A Collisional Origin for the Coexistence of Volatile-poor Super-Earths and Mini-Neptunes in the Proximity of Stars

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Exoplanetary Atmospheres and Habitability (Nice, 12-15, Oct.)
Prevalence of Low-Mass Planets with Atmospheres

Mass-radius relationship of transiting planets with mass of $< 30 M_\oplus$

- H$_2$O + 10wt% HHe
- MgSiO$_3$ + 10w% HHe
- H$_2$O
- MgSiO$_3$
- Fe
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Most of short-period planets should have atmospheres (typically $< 10$wt%)
A Weird Kepler-36 and Kepler-11 System

Kepler-36b @ 13.8 days
- Earth-like composition

Kepler-36c @ 16.2 days
- H/He atmosphere atop the core (~ 8.6 wt%) (Lopez & Fortney, 2013)

(Carter et al., 2012)
**A Weird Kepler-36 and Kepler-11 System**

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*Earth-like composition*

**Kepler-36c** @16.2 days

*H/He atmosphere* atop the core

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**Kepler-11b** @10.3 days

*A tenuous atmosphere* (0.5wt%)

**Kepler-11c** @13.0 days

*A relatively-thick atmosphere* (5.0wt%)
Compositional Dissimilarity of Low-Mass Planets On Adjacent Orbits Near Host Stars

The origin of a high density contrast b/w neighboring planets?

(1) **Degassing** from accreting material (e.g. Elkins-Tanton & Seager, 2008)

(2) **Photo-evaporation** via stellar XUV irradiation or a Parker wind (e.g. Owen & Wu, 2013)

(3) **Regulation of disk accretion** onto a core
   - in-situ accumulation in a dissipating disk (e.g. Ikoma & YH, 2012; Lee *et al.*, 2014)
   - rapid in/outflow of the disk gas (Ormel *et al.*, 2014)
   - magnetic suppression of gas accretion (?)
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Compositional diversity of close-in super-Earths likely reflects their **formation histories**
  (e.g.) planetary migration, core growth, and giant impacts
Possible Origin of A Closely-Packed MMR System

(Paardekooper et al., 2013)

7:6 MMR

Crossing of the 2:1 MMR

Convergent migration

Smooth Type I migration + Stochastic forcing due to turbulent density fluctuations

Time (yrs)

Amplitude of stochastic forces

Period ratio
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**A compact system in high-p MMR** like the Kepler-36 system
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A compact system in high-p MMR like the Kepler-36 system
Two migrating planets likely experience **collisions with embryos** in a turbulent disk during their excursion.

**Possible Origin of A Closely-Packed MMR System**

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Giant Impacts: Accretionary and Destructive

Accretion efficiency as a function of mass ratio (0.1 ▼, 0.5 ■, 1.0 ●), impact angle (0, 30, 45, 60°), and impact velocity (Asphaug, 2010)
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This study

Efficient accretion
Partial accretion
Hit-and-run collision
Erosion Disruption

Random velocity ($V_{\text{esc}}$)

Asphaug, 2010
Three-dimensional hydrodynamic simulations: **FLASH with the AMR**

(Fryxell et al., 2000)

- A pair of planets’ center of mass frame
- The width of a computational domain ~ 1 AU
- include the tidal force from a central star
- impose an open boundary condition
Modeling of a Giant Impact

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Three-Layered interior structures of a target and an impactor

- Tillotson EoS for rocky and iron material (Melosh, 1989)
  - rock (silicate) : iron = 2:1
- Only a target has an atmosphere (7.5wt%)
  - Polytropic EoS for H/He gas (H₂ : He = 7 : 3)

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Giant impacts (@ 0.1 AU)

- **Head-on collision**

  1. Low-speed model (accretion regime) : \( V_{\text{imp}} = V_{\text{esc}} \)
     
    \[4.3 \, M_\oplus \ & \ & 1.0 \, M_\oplus\]

  2. High-speed model (destructive regime) : \( V_{\text{imp}} = 3V_{\text{esc}} \)
     
    \[10 \, M_\oplus \ & \ & 1.0 \, M_\oplus\]
Simulation Movie: A High-Speed Head-On Collision

(Liu, YH, Lin, & Asphaug, 2015)
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Snapshots of Two Head-On Collisions: Density Contours

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Low-speed impact

Collision

1.56 hrs

The atmosphere is lost by ~30%

High-speed impact

Contact

15 mins

21.5 hrs
Snapshots of Two Head-On Collisions: Density Contours

Low-speed impact

The atmosphere is lost by ~30%

High-speed impact

The atmosphere is lost by ~80%

(Liu, YH, Lin, & Asphaug, 2015)
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The atmosphere is lost by \(~80\%\)

High-speed impact

The atmosphere is lost by \(~30\%\)

Low-speed impact

A hot atmosphere extends beyond the Hill radius and continues to lose via the Roche-lobe overflow
Snapshots of Material Mixing After Giant Impacts

(a) 18 hrs after a low-speed impact

(b) 21.5 hrs after a high-speed impact
Radial Distribution of Each Species After a Collision

**Low-speed impact**

**High-speed impact**
Radial Distribution of Each Species After a Collision

- An initial layered structure is partly maintained after the collision
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• An iron core of the target survives from the impact in both cases and grows in a coalescence manner
Radial Distribution of Each Species After a Collision

• An initial layered structure is partly maintained after the collision
• An iron core of the target survives from the impact in both cases and grows in a coalescence manner
• A fraction of rocky material is dredged up in a H/He atmosphere → the remaining atmosphere is polluted with heavy elements
Compositional Gradient Inside a Target After an Impact

\[
\begin{align*}
\Delta Z &\quad \text{low-speed model} \\
\Delta Z_{\text{SiO}_2} &\quad \text{high-speed model}
\end{align*}
\]

- Mass fraction of iron, silicate, & total
A low-speed head-on collision develops a hot and inhomogeneous interior → a steep, positive compositional gradient suppresses efficient heat transfer(?)
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For a high-speed head-on collision, refractory material is homogenized in the target’s interior.
Turbulence or Hydrodynamic Instability?

Species contour

Velocity-vector map
Turbulence or Hydrodynamic Instability?

Species contour

Velocity-vector map

- A **velocity shear** at the interface between two species after an impact
Turbulence or Hydrodynamic Instability?

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- A velocity shear at the interface between two species after an impact → **K-H instability** (at least for short wavelengths)
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• An impact-induced shock wave propagation → **R-T instability**
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However, 

**An impact-driven turbulence** is responsible for the **global mixing**
A protracted state of a hot and inflated atmosphere

(a) Mass loss via a **Parker wind** (Owen & Wu, 2015)

(b) Mass loss from the Roche lobe via a **stellar XUV irradiation**
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   About 80% of the remaining atmosphere is lost

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   XUV flux at the Hill radius:
   \[ L = 1.0 \times 10^{-7} \, L_\odot, \quad 1.5 \times 10^{-7} \, L_\odot \] for low- & high-speed model

   A heating efficiency in the upper atmosphere due to XUV photons
   \[ \epsilon = 0.1 \] (Yelle, 2004)
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   Mass loss rate \( \sim 3 \ M_\oplus/\text{Myr} , \ 2 \ M_\oplus/\text{Myr} \) for low, high-speed model
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   But, the Kelvin-Helmholtz contraction timescale:
   \( \sim 1 \, \text{Myr}, \; < \sim 10 \, \text{kyr} \) for low- & high-speed model

   A typical decay timescale of a XUV flux for a Sun-like star \( \sim 0.1 \, \text{Gyr} \)
   (Ribas et al., 2005)
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(Ribas *et al.*, 2005)

The target in the high-speed model is unlikely to lose the entire envelope
**Take-Home Messages**

Different histories of giant impacts result in

1. **compositional diversity** of super-Earths (Inadmar & Schlichting, 2015)
2. **homogeneous or inhomogeneous** interior  
   \[ \rightarrow \text{suppresses efficient heat transfer} \]
   \[ \text{(e.g.) double diffusive convection} \]
3. **a hot and inflated atmosphere** (extended beyond the Hill radius)  
   which **enhances mass loss** via photo-evaporation or a Parker wind
4. **the survival of a planetary iron core** through a merger
5. **dredge-up of rocky material into a H/He atmosphere** caused by turbulence driven by an impact-induced shock wave
6. **a partial disruption of a three-layered structure**

(cf) A violent head-on collision can account for thermal evolution of Neptune, i.e., a initially-hot and homogeneous interior  
(but a grazing impact would retain a stably-stratified interior)

(Liu, YH, Lin, & Asphaug, *in preparation*)