Formation of Planets around M & L dwarfs

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1 Disk life time is independent of $M_*$: similar available time
2 Disk accretion rate varies as $M_*^2$: Less gas content
3 Disk heavy element mass varies as $M_*^{1-2}$: Less metals
Preferred locations

Meteorites: Dry, chondrules & CAI’s

Enhancement factor > 4
Stellar mass dependence

\[ T(\text{snow line}) \sim 160\text{K}, \quad L \sim M^2 \]

\[ a(\text{snow line}) \sim (L)^{1/2}/T^2 \sim 2.7(M_*/M_\odot) \text{ AU} \]

\[ V_k(\text{snow}) \sim (M/a)^{1/2} \sim \text{Const}; \quad H/a \sim \text{Const} \]

Similar aspect ratio and Keplerian speed!

But shorter time scales \((a/V_k)\) for lower \(M_*\)

Water-rich planets form near low-mass stars
From planetesimals to embryos

Feeding zones:
\[ \Delta \sim 10 \, r_{\text{Hill}} \]

Isolation mass:
\[ M_{\text{isolation}} \sim \Sigma^{1.5} \, a^{3} \, M_{\ast}^{-1/2} \]

Initial growth: (runaway)

Shorter growth time scale at the snow line
\[ \alpha = 3/2 \]
\[ \Sigma_{1} = 1, 10, 100 \]

Disk Mass Dependence

\[ \tilde{b} = 11.5 \pm 1.7 \]
\[ \tilde{b} = 13.7 \pm 2.5 \]
\[ \tilde{b} = 15.1 \pm 5.1 \]
**M_* dependence**

Scaling disk models with M_*:

a) Solar system: Minimum-mass nebula
b) Other stars: \( \Sigma(a) = \Sigma_{SN}(a) h_d \)
   where \( h_d = (M_*/M_{sun})^{0,1,2} \)

c) Embryos with \( M_p > M_{earth} \) at formed outside snow line

**Importance of snow line:**
Interior to it: growth limit due to isolation
Exterior to it: long growth time scale

**Outside the snow line:**

\[
\begin{align*}
M_{\text{isolation}} & \sim 1.3(a/1\text{AU})^{3/4}(M_*/M_o)^{3/2}M_{\text{earth}} \\
\tau_{\text{embryos}} & \sim 0.033(a/1\text{AU})^{59/20}(M_*/M_o)^{-16/15}\text{Myr}
\end{align*}
\]

Can form \( >3M_{\text{earth}} \) embryos outside 5AU within 10Myr
Disk–planet tidal interactions

**type-I migration**

\[ M > (0.1 - 1)M_\oplus \]

**type-II migration**
Lin & Papaloizou (1985),...

\[ M > (10 - 100)M_\oplus \]

Virtually planet’s perturbation

\[ \tau_{\text{mig},\text{I}} \approx 0.05 \left( \frac{\Sigma_{g,SN}}{\Sigma_g} \right) \left( \frac{M_\oplus}{M_p} \right) \left( \frac{M_*}{M_o} \right)^{3/2} \left( \frac{a}{1\text{AU}} \right)^{3/2} \text{Myr} \]

\[ \tau_{\text{mig,II}} \approx \left( \frac{\Sigma_{g,SN}}{\Sigma_g} \right) \left( \frac{M_p}{M_J} \right) \left( \frac{10^{-3}}{\alpha} \right) \left( \frac{M_o}{M_*} \right)^{1/2} \left( \frac{a}{1\text{AU}} \right)^{1/2} \text{Myr} \]
Low-mass embryo (10 Mearth)

Cooler and invisic disks
(Mass) growth vs (orbital) decay

Embryos’ migration time scale

\[ \tau_{\text{mig}, I} \approx 0.04 \left( \frac{\Sigma_g(0)}{\Sigma_g(t)} \right) \left( \frac{M_o}{M_*} \right) \left( \frac{a}{1\text{AU}} \right)^{\frac{3}{4}} \text{Myr} \]

Outer embryos are better preserved only after significant gas depletion

\[ \left( \frac{\tau_{\text{embryo}}}{\tau_{\text{mig}, I}} \right) \approx \left( \frac{\Sigma_g(t)}{\Sigma_g(0)} \right) \left( \frac{a}{1\text{AU}} \right)^{\frac{11}{5}} \]

Critical-mass core: \( M_p = 5M_{\text{earth}} \)

\[ \tau_{\text{mig}, I} \approx 0.01 \left( \frac{\Sigma_g(0)}{\Sigma_g(t)} \right) \left( \frac{M_o}{M_*} \right)^{\frac{1}{2}} \left( \frac{a}{1\text{AU}} \right)^{\frac{3}{2}} \text{Myr} \]

Loss due to Type I migration
Flow into the Roche potential

Equation of motion:

\[
\left( \frac{DU}{Dt} \right) \approx -\left( \frac{C_s^2}{\rho} \right) \left( \frac{\partial \rho}{\partial r} \right)^{-1} + \nabla \varphi
\]

- Bondi radius \( R_b = \frac{GM_p}{c_s^2} \)
- Hill’s radius \( R_h = (\frac{M_p}{3M_*})^{1/3} a \)
- Disk thickness \( H = c_s a / V_k \)

If \( R_b > R_h \), a large decline in \( \rho \) (positive \( r \) gradient) would be needed to overcome the tidal barrier.

\[ R_b / R_h = 3^{1/3}(\frac{M_p}{M_*})^{2/3}(a/H)^2 \]

A small \( \rho \) at the Hill’s radius would quench the accretion flow.
Reduction in the accretion rate

Growth time scales:

Embryos’ emergence time scale: \( \sim 0.033 \left( \frac{a}{1 \text{AU}} \right)^{59/20} \left( \frac{M_*}{M_\odot} \right)^{-16/15} \text{Myr} \)

KH cooling/contraction of the envelope: \( \sim 10^{2-4} \left( \frac{M_p}{M_{\text{earth}}} \right)^{(3-4)} \text{Myr} \)

Uninhibited Bondi accretion: \( \sim (H/a)^4 \left( \frac{M_*^2}{M_p M_d} \right)/\Omega_k \sim 10^{2-3} \text{yr} (M_j/M_p) \)

Uninhibited accretion from the disk: \( \sim \frac{M_p}{(dM/dt)} \sim 10^{3-4} \text{yr} (M_p/M_j) \)

Reduction due to Hill’s barrier: \( > \tau_{\text{disk depletion}} \)

Tidal barriers suppress the emergence of gas giants around low-mass stars
Gap formation & type II migration

Viscous and thermal conditions

\[ M_{g, \text{vis}} \approx \frac{40 \nu}{a \Omega_K} M_\ast \approx 40 \alpha \left( \frac{h}{a} \right)^2 M_\ast \approx 30 \left( \frac{\alpha}{10^{-3}} \right) \left( \frac{a}{1 \text{AU}} \right)^{1/2} \left( \frac{M_\ast}{M_\odot} \right) M_\oplus. \]

\[ M_{g, \text{th}} \approx 3.8 \times 10^{-4} \left( \frac{a}{1 \text{AU}} \right)^{3/4} M_\ast \approx 1.2 \times 10^2 \left( \frac{a}{1 \text{AU}} \right)^{3/4} \left( \frac{M_\ast}{M_\odot} \right) M_\oplus. \]

Lower limiting mass for gas giants around low-mass stars

\[ \tau_{\text{mig}, \text{II}} \approx \left( \frac{\Sigma_{g, \text{SN}}}{\Sigma_g} \right) \left( \frac{M_p}{M_J} \right) \left( \frac{10^{-3}}{\alpha} \right) \left( \frac{M_\odot}{M_\ast} \right)^{1/2} \left( \frac{a}{1 \text{AU}} \right)^{1/2} \text{Myr} \]

Neptune-mass planets can open up gaps and migrate close to the stars
Hot Neptunes around low-$M_*$ stars

Radial extent is determined by $V_k > V_{\text{escape}}$
Migration-free sweeping secular resonances

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

Transitional disks
Dynamical shake up (Nagasawa, Thommes)

Bode’s law: dynamically porous terrestrial planets orbits with low eccentricities with wide separation
Formation of water worlds

Jupiter-Saturn secular interaction & multiple extrasolar systems

Sweeping secular resonance may be more intense in low-mass stars. But the absence of gas or ice giants would leave behind dynamically-hot earth-mass objects.
Summary

1. Snow line is important for the retention of heavy. Around low-mass stars, planets with mass greater than that of the earth are formed outside the snow line.

2. Planet-disk interaction can lead to depletion of first generation planetesimals, especially around low-mass stars.

3. Self regulation led to the stellar accretion of most heavy elements, the late emergence of planets, and perhaps the inner holes inferred from SED’s.

4. Around low-mass stars, gas accretion rate onto proto gas giants is also suppressed by a tidal barrier.

5. Neptune-mass embryos can open up gaps and migrate to the stellar proximity.

6. Residual planetesimals may have modest eccentricities.

7. There will be a desert of gas giants and an oasis of terrestrial planets, including short-period water worlds around dwarfs.