Characterizing planet-hosting stars

How to get the stellar mass, radius, and age

Valerie Van Grootel
(University of Liege)

Science Team WG A2: Target Characterization
(S. Sousa, F. Bouchy, and associates)
Why is stellar characterization so important?

\[ \text{Rp} \propto R^*_\star \]
\[ \text{Mp} \propto M^*_\star^{2/3} \]

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

(Sun: 4.57 Gyr, Earth: 4.54 Gyr)

CHEOPS = ultra-high precision photometry
We want to be both precise and accurate on stellar target
⇒ combination of techniques
The targets of CHEOPS

Main sequence nearby bright solar-like stars: F, G, and K-types

Direct techniques: interferometry ($R_*$), eclipsing binaries ($M_*$, $R_*$)

Indirect techniques: GAIA parallaxes ($R_*$), stellar evolution modeling ($M_*$, $R_*$, age), asteroseismology ($M_*$, $R_*$, age), transit light curve ($\rho_*$)

Note (M. Gillon): CHEOPS won’t provide accurate $\rho_*$ from transits (shape and $e \neq 0$)
Interferometry

To get $R_*$ to $\sim 1$-$2\%$
(dependending on size, distance and magnitude of the star)

Available now:
- CHARA (Mount Wilson USA, 330-m baseline)
- VLTI (Chile, 150-m baseline)

By the launch of CHEOPS: MROI (New Mexico, 400-m baseline)
GAIA parallaxes

To get $R_*$ to $\sim 1-2\%$

(normally not affected by GAIA's stray light issues)

Independently from interferometry $\Rightarrow$ increase the accuracy on stellar radius

Method:

\[
M_V = V + 5 + 5\log\pi - A_V
\]

\[
\log(L/L_{\odot}) = (M_{\text{bol, } \odot} - M_V - BC)/2.5
\]

\[
R = (L/4\pi\sigma T_{\text{eff}}^4)^{1/2}
\]

$\pi$: parallax
$A_V$: interstellar extinction
$BC$: bolometric correction
$T_{\text{eff}}$: effective temperature

(see Sousa et al. poster)
Stellar evolution modeling

To get $R_*$, $M_*$ and age

Stellar evolution codes: CLES (Liege), MESA (open source), Padova,…

Inputs:
- $T_{\text{eff}}$, $Z$ (from spectroscopy); $Z\sim[\text{Fe/H}]$ (better if other abundances)
- $\log g$ (spectroscopy), and/or $\rho_*$ (transits), and/or $L_*$ (parallax)

![Diagram showing stellar evolution models with ages and masses plotted against effective temperature.](image-url)

Valérie Van Grootel – CHEOPS workshop 2014
Stellar evolution modeling

To get $R_*$, $M_*$ and age

Pros:
- General method, always applicable
- Only require spectroscopic information, generally available (see S. Sousa et al. poster for specific issues on spectroscopy)
- Get $R_*$, $M_*$ and age

Cons:
- Not very precise:
  - Providing $\sim$50 K on $T_{\text{eff}}$, 0.05 dex on $[\text{M/H}]$ and 1% on $L_*$ (GAIA):
    - $R_*$ to $\sim$ 1-2%
    - $M_*$ to $\sim$ 5-10%
    - Age to 2-3 Gyr

Main uncertainties: from stellar interiors (helium initial abundance, efficiency of convection, importance of mixing processes)

Will be improved in the coming years from bulk asteroseismic results from CoRoT and Kepler?
Asteroseismology

To get $R_*$, $M_*$ and age

Principle:
Use stellar oscillations to constrain stellar interiors and to get structural parameters

For solar-like stars, main seismic indicators:
the large separation $\Delta \nu (\alpha \rho_*)$, frequency at maximum power $\nu_{\text{max}} (\alpha g/T_{\text{eff}}^{0.5})$, small separations $\delta \nu (\alpha \text{ age})$
Asteroseismology

To get $R_\ast$, $M_\ast$ and age

Principle:

Use stellar oscillations to constrain stellar interiors and to get structural parameters

For solar-like stars, main seismic indicators:

- the large separation $\Delta \nu (\alpha \rho_\ast)$,
- frequency at maximum power $\nu_{\text{max}} (\alpha g/T_{\text{eff}}^{0.5})$,
- small separations $\delta \nu (\alpha \text{ age})$
Asteroseismology

For CHEOPS targets:

- **Low-quality seismic data**: only $\Delta \nu \sim \rho_*$ to 5%
  \[
  \rho_* + R_* (\sim 1\text{-}2\%) \text{ by parallaxes/interferometry}
  \]
  \[\Rightarrow M^* \text{ to } 8\text{-}10\%\]

- **Mid-quality seismic data**: 1-month TESS, ground-based (ESPRESSO)
  - $\Delta \nu \sim \rho_*$ to 0.5% ($V=6$) + $R_*$ (\sim 1\text{-}2\% by parallaxes/interferometry)
  \[\Rightarrow M^* \text{ to } \sim 3\text{-}4\%\]
  - $\Delta \nu \sim \rho_*$ to 2% ($V=9$) + $R_*$ (\sim 1\text{-}2\% by parallaxes/interferometry)
  \[\Rightarrow M^* \text{ to } \sim 5\%\]

- **Age** still difficult to do better than 2\text{-}3 Gyr

- **High-quality seismic data**: not for CHEOPS 😞 (waiting for PLATO 😊)
  \[
  R_* \sim 1\text{-}2\%, \; M_* \sim 2\text{-}4\%, \; \text{age} \sim 10\% \text{ (!)}
  \]
About Eclipsing Binary Law

Enoch et al. (2010) proposed a $M_*(\rho_*, \text{Fe/H}, T_{\text{eff}})$ relation

$$\log M = a_1 + a_2 X + a_3 X^2 + a_4 \log \rho + a_5 \log \rho^2 + a_6 \log \rho^3 + a_7 [\text{Fe/H}]$$

<table>
<thead>
<tr>
<th>Mass, $a_i$</th>
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<tbody>
<tr>
<td>const.</td>
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<tr>
<td>$X$</td>
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<td>$X^2$</td>
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<td>$\log \rho$</td>
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<td>$\log \rho^3$</td>
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<td>[Fe/H]</td>
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$(X=\log(T_{\text{eff}})-4.1)$

based on 19 eclipsing binaries (38 stars) of Torres et al. (2010) (M$_*$ and R$_*$ model-independent)

Applied to Exoplanet-hosting stars (e.g. Gillon et al.):

Precision of 3-4% on M$_*$ (and then R$_*$ from $\rho_*$)
About Eclipsing Binary Law

Are eclipsing binaries representative stars?

No: they are in binaries, generally close ($P_{\text{orb}} < 5$ d)
⇒ More active stars than “normal”
⇒ Efficiency of envelope convection ($M_* < 1.1 M_{\text{sun}}$) is lower
⇒ Stellar Radius is larger (and density lower) than “normal”

Fernandes et al. (2012)
About Eclipsing Binary Law

The $M^*(\rho^*, \text{Fe/H}, T_{\text{eff}})$ relation is not unique

same $\rho^*, \text{Fe/H}, T_{\text{eff}}$, but not same $M^*$

(only the core extra-mixing is varied, in very reasonable proportion)
About Eclipsing Binary Law

The $M_*(\rho_*, \text{Fe/H}, T_{\text{eff}})$ relation is not unique

same $\rho_*, \text{Fe/H}, T_{\text{eff}}$ for a while, but not same $M_*$
(only the initial He abundance is varied, in very reasonable proportion)
Conclusion

• **Stellar radius**: accurate and precise up to 1-2% (GAIA, interferometry)

• **Stellar mass**:
  • Brightest targets with TESS seismic data: \( M_* \sim 3-4\% \) (asteroseismology)
  • More generally (9<V<12): \( M_* \sim 5-10\% \) (\( \rho_* + R_* \), stellar evolution modeling)

• **Stellar age**: not better than 2-3 Gyr (stellar evolution modeling, empirical methods)

Work to do in years to come:

- ✓ Explore the validity of Eclipsing Binary Law for any star
- ✓ Fully exploit high-quality seismic data from CoRoT and Kepler to improve accuracy on stellar mass and age from stellar models (constrain He, efficiency of convection, mixing processes)