Ana-Maria A. Piso, Andrew N. Youdin

The Structure and Stability of Atmospheres Accreting Around Protoplanetary Cores

ABSTRACT

The core accretion model proposes that giant planets form by the accretion of gas onto a solid protoplanetary core. Previous studies have found that there exists a "critical core mass" past which hydrostatic solutions can no longer be found and unstable atmosphere collapse occurs. In standard calculations of the critical core mass, planetesimal accretion deposits enough heat to alter the luminosity of the atmosphere, increasing the core mass required for the atmosphere to collapse. In this study we consider the extreme case in which planetesimal accretion is negligible and Kelvin-Helmholtz contraction dominates the luminosity evolution of the planet. We develop a two-layer atmosphere model with an inner convective region and an outer radiative zone that matches onto the protoplanetary disk, and we determine the minimum core mass for a giant planet to form within the typical disk life timescale for a variety of disk conditions. Our results are lower than results for large planetesimal accretion rates. We find that the absolute minimum core mass required to nucleate atmosphere collapse within the disk lifetime is smaller for planets forming further away from their host stars.

TWO-LAYER ATMOSPHERE MODEL

- Two-layer atmosphere model, consisting of an inner convective region and an outer radiative region that matches onto the disk.
- Assumes that the protoplanetary core no longer accretes planetesimals and remains at constant mass.
- The atmosphere is considered to be in hydrostatic equilibrium.
- Under these conditions, the structure of the atmosphere is determined by the following equations:

$$\frac{dP}{dr} = -\frac{Gm}{r^2}\rho \qquad \frac{dT}{dr} = \nabla \frac{T}{P}\frac{dP}{dr}$$

$$\frac{dm}{dr} = 4\pi r^2 \rho \qquad \frac{dL}{dr} = 4\pi r^2 \rho \varepsilon_g$$

$$\nabla = \begin{cases} \nabla_{ad} = \left(\dfrac{d\ln T}{d\ln P}\right)_{ad}, & \nabla_{ad} < \nabla_{rad} \\ \nabla_{rad} = \dfrac{3\kappa P}{64\pi G m \sigma T^4} L, & \nabla_{ad} \geq \nabla_{rad} \end{cases}$$

- The luminosity is assumed to be constant throughout the radiative region of the atmosphere: $\varepsilon_g = -T\, dS/dt = 0$
- Boundary conditions: we assume the atmosphere extends out to the boundary of the Hill sphere (beyond which material is gravitationally unbound from the planet), where it matches smoothly on to the disk: $T(R_H)=T_d$, $P(R_H)=P_d$.
- Disk model: minimum mass, passively irradiated (Chiang & Youdin 2010).
- Opacity: dust power law opacity $\kappa=\kappa_0\,(T/T_d)^\beta\,(P/P_d)^\alpha$, $\alpha=0$, $\beta\sim2$

PLANETESIMAL ACCRETION VS. GAS CONTRACTION

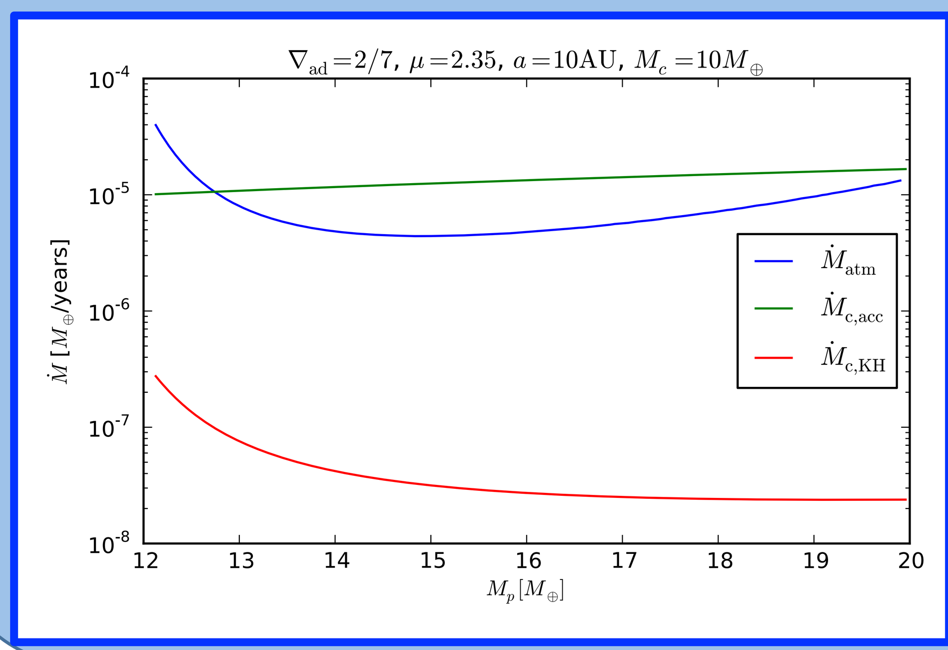

Fig. 1: For Kelvin-Helmholtz contraction to dominate the atmosphere growth, the maximum planetesimal accretion rate during the gas contraction phase (in red) has to be ~3 orders of magnitude lower than the accretion rate of the atmosphere (in blue) => our model assumes that the fastest way to form a planet is to grow the core first, then let the atmosphere cool. In this case, runaway gas accretion is initiated after *T*~1.2 Myrs. For comparison, we also plot (in green) the planetesimal accretion rate necessary to grow a core on the same time scale.

ENERGETICS AND COOLING MODEL

- In order to determine the time evolution of the atmosphere, we use a global cooling model for a protoplanetary atmosphere embedded in a gas disk:

$$L = L_c + \Gamma - \dot{E} + e_{acc}\dot{M} - P_M\frac{\partial V_M}{\partial t}$$

- The cooling model applies at any radius *R* where the mass enclosed is *M*. This radius can be the Hill radius, the Bondi radius, or at the boundary between the radiative and convective regions of the atmosphere (RCB).

NUMERICAL METHOD

M_i = total atmosphere mass → L_{guess} = guess value for constant luminosity *L* corresponding to M_i → integrate inwards → $M_{c,\,guess}$ = core mass value corresponding to trial luminosity

adjust L_{guess} until $M_{c,\,guess}$ → M_c

- The time step Δt_i between two consecutive models with masses M_i and M_{i+1} is found from the global cooling equation:

$$\Delta t_i = -\Delta E + \langle e_{acc}\rangle \Delta M - \langle P_{\langle M\rangle}\rangle \Delta V_M$$

RESULTS

ATMOSPHERE PROFILES

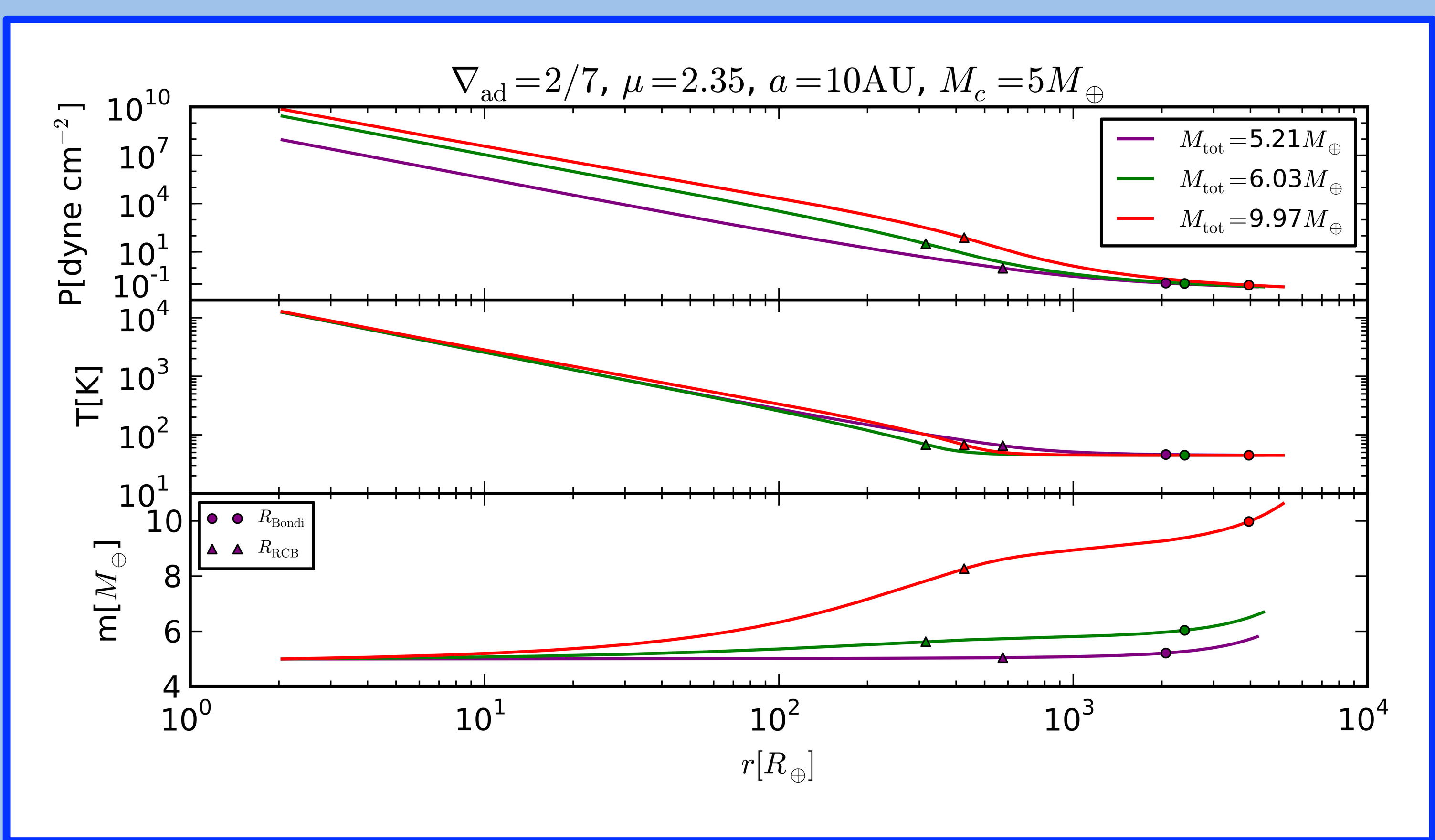

Fig. 2: Example pressure, temperature and mass profiles as a function of radius.

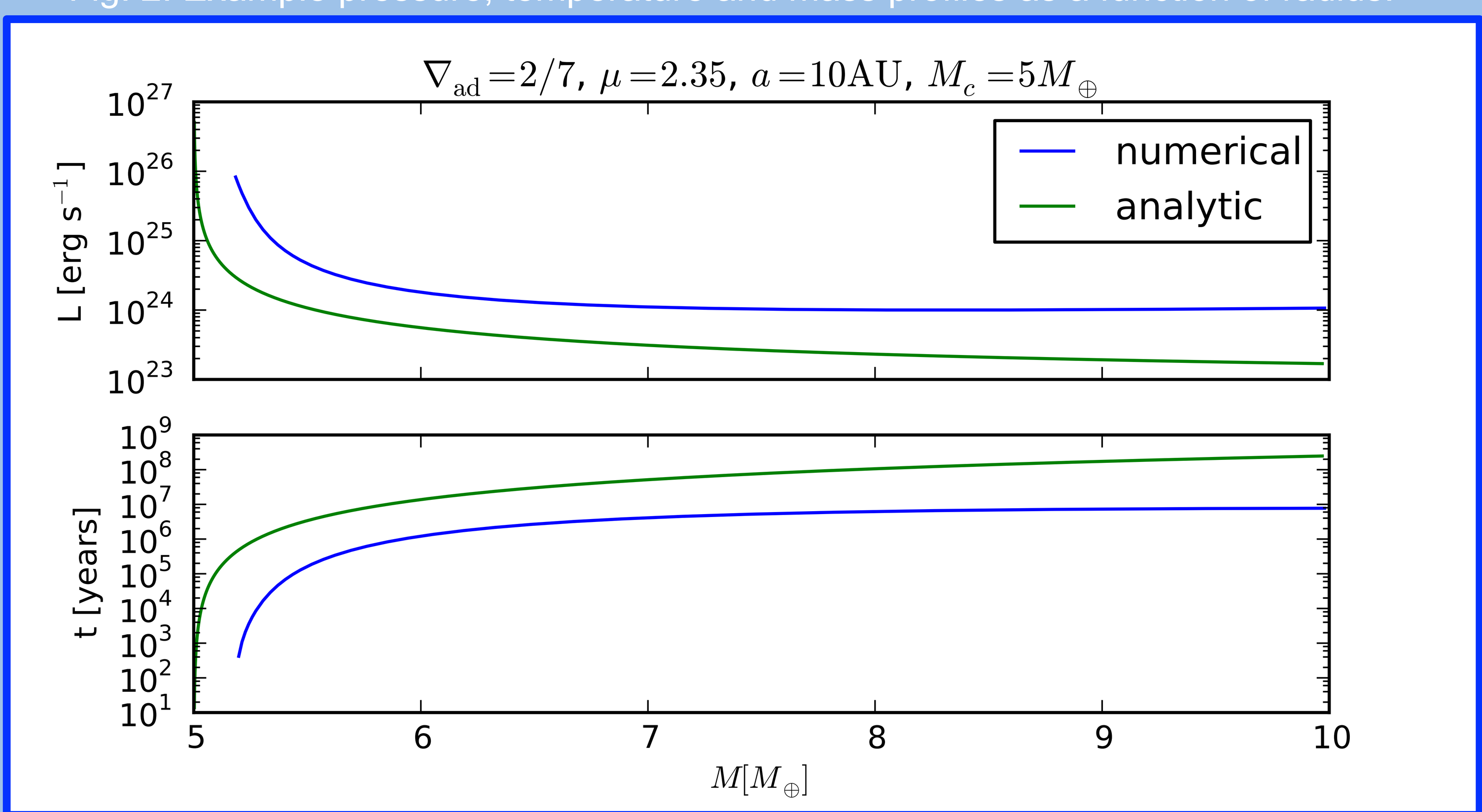

Fig. 3: Luminosity and time evolution with mass.

CRITICAL CORE MASS

- As the atmosphere mass becomes roughly the same as the core mass, runaway accretion commences. As such, the timescale on which the atmosphere evolves is given by the time that it takes to reach the mass doubling.
- We define this mass as the *critical core mass.*

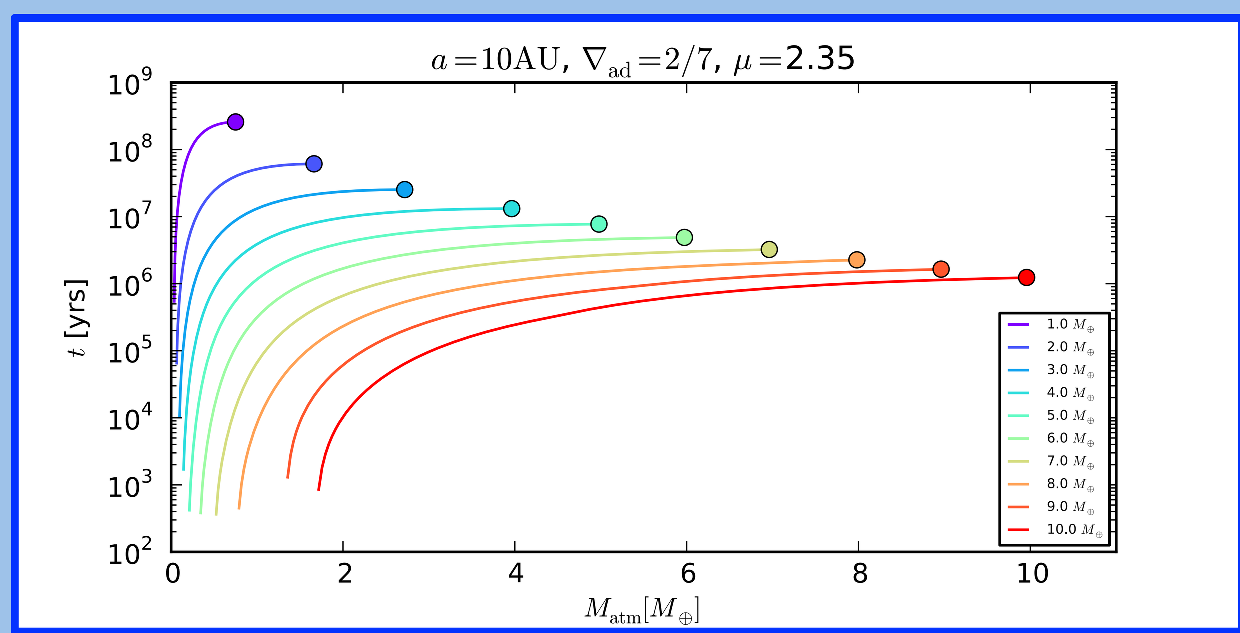

Fig. 4: Time evolution as a function of atmosphere mass for a range of core masses. The circles mark the time when the atmosphere becomes 'critical'.

- Once the time evolution is obtained, we are interested in knowing the minimum core mass for an atmosphere to form within the life time of the protoplanetary disk (typically of the order of few million years).

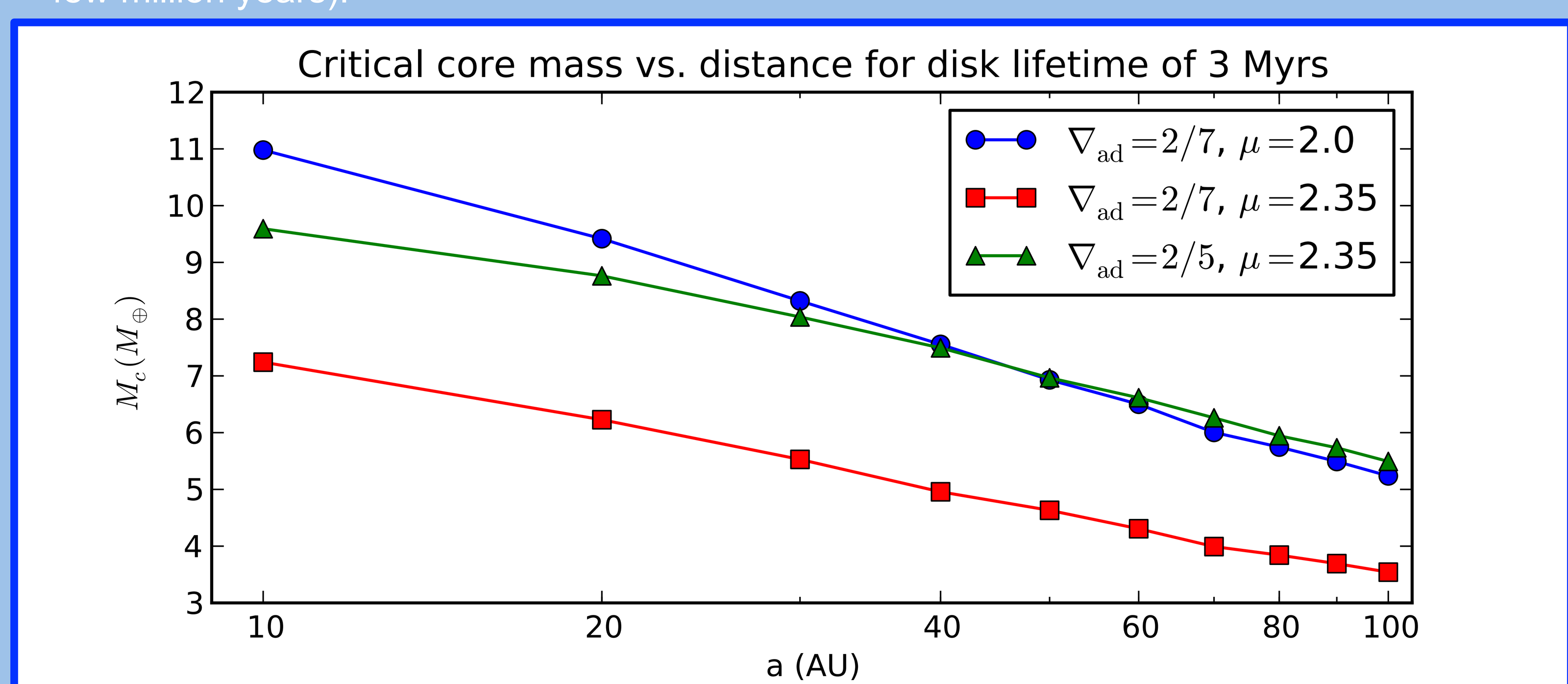

Fig. 5: The minimum core mass for an atmosphere to become 'critical' within the lifetime of the disk as a function of semi-major axis, for different adiabatic indices and molecular weight of the nebular gas.

FUTURE PROSPECTS

- ***Time dependent model:*** our model consists of series of quasistatic atmospheres with constant luminosity in the outer radiative region. A time dependent model in which the luminosity is allowed to vary is currently being developed; however, we do not expect qualitatively different results.
- ***Equation Of State:*** the model currently assumes an ideal gas polytropic equation of state. However, non-ideal interactions, dissociation and ionization effects should be taken into account. We are using the Saumon et al. (1995) equation of state tables to model the H/He mixture.

CONCLUSIONS

- The minimum core mass necessary to form a giant planet is smaller for planets forming further out in the protoplanetary disk.
- We find that the critical core mass to form a giant planet before the dissipation of the protoplanetary disk is smaller than typical values of the critical core mass when planetesimal accretion dominates the atmosphere growth (e.g., Rafikov 2006).

For more information please contact apiso@cfa.harvard.edu