Planet Formation around Stars of Various Masses: the Snow Line and the Frequency of Giant Planets

By G. M. Kennedy and S. J. Kenyon

Motivation

- Current theory suggests that planets form in similar ways around all stars. However, we can see an increasing diversity in this area
- Snow line position is considered to be fixed in a disk around a MS star, but actually it may move considerably during PMS stage and influence the planet formation
- Develop a new time-dependent model for gas giants formation, and in this model, the movement of snow line due to the PMS evolution of stellar luminosity and disk accretion is taken into consideration

Background

- Lifetime of the primordial, optically thick, dusty component of the disk is ≲10 Myr (median time scale ~ 3 Myr)
  (Strom et al. 1993; Haisch et al. 2001b)
- Gaseous component of the disk is probably removed by viscous accretion and photoevaporation on similar timescales.
  (Lynden-Bell & Pringle 1974; Hollenbach et al. 2000; Adames et al. 2004; Alexander et al. 2006; Zuckerman et al. 1995; Pascucci et al. 2006)
- Protoplanets need to reach masses of 5-10 $M_\oplus$ in this timescale to further attract significant atmosphere and form gas planets

  (Pollack et al. 1996; Ikoma et al. 2000)

Background

- Formation of "isolated" Protoplanets:

$$M_{\text{iso}} = \frac{\left(4\pi B\sigma a^2\right)^{3/2}}{\left(3M_*\right)}$$

Protoplanets are spaced at $2BR_H$~$8R_H$ intervals, where R_H is the Hill radius:

$$R_{\text{H}} = a\left(M_{\text{iso}} / 3M_*\right)^{1/3}$$

- "Minimum-mass solar nebula"

$$\sigma = a^{-\delta}, \text{ where } \delta = 1\text{-}1.5$$

Background

- Snow line
  - Condensation of ices outside snowline increases the disk density by a factor f_{ice}~3
  - Condensation of ices also leads to a shorter growth times, since the timescale for planet growth is

$$t \propto P/\sigma \propto a^3, \text{ for } \sigma \propto a^{-3/2}$$

- Isolation time: t_{iso}

Background

- Previous work:
  - Kornet et al. 2006: Low mass stars are more likely to form gas giant due to the increased inward migration rate and consequent higher surface density around low-mass stars
  - Ida & Lin, 2005: Applied the Monte Carlo method on the MMSN and considered the type II migration, and concluded that the probability of gas planets formation increases with the stellar mass up to solar mass. But in their model the snow line position is based on MS luminosity

Location of Snow Line

- Midplane temperature:

$$T_{\rm mid}^4 = T_{\rm mid,accr}^4 + T_{\rm irr}^4$$

- Midplane temperature arising from viscous accretion:

$$T_{\rm mid,accr}^4 \sim \frac{3\tau}{8} T_{\rm eff,accr}^4, \quad \text{where } \tau = \kappa \sigma_{\rm g} / 2$$

- $T_{\rm eff}$: effective disk temperature from viscous accretion

$$T_{\rm eff,accr}^4 = \frac{3}{8\pi} \frac{G M_* \dot{M}}{\sigma_{\rm sb} a^3} \left(1 - \sqrt{\frac{R_*}{a}} \right)$$

$$\dot{M} \propto M_* \qquad \dot{M} \propto (t / 10^6\,{\rm yr})^{-\gamma}, \text{ and } \gamma = 1.5 - 2.8$$

for ~1 Myr old solar-type star $\dot{M} = 10^{-8} M_\odot {\rm yr}^{-1}$

Location of Snow Line

- Midplane temperature:

$$T_{\mathrm{mid}}^4 = T_{\mathrm{mid,accr}}^4 + T_{\mathrm{irr}}^4$$

- Temperature contribution from irradiation:

$$T_{\mathrm{irr}} = T_* \left(\frac{\alpha}{2}\right)^{1/4} \left(\frac{R_*}{a}\right)^{3/4}$$

where $\alpha \approx 0.005 / a_{\mathrm{AU}} + 0.05 a_{\mathrm{AU}}^{2/7}$

- Snow line: where T_{mid}=170K

Location of Snow Line

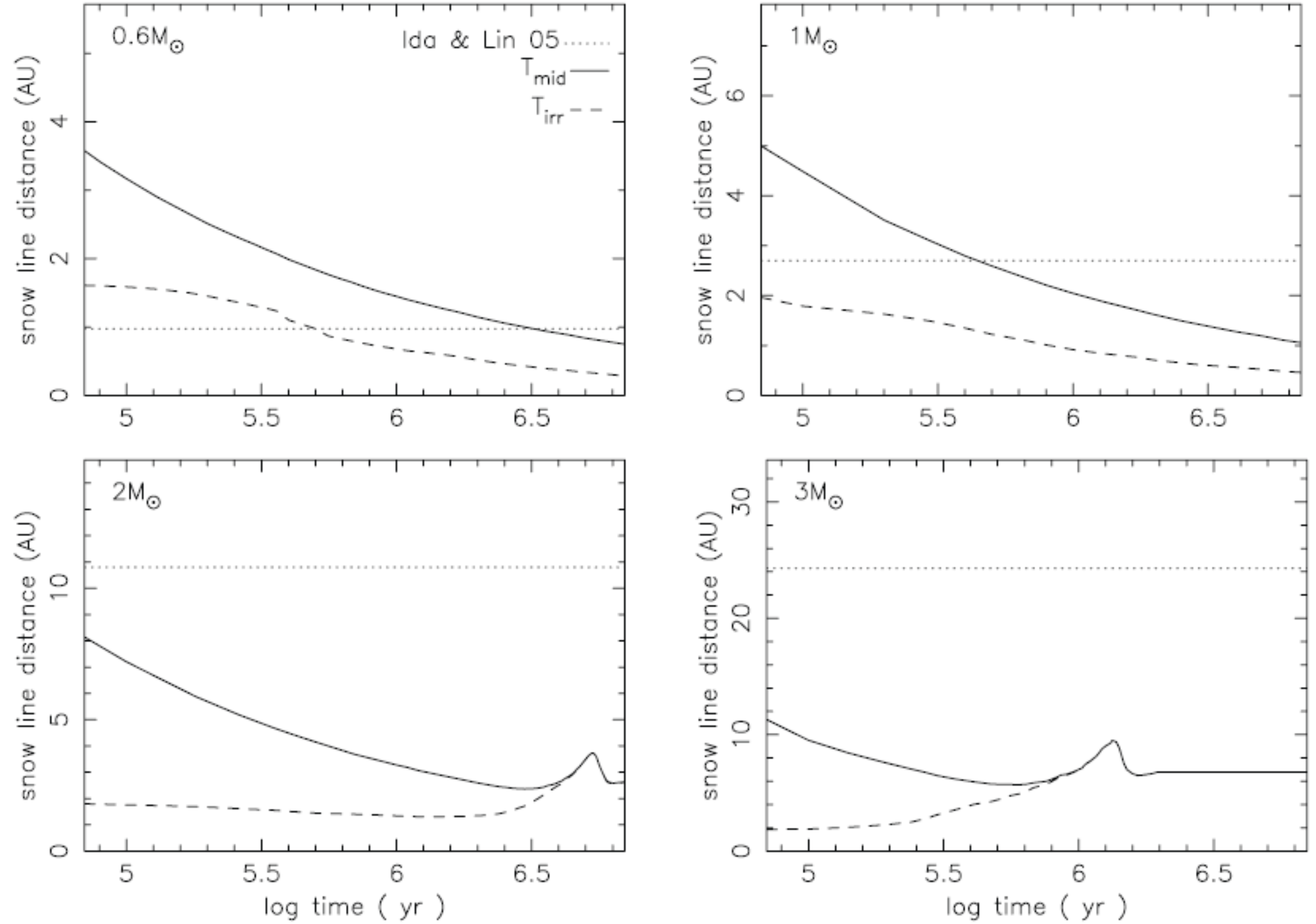

FIG. 1.—Location of the snow line (a at $T_{mid} = 170$ K) over time for 0.6, 1, 2, and 3 $M_\odot$ stars (*left to right, and down*) with irradiation only (using Palla & Stahler [1999] PMS tracks, *dashed line*), and irradiation + accretion (*solid line*). The disks have surface densities $\sigma = \sigma_{MMSN}\ M_*/M_\odot$. Included for reference is $a_{snow} = 2.7\ M_*/M_\odot$ AU as used by Ida & Lin (2005; *dotted line*).

Protoplanet Formation Model

- Surface density:

$$\sigma(a,t) = \sigma_0 \eta f_{\mathrm{ice}} \frac{M_*}{M_\odot} a_{\mathrm{AU}}^{-\delta}$$

where $\sigma_0 = 10 \text{ g cm}^{-2}$ $\delta = 1.5$

$$\eta \sim 0.5 - 5 \ \ (M_{\mathrm{disk}} = 0.01 - 0.1 M_*)$$

- Isolation timescale

$$t_{\mathrm{iso}} \propto (\eta\sigma)^{-1} a^{3/2} M_*^{-1/2}$$

(for σ=10 g cm^{-2} at 5 AU, t_{iso}=10^5 yr)

A "successful" Gas Giant Cores

- Previous studies showed that the minimum core mass to form a gas giant in less than 10^7 yr is 5-10 earth-mass. Therefore, in this new model, the minimum core mass M_{core} = 10 earth-mass
- Disk mass decreases significantly (~60%) in 1 million years, so they adopt t_{core} = 1 Myr as a typical maximum core formation time
- A "successful" gas giant core means:

$$M_{\mathrm{iso}} > M_{\mathrm{core}}$$

$$t_{\mathrm{iso}} < t_{\mathrm{core}}$$

The Solar Example

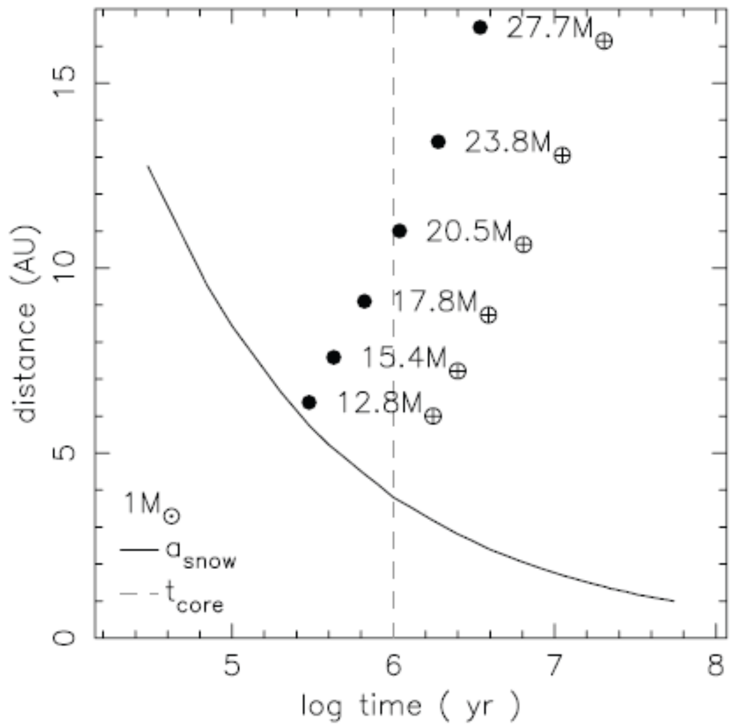

FIG. 2.—Isolation mass (*filled circles, labeled with* M_{iso}) as a function of radial distance and PMS model time, for a solar mass star with the MMSN model with $\eta = 4$ and $\delta = 3/2$. Masses are spaced at $8R_H$ intervals and only shown outside the snow line. The solid line shows a_{snow} over time, and the dashed vertical line is the time $t_{core} = 1$ Myr.

An Range of Stellar Masses

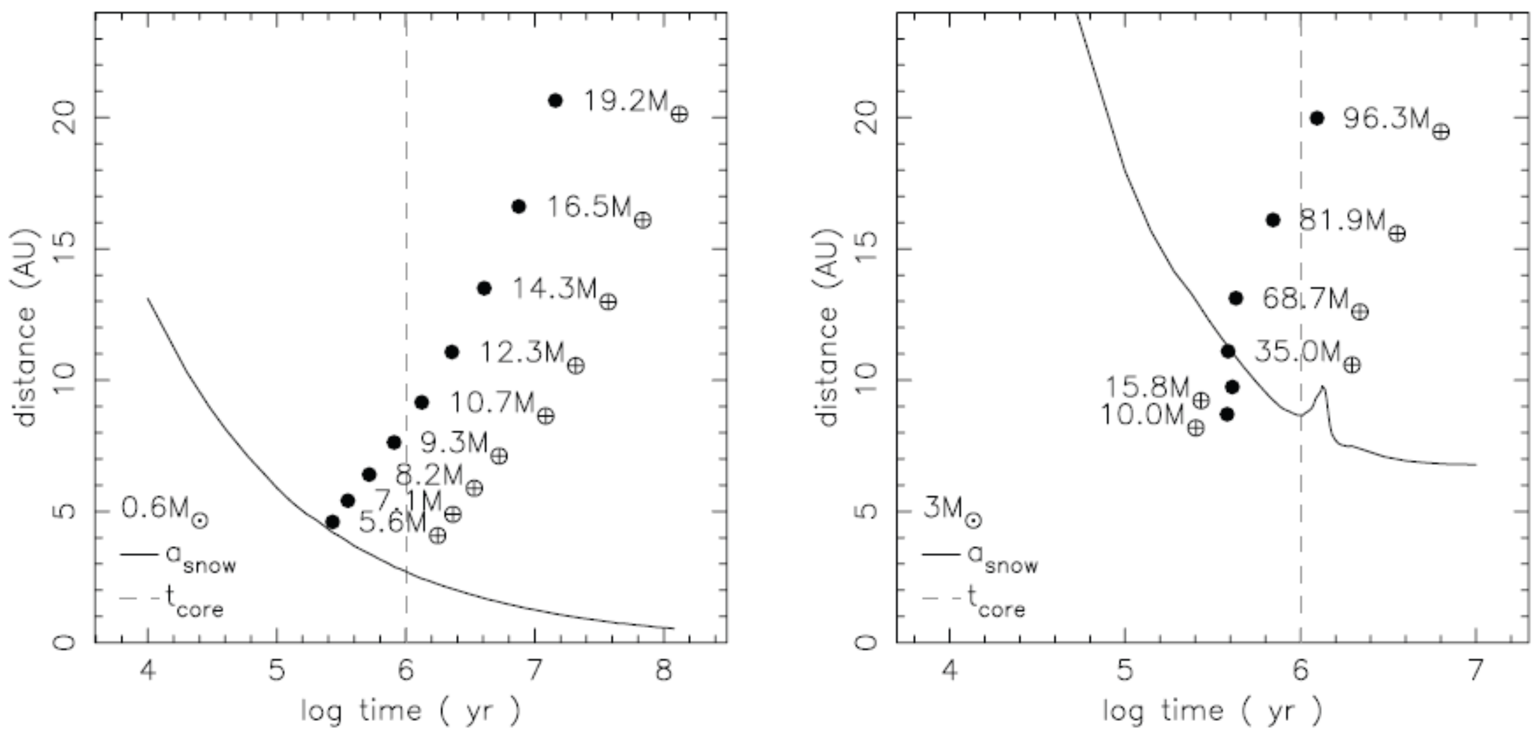

FIG. 3.—Same as Fig. 2, but for 0.6 $M_\odot$ (*left*) and 3 $M_\odot$ (*right*). Isolation masses are only plotted outside the snow line, or where $M_{iso} > M_{core}$.

An Range of Stellar Masses

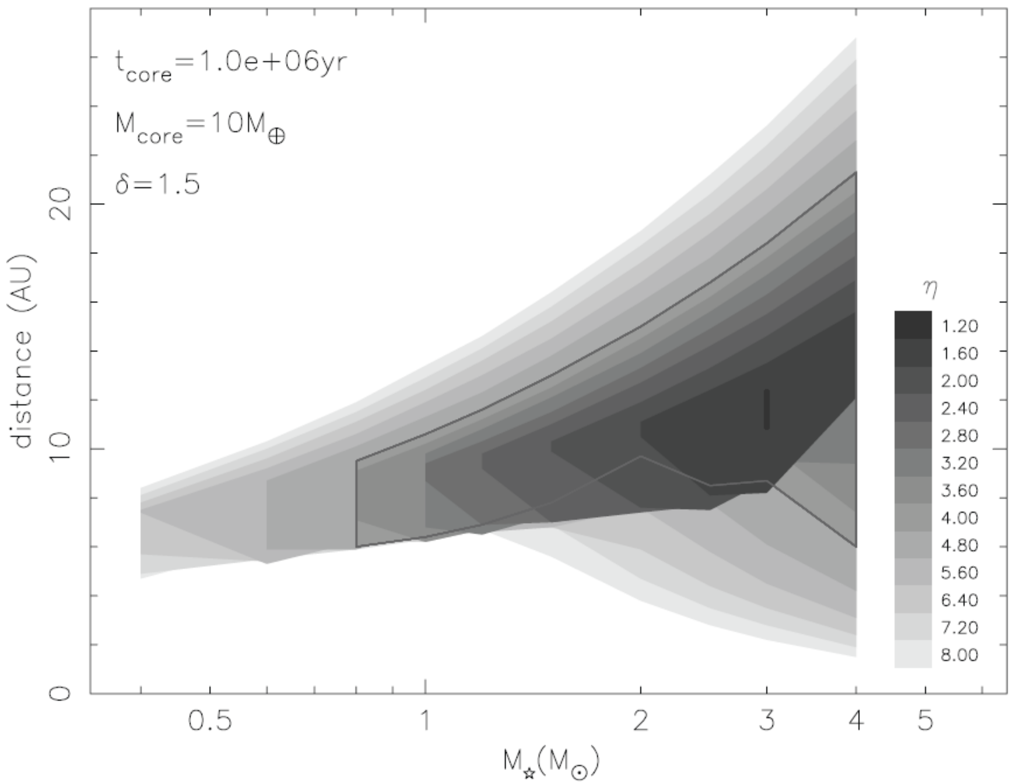

FIG. 4.—Regions where 10 $M_{\oplus}$ cores form in $\leq 10^6$ yr as a function of radial distance and stellar mass. Each contour represents the inner, outer, and stellar mass limits for particular η (and corresponding M_{disk}), as shown by the legend. Our baseline model, $\eta = 4$, is outlined. For $\eta = 1.2$, only 3 $M_{\odot}$ stars form cores.

Failed Cores

- Neptune and Uranus --- Failed cores
- Three ways to form a failed core:
  - Formed too small or too late;
  - Big and early enough, but might be ejected into some low surface density regions due to dynamical interactions between the cores;
  - Collisions between the cores or planet over long timescales

- Ocean planet

Sensitivity to Model Assumptions

- Critical input parameters:
  - M_{core}
  - T_{core}
  - δ, which determines the surface density profile
  - η, which determines the relative disk mass
  - Size of planetesimals

- Type I and II migration are not taken into consideration in this model

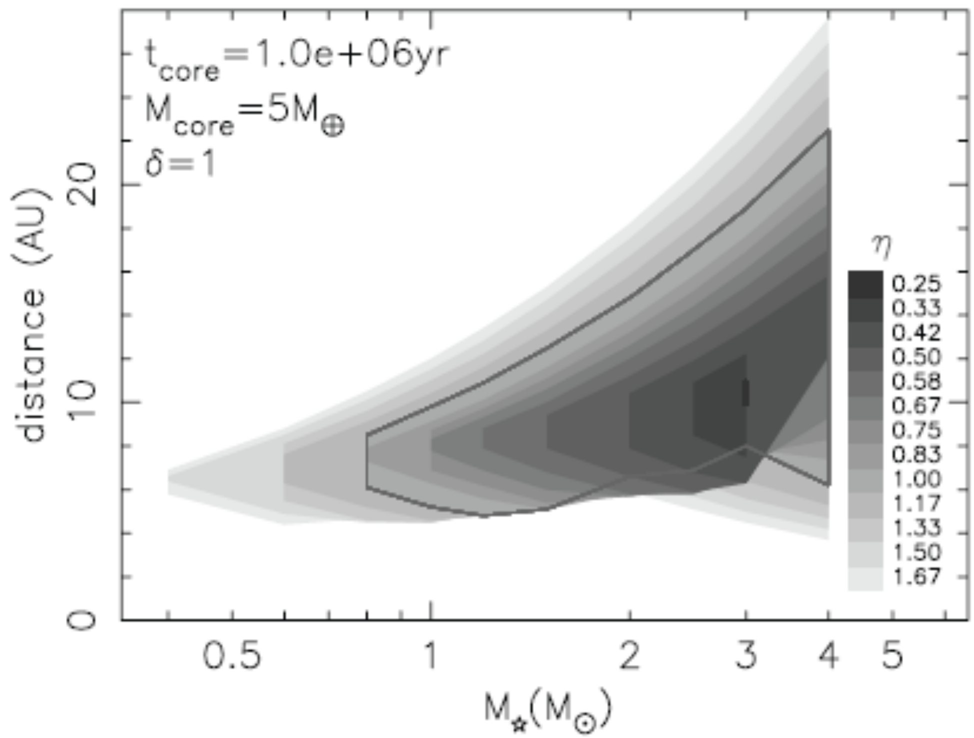

FIG. 5.—Same as Fig. 4, but for $\delta = 1$ and $M_{core} = 5\ M_\odot$. For $\eta = 0.25$, only 3 $M_\odot$ stars form cores. Although the $\delta = 1$ disk has different η, it covers the same range of disk masses as Fig. 4 with $\delta = 3/2$, with the exception of the lowest disk mass ($\eta = 1.2$) from that figure.

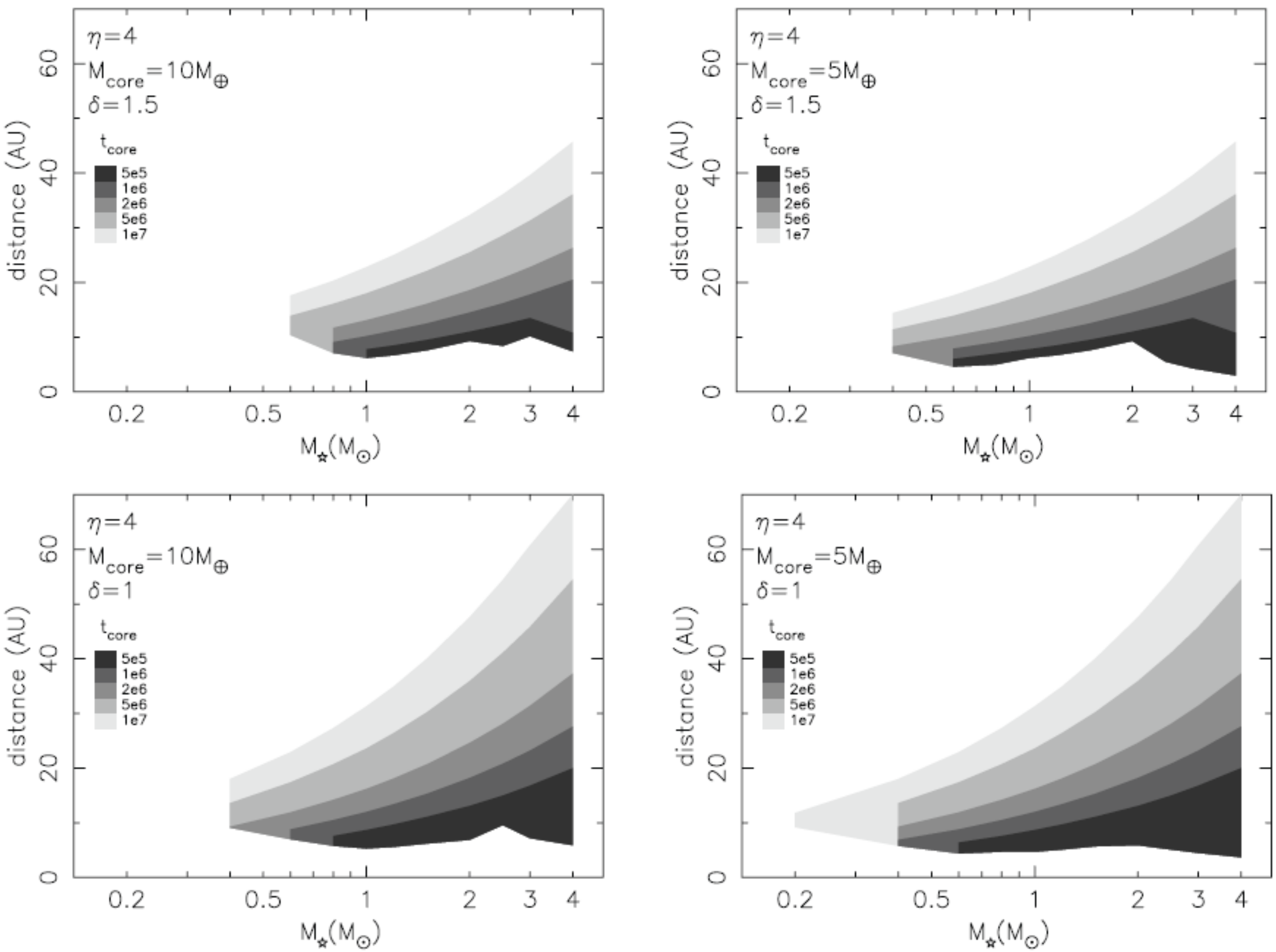

FIG. 6.—Similar to Fig. 4, but for fixed $\eta = 4$. Contours represent different t_{core} as indicated by legends. Top (bottom) panels are $\delta = 1.5$ ($\delta = 1$), and left (right) panels are $M_{core} = 10\ M_{\oplus}$ ($M_{core} = 5\ M_{\oplus}$).

Discussion

- Assuming all stars are born with a distribution of disk masses, we can estimate the probability P_{GG} of a star forming at least one gas giant as a function of stellar mass
- Adopt a Gaussian distribution in terms of

$$x = \log M_{\text{disk}} / M_*$$

and

$$P_{\text{disk}} \propto \exp\left[-(x-\mu)^2 / 2\sigma_{\ln}^2\right]$$

where

$$\sigma_{\ln} = 1/3,\ \mu = -1.5\ (\text{e.g., } M_{\text{disk}} = 0.03 M_*)$$

- The result is normalized to 6% for solar mass stars

Discussion

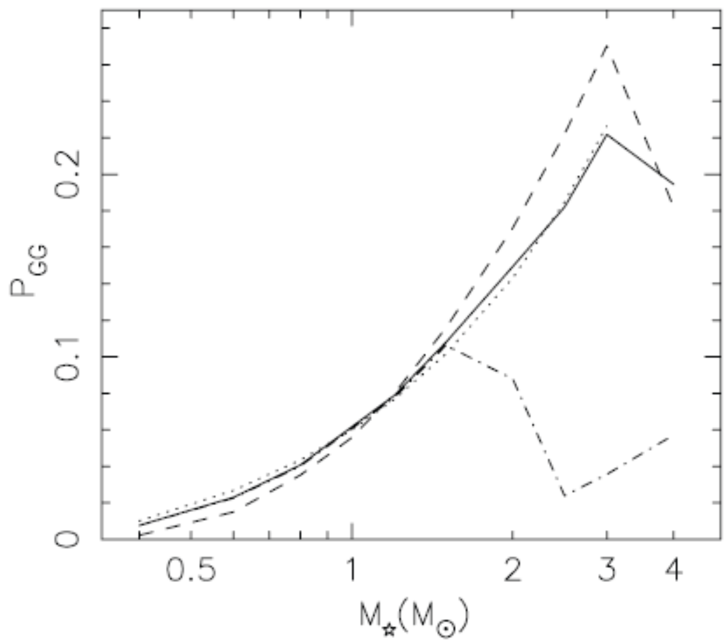

FIG. 7.—Probability of a star harboring at least one gas giant planet as a function of stellar mass for our baseline model (*solid line*), and $\delta = 1$ and $M_{core} = 5\ M_\oplus$ (*dashed line*). The thin dotted line is a fitted line of constant slope $P_{M_\star} = 0.20 M_\star - 0.06$. The dot-dashed line has $a_{snow} \propto 2.7 M_\star^2$ AU for comparison with Ida & Lin (2005) . All curves are normalized to 6% at 1 $M_\odot$ via a straight line fit.

P_{GG}=1% (for 0.4$M_\odot$) and 10% (for 1.5$M_\odot$)

Conclusions

- Snow line generally moves inward over time;
- The inner and outer boundary of the gas giant forming region are determined by the snow line movement and gas dissipation timescale, resp.;
- Super-earths and ocean planets can be explained by failed cores;
- The probability that a star has at least one gas giant increase linearly with stellar mass from 0.4 to 3 solar masses;
- Although sample numbers are small, it appears that observable gas giant frequency increases with stellar mass across a wide range of host masses (Johnson et al. 2007).