Formation of terrestrial planets in extrasolar planetary systems

Philip Nutzman

Ay 200

December 15, 2004

Planet Formation by Disk Instability

- Gas Giants are created efficiently by Disk Instability
- For some ranges of circumstellar disk mass, disk may develop an instability
- Clump may lead to protoplanet if dense and stable enough.
- The process would be very efficient at creating Gas Giants

Why Controversial?

A small sample of objections:

- Not a simple explanation for why Neptune and Uranus have a thin atmosphere while Saturn and Jupiter have very thick atmospheres
- If Uranus or Neptune starting out massive might be inconsistent with the abundance of comets and other Kuiper belt objects

In this talk

- Stages of Planet Formation:
  - Dust accumulates to form planetesimals
  - Planetary embryos grow through the runaway accretion of planetesimals
  - Oligarchic Growth
  - Cleanup
- Focus on terrestrial planets

Planet Formation

The dust bunnies under your bed grow in a similar way. And after a million years, a dust bunny can get pretty big.

Scott Kenyon

Some Observations

- Stars older than a few million years don’t have massive disks.

- Most known giant planets orbit stars with above average abundances of dust-forming elements.

From Dust to Planetesimals

- Stage is responsible for the growth from dust grains to ~ 1km sized planetesimals
- Problem: growth from .1-10 m to 1 km sized planetesimals must occur rapidly!
  - g_{eff} for the gas in the disk is reduced by a negative pressure gradient.
    - gas rotates at sub-Keplerian rate
    - Small particles which are strongly coupled to the motions of the gas move at the same speed
  - 1km size objects have small surface area/mass ratio
    - Weakly coupled to the gas
    - Move at Keplerian speeds
  - m size objects?

From Dust to Planetesimals

- Objects around a meter in size
  - too large to move at the speed as the gas, but too small to be totally unaffected by the gas
  - Since the gas orbits more slowly, the meter sized object feels a headwind
  - Headwind robs angular momentum-> orbit decays
    - 1 m sized object at 1 AU would decay into the sun in as little as 500 years
- The understanding of planetesimal formation is incomplete- yet several plausible mechanisms to account for the fast growth have been posited

Planetesimals and Embryos

- Much more understood part of the story!
- Planetesimals interact with each other through gravitational interactions or through collisions.
  - numerous gravitational interactions will cool the random velocities at this stage
  - Collisions typically lead to mass accretion if the collision speed << escape velocity
- For better understanding, we look at the effective collision cross-section

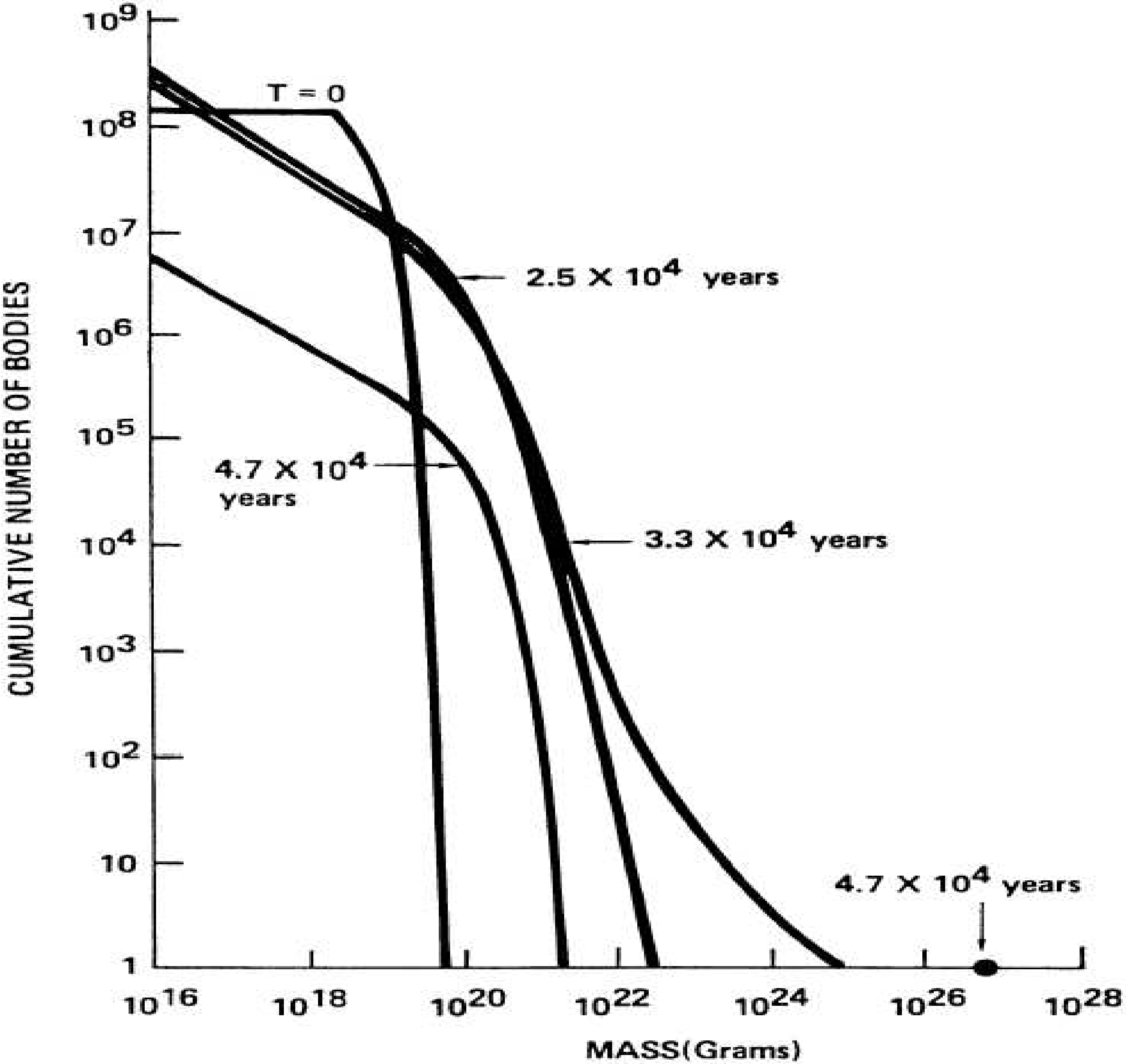
Philip at the chalkboard

Chalkboard Summary

- The "gravitational focusing" of the cross-section goes as $(v_{escape}/v_{relative})^2$
  - A sea of small bodies have relative velocities greater than their v_{escape}. The small bodies whiz by each other
  - Due to the cooling of relative velocities, and to the large escape velocity of the big bodies, big bodies will suck in many small bodies

Planetesimals and Embryos

- More massive planetesimals will have a larger growth rate
- Runaway growth for the largest planetesimals!
- End result is many embryos (protoplanets) dominating their own “feeding zones”


CUMULATIVE NUMBER OF BODIES
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
T = 0
2.5 X 10^4 years
4.7 X 10^4 years
3.3 X 10^4 years
4.7 X 10^4 years
10^16
10^18
10^20
10^22
10^24
10^26
10^28
MASS(Grams)

Oligarchic Growth

- Runaway growth subsides– no super-embryo
- The ratio of the mass of an embryo to a smaller planetesimal becomes large
- Gravitational perturbation of the smaller bodies due to the larger bodies becomes significant
  - The more massive the embryo, the more the relative velocities of neighboring smaller bodies are heated up
  - More massive embryos will grow more slowly than smaller embryos
- Growth becomes more regular

Story Diverges Here

- The story so far has described a process which is responsible for terrestrial and uranian (icy) planets, and the cores of jovian planets
- Terrestrial planets are small, rocky planets like Earth. Not yet possible to see in extrasolar systems.
  - Can use models (e.g. Ida & Kokubo 2002) to get a glimpse

Terrestrial Planets

- Disk temperature decreases with a
- Region “habitable” by terrestrial planets is constrained by the temperature at which elements like water condense.
- Beyond the boundary where ice condense uranian planets form.

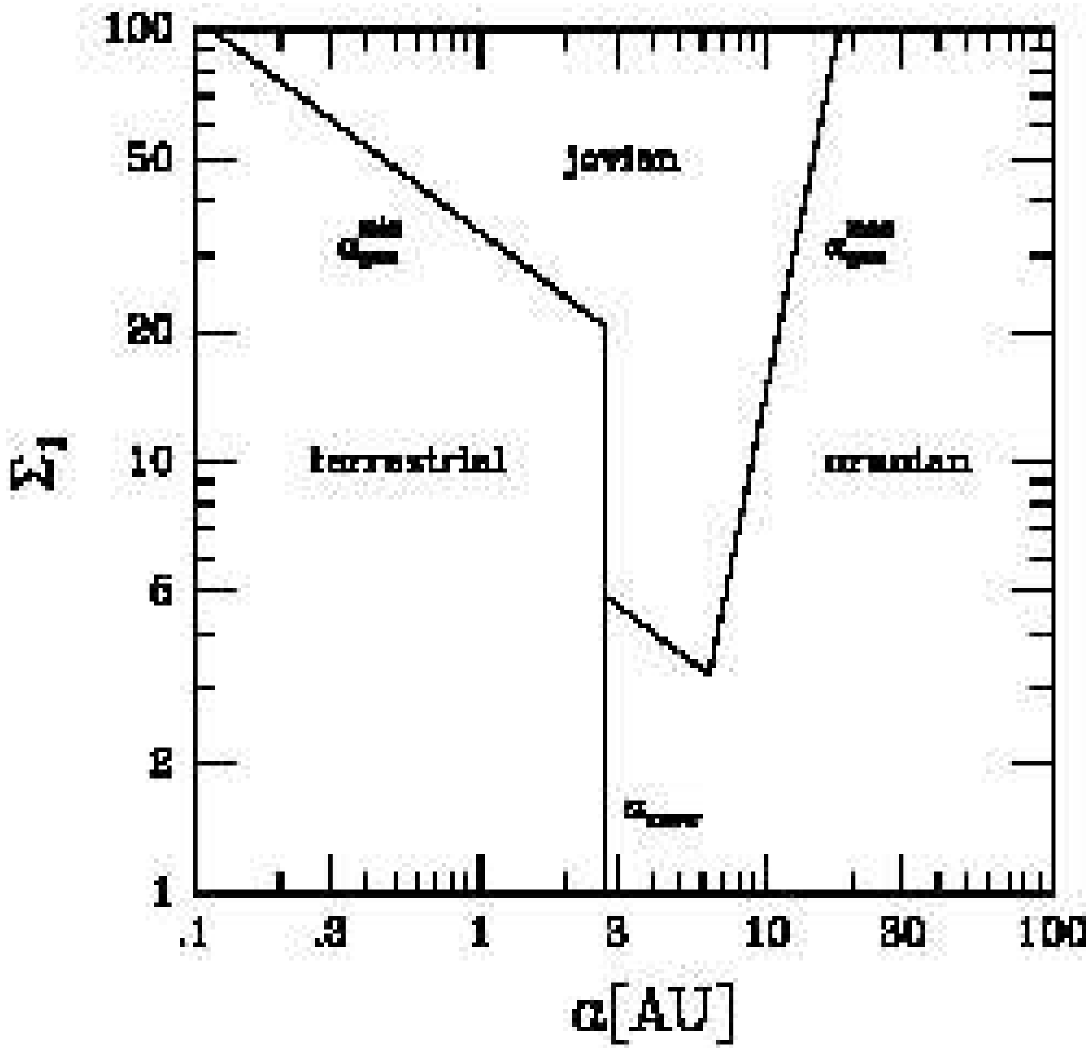


Figure 4: Habitat segregation of planets based on $a_{\rm gas}^{\rm min}$, $a_{\rm gas}^{\rm max}$, and the snow line $a_{\rm snow}$ for $T_{\rm disk} = 10^8$ years against Σ_1 for $\alpha = 3/2$ and $b = 10$.

Considering Observations

TABLE 1

ORBITAL PARAMETERS

Parameter	47 UMa b	47 UMa c
P (days)	1089.0 (2.9)	2594 (90)
T_p (JD)	2,453,622.9 (33.6)	2,451,363.5 (495.3)
e	0.061 (0.014)	0.005 (0.115)
ω (deg)	171.8 (15.2)	127.0 (55.8)
K_1 (m s^{-1})	49.3 (1.2)	11.1 (1.1)
a (AU)	2.09	3.73
$a_1 \sin i$ (AU)	4.94×10^{-3}	2.64×10^{-3}
$f_1(m)$ ($M_\odot$)	1.35×10^{-8}	3.67×10^{-10}
$M_2 \sin i$ ($M_{\rm Jup}$)	2.54	0.76
[1] $N_{\rm obs}$	90	90
rms (m s^{-1})	7.4	7.4
χ^2	1.06	1.06

Finally

- Laughlin, G.; Chambers, J.; Fischer, D (2004) Consider dynamics of the system
- Possible for Earth-mass planets to survive interior to the inner Giant
  - But… Using the model described in this talk, calculations show its unlikely that Earth-mass terrestrial planets were formed here