Gaia PLUS INTERFEROMETRIC OBSERVATIONS

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Sagan Exoplanet Summer Workshop
Exoplanet Science in the Gaia Era

July 26, 2022
EXOPLANETS: where do we stand?

~ 5000 exoplanets detected so far
Wide diversity of methods
Raise many questions!

![Graph showing distribution of exoplanets by mass and semi-major axis with various detection methods indicated.]
EXOPLANETS: where do we stand?

~ 5000 exoplanets detected so far
Wide diversity of methods
Raise many questions!

Lack of continuum

Diagram showing the relationship between semi-major axis and mass of exoplanets, with various detection methods indicated.
~ 5000 exoplanets detected so far
Wide diversity of methods
Raise many questions!

Lack of continuum

Fulton gap

EXOPLANETS: where do we stand?
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~ 5000 exoplanets detected so far
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Raise many questions!

Fulton gap

Desert:
Observational gap

Lack of continuum

Fig. 7.—
Top:
Completeness-corrected histogram of planet radii for planets with orbital periods shorter than 100 days. Uncertainties in the bin amplitudes are calculated using the suite of simulated surveys described in Section C. The light gray region of the histogram for radii smaller than $1.14 R_{\text{sun}}$ shows light gray regions from low completeness. The histogram plotted in the dotted grey line is the same distribution of planet radii uncorrected for completeness. The median radius uncertainty is plotted in the upper right portion of the plot.

Bottom:
Same as top panel with the best-fit spline model over-plotted in the solid dark red line. The region of the histogram plotted in light gray is not included in the fit due to low completeness. Lightly shaded regions encompass our definitions of “super-Earths” (light red) and “sub-Neptunes” (light cyan). The dashed cyan line is a plausible model for the underlying occurrence distribution after removing the smearing caused by uncertainties on the planet radii measurements. The cyan circles on the dashed cyan line mark the node positions and values from the spline fit described in §4.3.
Several problematics

• Nature of the planets?
  ➔ Composition, size…

• Formation?
  ➔ Place of birth, migration…

• « Habitability »?
  ➔ Distance to the star (temperature), tectonic…

• Is our solar system unique?
  ➔ Need to probe many systems!
Indirect detection methods

Transit method

\[ \frac{\Delta F}{F} = \left( \frac{R_p}{R_\star} \right)^2 \]

→ Knowing \( R_p \) depends on \( R_\star \)
Indirect detection methods

Transit method

\[ \frac{\Delta F}{F} = \left( \frac{R_p}{R_*} \right)^2 \]

→ Knowing \( R_p \) depends on \( R_* \)
Indirect detection methods

Radial velocity method

\[
\frac{(m_p \sin i)^3}{(M_\star + m_p)^2} = \frac{P}{2 \pi G} K^3 (1 - e)^{3/2}
\]

→ Knowing \( M_p \) depends on \( M_\star \)
Indirect detection methods

Radial velocity method

\[ \frac{(m_p \sin i)^3}{(M_\star + m_p)^2} = \frac{P}{2\pi G} K^3 (1 - e)^{3/2} \]

→ Knowing \( M_p \) depends on \( M_\star \)
Direct detection method

Direct imaging

PDS70, SPHERE
Muller+ 2018

HR8799 (Wang, Marois)

2009-07-31
20 au

→ Need the stellar age

H2 (1.593μm)

IRDIS-H2H3 (Feb 7th, 2017)
HIP65426, SPHERE
Chauvin+ 2017

GJ504, SPHERE
Bonnefoy+ 2018

Macintosh+2015

HD131399, SPHERE
Wagner+ 2016

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frames to ensure we could run the ADI algorithms entered the frames fitting a two-dimensional monamorphism correction to the IRDIS and IFS data. We registered pixels for the IFS data (Mesa et al. 2015). It also applied the current, and flat field. The DC performed an improved wavefront correction. The DRH carried out the basic corrections for bad pixels, dark current, and focus. The reduction and handling (DRH) pipeline (Pavlov et al. 2008).

2. Observations

We temporally binned some of the registered cubes of IRDIS data. The target was observed on May 6, 2015, June 3, 2015, and 2016 (HR8799) respectively. The total field of view (FoV) is 1.7\(^\circ\) IFS FoV (Ligi+ 2018b). During the course of observation the average contrast values was performed by injecting negative point sources (H2, H3) in the same way as the main science object. The outer disk and the planetary companion inside the gap are clearly visible. In addition, there are multiple objects at the same distance from the host star. The companion is therefore re-recognized.

3. Data Reduction

We discuss our results in Section 8 and summarize our findings in Table 1. We also used the Principal Component Analysis (PCA) to extract the flux and position of such companions with a high fidelity (Chauvin et al, in prep). We also used the Principal Component Analysis (PCA) to extract the photometry and astrometry of the companion inside the gap of the disk around HD131399, SPHERE (Wagner+ 2016). Figure 1. A spectrum covering the spectral range of 0.75–1.7\(\mu\)m and contrast values was performed by injecting negative point sources (H2, H3) in the same way as the main science object. The outer disk and the planetary companion inside the gap are clearly visible. In addition, there are multiple objects at the same distance from the host star. The companion is therefore recognized.

4. Summary

The target was observed on May 6, 2015, June 3, 2015, and 2016 (HR8799) respectively. The total field of view (FoV) is 1.7\(^\circ\) IFS FoV (Ligi+ 2018b). During the course of observation the average contrast values was performed by injecting negative point sources (H2, H3) in the same way as the main science object. The outer disk and the planetary companion inside the gap are clearly visible. In addition, there are multiple objects at the same distance from the host star. The companion is therefore recognized.

Table 1. Parameters for the system in Section 3. We analyse the companion photometry and astrometry of the companion in Section 6. The stellar models adopted to compute the stellar properties based on interferometric measurements, high angular differential imaging (ADI) observations obtained with VLT/SPHERE, and we assume no covariance between them. The value provided by the SHINE GTO program (Claudi et al. 2018) is used for reference. The value reported here from the MCMC posterior draws is identical to the values used by other stellar evolutionary models (see Choi et al. 2018). The stellar models adopted to compute the flux and position of such companions with a high fidelity (Chauvin et al., in prep). We also used the Principal Component Analysis (PCA) to extract the photometry and astrometry of the companion inside the gap of the disk around HD131399, SPHERE (Wagner+ 2016). Figure 1. A spectrum covering the spectral range of 0.75–1.7\(\mu\)m and contrast values was performed by injecting negative point sources (H2, H3) in the same way as the main science object. The outer disk and the planetary companion inside the gap are clearly visible. In addition, there are multiple objects at the same distance from the host star. The companion is therefore recognized.

Table 2. Summary of photometry and astrometry of the companion inside the gap of the disk around HD131399, SPHERE (Wagner+ 2016). Figure 1. A spectrum covering the spectral range of 0.75–1.7\(\mu\)m and contrast values was performed by injecting negative point sources (H2, H3) in the same way as the main science object. The outer disk and the planetary companion inside the gap are clearly visible. In addition, there are multiple objects at the same distance from the host star. The companion is therefore recognized.
The internal composition of exoplanets is inferred from planetary interior models:

- **Need parameters** as inputs (stellar and planetary)
- **Hint toward formation and habitability**
- **Suffer from degeneracy**

Need ~2-3% precision on $R_p$ to derive an internal structure

Valencia+ 2013
(Bulk Composition of GJ 1214b and Other Sub-Neptune Exoplanets)
Find planets with suitable atmosphere and liquid water in the habitable zone

\[ T_{\text{eff}}, L \star \]
Links between exoplanet occurrence and stars

While there is significant scatter in occurrence rates at similar effective temperatures, there is a general consensus that giant planet occurrence rates increase with host metallicity. Significant planet occurrence rates were re-scaled assuming uniform distribution. The first indications of a planet-metallicity correlation were found by Gonzalez (2005) and later confirmed by Mayor et al. (2011), who show that planets less massive than 30-40 Earth masses are equally common around metal-poor and metal-rich stars. The same metallicity-metallicity relation is seen in radial velocity surveys of sun-like stars, M dwarfs, and evolved stars, and has also been identified for transiting planets in the Kepler mission.

The giant planet occurrence rate within 2.5 au increases by a factor of 3 from M dwarfs to sun-like stars (Butler et al. 2006; Cumming et al. 2008). Planet occurrence rates for a sample of late K dwarfs support the positive correlation with stellar mass (Howard et al. 2012). For low-mass M dwarfs, other studies find a decrease in occurrence rate with host metallicity compared to sun-like stars (Laws et al. 2003; Endl et al. 2006). The giant planet occurrence rate is lower in metal-poor stars than in metal-rich stars. For planets between 1-4 Earth radii, the occurrence rate is lower in metal-poor stars than in metal-rich stars. Positive giant planet-metallicity correlations have also been identified in radial velocity surveys of sun-like stars (Mayor et al. 2007; Pepe et al. 2007) and in the Kepler mission (Knutson et al. 2011). The main challenge lies in correcting for the detection bias in planet searches with radial velocity surveys.

Metallicity of Planet Hosts

![Metallicity of Planet Hosts](image)

Figure reproduced from Fischer and Valenti (2005) with permission from the authors.

Planet Occurrence within 50 days

![Planet Occurrence within 50 days](image)

Figure 4

Giant planet occurrence as a function of stellar mass, from Johnson et al. (2010) figure 4. The blue line shows the stellar-mass dependence at solar metallicity; compare to the predicted relation from the In Situ planet formation models by Dawson et al. (2015) shown in cyan. The expected range of planet radii from Buchhave et al. (2014) and for a continuous planet radius-metallicity relation (Schlaufman 2015) is shown with the dashed purple line. The expected range of planet radii from Buchhave et al. (2014) and for a continuous planet radius-metallicity relation (Schlaufman 2015) is shown with the dashed purple line.

Selection effects

![Selection effects](image)

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Stellar parameters drive our knowledge of exoplanets.

- Direct and indirect methods do not provide the same observables.
- Need of stellar parameters to derive exoplanets properties.
- The « basic » planetary parameters depend on the stellar mass, radius, density...
- Often, need of a model to derive additional parameters, that are important to characterize the system (like the stellar age).
- Open questions on the link between stellar parameters and exoplanets population.

Interferometry can help in this context by providing stellar parameters.

See Dan and Orlagh’s talks!
Interferometers worldwide

CHARA

SUSI

VLTI

NPOI
Principles of interferometry

Classical telescope

Angular resolution \( \approx \lambda/D \)
- larger sensitivity
- fainter objects

Interferometer

Angular resolution \( \approx \lambda/B \)
- larger resolution
- smaller objects

\( B > D \)
Contrast of fringes
= Complex visibility ($V$)
= FT of the surface brightness distribution of the star
(van Cittert-Zernike theorem)

In the case of a uniform disk:

$$V^2 \left( \frac{B}{\lambda} \right) = 4 \left| \frac{J_1(z)}{z} \right|^2$$

with

$$z = \pi \theta_{UD} \frac{B}{\lambda}$$

angular diameter of the star
Principles of interferometry

**Point source** → contrast = 1 (Young).

**Extended source**
→ several fringe patterns which don’t overlap exactly
→ contrast < 1, depends on telescope separation (baseline).
Principles of interferometry

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Point source $\rightarrow$ contrast $= 1$
(Young).

Extended source $\rightarrow$
several fringe patterns which
don’t overlap exactly
$\rightarrow$ contrast $< 1$, depends on
telescope separation (baseline).
Principles of interferometry
The problem of limb-darkening

Claret & Bloemen 2011

the linear law
\[
\frac{I(\mu)}{I(1)} = 1 - u(1 - \mu),
\]
the quadratic law
\[
\frac{I(\mu)}{I(1)} = 1 - a(1 - \mu) - b(1 - \mu)^2,
\]
the square root law
\[
\frac{I(\mu)}{I(1)} = 1 - c(1 - \mu) - d(1 - \sqrt{\mu}),
\]
the logarithmic law
\[
\frac{I(\mu)}{I(1)} = 1 - e(1 - \mu) - f\mu \ln(\mu),
\]

• Difficult to measure the LD
• Discrepancies between transit/interferometry and different laws
• Impact on final radius

Fig. 9. Comparison of the best-fit power law intensity profiles of \(\alpha\) Cen A and B (red curves) with the observed solar profile in the H band (orange curves) measured by Pierce et al. (1977). The horizontal scale is the same for both diagrams to show the difference in size of the two stars.

Fig. 2. Comparison of different parametric limb darkening models of the Sun with the observed limb darkening profile measured by Pierce et al. (1977) in the H band. The residuals in percentage of the observed intensity profile are shown in the lower panel.

Kervella+ 2017
Gaia and INTERFEROMETRY
The magic combo
**Stellar radius**

Interferometers measure the **angular diameter of stars. Coupled with the distance, we get the stellar radius!**

Interferometric angular diameter

\[ R_{\star}[R_{\odot}] = \frac{\theta_{\text{LD}[\text{mas}]} \times d_{[\text{pc}]}}{9.305} \]

![Diagram of stellar radius calculation](Image)

HD75732

\[ \theta_{\text{LD}} = 0.724 \pm 0.012 \text{ mas} \]

Ligi+ 2016
Stellar effective temperature

The angular diameter is also used to derive the effective temperature of stars.

\[
T_{\text{eff}, \star} = \left( \frac{4 \times F_{\text{bol}}}{\sigma_{\text{SB}} \theta_{\text{LD}}^2} \right)^{0.25}
\]

Interferometric angular diameter

Catalogues:
- Gaia
- 2MASS
- ... 

→ see Photometric Viewer (CDS)

e.g.
Stellar density and mass

Measure of stellar density $\rho_\star$ : $P/T^3 = (\pi^2 G/3) \rho_\star$

(Maxted et al. 2015, Seager & Mallén-Ornelas 2003)

$$\rho_\star \equiv \frac{M_\star}{R_\star^3} = \left( \frac{4\pi^2}{P^2 G} \right) \left\{ \frac{(1 + \sqrt{\Delta F})^2}{\sin^2(t_T \pi/P)} - b^2 \left[ 1 - \sin^2(t_T \pi/P) \right] \right\}^{3/2}$$

with $\Delta F \equiv \frac{F_{\text{no transit}} - F_{\text{transit}}}{F_{\text{no transit}}} = \left( \frac{R_p}{R_\star} \right)^2$
Stellar density and mass

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with $\Delta F \equiv \frac{F_{\text{no transit}} - F_{\text{transit}}}{F_{\text{no transit}}} = \left( \frac{R_p}{R_\star} \right)^2$

Measure of stellar mass $M_\star = (4\pi/3) R_\star^3 \rho_\star$

Interferometry
Stellar density and mass

From the PDF of $R_\star$ and $\rho_\star$, analytic joint PDF of $M_\star - R_\star$.

$$\mathcal{L}_{MR\star}(M, R) = \frac{3}{4\pi R^3} \times f_{R\star}(R) \times f_{\rho\star}(\frac{3M}{4\pi R^3})$$

→ Strong correlation: 0.85! (Crida+ 2018a)
→ Different $M_\star$ than von Braun+ 2011 based on isochrones.
Stellar density and mass

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Taking the values of $R_\star$ and $M_\star$ from Ligi+ 2016, one gets the large, wrong blue ellipse.
Stellar density and mass

Probability Distribution Function of $M_p$ and $R_p$

$$ f_p(M_p, R_p) \propto \int \int \exp \left( -\frac{1}{2} \left( \frac{K(M_p, M_*) - K}{\sigma_K} \right)^2 \right) \times \exp \left( -\frac{1}{2} \left( \frac{\Delta F(M_p, M_*) - \Delta F}{\sigma_{\Delta F}} \right)^2 \right) \times L_{MR*}(M_*, R_*) \, dM_\ast \, dR_\ast . $$

$\leftarrow$ RV measurements

$\leftarrow$ transit measurements

**Blue:** our first estimate, with **Hipparcos** parallax + poor transit light-curve.
Correlation: $0.3$.
$\rightarrow \rho_p = 1.06 \pm 0.13 \, \rho_{\oplus}$

**Black:** our second estimate, with **Gaia** parallax + refined HST light-curve and radial velocity.
Correlation: $0.54$.
$\rightarrow \rho_p = 1.164 \pm 0.062 \, \rho_{\oplus} = 6421 \pm 342 \, \text{kg.m}^{-3}$

---

55 Cnc e

![Diagram showing correlation between mass and radius](image)

**Low correlation**

**High correlation**

**No correlation**

* Bourrier+ 2018

Crida+ 2018a,b
Stellar density and mass

\[ c = 0.85 \]
Stellar density and mass

Uncertainties on TD and K degrade the correlation

$c=0.30$

$c=0.85$
Stellar density and mass

\[ c = 0.85 \]

Neglecting stellar uncertainties

Wrong!

Uncertainties on TD and K degrade the correlation

\[ c = 0.30 \]
Stellar density and mass

If TD and K were exactly known

Neglecting stellar uncertainties

Uncertainties on TD and K degrade the correlation

Wrong!

Dream!

$c = 0.85$

$c = 0.30$
Stellar abundances and exoplanet interiors

Input:
- Original data mp
- Correl. mp-Rp (0.30)
- Hypothetical corr. (0.85)
- Abundances

Results:
- A → composition of the mantle
- C → gas layer
- H → could rule out pure solid composition

Model from Dorn+ 2017
Stellar abundances and exoplanet interiors

Atmosphere thickness = 3% of $R_p$

→ not a good target for transmission spectroscopy

→ chemistry of the interior non necessarily carbon-rich

\[
\frac{r_{\text{solide}}}{R_p} = 0.97 \pm 0.02 \\
\frac{r_{\text{gaz}}}{R_p} = 0.03 \pm 0.02
\]
Stellar abundances and exoplanet interiors

Gaia also provides stellar abundances in a homogeneous way for millions of stars. Stellar abundances are introduced into planetary models to derive exoplanet internal structure.
Stellar density and mass

**HD219134**

Smaller planets than previous estimates

→ These new radii put the planets on the left side of the evaporation valley, while they were thought to be in the gap.

<table>
<thead>
<tr>
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<td>Radius $[R_\oplus]$</td>
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<td>Mass $[M_\oplus]$</td>
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\(\rho_b/\rho_c = 0.905 ± 0.131\) (0.95 for Venus/Earth)

→ 50 % chance that their densities differ more than 2× more than those of Venus and Earth...

The more massive one (b) is the less dense.

→ Different core/mantle ratio? Thick gas envelope? Enrichment in refractory elements?
Stellar density and mass

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Bower+ 2019: a molten mantle is 25% less dense than a solid one. Could HD219134 b be partially molten?
Stellar density and mass

Tidal heating from the host star dissipates energy and circularizes the orbit.

→ Sustainable energy source if and only if the eccentricity is pumped by other planets (ex: Io).

N-body simulations of the system:
\(e_b\) oscillates between 0.005 and 0.037.

→ tidal heating up to 100 times more than Io!

HD219134 c: less tidal heating than Io (because further from the star).
Stellar density and mass

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HD219134 c: less tidal heating than Io (because further from the star).

**Result**

→ N-body simulations: planet b’s eccentricity is excited despite not measurable.

→ Assuming a dissipation inside this planet equivalent to that of Earth, this strongly suggests that this planet could be at least partially molten, explaining its lower density than its neighbor HD219134 c, even if they have identical composition.
Error budget

Error budget for $\rho_p$ of HD219134 and 55 Cnc

$$\tilde{\sigma}_{\rho p}^2 = \frac{4}{9} \tilde{\sigma}_{\rho \star}^2 + \tilde{\sigma}_{R\star}^2 + \frac{9}{4} \tilde{\sigma}_{\Delta F/F2}^2 + \tilde{\sigma}_K^2$$

55 Cnc e

- Relative error: 5.3%
- Absolute error: $24 \cdot 10^{-4}$
- Relative error: 0.5%
- Absolute error: $0.1 \cdot 10^{-4}$
- Relative error: 1.6%
- Absolute error: $2.6 \cdot 10^{-4}$
- Relative error: 1.6%
- Absolute error: $5.4 \cdot 10^{-4}$
- Relative error: 4.0%
- Absolute error: $16 \cdot 10^{-4}$

HD219134 b

- Relative error: 10.4%
- Absolute error: $48 \cdot 10^{-4}$
- Relative error: 1.9%
- Absolute error: $3.6 \cdot 10^{-4}$
- Relative error: 6.7%
- Absolute error: $45 \cdot 10^{-4}$
- Relative error: 6.0%
- Absolute error: $36 \cdot 10^{-4}$
- Relative error: 4.4%
- Absolute error: $9.9 \cdot 10^{-4}$

HD219134 c

- Relative error: 106\%?
- Absolute error: $48 \cdot 10^{-4}$
- Relative error: 1.9%
- Absolute error: $3.6 \cdot 10^{-4}$
- Relative error: 4.4%
- Absolute error: $19 \cdot 10^{-4}$
Error budget for $\rho_p$ of HD219134 and 55 Cnc

\[ \tilde{\sigma}_{\rho_p}^2 = \frac{4}{9} \tilde{\sigma}_{\rho_\star}^2 + \tilde{\sigma}_{R_\star}^2 + \frac{9}{4} \tilde{\sigma}_{\Delta F/F_2}^2 + \tilde{\sigma}_K^2 \]

55 Cnc e
\[ \sim 22\% \quad 24 \times 10^{-4} = 0.1 \times 10^{-4} + 2.6 \times 10^{-4} + 5.4 \times 10^{-4} + 16 \times 10^{-4} \]

HD219134 b
\[ \sim 106 \times 10^{-4} = 48 \times 10^{-4} + 3.6 \times 10^{-4} + 45 \times 10^{-4} + 9.9 \times 10^{-4} \]

HD219134 c
\[ \sim 106 \times 10^{-4} = 48 \times 10^{-4} + 3.6 \times 10^{-4} + 45 \times 10^{-4} + 9.9 \times 10^{-4} \]

Can be resolved with new missions for transits (TESS, PLATO)
Error budget

Error budget for $\rho_p$ of HD219134 and 55 Cnc

\[ \tilde{\sigma}_{\rho_p}^2 = \frac{4}{9} \tilde{\sigma}_{\rho\star}^2 + \tilde{\sigma}_{R\star}^2 + \frac{9}{4} \tilde{\sigma}_{\Delta F/F2}^2 + \tilde{\sigma}_{K}^2 \]

<table>
<thead>
<tr>
<th>Component</th>
<th>55 Cnc e</th>
<th>HD219134 b</th>
<th>HD219134 c</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{\sigma}_{\rho_p}^2$</td>
<td>$4.5 \cdot 10^{-4}$</td>
<td>$48 \cdot 10^{-4}$</td>
<td>$9 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$\tilde{\sigma}_{\rho\star}^2$</td>
<td>$0.5 \cdot 10^{-4}$</td>
<td>$10.4 \cdot 10^{-4}$</td>
<td>$45 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$\tilde{\sigma}_{R\star}^2$</td>
<td>$1.6 \cdot 10^{-4}$</td>
<td>$1.9 \cdot 10^{-4}$</td>
<td>$36 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$\tilde{\sigma}_{\Delta F/F2}^2$</td>
<td>$4.0 \cdot 10^{-4}$</td>
<td>$6.7 \cdot 10^{-4}$</td>
<td>$9.9 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$\tilde{\sigma}_{K}^2$</td>
<td>$4.0 \cdot 10^{-4}$</td>
<td>$6.0 \cdot 10^{-4}$</td>
<td>$4.4 \cdot 10^{-4}$</td>
</tr>
</tbody>
</table>

Relative error:
- 55 Cnc e: 5.3%
- HD219134 b: 10.4%
- HD219134 c: 106.10^(-4)

Absolute error:
- 55 Cnc e: $4.4 \cdot 10^{-4}$
- HD219134 b: $48 \cdot 10^{-4}$
- HD219134 c: $9 \cdot 10^{-4}$

Can be resolved with new missions for transits (TESS, PLATO)
Can be resolved with new generation spectrographs (ESPRESSO...)
Error budget for $\rho_p$ of HD219134 and 55 Cnc

$$\tilde{\sigma}_{\rho_p}^2 = \frac{4}{9} \tilde{\sigma}_{\rho_\star}^2 + \tilde{\sigma}_{R_{\star}}^2 + \frac{9}{4} \tilde{\sigma}_{\Delta F/F_2}^2 + \tilde{\sigma}_K^2$$

55 Cnc e
- $\tilde{\sigma}_{\rho_p}^2 = 5.3\%$
- $24 \cdot 10^{-4}$
- $\sim 22\%$
- $24 \cdot 10^{-4}$
- Can be resolved with interferometry + Gaia
- mas $\rightarrow$ $\mu$as

HD219134 b
- $\tilde{\sigma}_{\rho_p}^2 = 0.5\%$
- $0.1 \cdot 10^{-4}$
- $10.4\%$
- $48 \cdot 10^{-4}$
- Can be resolved with new missions for transits (TESS, PLATO)

HD219134 c
- $\tilde{\sigma}_{\rho_p}^2 = 1.6\%$
- $2.6 \cdot 10^{-4}$
- $1.9\%$
- $3.6 \cdot 10^{-4}$
- Can be resolved with new generation spectrographs (ESPRESSO...)

Relative error
- $5.3\%$
- $0.5\%$
- $1.6\%$
- $4.0\%$

Absolute error
- $24 \cdot 10^{-4}$
- $0.1 \cdot 10^{-4}$
- $2.6 \cdot 10^{-4}$
- $5.4 \cdot 10^{-4}$
- $45 \cdot 10^{-4}$
- $3.6 \cdot 10^{-4}$
- $4.4\%$
- $16 \cdot 10^{-4}$
- $9.9 \cdot 10^{-4}$
- $19 \cdot 10^{-4}$
Stellar models

Integration of the stellar radius from interferometry

HD97658 (Ellis+ 2020)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Source</th>
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<tbody>
<tr>
<td>Transit Depth [ppm]</td>
<td>712±38</td>
<td>Exofast</td>
</tr>
<tr>
<td>Period [days]</td>
<td>9.48971157 ± 0.00000077</td>
<td>Exofast</td>
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<tr>
<td>$T_0$ [BJD]</td>
<td>2458904.9366 ± 0.0008</td>
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<td>$R_p/R_*$</td>
<td>0.02668±0.0007</td>
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<td>Inclination [deg]</td>
<td>89.05±0.41</td>
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<td>Impact Parameter</td>
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<tr>
<td>Eccentricity</td>
<td>0.054±0.039</td>
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<tr>
<td>Mass [M$_\odot$]</td>
<td>7.52±0.86</td>
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<tr>
<td>$a/R_*$</td>
<td>24.16 ± 0.69</td>
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<td>$R_p$ [R$_\odot$]</td>
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Stellar and Planetary Properties from Transit Observables

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<td>3.11 ± 0.27</td>
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<td>$M_*$ [M$_\odot$]</td>
<td>0.85 ± 0.08</td>
<td>§4</td>
</tr>
<tr>
<td>log($g$) [cgs]</td>
<td>4.64±0.04</td>
<td>§4</td>
</tr>
<tr>
<td>Corr($R_<em>,M_</em>$)</td>
<td>0.41</td>
<td>§4</td>
</tr>
<tr>
<td>$\rho_p$ [g cm$^{-3}$]</td>
<td>4.835±0.70</td>
<td>§4</td>
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<tr>
<td>$R_p$ [R$_\odot$]</td>
<td>2.11±0.069</td>
<td>§4</td>
</tr>
<tr>
<td>Mass [M$_\odot$]</td>
<td>8.25±1.01</td>
<td>§4</td>
</tr>
<tr>
<td>Corr($R_p,M_p$)</td>
<td>0.09</td>
<td>§4</td>
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• Discrepancies between models, methods, measures
• Need measures to calibrate models
• → Interferometry + planetary transits can bring very important information on usually non-measurable properties
Stellar models

Integration of the stellar radius from interferometry

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- Discrepancies between models, methods, measures
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- → Interferometry + planetary transits can bring very important information on usually non-measurable properties
Stellar models

→ Inconsistency in stellar parameters perturbs the exoplanet composition
→ Composition of planets that we do not find in our solar system?
Surface-brightness color relationship

- We can’t measure the angular diameter of all stars
- SBCR are here for that!
- We can’t measure the angular diameter of all stars
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**Before**

Discrepancy up to 18%
• We can’t measure the angular diameter of all stars
• SBCR are here for that!

Before

Discrepancy up to 18%

After

Precision between 1 and 2% with photometric precision better than 0.04 mag

$$\theta_{LD} = 10^{8.4392 - 0.2V_0 - 2F_{V0}}.$$
CONCLUSION
Conclusion

- Stellar parameters are very important for exoplanetary characterization.
- Interferometry can help in many direct and indirect ways.
- The most important parameter derived from interferometry plus distances (Gaia) is the stellar radius:
  - Mandatory for determining exoplanet radius.
  - Incorporated in stellar models that is used for exoplanets characterization.
  - Incorporated in exoplanet interior models.
• Gaia brings unprecedented precisions on distances, which brings very precise radii.
• New interferometric developments like SPICA/CHARA will allow the study of a bench of exoplanet host stars.

• Gaia is not only useful for interferometry, but also for detection through astrometry and transits.
• Gaia also provides stellar abundances that are used to determine exoplanet interiors.
THANK YOU!