Super-Earth Formation and Stellar Evolution

Grant M. Kennedy[†] and Scott J. Kenyon[‡]

Introduction

- It is generally believed that planets form in the circumstellar disks of dust and gas that surround young stars. The mass in these disks is described in terms of the surface density σ. At the radial distance from the star known as the 'snow line' – where the temperature drops low enough for nebular gas to condense into ices – there is a significant increase in the surface density of solids.
- There are two main mechanisms proposed for the formation of planets: (i) **Disk instability**, whereby large planets form rapidly when the disk becomes gravitationally unstable, and (ii) **Coagulation** – the process which formed the Earth – where planets form through repeated collisions and mergers over long timescales. Both mechanisms are dependent on the surface density of gas and solids in the disk.
- In the coagulation model there are two main steps: (i) protoplanet formation, which takes ∼0.1–1 Myr, and (ii) a ∼10–100 Myr chaotic, n-body like, merger period. Approximately ten protoplanets merge to build a planet like Earth during chaotic growth.
- The speed with which protoplanets and planets are formed in the disk, and their final masses, are dependent on the surface density.

Motivation

- Circumstellar disks are known to evolve in time. Mass is shifted and removed by processes such as accretion and photoevaporation.
- Planet formation models generally assume a static surface density.
- The recent discovery by microlensing of a 5.5 $M_\oplus$ planet, orbiting a 0.22 $M_\odot$ star, at 2.5 AU by Beaulieu et al. (2006) provides evidence that 'super-Earth' mass planets are common around M Dwarfs.
- Boss (2006) suggests that these super-Earths can form around M Dwarfs via disk instability, and subsequent photoevaporation of the gaseous envelope by nearby O-type stars.
- There has been no demonstration that they can form by coagulation.
- Protoplanet formation is fast compared to stellar pre-main sequence contraction, so the timing is important within the context of this evolution.

A Disk Evolution Model

- We adopt a simple disk model, in which the disk mass decreases in proportion with the radius of the central star as it contracts.
- As a result of the decreasing pre-main sequence luminosity of the star, the snow line moves monotonically inward with time. At a fixed distance from the star, σ will be enhanced by ices when the snow line passes, as illustrated by Figure 1.

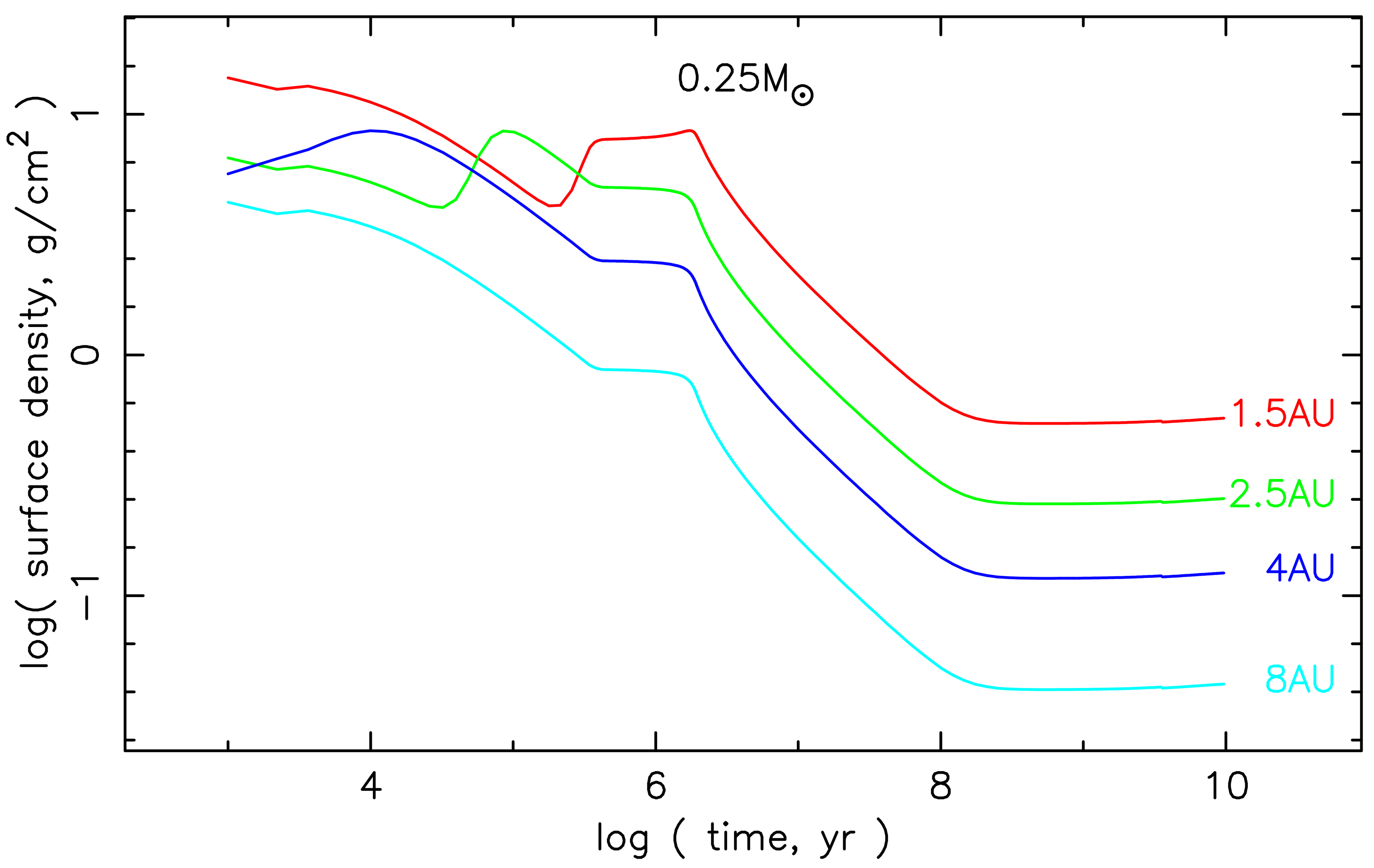

Figure. 1: Surface density evolution during contraction of the central star at a series of fixed radii, using the Siess et al. (2000) pre-main sequence tracks.

Surface Density Evolution: Two distinct snow line effects

- At 1–2 AU, protoplanets form before the snow line passes. When it does, the increase in σ augments the protoplanets masses, and prolongs this phase of growth while the new material is accreted.
- At 2–3 AU, the increase in σ shortens the timescale for building protoplanets, and results in a ∼1 Myr period favourable for large rocky/icy protoplanet formation.

Isolation masses – super-Earth building blocks

- We can predict the mass of protoplanets just before they start to undergo chaotic growth. This mass is known as the isolation mass M_{iso}. Figure. 2 shows the evolution of M_{iso} with time in our model.

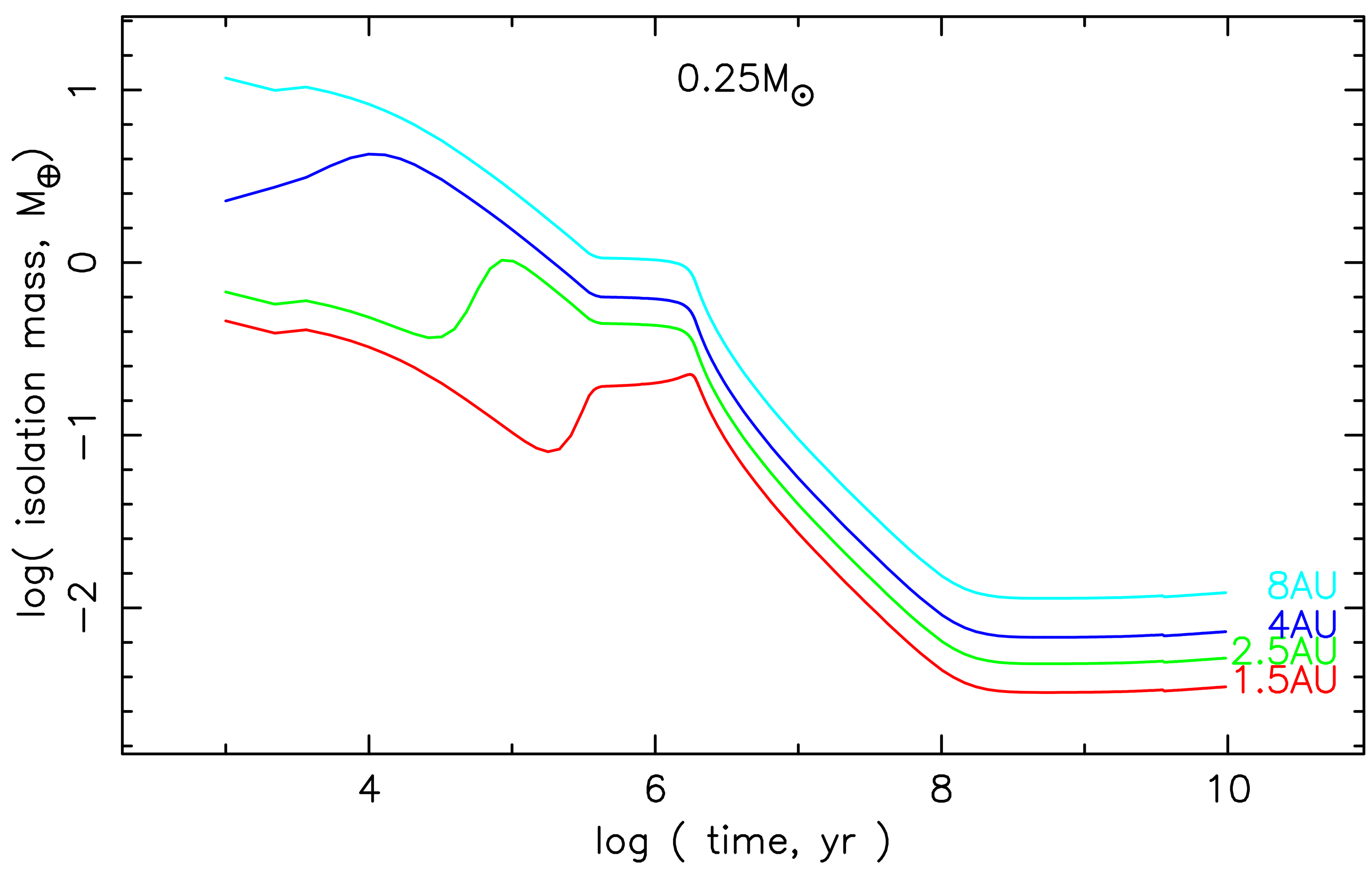

Figure. 2: Isolation mass at fixed radii as the disk evolves. The analytical timescale for isolation is ∼0.1–1 Myr (Goldreich et al., 2004). The isolation mass is ∼0.1–0.5 $M_\oplus$ at ∼1–3 AU.

Formation of super-Earths

- We appeal to numerical simulations of Earth formation (e.g. Kenyon & Bromley, 2006), to argue that protoplanets nearing isolation will undergo a period of chaotic growth, during which ∼10 bodies will coalesce to form planets of 1–5 $M_\oplus$ at 1–3 AU.
- Scaling from the Earth formation time at 1 AU of ∼10–100 Myr, the formation timescale for super-Earths at 1–3 AU is ∼50–500 Myr.

Summary: Two main ideas

- **The movement of the snow line as the star contracts helps to define how and when protoplanet formation proceeds.**
- **It is possible to form icy super-Earths around M Dwarfs, in a manner similar to Earth, through chaotic growth over ∼50–500 Myr timescales.**

References

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[†]Research School of Astronomy and Astrophysics, ANU, Australia
email: grant@mso.anu.edu.au, web: www.mso.anu.edu.au/∼grant
[‡]Smithsonian Astrophysical Observatory, Cambridge, MA, USA

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