The Snow Line and Predicting Giant Planet Frequency vs. Stellar Mass

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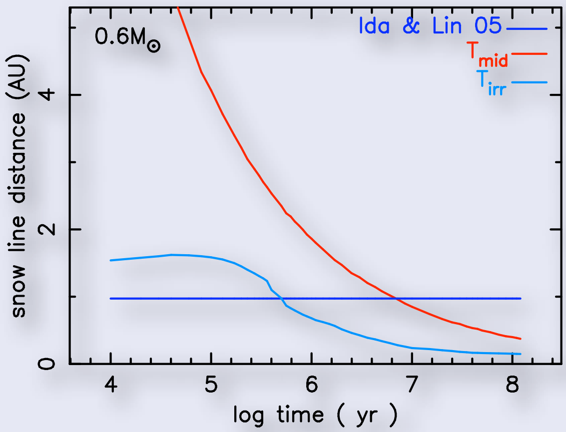
abstract

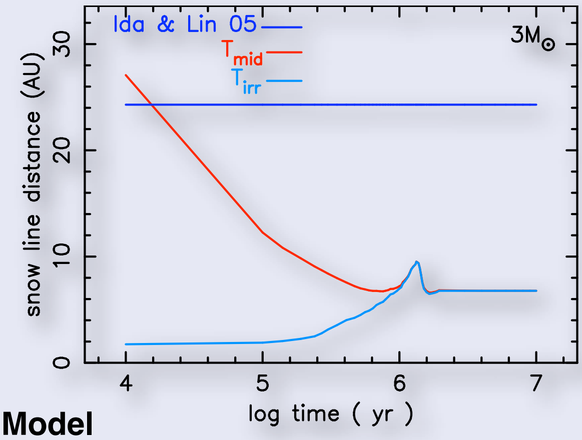
Using simple analytical relations for disk mid-plane temperatures due to irradiation and accretion, and for protoplanet 'isolation' masses, we construct a picture of where gas giant cores form over a range of stellar and disk masses. Combined with a probability distribution of disk masses, the model yields the likelihood of finding a star with at least one gas giant as a function of stellar mass. Normalised probabilities are 1% for 0.4 M_{sun} and 10% for 1.5 M_{sun} stars, if 6% of Solar mass stars have gas giants.



Snow line

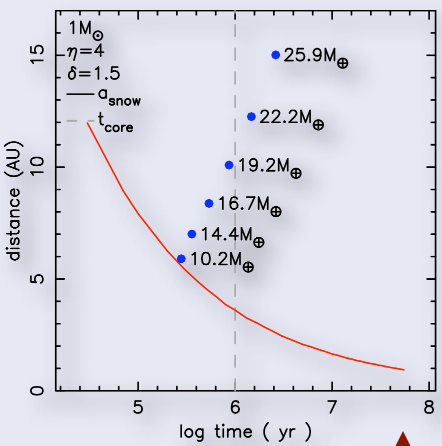
$$T_{mid}^4 = \tau T_{accr}^4 + T_{irr}^4$$

These figures show the snow line distance (170K at the mid-plane) for 0.6 and 3 M_{sun} stars, including irradiation and decay of viscous accretion (eq.5). Irradiation dominates for higher mass stars as they reach the main-sequence.



Model

We use a minimum mass solar nebula disk model,[1] scaled linearly with stellar mass (eq.1). The isolation mass contains all mass within 8 Hill radii of the protoplanet[2] (eq.2). The isolation timescale is proportional to the local surface density and the orbital period[3] (eq.3). A protoplanet core forms a gas giant by core accretion if it forms before 1Myr (an estimate of the gas disk lifetime[4]), and is more massive than 10 M_{Earth}.

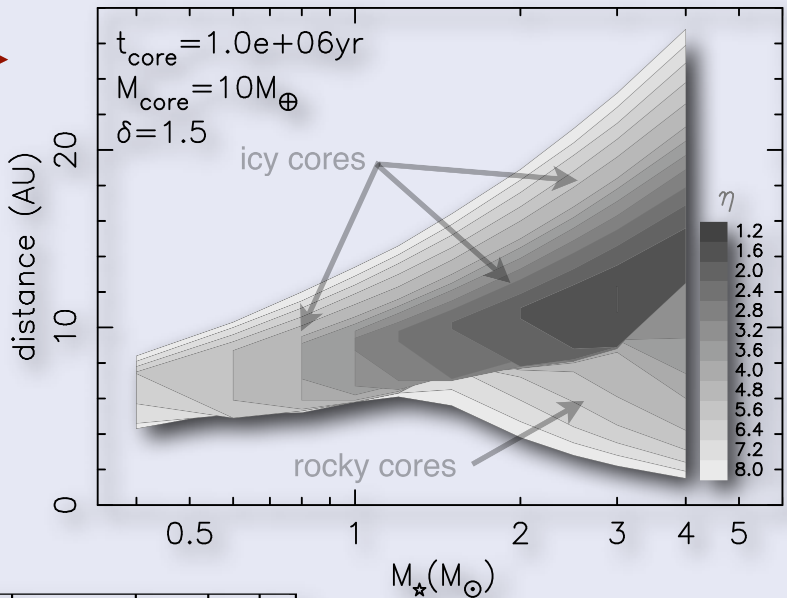


Solar System example

The above figure shows isolation masses and times for a solar system example. The location of the innermost gas giant core is determined by the snow line, and the outermost by the condition that it forms before the gas disk dissipates (1Myr)

Core forming regions

The figure shows regions that form >10M_{Earth} cores before 1Myr, for a range of disk and stellar masses. Darker contours are less massive disks. Most cores form outside the snow line, but some rocky cores form for higher stellar and disk masses.



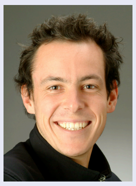
(1) $\sigma \propto \eta M_\star a^{-3/2}$

(2) $M_{iso} \propto \left(\sigma a^2\right)^{3/2} M_\star^{-1/2}$

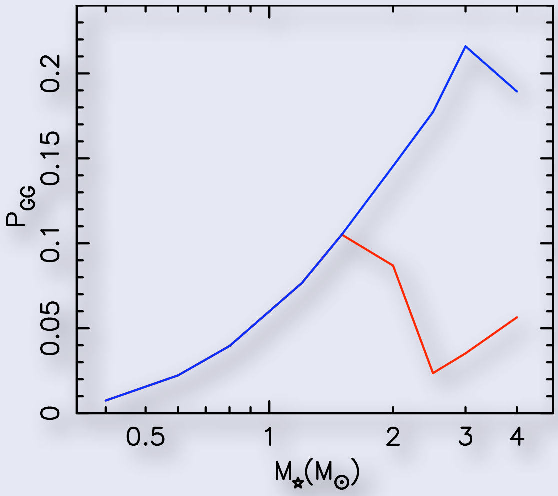
(3) $t_{iso} \propto \sigma / P$

(4) $a_{snow} \propto 2.7\, M_\star^2$ AU

(5) $\dot{M} \propto M_\star t^{-1.5}$



[1] e.g. Weidenschilling 1977
[2] e.g. Lissauer 1993
[3] e.g. Kenyon & Bromley 04
[4] e.g. Pascucci et al 2006
[5] Ida & Lin 2005



Result

For a probability distribution of disk masses, the likelihood of forming at least one giant planet increases linearly with stellar mass to 3 M_{sun} (blue line). We expect 1% (10%) around 0.4 (1.5) M_{sun} stars, if 6% of Solar mass stars harbour gas giants. The result is not particularly sensitive to model parameters. A model with a fixed snow line (red line, eq.4)[5] is shown for comparison.