HD 97658 and its super-Earth

Spitzer & MOST transit analysis and seismic modeling of the host star

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1. Introducing HD 97658 and its super-Earth

The second brightest star harboring a transiting super-Earth

**HD 97658 (V=7.7, K=5.7)**

- $T_{\text{eff}} = 5170 \pm 50$ K (Howard et al. 2011)
- $[\text{Fe/H}] = -0.23 \pm 0.03 \Rightarrow \sim Z$
- $d = 21.11 \pm 0.33$ pc ; from Hipparcos (Van Leeuwen 2007)

**HD 97658 b, a transiting super-Earth**

- Discovery by Howard et al. (2011) from Keck-Hires RVs:
  - $M_p \sin i = 8.2 \pm 1.2$ $M_{\text{earth}}$
  - $P_{\text{orb}} = 9.494 \pm 0.005$ d
- Transits discovered by Dragomir et al. (2013) with **MOST**: $R_p = 2.34 \pm 0.18$ $R_{\text{earth}}$

From Howard et al. (2011)

From Dragomir et al. (2013)
2. Modeling the host star HD 97658

$R_p \propto R_*$

$M_p \propto M_*^{2/3}$

+ the **age** of the star is the best proxy for the age of its planets

(Sun: 4.57 Gyr, Earth: 4.54 Gyr)

- With Asteroseismology: T. Campante, V. Van Eylen’s talks
- Without Asteroseismology: stellar evolution modeling
2. Modeling the host star HD 97658

- $d = 21.11 \pm 0.33$ pc, $V = 7.7 \Rightarrow L_* = 0.355 \pm 0.018$ $L_{\odot}$
- $+T_{\text{eff}}$ from spectroscopy: $R_* = 0.74 \pm 0.03$ $R_{\odot}$
- Stellar evolution code CLES (Scuflaire et al. 2008)
  \[ \Rightarrow M_*, \text{ age with } T_{\text{eff}}, [\text{Fe/H}] \text{ and } L_* \text{ as inputs (with 1}\sigma\text{ uncertainties) } \]

\[ M_* = 0.77 \pm 0.05 \, M_{\odot} \]
- No constrain on age

\[ \alpha_{\text{MLT}} = 1.8; \text{ no overshooting} \]
Mixture AGSS09
CEFF EoS
Opacities OPAL05+Ferguson06
Several $Y_{\text{ini}}$

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3. Spitzer observations

- « Warm » Spitzer IRAC camera at 4.5μm
- As part of the program to search transits for low-mass planets found in RV (Programs 60027 and 90072, PI M. Gillon)
- 6h-long lightcurve acquired on Aug 10, 2013 after MOST’s ephemeris

Blue dots: raw data
Red curve: photometric model
(= Spitzer systematics)
3. Spitzer observations

**MOST transit window (17 orbits after)**

Spitzer fully confirms, within 1σ, the MOST ephemeris
4. The MCMC method to characterize HD 97658b

I used Monte-Carlo Markov Chain (MCMC) code of Gillon et al. (2012), with jump parameters (those for which the chain is varying):

• With uniform prior distribution: mid-transit time $T_0$, transit depth $d_F$, transit width $W$, $P_{\text{orb}}$, …
• With Gaussian prior distribution: stellar mass $M_*$ ($0.77 \pm 0.05 \, M_\odot$), luminosity ($0.355 \pm 0.018 \, L_\odot$), $T_{\text{eff}}$ ($5170 \pm 50 \, K$) and metallicity ($[\text{Fe/H}] = -0.23 \pm 0.03$)

Jump parameters $\Rightarrow$ model to compare to data through a merit function

$$Q_n^2 = \sum_{k=1}^{l} \frac{(\nu_k - \mu_k)^2}{\sigma^2_{\nu_k}} + \sum_{j} \frac{(P_{n,j} - P_{0,j})^2}{\sigma^2_{P_{0,j}}}$$

- data
- model
- penalty for jump parameter with Gaussian prior

• Results: Probability Density Functions (PDFs) for each jump parameter + for derived parameters: planet mass, radius,…

![Stellar mass](stellar_mass.png)

![Transit depth](transit_depth.png)
5. Global MCMC analyses of RVs, Spitzer and MOST

171 Keck-Hires RVs + 1 Spitzer transit + 3 MOST transits

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jump parameters</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Jump parameter, uniform prior</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Transit depth, <em>Spitzer</em></td>
<td>$dF$</td>
<td>$773 \pm 42$</td>
<td>ppm</td>
</tr>
<tr>
<td>Transit width</td>
<td>$W$</td>
<td>$0.1187 \pm 0.0012$</td>
<td>days</td>
</tr>
<tr>
<td>Mid-transit time-2450000</td>
<td>$T_0$</td>
<td>$6523.12540^{+0.00060}_{-0.00056}$</td>
<td>BJD-TDB</td>
</tr>
<tr>
<td>Impact parameter $b' = a \cos i / R_*$</td>
<td></td>
<td>$0.35^{+0.13}_{-0.21}$</td>
<td>$R_*$</td>
</tr>
<tr>
<td>Orbital period</td>
<td>$P$</td>
<td>$9.4903^{+0.0016}_{-0.0015}$</td>
<td>days</td>
</tr>
<tr>
<td>Derived planet parameters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planet radius (at 4.5μm)</td>
<td>$R_P$</td>
<td>$2.247^{+0.098}_{-0.095}$</td>
<td>$R_\oplus$</td>
</tr>
<tr>
<td>Planet mass</td>
<td>$M_P$</td>
<td>$7.55^{+0.83}_{-0.79}$</td>
<td>$M_\oplus$</td>
</tr>
<tr>
<td>Planet density</td>
<td>$\rho_P$</td>
<td>$3.90^{+0.70}_{-0.61}$</td>
<td>g cm$^{-3}$</td>
</tr>
<tr>
<td>Planet surface gravity</td>
<td>$\log g_P$</td>
<td>$3.166^{+0.059}_{-0.061}$</td>
<td></td>
</tr>
<tr>
<td>Orbital inclination</td>
<td>$i$</td>
<td>$89.14^{+0.52}_{-0.36}$</td>
<td>deg</td>
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<tr>
<td>Orbital semi-major axis</td>
<td>$a$</td>
<td>$0.080^{+0.0017}_{-0.0018}$</td>
<td>AU</td>
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<tr>
<td>Orbital eccentricity</td>
<td>$e$</td>
<td>$0.078^{+0.057}_{-0.053}$</td>
<td></td>
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<tr>
<td>Argument of the periastron</td>
<td>$\omega$</td>
<td>$71^{+65}_{-63}$</td>
<td>deg</td>
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<tr>
<td>RV orbital semi-amplitude</td>
<td>$K$</td>
<td>$2.73^{+0.26}_{-0.27}$</td>
<td>m/s</td>
</tr>
</tbody>
</table>
6. HD 97658b, a key object for super-Earth characterization

Just a word about the uncertainties

Host star:  
-3% on $R_*$  
-8% on $M_*$

Planet:  
-5% on $R_P$  
-11% on $M_P$  
+ Spitzer & Keck RVs systematics

CHEOPS: uncertainties on planet will come from the star
PLATO and asteroseismology: star + planet < 5%

Note: Dragomir et al. (2013), with the same MOST light curves:

$$R_P = 2.34 \pm 0.18 \ R_{\text{earth}} \ (8\%)$$

BUT they used spectroscopic log $g$ and not $L_*$ from Hipparcos
6. HD 97658b, a key object for super-Earth characterization

« True » super-Earth, water-world, mini-Neptune, dwarf gas planet ?
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« True » super-Earth, water-world, mini-Neptune, dwarf gas planet ?

$$R_P = 2.247^{+0.098}_{-0.095} \quad R_{\text{Earth}}$$
$$M_P = 7.55^{+0.83}_{-0.79} \quad M_{\text{Earth}}$$

$$\rho_P = 3.90^{+0.70}_{-0.61} \quad \text{g cm}^{-3}$$

$$\rho_{\text{Earth}} = 5.5 \text{ g cm}^{-3}$$
$$\rho_{\text{Jupiter}} = 1.3 \text{ g cm}^{-3}$$
6. HD 97658b, a key object for super-Earth characterization

Internal composition (D. Valencia)

\( T_{\text{eq}} \sim 750 \text{ K} \)

HD 97658b
\( M = 7.55 \, M_\oplus \)

Rocks > 60%
Water+Ices 0-40%
H-He 0-2%

Ices: methanene-ammonia

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6. HD 97658b, a key object for super-Earth characterization

Planet atmosphere (H. Knutson)

Hubble Space Telescope WFC3 (19 bandpasses in 1.1-1.6 μm)

Excluded: • Cloud-free solar and 50x solar composition atmosphere (red)
Possibilities: • Water atmosphere (blue)
(2σ…) • Solar composition atmosphere with cloud/hazes at 1 mbar (green)

Knutson et al. (2014)
ArXiv1403.4602
7. What asteroseismology can bring to HD 97658

- I computed oscillation adiabatic properties of stellar (consistent) models that respect the $T_{\text{eff}}$, $L_*$, $[\text{Fe/H}]$ observational constraints.
- Large separations $\Delta \nu = \nu_{n+1,0} - \nu_{n,0}$ and small separations $\delta \nu = \delta \nu_{2n,0} = \nu_{n,0} - \nu_{n-1,2}$ are given here at their $\nu_{\text{max}}$'s (where the observed pulsation spectrum is expected to be).

C-D diagram

$\sim 1 \mu\text{Hz}$ accuracy on $\Delta \nu$ and $\delta \nu_{2n,0}$ will help to get better stellar mass & age.
8. Conclusion & Prospects

Conclusion:

**HD 97658b is a key transiting super-Earth**

- HD 97658b is an intermediate density super-Earth ⇒ composition of such objects? (internal composition? Volatiles? Thick atmosphere?)
- Orbiting a bright star (V=7.7, K=5.7) ⇒ very important for future atmospheric characterization (JWST, ...)
- Formation of such a planet?
- Characterizing the host star (mass, radius, age) is essential

Future observations:

- Coming: 3 more transits with Spitzer (PI D. Dragomir)
- GAIA ⇒ very accurate distance, luminosity, and stellar radius (but not sufficient to have $Y_{\text{ini}}$ and $\alpha_{\text{MLT}}$)
- CHEOPS & TESS: Accurate planet radius in visible
- Asteroseismic observations to improve the stellar mass and age ⇒ we need PLATO!