How do systems of hot super-Earths and sub-Neptunes form?

Sean Raymond
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planetplanet.net

with Christophe Cossou, Andre Izidoro, Alessandro Morbidelli, Arnaud Pierens, Franck Hersant
Hot Super Earths

- **Exist around 30-50% of main-sequence stars** (Mayor et al 2011; Howard et al 2010, 2012; Fressin et al 2013; Petigura et al 2013)

- **Multiple systems** (e.g., Lovis et al 2011; Lissauer et al 2011a, many more)

- **Compact, non-resonant orbits** (Lissauer et al 2011b; Fabrycky et al 2014)

Raymond et al 2014 PP6 chapter; Kepler data from Batalha et al 2013 and Rowe et al 2014
Hot Super Earths

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- Multiple systems (e.g., Lovis et al. 2011; Lissauer et al. 2011a, many more)

- Compact, non-resonant orbits (Lissauer et al. 2011b; Fabrycky et al. 2014)

How did these systems form?
Stages of Planet Formation
Stages of Planet Formation
Grains
Stages of Planet Formation

- Grains
- Pebbles
Stages of Planet Formation

Grains

Pebbles

Planetesimals
Stages of Planet Formation

1. Grains
2. Pebbles
3. Planetesimals
4. Planetary Embryos
Stages of Planet Formation

- **Grains**
- **Pebbles**
- **Planetesimals**
- **Planetary Embryos**

While gas remains in disk.
Stages of Planet Formation

Grains → Pebbles → Planetesimals → Planetary Embryos

while gas remains in disk

Aerodynamic drift
Stages of Planet Formation

- Grains
- Planetesimals
- Planetary Embryos

Type I migration

while gas remains in disk

Aerodynamic drift
Stages of Planet Formation

- Grains
  - Pebbles
    - Planetesimals
      - Planetary Embryos

While gas remains in the disk, pebbles form into planetesimals, which then form planetary embryos. Gas accretion and type I migration play roles in this process.

Aerodynamic drift also occurs, affecting the motion of particles in the disk.
Stages of Planet Formation

- Grains
- Planetesimals
- Pebbles
- Planetary Embryos

Type 1 migration

while gas remains in disk

No more gas

gas accretion

Aerodynamic drift
Stages of Planet Formation

- **Grains**
- **Pebbles**
- **Planetesimals**
- **Planetary Embryos**

Types of migration:
- **Type 1 migration**

While gas remains in disk:
- **Accretion**

No more gas:
- **Last giant impacts**

Aerodynamic drift:
Stages of Planet Formation

- **Grains**
  - Type I migration
  - while gas remains in disk

- **Pebbles**
  - gas accretion

- **Planetesimals**
  - No more gas

- **Planetary Embryos**
  - super-Earths/mini-Neptunes

- **Last giant impacts**

Aerodynamic drift
<table>
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<tr>
<th>“Hot Earth” formation model</th>
<th>System Architecture</th>
<th>Hot Earth Composition</th>
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<tr>
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<td>Giant planet shepherding</td>
<td>Hot Earth just inside strong giant planet resonances (2:1)</td>
<td>Moderate: few percent water by mass</td>
</tr>
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<td>Hot Earths with two interacting giants</td>
<td>?</td>
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<td>Photo-evaporated gas giant</td>
<td>Correlation with stellar age</td>
<td>Icy (giant planet core)</td>
</tr>
<tr>
<td>Tidal Circularization</td>
<td>Isolated hot Earth, eccentricity source</td>
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Raymond et al 2008, 2014
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Still viable

Raymond et al 2008, 2014
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Still viable

Raymond et al 2008, 2014
Orbital distance

1-4 $R_{\text{Earth}}$

Size

Hot super-Earths

Slide inspired by KITP discussions with Eric Ford, Geoff Marcy and Jack Liskeur
1. In-situ accretion

Size

1-4 R\text{Earth}

Orbital distance

Hot super-Earths

Slide inspired by KITP discussions with Eric Ford, Geoff Marcy and Jack Lissauer
Orbital distance

1. In-situ accretion

2. Radial (aerodynamic) drift

Size

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1. In-situ accretion
2. Radial (aerodynamic) drift
3. Inward (type 1) migration

Slide inspired by KITP discussions with Eric Ford, Geoff Marcy and Jack Lissauer
1. In-situ accretion

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4. Mixed drift/migration

Size

Orbital distance

Hot super-Earths

1-4 R_{Earth}

Slide inspired by KITP discussions with Eric Ford, Geoff Marcy and Jack Linaeur
1. In-situ accretion: planets form fast in high-mass disks

Bolmont, Raymond et al 2014

~15 ME in inside 0.5 AU
Gaseous protoplanetary disks last a few Myr

Fraction of stars with disks (%) vs. Age (Myr)

$f_{\text{disk}} = \exp\left(-t/\tau_{\text{disk}}\right)$

$\tau_{\text{disk}} = 2.5 \text{ Myr}$

Mamajek 2009; Haisch et al. 2001; Hillenbrand 2008
Gaseous protoplanetary disks last a few Myr

If hot super-Earths form in-situ then gaseous disks must still be present when planets are big

\[
f_{\text{disk}} = \exp\left(-\frac{t}{\tau_{\text{disk}}}\right)
\]

\[
\tau_{\text{disk}} = 2.5 \text{ Myr}
\]

Gaseous disk causes orbital decay

Neptune

Earth

1000 km

1 km

“pebbles”

dust
Gaseous disk causes orbital decay

- Neptune
- Earth
- 1000 km
- 1 km
- "pebbles"
- Dust
Gaseous disk causes orbital decay

Type I migration

Aerodynamic drag

Neptune

Earth

1000 km

1 km

“pebbles”

dust
Planets that form in-situ should migrate
Even aerodynamic drag causes planets to drift.
Even aerodynamic drag causes planets to drift

Punchline: if hot super-Earths form in-situ then they must interact strongly with gaseous disk

Inamdar & Schlichting 2015
Even aerodynamic drag causes planets to drift.

Punchline: if hot super-Earths form in-situ then they must interact strongly with gaseous disk.

Because they drift or migrate, hot super-Earths can’t form “in-situ”!

Inamdar & Schlichting 2015
2. Radial drift of small bodies

3. Forming hot super-Earths by type 1 migration
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3. Forming hot super-Earths by type 1 migration
Type 1 migration

- Inward or outward

- Timescale
  \(~10-100\) kyr
  (bigger=faster)

Migration stops at the inner edge of the disk

Migration stops at the inner edge of the disk

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A type I migration map

Evolution of the total torque $\Gamma_{\text{tot}}/\Gamma_0$

Cossou et al 2014;
see also Lyra et al 2010, Paardekooper et al 2011; Kretke & Lin 2012; Bitsch et al 2013, 2014ab
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Resonant chains usually go unstable as or after the gas disk dissipates.

Cossou, Raymond et al. 2014
Resonant chains usually go unstable as or after gas disk dissipates.

Punchline: most hot super-Earths that form by migration do not remain in resonant chains (Terquem & Papaloizou 2007; Goldreich & Schlichting 2014; Cossou et al 2014).

Migration during 3 Myr gas disk lifetime.
Why no hot super-Earths in Solar System?
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- Fast-forming gas giants can act as a barrier to inward-migrating super-Earths (Izidoro et al 2015)
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- Fast-forming gas giants can act as a barrier to inward-migrating super-Earths (Izidoro et al. 2015)
- Prediction: systems of hot super-Earths should be anti-correlated with giant planets on more distant (1-5 AU) orbits.
Uncertainties in migration model
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- Initial conditions poorly constrained: how many cores? What sizes? How do they form?
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- Sensitivity of type I migration to disk conditions
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- How efficient is atmospheric accretion during migration?
Uncertainties in migration model

- Initial conditions poorly constrained: how many cores? What sizes? How do they form?
- Sensitivity of type I migration to disk conditions
- How efficient is atmospheric accretion during migration?
- Strength and importance of turbulence (Laughlin et al 2004; Nelson 2005; Pierens et al 2012; Rein 2012)
Composition of planetary building blocks

Composition of planetary building blocks

Migration:

In-situ or drift: rocky planets

Migration: sample a range of compositions

Conclusions
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- If hot super-Earths form in-situ they should interact strongly with gas disk and suffer migration and/or strong aerodynamic drag (so not “in-situ”)
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• Migration: hot super-Earths and giant planet cores from same model

Cossou, Raymond et al 2014
Extra Slides
In-situ accretion

- Planets formed where you see them
- Planets remember their initial conditions (minimum-mass nebula model) and this reflects gas disk
- Migration of low-mass planets does not happen

Chiang & Laughlin 2013; see also Kuchner 2004
Minimum-mass disks in multi-planet systems

Median disk: $\Sigma \propto r^{-1.45}$

MMSN estimates

Raymond & Cossou 2014
Atmospheres

In-situ:
thin (~10^{-3}-10^{-2} or less) atmospheres
(Lee et al 2014; Inamdar & Schlichting 2015).

Migration: lose ~half of atmosphere per giant impact

Inamdar & Schlichting 2015
# In-situ accretion

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- Some planets closer to stars than dust sublimation radius (Swift et al 2013)
- Cannot produce planets with thick atmospheres (Hori & Ikoma 2012; Inamdar & Schlichting 2015; Lee et al 2014)

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Pebble drift

Strengths

Weaknesses

Chatterjee & Tan 2014, 2015; Boley & Ford 2013; Hu et al 2014
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• Needs further study

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• Sensitivity of type I migration to disk conditions

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**Weaknesses**
- Initial conditions unconstrained: how many cores? What sizes?
- Sensitivity of type I migration to disk conditions
- Importance of turbulence (studies underway)

Case study: Kepler-444

Campante et al. 2015
## Kepler-444

### Table 4. Planetary and orbital parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Kepler-444b</th>
<th>Kepler-444c</th>
<th>Kepler-444d</th>
<th>Kepler-444e</th>
<th>Kepler-444f</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_0$ (BJD − 2,454,833)</td>
<td>133.2599$^{+0.0018}_{-0.0018}$</td>
<td>131.5220$^{+0.0013}_{-0.0013}$</td>
<td>134.7869$^{+0.0015}_{-0.0015}$</td>
<td>135.0927$^{+0.0018}_{-0.0018}$</td>
<td>134.8791$^{+0.0011}_{-0.0011}$</td>
</tr>
<tr>
<td>$P$ (days)</td>
<td>3.6001053$^{+0.0000083}_{-0.0000080}$</td>
<td>4.5458841$^{+0.0000070}_{-0.0000071}$</td>
<td>6.189392$^{+0.000012}_{-0.000012}$</td>
<td>7.743493$^{+0.000017}_{-0.000016}$</td>
<td>9.740486$^{+0.000013}_{-0.000013}$</td>
</tr>
<tr>
<td>$R_p/R_*$</td>
<td>0.00491$^{+0.00017}_{-0.00014}$</td>
<td>0.00605$^{+0.00025}_{-0.00020}$</td>
<td>0.00644$^{+0.00023}_{-0.00020}$</td>
<td>0.00664$^{+0.00016}_{-0.00014}$</td>
<td>0.00903$^{+0.00046}_{-0.00047}$</td>
</tr>
<tr>
<td>$R_p/R_\oplus$</td>
<td>0.40$^{+0.016}_{-0.014}$</td>
<td>0.497$^{+0.021}_{-0.017}$</td>
<td>0.530$^{+0.022}_{-0.019}$</td>
<td>0.546$^{+0.017}_{-0.015}$</td>
<td>0.741$^{+0.041}_{-0.040}$</td>
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<tr>
<td>$b$</td>
<td>0.40$^{+0.17}_{-0.25}$</td>
<td>0.42$^{+0.22}_{-0.27}$</td>
<td>0.53$^{+0.13}_{-0.23}$</td>
<td>0.29$^{+0.16}_{-0.17}$</td>
<td>0.79$^{+0.07}_{-0.13}$</td>
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<tr>
<td>$e \sin \omega$</td>
<td>0.01$^{+0.08}_{-0.12}$</td>
<td>0.18$^{+0.10}_{-0.15}$</td>
<td>0.03$^{+0.12}_{-0.12}$</td>
<td>$-0.008^{+0.040}_{-0.090}$</td>
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<td>$e$</td>
<td>0.16$^{+0.21}_{-0.10}$</td>
<td>0.31$^{+0.12}_{-0.15}$</td>
<td>0.18$^{+0.16}_{-0.12}$</td>
<td>0.10$^{+0.20}_{-0.07}$</td>
<td>0.29$^{+0.20}_{-0.19}$</td>
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<tr>
<td>$a/R_*$</td>
<td>11.951$^{+0.046}_{-0.046}$</td>
<td>13.961$^{+0.053}_{-0.053}$</td>
<td>17.151$^{+0.066}_{-0.066}$</td>
<td>19.913$^{+0.076}_{-0.076}$</td>
<td>23.205$^{+0.089}_{-0.089}$</td>
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<tr>
<td>$a$ (AU)</td>
<td>0.04178$^{+0.00079}_{-0.00079}$</td>
<td>0.04881$^{+0.00093}_{-0.00093}$</td>
<td>0.06000$^{+0.0011}_{-0.0011}$</td>
<td>0.0696$^{+0.0013}_{-0.0013}$</td>
<td>0.0811$^{+0.0015}_{-0.0015}$</td>
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<tr>
<td>$i$ (deg)</td>
<td>88.0$^{+1.2}_{-0.6}$</td>
<td>88.2$^{+1.2}_{-1.0}$</td>
<td>88.16$^{+0.81}_{-0.55}$</td>
<td>89.13$^{+0.54}_{-0.52}$</td>
<td>87.96$^{+0.36}_{-0.31}$</td>
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Mass (ME) [assuming Earth-like composition]

0.035  0.075  0.095  0.11  0.33

Campante et al 2015
Migration timescales are long
Minimum-mass disk

Kepler-444

$\Sigma(r) = 12000 (r/1 \text{ AU})^1 \text{ g cm}^{-2}$
Accretion simulations

Kepler-444

Semimajor Axis (AU)
Planet size vs orbital distance

Kepler-444

Semimajor Axis (AU)

Radius (Earths)
Planetary spacing

Kepler-444

Mean inter-planetary orbital radius \((a_1a_2)^{1/2}\) (AU)

Orbital period ratio \(P_2/P_1\)
How did Kepler-444 form?
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- In-situ growth works well....
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- But requires a very odd disk profile
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- Migration of large bodies is too slow
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- Best candidate: inward drift model