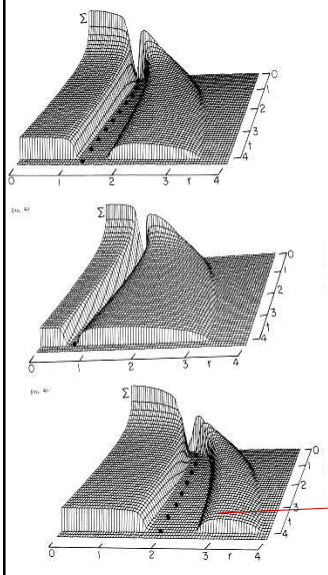


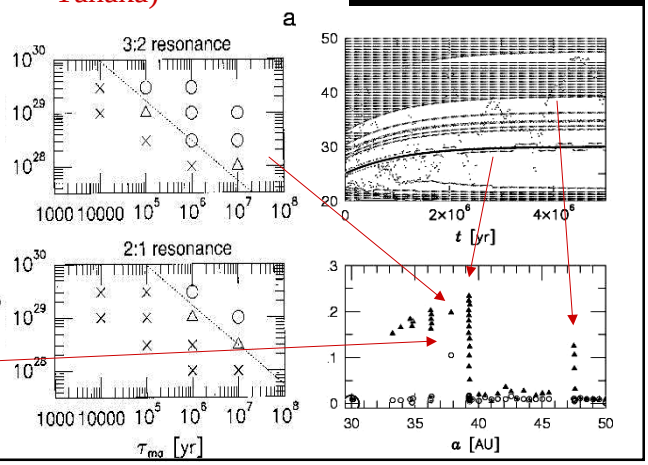


Resonant KBO's capture

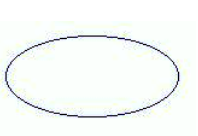
Early Formation
Migration time
a few Myr
(Ida, Bryden, Tanaka)



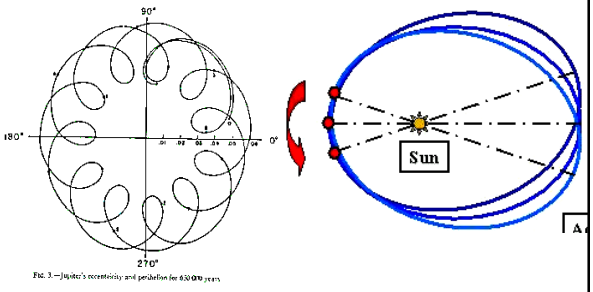


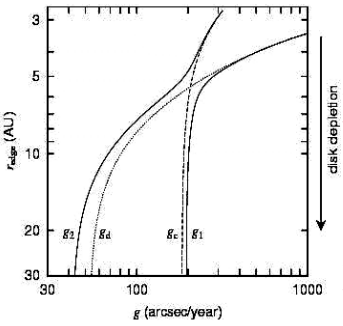


Sweeping secular resonances

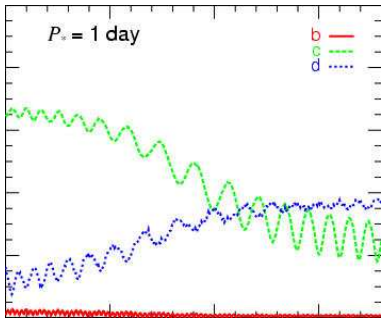


Precession due to planets' interaction with disk and planets

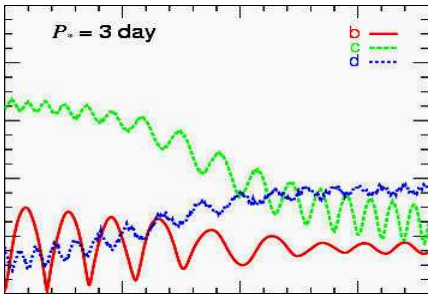


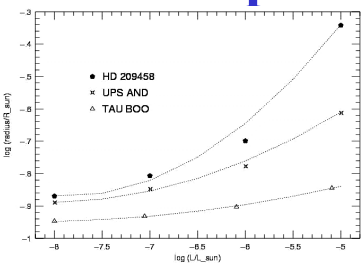


Resonant secular perturbation $M_{disk} \sim M_p$ (Ward, Ida, Nagasawa) Ups And

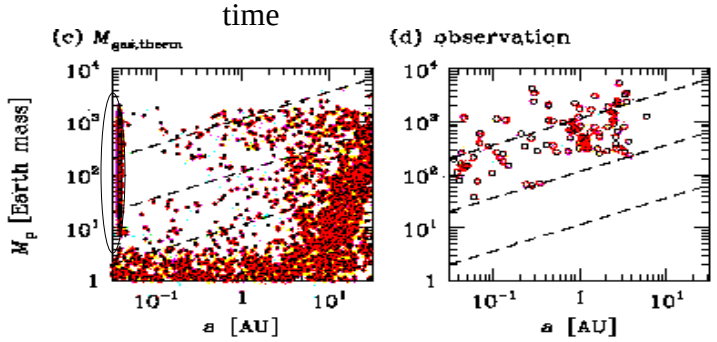


Tidal disruption of hot Jupiters





(Bodenheimer, Mardling, Gu)

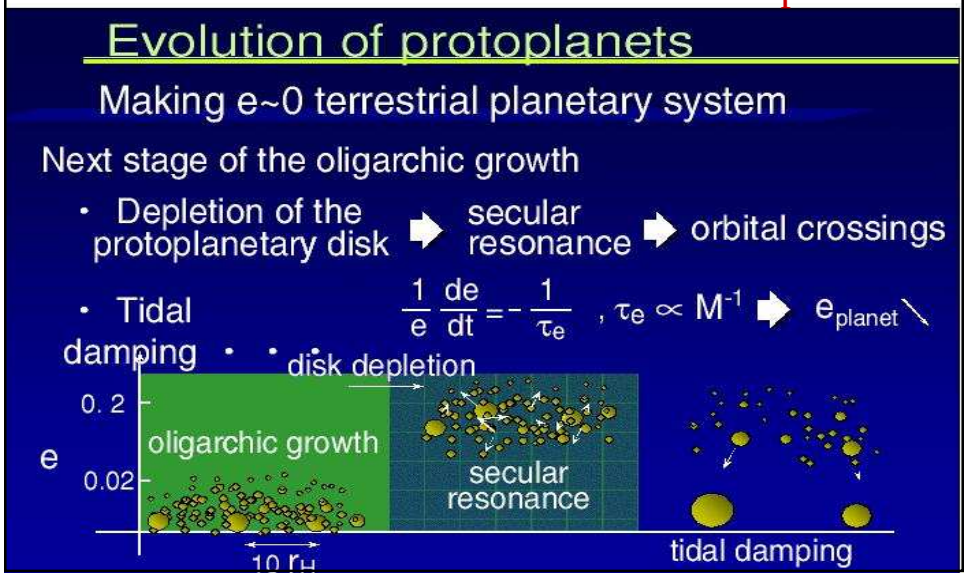


Observation:
1) No pile up
2) 3-day cut off

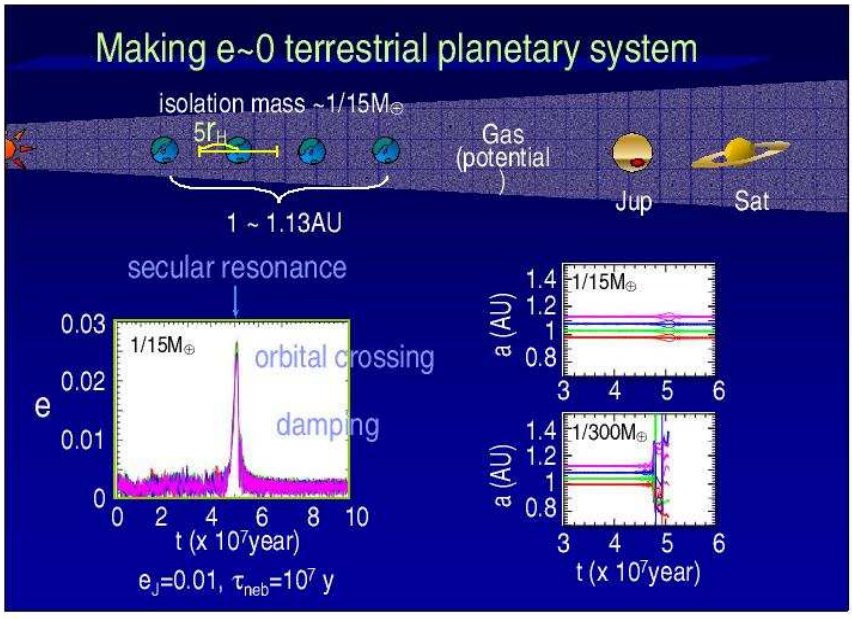
Proposition:
Tidal disruption

Dynamical shake up (Nagasawa, Ward)

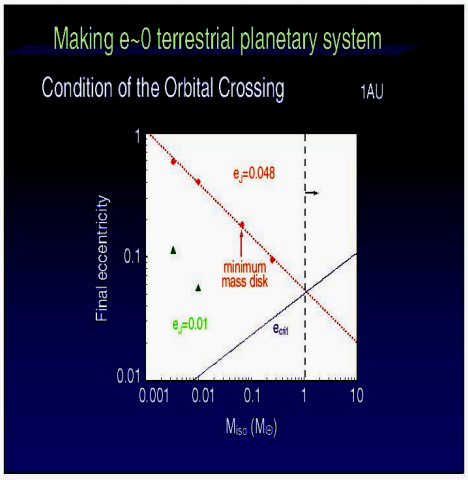
Bode's law: dynamically porous terrestrial planets orbits with low eccentricities with wide separation

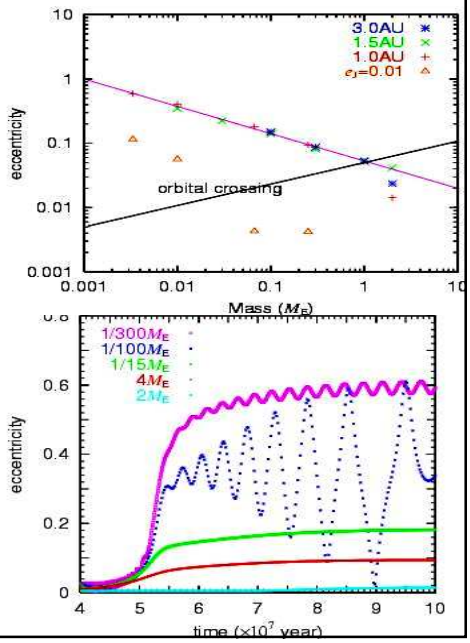


Differential e-Excitation



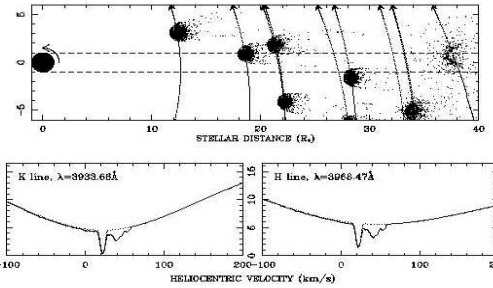
Transition to Metastable Systems





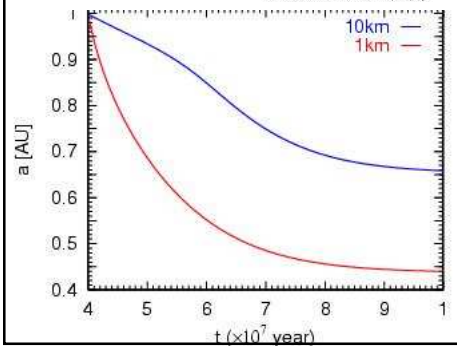
Final assemblage of planets
Emergence of Bodes law
e & a of small vs large cores

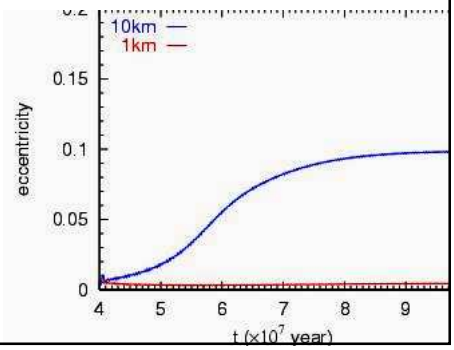
Sweeping clear of planetesimals



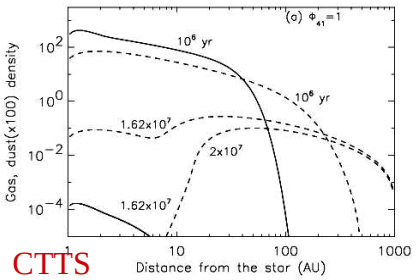
Sweeping secular resonance & gas drag

Beta Pic
Duncan, Levison, Wetherill, Nagasawa

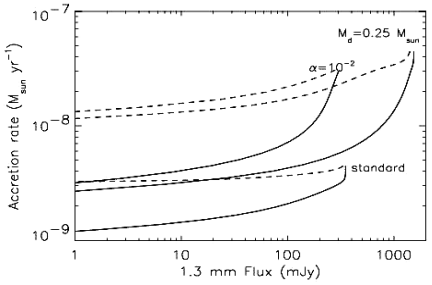




Clearing of debris(Takeuchi, Clarke)

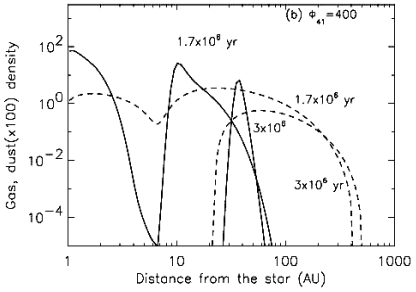


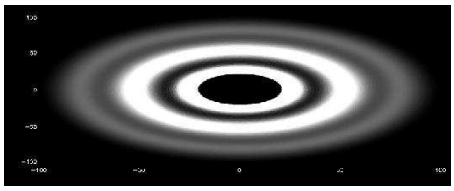
CTTS



Dust signature declines rapidly

WTTS

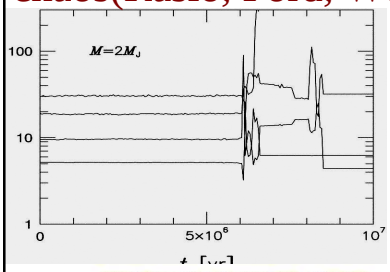


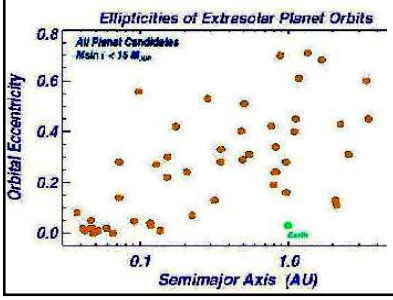


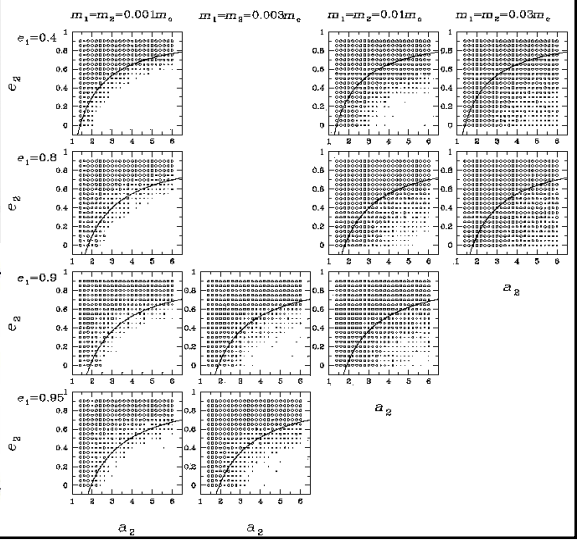
Radiation pressure
(Klahr, Artymowicz, Takeuchi)

Post Depletion Dynamical Stability

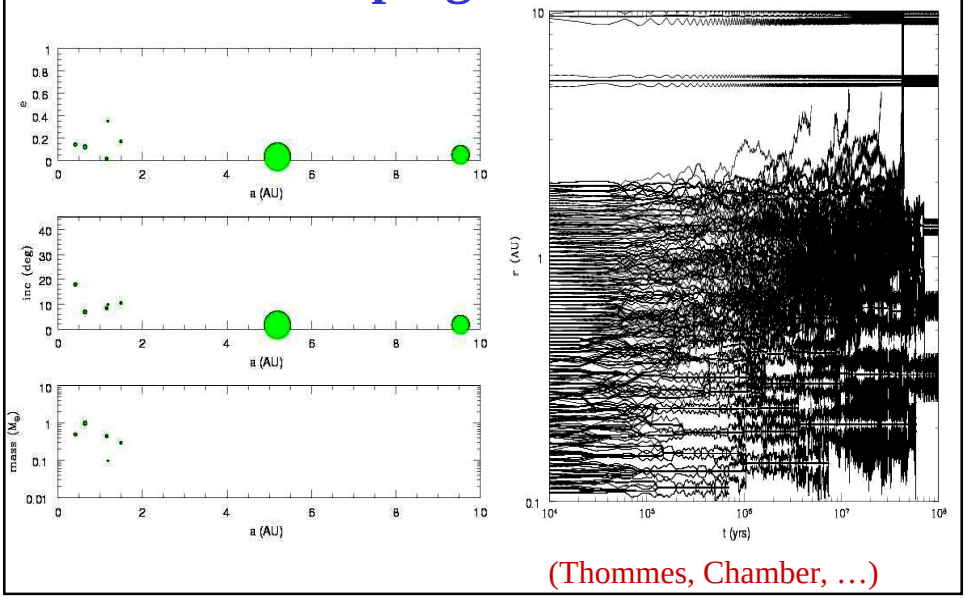
Dynamical filling factor: eccentricity excitation & chaos(Rasio, Ford, Weidenschilling, Ida, Mardling, etc







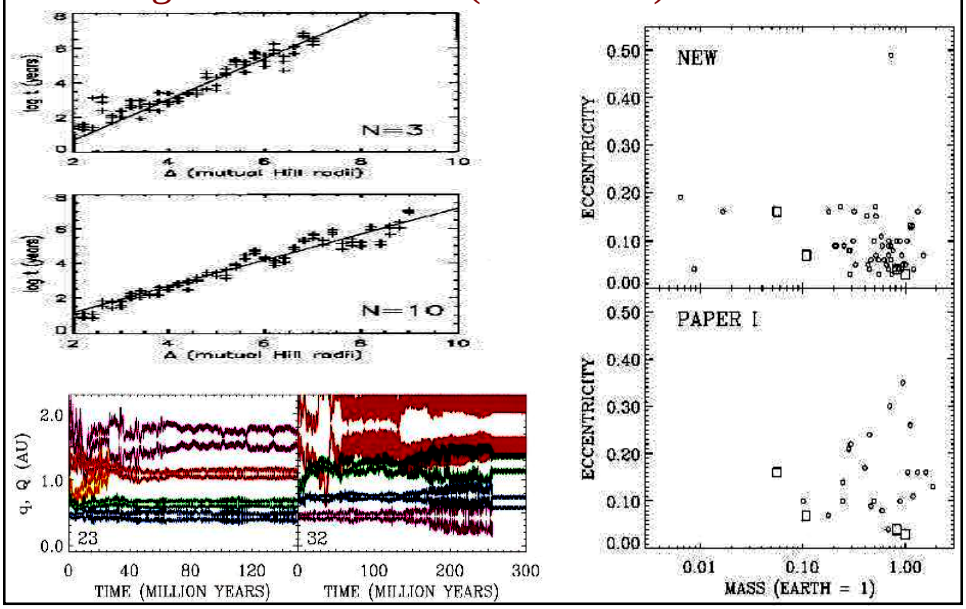
Post fast-gas-depletion embryo evolution without sweeping secular resonance



(Thommes, Chamber, …)

Inner Solar System Dynamics

Post Oligarchic Evolution (Chambers)



Stellar pollution & late bombardment

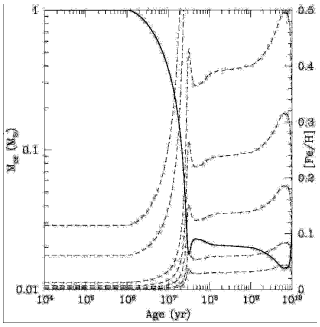
Reduction of damping & precession

Long time scales for clearing of residual planetesimals

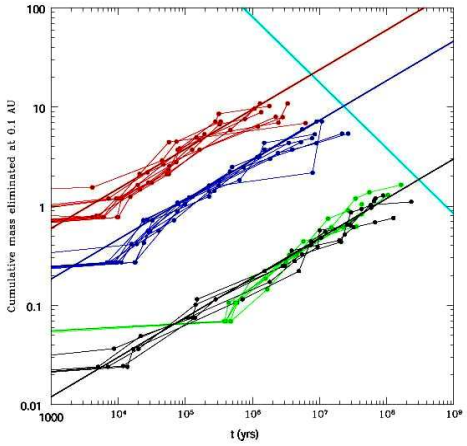
Retraction of stellar convection zone

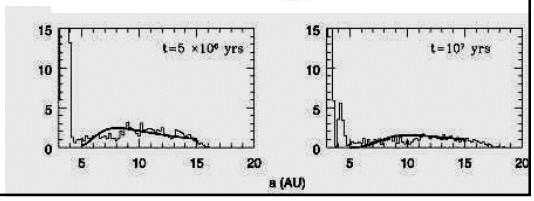
Limit on the metal consumption after 30 Myr is less than 5 M_{earth}

Fe...	7.44 ± 0.021	7.54	7.51



Wilden et al, Thommes





Summary & Propositions

1) Protoplanetary cores formed through enhanced concentration of heavy elements at the sublimation fronts.
2) Gas damping & high Σ leads to rapid growth & large isolation masses. Jupiter formed prior to the final assemblage of terrestrial planets within a few Myrs.

3) Emergence of the first gas giants enhances possibility of sibling-gas giant planet formation.
4) Saturn & Ice giants formed prior to gas depletion. Neptune orbital evolution is due to type II gas migration.

5) Gas depletion cleared out the dust. Sweeping secular resonance + gas damping cleared the planetesimals.
6) Shake up led to the dynamically porous configuration of the