Hot Super-Earths

the observational signatures
of scattering and migration

Grant Kennedy (RSAA)

with:
Scott Kenyon (Harvard-CfA)
different models have different signatures

planet detections reaching ~Earth masses

larger samples will reveal trends

(in this case stellar mass)

compare trends to predictions
transits
$M_{pl}$, density

radial velocity
$M_{pl} \sin i$

Brown et al. 2001

Cochran et al. 2007

brightness

radial velocity

$P = 195.0 \text{ d}$

$P = 530.3 \text{ d}$
Bayliss, Sackett posters

this talk

transits

~300 planets from exoplanet.eu
what is a super-Earth?

planets $>10 \ M_{\text{Earth}}$ accrete gas rapidly and become giants

• more massive than Earth (detection limit)
• less massive than $\sim10 \ M_{\text{Earth}}$ (not a giant)

mini-Neptunes? need transits...
why hot ones?

detectable
transits
average density
composition?
origin??
where do super-Earths form?

newest super-Earth system has $20 \, M_{\text{Earth}}$ within 0.5 AU

Solar System only has a few $M_{\text{Earth}}$ within 1 AU

probably not enough mass to form *in situ*

hot planets originate outside where they orbit...

Mayor et al 2008
they form at the snow line

enough to make super Earths

varies linearly with stellar mass (see poster)
scattering

formation on circular orbits

inner planet gets close periastron

jupiters: maybe
earths: unlikely

circularised?
scattering simulations

Two 10 M\textsubscript{Earth} objects start near snow line

\textit{n}-body simulation for 1 Gyr, Mercury code

planets interact $\rightarrow$ eccentric orbits

look at closest periastron distances
more conjunctions and start closer

filled: survivors
grey: ejected
blank: collisions

start farther and fewer conjunctions

closest periastron

snow line
scattering results

- scattering to small periastra possible
- low mass stars with close snow line
- circularisation unlikely (Raymond et al 2008)

summary

- possible around low mass stars
- hard to detect (long periods)
Migration

Planets stop at inner disk edge
Bigger planet = faster migration

Disk gone 1-10 Myr
migration model

The diagram illustrates the relationship between Stellar mass (M$_{\text{Sun}}$) and Planet mass (M$_{\text{Earth}}$), showing the regions where Hot super-Earths and No hot super-Earths are predicted to exist.
migration results

works for a range of stellar masses

harder for higher stellar masses
summary

snow line important in both models

scattering: eccentric planets, hard to find

migration: possible, observational signatures
The Snow Line and Predicting Giant Planet Frequency vs. Stellar Mass

Grant M Kennedy (ANU) & Scott J Kenyon (SAO)

**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 $M_\odot$ and 10% for 1.5 $M_\odot$ stars, if 6% of Solar mass stars have gas giants.

**Snow Line**

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

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

**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).

1. $\sigma \propto \eta M a^{-3/2}$
2. $M_{iso} \propto (\sigma a^2)^{3/2} M_\star^{-1/2}$
3. $t_{iso} \propto \sigma / P$
4. $a_{snow} \propto 2.7 M_\star^2$ AU
5. $M \propto M_\star t^{-1.5}$

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

**Core forming regions**

The figure shows regions that form >10 $M_\oplus$ 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.

**Result**

For a probability distribution of disk masses, the likelihood of forming at least one giant planet increases linearly with stellar mass to 3 $M_\odot$ (blue line). We expect 1% (10%) around 0.4 (1.5) $M_\odot$ 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) is shown for comparison.