Tackling Some Issues in Planet Formation — From Mars's Size to a Fast Formation of Neptune

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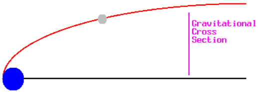
An Apple- and Microsoft-Free Presentation

The 'Standard' $6\frac{1}{2}$ Steps of Planet Formation in the Solar System

- Step 0.5: The disk forms dust settles to a the mid-plane.
- Step I: Planetesimal Formation.
  - Particles concentrate due to turbulence $\Longrightarrow$ gravitational instabilities. *(Cuzzi et al.; Johansen et al.)*
- Step II: Runaway Growth *(Greenberg et al.; Wetherill & Stewart)*

$$\dot{M} \quad \propto \quad \sigma \quad \propto \quad R^2 \left[1 + \left(\frac{v_{esc}}{v_{rel}}\right)^2\right]$$

$$\Longrightarrow \qquad \dot{M} \propto R^4 \propto M^{4/3}.$$



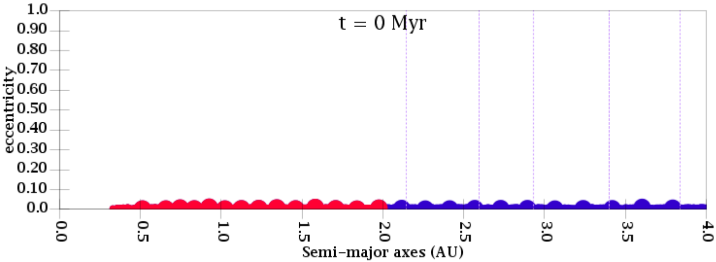
- Step III: *Oligarchic Growth* *(Kokubo & Ida; Thommes et al.; Chambers)*
  - Stirring causes v_{esc}/v_{rel} is $\sim$ constant with mass, so $\dot{M} \propto M^{2/3}$.
  - So, smaller oligarchs can catch up with larger ones.
- Step IV: *Late Stage* *(Chambers & Wetherill; Agnor et al.; O'Brien et al.)*
  - Violent endgame for terrestrial planets $\Longrightarrow$ much mixing.
- Step V: *Gas Accretion* *(Mizuno)*
- Step VI: *Instabilities* *(Thommes et al.; Tsiganis et al.)*
  - Time of *Nice* model. *(Gomes et al.)*

Step IV:

Late Stage

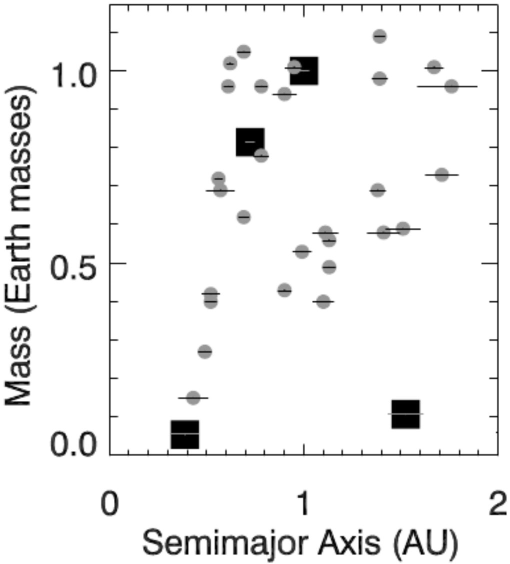
- Oligarchic growth ends when damping (via small guys) is too week to keep the big guys well behaved.
- Embryos scatter each other $\Longrightarrow$ all hell breaks lose.

(O'Brien, Morbidelli, & Levison 2006)



- Widespread radial mixing over the entire inner Solar System.
- Terrestrial planets in Solar System: *(Chambers & Wetherill; Raymond et al.)*
  - Usually get 2 or 3 big planets and some little guys. ✓
  - Note: There usually is nothing beyond $\sim 2AU$. ✓
  - Takes between ~ 30 and ~ 200 Myr. ✓
  - However, Mars is toooooo big. ×

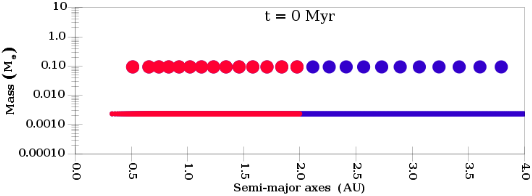
From Raymond et al. (2009):



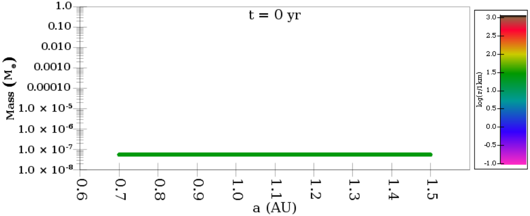
A Complication: Huge Dynamic Range

- First macroscopic objects were ~ 10 — ~ 100 km $\Longrightarrow$ $10^{\sim 14}$ objects.
- There is no single published code that can accurately go from 10 km planetesimals to Earths.
- The response is to do the problem in pieces. For example:

(O'Brien, Morbidelli, & Levison 2006)



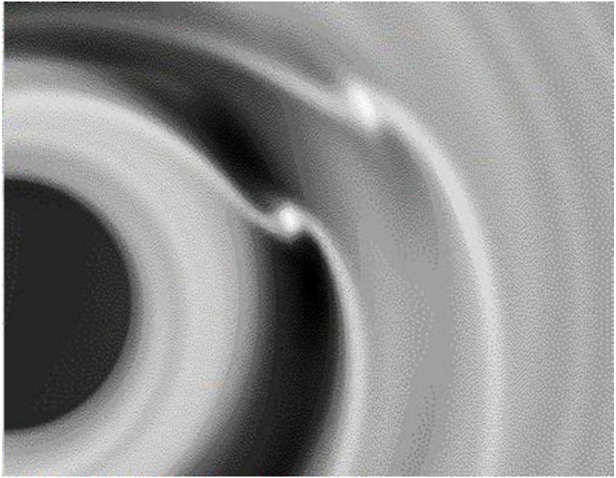
- However, in reality growth occurs from the inside out:



I think that this has led us to miss an important process.

Step V:

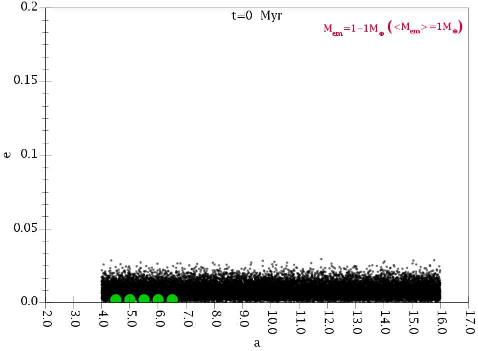
Gas Accretion *(Mizuno)*



- If objects grow bigger than $\sim 10\,M_\oplus$, they will accrete gas directly.
- Indeed, this can be very fast, depending on disk masses and opacities.

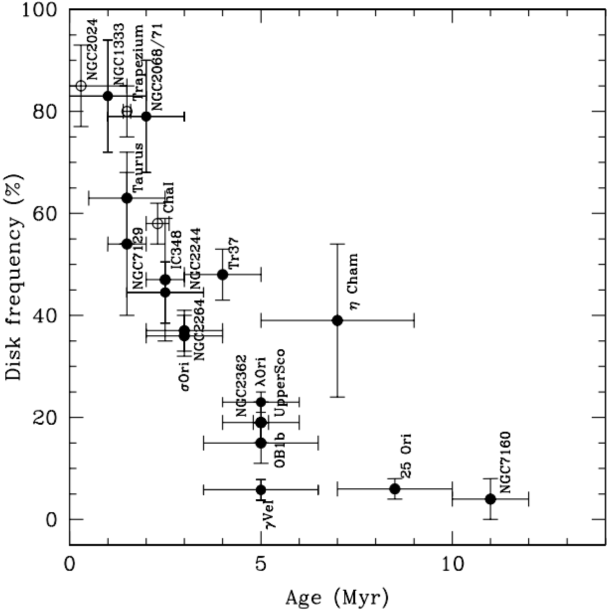
A Complication: The Giant Planet Core Time-Scale Problem

- Cores of Jupiter and Saturn have to form before the gas goes away.
  - Disks last 3-5 Myr. (Earth took between 50 and 100 Myr to form!)
- This can only happen if system is dynamically cold.
  - Recall that $\dot{M} \propto \sigma \propto R^2 \left[1 + \left(\frac{v_{esc}}{v_{rel}}\right)^2\right]$.
  - However, the embryos want $v_{rel} \sim v_{esc}$.
  - Need some damping to keep v_{rel} small.
  - There has been much effort in the literature to do this *(e.g. Rafikov, Goldreich et al., Chambers)*
    - Still need 5 – $10\times$ MMSN disk!



But, systems damped enough for $\dot{M}$ to be large always open gaps. *(Levison, Duncan, & Thommes)*

- Think Saturn's rings.
- Example:
  - 5 embryos of $1\,M_\oplus$.
  - $5\times$ MMSN disk.

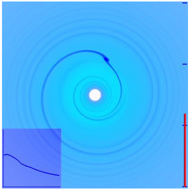


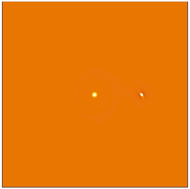
From NIR excess (Hernadez et al. 2009)

A Complication: Gas-Driven Planet Migration

- Gravitational interaction between a growing planet and gas disk causes the planets to move. *(Goldreich & Tremaine; Ward)*
- Two basic types are often invoked.

Type I: Planet is too small to effect the Σ of the disk. Moves inward with respect to disk.





Type II: Planet opens a gap. Moves with disk.

- This is probably responsible for the plethora of large planets close to their stars.
- This most likely did not happen to any great extent here.
  - There is no hot Jupiter here (?)
  - More importantly, the terrestrial planets are very dry ($\lesssim 0.2\%$).

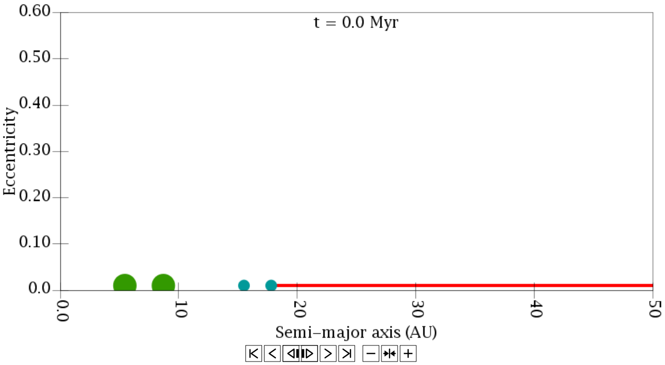
Planetesimal-Driven Migration vs. Type I

- Planets will migrate when placed in a disk of planetesimals.
  - First seen by Fernandez and Ip for Uranus and Neptune.
  - Assumed unimportant during formation. *(although see Levison et al. 2010)*
- Time-scales for massive disks:
  - Type I: $t_{\rm I} \sim 8 \times 10^5\,{\rm yr} \left(\frac{M}{1\,M_\oplus}\right)^{-1} \left(\frac{\Sigma_{1,\rm gas}}{\Sigma_{1,\rm MMSN}}\right)^{-1} \left(\frac{a}{5\rm AU}\right)^{3/2} \left(\frac{c_a}{2.8}\right)^{-1}$

    (Tanaka et al. 2002)
  - PDM: $t_p \sim 2 \times 10^5\,{\rm yr} \left(\frac{\Sigma_{1,\rm gas}}{\Sigma_{1,\rm MMSN}}\right)^{-1} \left(\frac{\mathcal{Z}}{0.017}\right)^{-1} \left(\frac{a}{5\rm AU}\right)$

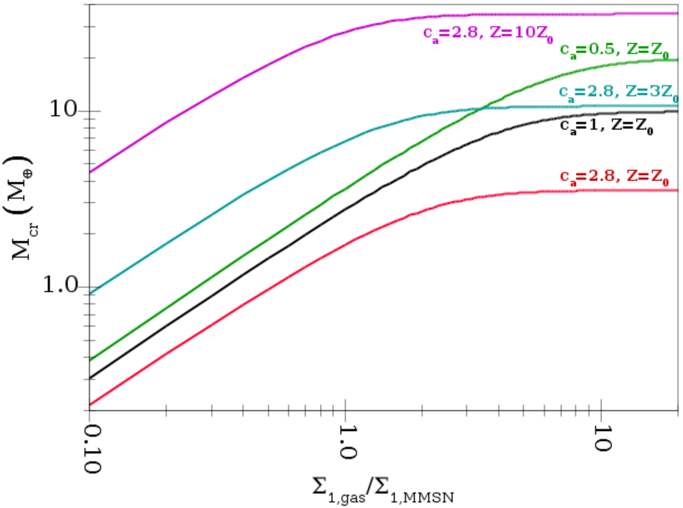
    (Ida et al. 2000; Kirsh et al. 2009)
  - For a solar $\mathcal{Z}$ disks $t_p < t_{\rm I}$ if planet is less than $4\,M_\oplus$ at $5\,$AU.
    - However, planetesimal formation might require metal-rich disk.
    - Also, Type I is weaker for more realistic equation-of-state.
- When both are included in *N*-body simulations,
  Planetesimal-driven migration usually wins!

If you accept this, P-D migration can do some wonderful things.



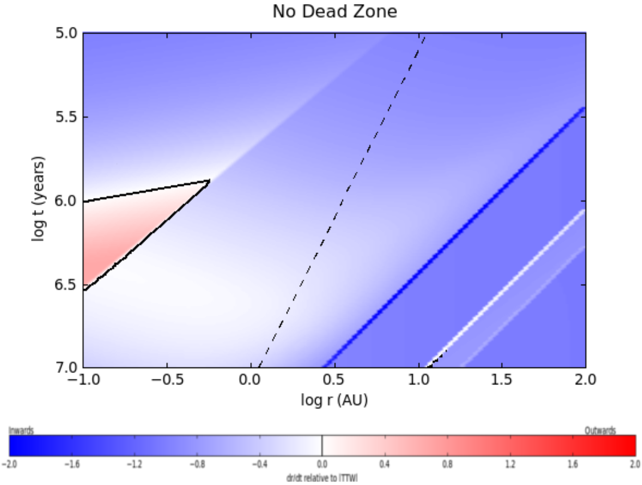
t = 0.0 Myr
Eccentricity
0.60
0.50
0.40
0.30
0.20
0.10
0.0
0.0
10
20
30
40
50
Semi–major axis (AU)

The mass below which rPDM dominates at $5\,AU$:

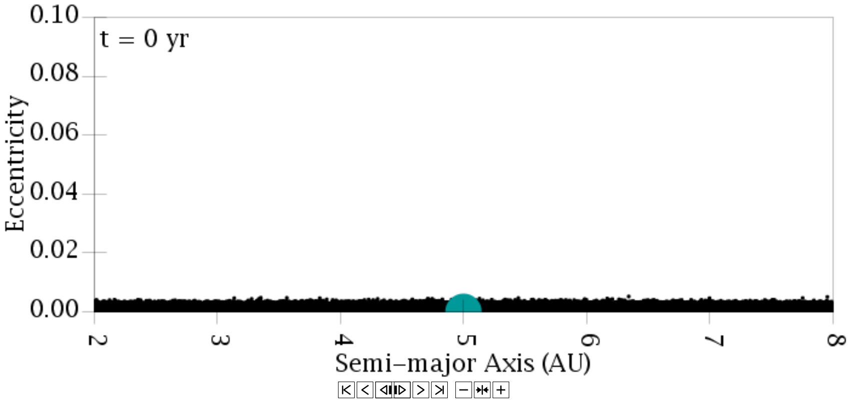


For $\Sigma \propto r^{-1}$. $\mathcal{Z}_0 = 0.017$

(Kretke & Lin 2007)



- 1/4 Earth-mass embryo.
- 5 X MMSN disk.



Note: Type I included as fictitious force. We have yet to do hydrodynamic/N-body calculations.

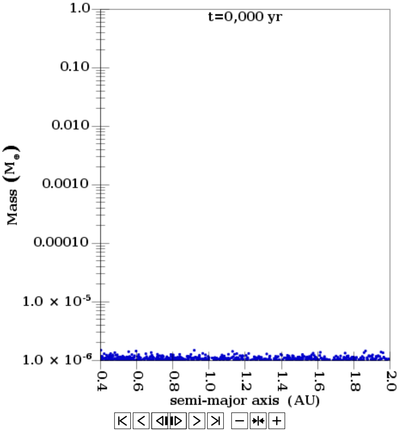
Planetesimal-Driven Migration: The Case for Mars

(Minton & Levison 2012)

- Current terrestrial planet formation simulations cannot make Mars.
  - It is tooooooo small.
- But they assume:
  1. That all embryos form at the same time $\Rightarrow$ no migration.
  2. A MMSN (i.e. they ignore collisional grinding, which is important).
- Unfortunately, we still do not have a code that can do this problem.
  - We developed a new MC code that can do the growth correctly, but not migration.
  - We run this and check to see if there are any migration candidates.
  - If so, we put this in an N-body code.
- Through N-body simulation we have found an object can migrate if:
  1. $M_P \lesssim$ mass disk within $3.5 r_H$.
  2. $M_P \gtrsim 100\ m_{\rm median}$.
  3. $e_{\rm RMS} \lesssim 3 e_H$.
  4. No large object in the way ($\sim 5\times$ larger then neighbors).
     - Migrates faster than accretion front.
- We find a few migration candidates per run.
  - Masses roughly the mass of Moon.
  - Located between ~ 0.8 and ~ 1.2 AU.

Our new code:

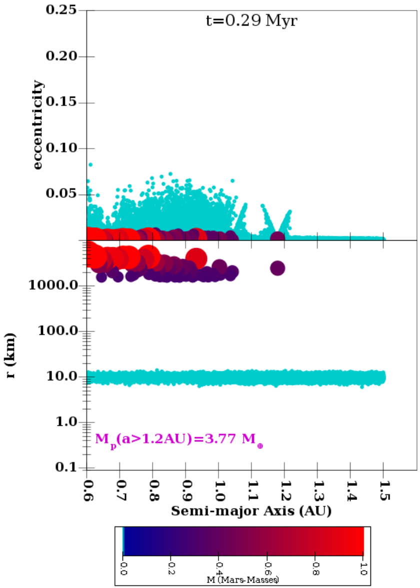
- Start with a large number of planetesimals. (55M $R \sim 50\,\mathrm{km}$ objects)
- $2.5\times$ MMSN.
- Allow them to merge using Monte Carlo algorithm.
- Velocity evolution is handled analytically.
- **NO** migration.



From this we can identify objects that satisfy our 4 migration criteria.

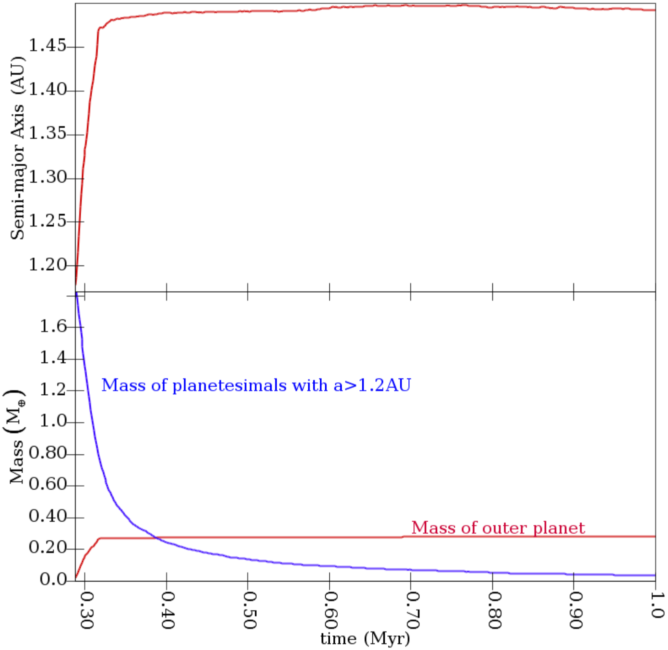
Planetesimal-Driven Migration: The Case for Mars (cont)

- When we put one of these into an N-body code, it takes off.



- And grows like crazy.
  - It migrates faster than it can excite disk $\Rightarrow$ planetesimals are dynamically cold.
  - The further it migrates the bigger it is.
  - Is $\sim$Mars-mass when it get to 1.5 AU.
- Leaves an excited disk between 1 and 1.5 AU.
  - Outer regions get excited enough for the planetesimals to grind.
  - Leaving Mars isolated and small.

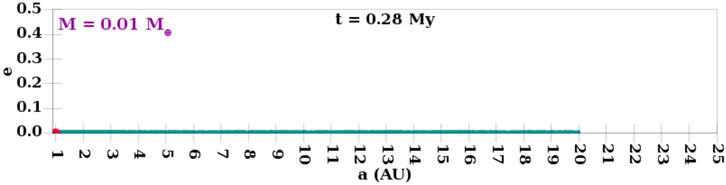
Naturally explains Mars's mass, chemical differences (if any), *and* old age.



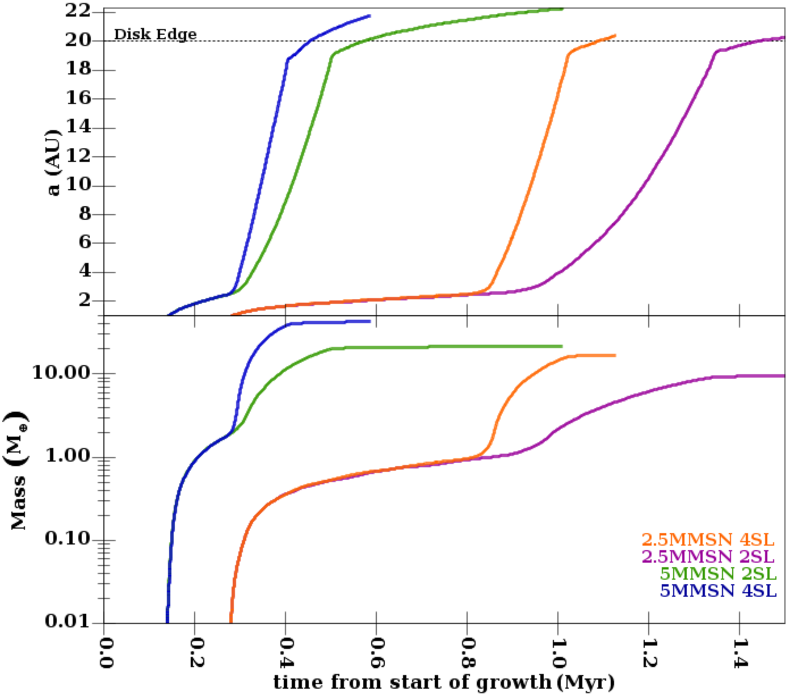
Semi-major Axis (AU)
1.45
1.40
1.35
1.30
1.25
1.20
Mass (M⊕)
1.6
1.4
1.2
1.0
0.80
0.60
0.40
0.20
0.0
Mass of planetesimals with a>1.2AU
Mass of outer planet
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.0
time (Myr)

An EXTREME Case of Planetesimal-Driven Migration

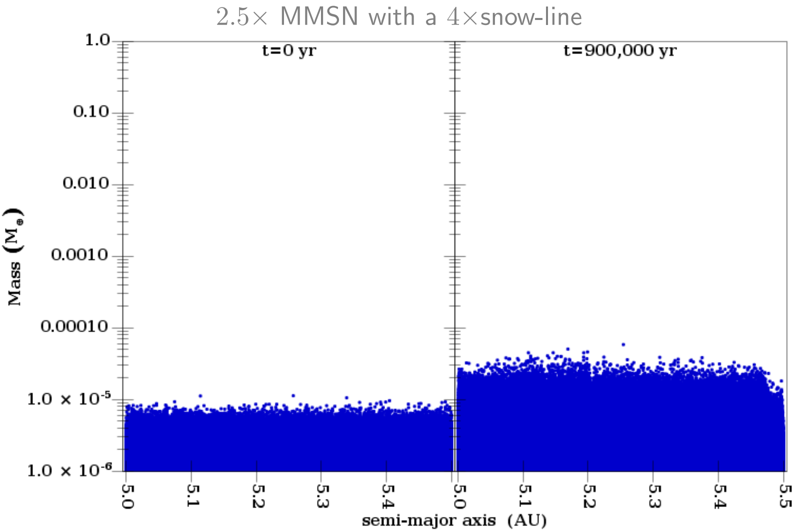
- Embryo takes off:



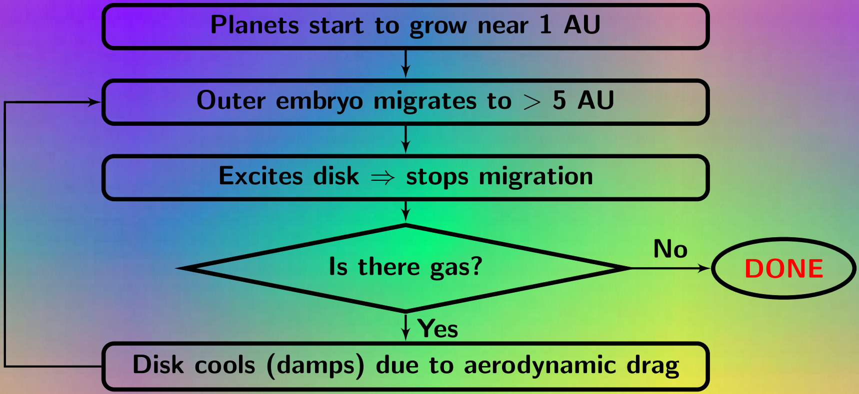
- Grows like mad.
  - Stirring timescale slower than migration timescale
    $\Longrightarrow$ disk is dynamically cold.
  - We get large embryos (giant planet cores?) at $a > 5$ AU.
  - In the above example with $2.5\times$ MMSN:
    - Core is $5M_{\oplus}$ at 5.4 AU after $900,000$ yr.
    - Core is $14M_{\oplus}$ at 15 AU after $1,000,000$ yr.
  - Takes less time than growing something at 5 AU
    $\Longrightarrow$ Indeed, it solves a long-standing timescale problem.



Disk Edge
a (AU)
Mass ($M_\oplus$)
time from start of growth (Myr)
2.5MMSN 4SL
2.5MMSN 2SL
5MMSN 2SL
5MMSN 4SL



2.5× MMSN with a 4×snow-line
t=0 yr
t=900,000 yr
Mass (M⊕)
1.0
0.10
0.010
0.0010
0.00010
1.0 × 10-5
1.0 × 10-6
5.0
5.1
5.2
5.3
5.4
5.5
semi-major axis (AU)



- This occurs 4 times before the disk goes away.
- Mars tried after gas was gone, but stalled because the disk was excited.

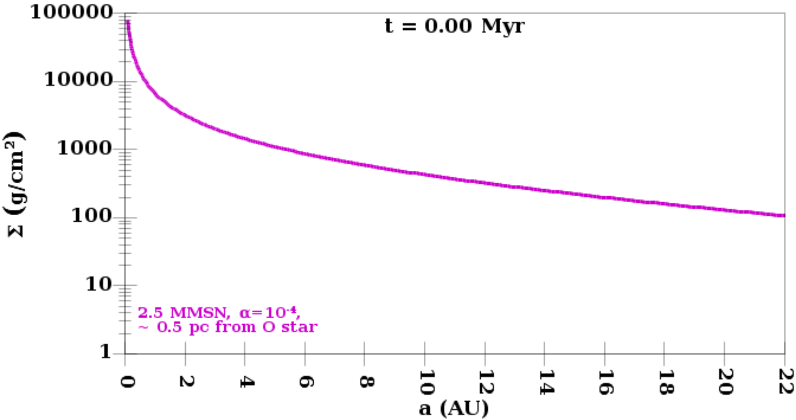
Possible Implications of our New Fairy Tale

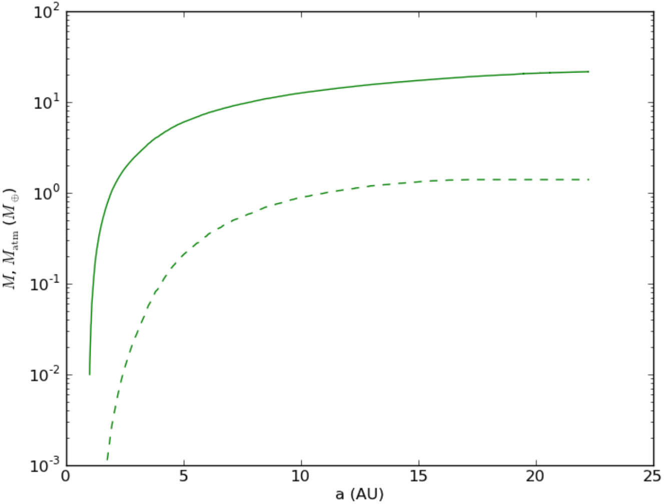
Disclaimer: Our modeling effort is just beginning.

- We have yet to study the multi-planet case.

So, having said that:

1. Neptune is the oldest planet in the Solar System.
   - If so, why isn't it a gas giant? Our hypothesis is:
     - The sun probably formed in a cluster that contained massive stars.
     - UV radiation would photo-evaporate the outer regions of the disk.
     - Neptune and Uranus migrated beyond the edge.
       - Grab a small amount of nebular gas.
       - This is regulated by the solid accretion rate.
     - Jupiter and Saturn stopped when in nebula.
2. Jupiter forms just as the gas is going away.
   - Perhaps this can explain why it is so metal rich.
3. Predicts (?) increasing core mass with heliocentric distance.
   - This is basically what we observe.


t = 0.00 Myr
Σ (g/cm²)
a (AU)
2.5 MMSN, α=10⁻⁴,
~ 0.5 pc from O star


10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
M, $M_{\rm atm}$ ($M_\oplus$)
0
5
10
15
20
25
a (AU)

Conclusions

- There are some significant issues with our current understanding of planet formation.
  1. Type I migration pushes icy material to 1 AU.
  2. Mars is too small.
  3. Core of giant planets take too long to form.
- We argue that planet-driven migration might solve these problems.
- In particular, we present a new scenario:
  - All planets in the Solar System started to form near 1 AU.
  - If gas is still around, they migrated to outer Solar System.
  - Implies that Neptune is the oldest planet.

This talk can be found at www.boulder.swri.edu/~hal/talks.html.
We thank NASA's NLSI program and the NSF for support.