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THE CHARACTERISATION OF EXOPLANETARY SYSTEMS WITH HIGH ANGULAR RESOLUTION

R. Ligi[1]

Abstract. After the discovery of thousands of exoplanets, one of the biggest goal in Astrophysics has become their charaterisation. Their mass and radius allow us to derive their bulk composition, but only if their host star is well characterised. In particular, the stellar radius plays an important role in the determination of planetary parameters. High angular resolution (HAR) gathers precise techniques to probe exoplanetary systems, like interferometry to measure the angular diameter of stars, and direct imaging to investigate planetary formation. However, some discrepancies between these measurements in one hand, and with those from other techniques on the other hand, remain. We present here an brief overview of some important results in HAR related to exoplanets and of the limitations in the interferometric measurements.

Keywords: Star : fundamental parameters, Exoplanetary systems, Technique : high angular resolution.

1 Introduction

The discovery of thousands of exoplanetary systems in the last decades have brought us to the era of exoplanets characterisation. These detections raise the questions of exoplanets habitability, their formation and evolution. This also implies to have a global view on planetary systems, from their formation to their final properties.

The mass and radius of planets are a direct information about their nature. One intriguing result in exoplanets detection is that most of them do not have an equivalent in our solar system, as a majority lie between the super-Earth and mini-Neptune size regimes. Then, knowing the density of exoplanets bring insights on their rocky or gazeous nature, and their ability to retain an atmosphere. Starting from these properties, one can derive with atmospheric and evolution models the internal structure of exoplanets, and extrapolate on possible liquid water, habitable atmosphere, plate tectonics.

All these planetary properties cannot be directly measured : *if you don't know the star, you don't know the planet.* Indeed, the transit method, who provided us with the majority of known exoplanets (in particular thanks to the *Kepler* mission), actually measures the ratio of the planetary to the stellar radius $R_{\rm p}/R_\star$. Similarly, radial velocity (RV) measurements give the ratio of the planetary to the stellar masses $m_{\rm p}\sin(i)/M_\star$. It is then often assumed that the planetary and stellar abundances are equal, which allows us to use the stellar abundances to decrease the intrinsic degeneracy of exoplanet interiors (e.g., Dorn et al. 2017b,a). It is thus obvious that with erroneous or unprecise stellar parameters, we cannot access the planetary properties, even if transit and RV measurements are known with high precision.

So far, only a handful of exoplanets are charaterized with better than 5% uncertainty of $m_{\rm p}$ and $R_{\rm p}$ (see Fig. 1). The direct measurements of global stellar properties (radius $R_\star$, mass $M_\star$, effective temperature $T_{\rm eff}$, age) is kept to a few privileged ones : brights stars in general, are for example accessible to interferometry, a high angular resolution technique that is aimed at measuring the angular diameter of stars with precision of $\sim 1-2\%$ (see Sec. 3). Asteroseismology is a powerful tool to probe the interior of stars and derive their age – a parameter that cannot be directly measured otherwise. The stellar mass can only be directly inferred in binary systems. Combining both interferometry and asteroseismology provides stellar masses with up to 3% precision (Creevey et al. 2007) and ages with 10% precision (Lebreton & Goupil 2014). To access the stellar parameters of fainter stars, we have to rely on empirical relations based on measurements on brighter stars.

On the other side, the advent of high-contrast imagers have brought incredible insights on planetary formation. To date, the common models of planetary formation are the core accretion (CA, Pollack et al. 1996), which

[1] INAF-Osservatorio Astronomico di Brera, Via E. Bianchi 46, I-23807 Merate, Italy (roxanne.ligi@inaf.it)

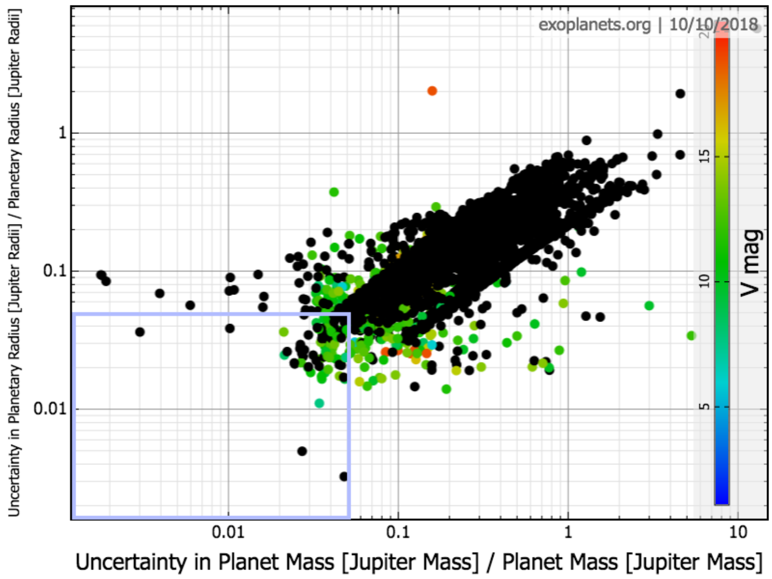

Fig. 1. Uncertainty in planetary radius according to the uncertainty in planetary mass (slightly zoomed) from `exoplanets.org`. Most of exoplanets known to date are not well constrained which can be explained by the faintness of their host star (a large proportion of black circles are *Kepler* stars). The purple box delimits the exoplanets known with better than 5% on both mass and radius.

would be more favorable to form giant planets close to the star (<50 au), and the gravitational instability (GI, Boss 1997) which would tend to form giant planets at large separation. To test these mechanisms, a general view of planetary systems is mandatory. Direct imagers like SPHERE/VLT Beuzit et al. (2008), GPI (Macintosh et al. 2014), ALMA led to a new era showing new evidences of forming planets, protoplanetary disks, gaps and rings through scattered and polarized light. Proto-planetary discs are direct witnesses of the environment where planets form, like for example HD 169142 (see e.g. Ligi et al. 2018), LkCa 15 (Kraus & Ireland 2012), HD 100546 (Brittain et al. 2013). Observing young systems also leads to the discovery of giant exoplanets (e.g. HR 8799, β Pic, HD 95086, Marois et al. 2008; Lagrange et al. 2010; Rameau et al. 2013, respectively) which helps understanding formation processes.

We present here a brief overview of the interferometric measurements that led to a better characterisation of exoplanetary systems and how the combination of direct imaging and interferometry helps understanding formation processes in a challenging system (Sec. 2). We also show that interferometry (as other techniques) present some limitations (Sec. 3). In the near future, they are expected to significantly decrease (Sec. 4).

2 The point of view of HAR in exoplanetary science

Transiting exoplanets

Some of the favorite targets concerning HAR and planetary science are the stars hosting transiting exoplanets, because with a direct measurement of the stellar radius, the planetary radius can directly be inferred. The best characterised exoplanet to date is 55 Cnc e. Several measurements of 55 Cnc's diameter brought values of 0.711±0.004 mas (von Braun et al. 2011) and 0.724±0.012 (Ligi et al. 2016), both in good agreement. Combining these measurements with the stellar density extracted from the photometric transit measurements, Crida et al. (2018b,a) derived the mass-radius correlation of the star (0.995) and of the planet (0.54), narrowing the possibilities for the planet interior (see also proceeding of Crida et al. 2018, this conference). Other transiting exoplanets have been characterised, although not as deeply because their host star are fainter. The well known HD189733 and HD209458 stars have been measured with PAVO (Boyajian et al. 2015), bringing diameters of 0.3848±0.0055 and 0.2254±0.0072 mas, respectively. While the stellar parameters of HD209458 are in good agreement with indirect spectroscopic estimates, models cannot reproduce the parameters of HD189733. Thus, further investigation is needed.

The case of GJ 504

As stated in Sec. 1, direct imaging brings new insights on planetary formation, and on planets at large separation. It thus constitutes a complementary view of exoplanetary systems to the other methods (transits and RV). Only few systems can be characterised with many ground-based instruments. Among them, the system of GJ 504 has been followed with RV (SOPHIE/OHP), direct imaging (SPHERE/VLT), interferometry (VEGA/CHARA) (Bonnefoy et al. 2018). Although not transiting, a companion (GJ 504 b) has been detected 44 au away from the star (Kuzuhara et al. 2013). The mass of the companion strongly depends on the age of the star : if the system is young (∼Myr), models of planetary interiors predict a giant-planet mass, whereas an old age (∼Gyr) infers a brown dwarf mass. In both cases, the companion lies in a desert in the distance-mass diagram. Many investigations of the stellar parameters have been performed based on various indicators (e.g., Fuhrmann & Chini 2015; D'Orazi et al. 2017; Bonnefoy et al. 2018), without finding a clear agreement on the age. The interferometric measurement of the host star could not either make the two age solutions converge, but helped concluding that spots at the stellar surface (which could affect the luminosity and $T_{\rm eff}$ estimates) would not affect the angular diameter measurement because of the dispersion of the data. The probable spin-orbit misalignment of GJ 504 b, its position in the brown-dwarf desert and its mass and separation from the star (which depend on the stellar age) challenge its formation mechanism. This illustrates that precise and accurate measurements are mandatory to fully characterise exoplanetary systems.

3 Stellar parameters from HAR : some limitations

Interferometry is a direct technique massively used to measure the angular diameter of stars. Combined with the distance (now provided by *Gaia* with a precision better than 1% for many stars), it directly provides the stellar radius. Its success holds in the precision of the interferometric measurements : they generally reach up to 1-2% for bright stars (see e.g. Baines et al. 2010; Ligi et al. 2016; Boyajian et al. 2012a,b). This technique is thus very useful to characterise exoplanet host stars (e.g. Baines et al. 2008; Ligi et al. 2012; von Braun et al. 2014; Ligi et al. 2016). For instance, Ligi et al. (2016) performed an interferometric analysis of ten exoplanetary systems, leading to a better determination of the 18 exoplanet minimum masses, semi-major axis and stellar habitable zones. But such surveys are also important for calibrating empirical laws (see e.g., Kervella et al. 2004), which in turn provide diameters of stars too faint to be directly accessible with interferometers. Comparisons between angular diameters obtained directly and indirectly (Kervella et al. 2004; Casagrande et al. 2010) show good agreement in general.

However, some discrepancies between the diverse interferometric measurements remain at different levels according to the stellar type. It is for example the case of the brightest *Kepler* star θ Cyg (F4V star), which diameter is measured with 0.4 to 1.7% discrepancy according to the instrument used : VEGA/CHARA measured 0.76±0.003 mas (Ligi et al. 2012), while diameters of 0.861±0.015 mas and 0.753±0.009 mas were obtained with CLASSIC (Boyajian et al. 2012a) and PAVO (White et al. 2018), respectively. The question also arises for HD167042, a giant star for which differences of up to 7% has been found in the measured diameter (Baines et al. 2008; Ligi et al. 2016; White et al. 2018). More generally, White et al. (2018) found discrepancies up to 30% comparing the angular diameters of A stars measured with different instruments on the CHARA array. Ligi et al. (2016) find a lower discrepancy of 3% but their sample gathers mainly FGK stars (Fig.2). These differences translate into discrepancies in the other stellar parameters derived from interferometry, like $T_{\rm eff}$. In their sample, Boyajian (2013) found a diffference of −1.7% between spectroscopic and interferometric determinations. White et al. (2018) in turn show that discrepancies can reach several tens of Kelvin in some cases although no trend has been noticed. In Casagrande et al. (2014)'s sample, the difference can reach 400 K. Finally, Ligi et al. (2016) observe an over-estimation of $T_{\rm eff}$ for stars hotter than 6000 K (V and IV stars) and an under-estimation for cooler stars (class II and III stars, see Fig.2).

A comparison of direct (or quasi-direct) measurements of the radius could be a solution to better understand these differences. Asteroseimology is of course a very powerful technique to derive $R_\star$. Huber et al. (2012) compared the radii of 10 stars obtained with both techniques, and found very good agreement, the larger uncertainties attributed to the giant stars in the sample being due to the error on the parallax. This analysis agrees with Baines et al. (2014)'s comparison of asteroseismic and interferometric radii, for which the scatter is larger for giant stars.

Other parameters should be taken into account to understand the discrepancies between interferometric measurements, like the limb-darkened model (LD) used to infer the LD diameter, the calibrators used, stellar activity, etc., that all deserve detailed investigation.

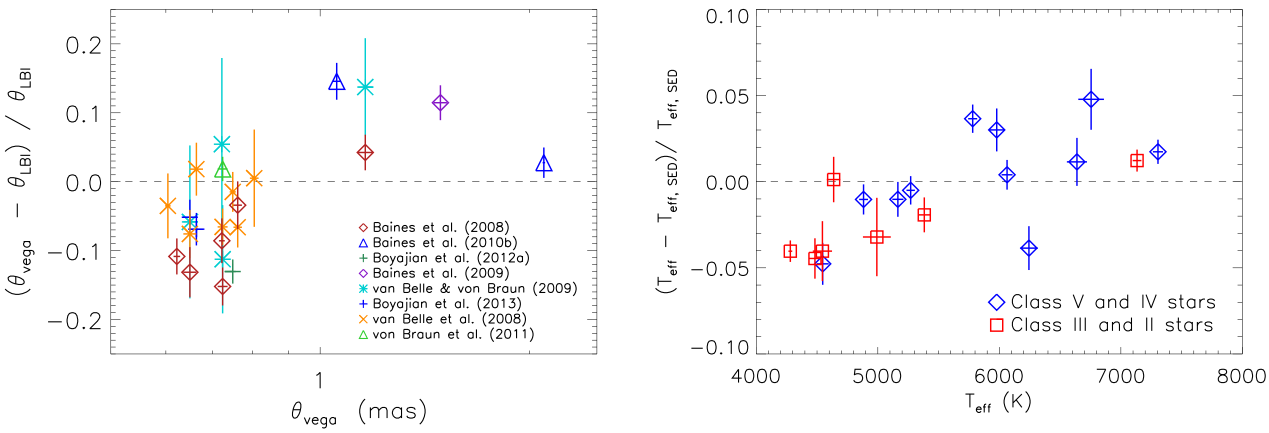

Fig. 2. Left : Comparison between angular diameters measured with VEGA and with other instruments. Right : Comparison between interferometric temperatures and temperatures derived from SED. Dwarfs and subgiants stars are plotted with blue diamonds, and giants and bright giants with red squares (Ligi et al. 2016).

4 Future complementary programs and missions

The mission *Kepler* provided us with most of exoplanets known to date. However, one of the biggest limitation of this mission is that its targets were very faint, thus difficult to observe with ground-based instruments. The parameters of the *Kepler* stars are thus constrained with large uncertainty which translates into a large uncertainty on exoplanet parameters. This will change in the near future. The TESS mission has been launched in April 2018, and already provides promising results (Vanderspek et al. 2018; Gandolfi et al. 2018). The CHEOPS mission is on its way, and PLATO is expected for 2026. One of the big difference with the previous *Kepler* and CoRoT missions is that they will target bright stars accessible from the ground. It will thus be possible to well characterise the stars, with precision of a few percents for the radius, mass and age. This will be of course strenghtened by the fact that TESS and PLATO's goals are also to perform asteroseismology on the host stars. Concerning the ground, the SPICA project (Mourard et al. 2018) will revolutionise the field of optical interferometry. It will allow us to use the 6 telescopes of the CHARA array, to take advantage of the adaptative optics recently installed, while staying at visible wavelengths, pushing the limits of its predecessor (and still in use) VEGA instrument. The main objectives are a large survey of stellar angular diameters measurements, and imaging of stellar surfaces. This will provide a bench of directly characterised exoplanet hosts (among them, TESS and PLATO targets), and help refining surface-brightness relations to decrease the discrepancies between found them and increase their precision. Hence, it will constitute an important complement to spatial missions dedicated to exoplanetary systems and stellar characterisation.

5 Conclusions

High angular resolution constitutes an important tool to bring a full view of planetary systems, from the inside out ; from rocky Earth-like planets to giant gazeaous ones ; from small to large separation ; form forming to fully formed exoplanets. To investigate most of the questions related to planets (formation, evolution, habitability...) these systems must be probed with as many techniques as possible. Interferometry is an efficient tool to determine stellar parameters, but further investigation to better understand the discrepancies in the measurements are needed. This technique will be essential to take full advantage of future missions dedicated to explanetary detection and characterisation, like TESS, CHEOPS and PLATO.

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