Setting a New Standard in the Analysis of Binary Stars
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STELLAR DIAMETERS AND TEMPERATURES ALONG THE MAIN SEQUENCE

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Abstract. We discuss results associated with ongoing surveys to measure the diameters and temperatures of main-sequence stars with interferometry. Empirical data such as these are used to calibrate less direct relationships to extend our knowledge to a large number of stars. The data are also used to identify weaknesses in stellar atmosphere and evolutionary models as well as provide empirical constraints to aid in the development of new models.

1 "A standard" *versus* "the standard"

A legacy extending over a century, observations of binary stars play a fundamental role for the astronomical community. It is the analysis/observation of a double-lined spectroscopic + eclipsing binary (DSEB) which allows precise measures of component masses and radii. These observations undoubtedly provide us with robust constraints in stellar evolution and atmosphere modeling, ultimately having the ability to make better models (Andersen 1991; Torres *et al.* 2010). In-as-much, we define such systems as "standards", to which all of our knowledge and inference of the rest of the universe is calibrated against.

We find it appropriate now to take a philosophical break to discuss this terminology in more detail. A standard is a standard compared to what? When does such a standard become useful? And when identified as useful, what purpose does this standard play?

Backtracking, we have already identified the value of a standard, where accurate measurements may be used in testing current stellar models, in aspirations to extend our knowledge to a large number of stars. We may also identify that observations of standards become worthwhile when the analysis yields stellar properties to better than a couple percent (*e.g.*, Torres *et al.* 2010), where one can really push the limits of the input physics in the models. However, the most simple

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question remains the most ambiguous to a room full of binary star astronomers: a standard compared to what? Although most stars are in multiple systems, is it legit to transfer our knowledge of binaries to a population of (dynamically) single stars in order to derive their properties? To what extent is it a valid approach to use binaries to calibrate models? Are the goals in identifying *the* standard the same as identifying *a* standard?

In the following paper, we outline the cooperative information readily obtained from studying single and binary stars – where the measurements of single stars come from optical interferometry and the measurements of binary stars come from spectroscopy and photometry of detached (*i.e.*, non-interacting) DSEBs. Generally speaking, both cases of study have their limitations, and complementary data is needed in order to reach potential breakthroughs in the field of fundamental stellar astronomy.

2 Two different views – one thing in common

Of the fundamental stellar properties, the stellar radius is the quantity in common that is empirically measured for both single and binary stars. Each class of star brings additional information of the stellar properties: the effective temperature, mass, and chemical abundance – neither which are matched by the other techniques capability.

2.1 *Single stars*

Even the most nearby main-sequence stars have angular sizes <1 milliarcsecond (mas). This is simply due to their small intrinsic linear size, and thus the angular size is inversely proportional to the star's distance. Precisely resolving the sizes of single stars along the main-sequence is owed to successful advances in high-angular resolution astronomy, in particular the technique of long-baseline optical/infrared interferometry (*e.g.*, see Boyajian *et al.* 2013a, and references therein). With a known distance[3], the stellar radius and effective temperature are direct observables from this method. These measurements can be readily complemented by (model-dependent) stellar abundance estimates via spectroscopy of photometry. Stellar masses are *not* directly measured for single stars unless asterosiesmic data is available for intense analysis. Instead, masses for single stars are typically obtained by using mass-luminosity relations derived from DSEBs, or from stellar models. The interferometric data set is comprised of stars having no known companion closer than $\sim$3 arcseconds, and thus are considered to be dynamically single.

2.2 *Binary stars*

DSEB observables are masses and radii with unmatching precision - the remainder of these proceedings give a fabulous introduction to binary star side of things, and

[3]Hipparcos parallaxes (van Leeuwen 2007) are excellent for such a sample, which extends no more than a few tens of parsecs.

we assume that the reader is following accordingly. A DSEB analysis also yields *relative* temperatures of the system's components. Solving this temperature ratio for the temperatures of each individual component is left to picking a primary temperature through the use of (hopefully) a variety of techniques, a approach considered to be only semi-empirical in nature at best. In a DSEB, the presence of starlight from the two components make it extremely difficult to measure good abundances even with sophisticated spectral disentangling or tomographic reconstruction techniques. However, in special cases, a constraint may be made to the system's metallicity with analysis of a wide companion or even cluster membership. Stellar ages are arbitrary to each method, where *absolute* ages always fall back on stellar evolutionary models. It is such a strong case to test the coeval nature of a binary to validate the consistency within models for stars of different masses in a binary system.

3 A link: Surface-brightness relations

A direct connection to single and binary star science is through the surface brightness relation, also known as the Barnes-Evans relation. In such a formulation, the surface brightness of an object is directly related to its broad-band color (Wesselink 1969), and it also a function of its apparent magnitude and angular size (Barnes & Evans 1976; Barnes *et al.* 1976). Connecting the observed colors to angular size is a method straightforward and entirely model independent if the calibration data exists. Until recently, a paucity of precisely measured angular diameters from interferometry existed in the literature, hindering a robust determination of surface brightness relations. The most recent analysis of the data in Boyajian *et al.* (2013a) are shown to provide predictions of the stellar angular size down to a few percent uncertainty.

Since the linear radii are known for components in a DSEB, and apparent magnitudes are observed in its photometric light curve, application of the surface brightness relation allows for a model independent determination of the systems distance. This application was introduced by Lacy (1977), where the distances to nine systems were derived. Since the DSEB occurrence rate is ∼1.5% (Prša *et al.* 2011), the practicality of using DSEBs as standard candles to derive distances using surface brightness techniques is becoming more applicable with the large ground-based and space-based photometric surveys available (*e.g.* eclipsing binaries from the *Kepler* Mission and the Optical Gravitational Lensing Experiment (OGLE); Prša *et al.* 2011; Graczyk *et al.* 2011, respectively). This synergy of information of single star and binary star data has recently provided distance to the Large Magellanic Cloud with uncertainties on the order of 2% (Pietrzyński *et al.* 2013).

4 New insights reveal consistent explanation

A reoccurring theme in low-mass star research is that current models tend to under-predict stellar radii for a given mass (*e.g.*, Spada *et al.* 2013;

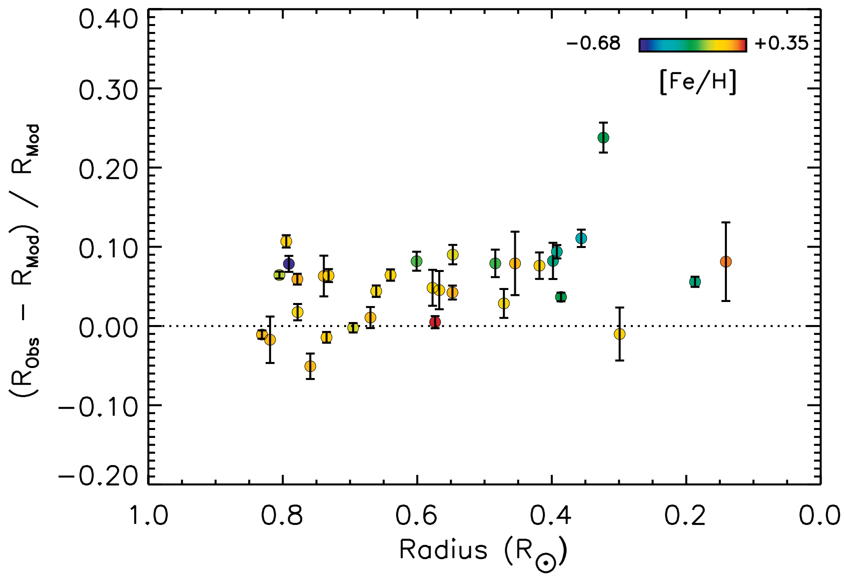

Fig. 1. The measured radii in Boyajian *et al.* (2012) compared to fractional offset with respect to the Dartmouth model isochrones (Dotter *et al.* 2008). Each model was run for the star's observed metallicity with an age of 5 Gyr, where the model radius R_{Mod} is defined to be where the luminosity matches to the observed value.

Feiden & Chaboyer 2012, and references therein). Over recent years, the cause of this discrepancy has been mainly attributed to models not accurately representing the influence of strong magnetic fields – a complicated problem as well as computationally challenging. The radius offset has been observationally tested for correlations in magnetic activity indicators such as H-α emission, X-ray luminosity excess (L_X/L_{Bol}), as well as binary properties such as the orbital period. However, the small number statistics makes any theoretical improvement difficult to robustly implement. Thankfully however, the parameter space is currently being expanded and further populated for low-mass binary star fundamental properties (*e.g.*, Deshpande *et al.* 2013).

However, recent work by Feiden & Chaboyer (2013) has shown that unrealistic magnetic field strengths must be present to account for the observed radius offset. The data for single stars support this conclusion that magnetic fields are not the cause of disagreement. In Boyajian *et al.* (2012), the radii and temperatures of 33 low-mass (single) stars measured with interferometry are presented. They use this data to test the Dartmouth models (Dotter *et al.* 2008) ability to reproduce the observed stellar properties. Figure 1 is a reproduction of a figure from Boyajian *et al.* (2012) showing the fractional residuals of the measured stellar radii compared to model predictions.

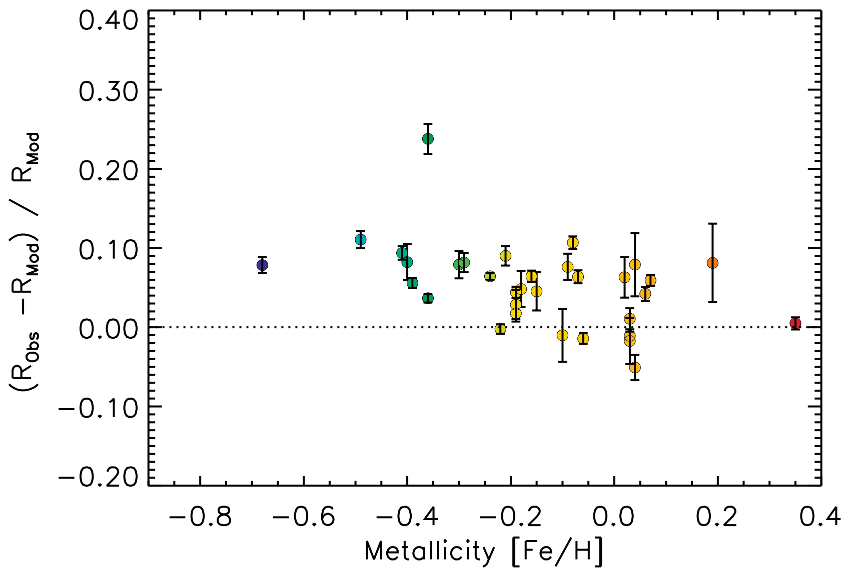

Fig. 2. The fractional offset in radii for stars in Boyajian *et al.* (2012) as a function of stellar metallicity. A possible slight trend is seen for radius offset with respect to metallicity. (The color of the data point is redundant to the stellar metallicity.)

Clearly, the Boyajian *et al.* (2012) analysis of single star radii shows a consistent conclusion as with the binary stars: the observed radius is offset compared to model predictions. However, any correlation proposed by a binary star induced property is not, by definition, applicable for the population of single stars. As such, *any theory to reconcile the radius discrepancy must work for both populations.* The X-ray activity levels for the interferometric sample of single stars are 3 orders of magnitude less than the binaries, they exhibit zero emission in H-α, and, as single stars, orbital period is a meaningless diagnostic.

This is strong supporting evidence that magnetic fields are not the cause to the observed discrepancy. An alternate theory is that the opacity in the model is not perfectly accounted for – creating an offset in the predicted radius with respect to the stellar metallicity. This solution has mainly been proposed to explain the observed discrepancy of low-mass stellar radii in interferometric studies (*e.g.* Berger *et al.* 2006; Boyajian *et al.* 2012). In Figure 2, we show the radius offset of the single stars in Boyajian *et al.* (2012) as a function of metallicity. Unfortunately, measuring metallicity of stars in a binary system is difficult, thus hindering a complementary analysis to support the conclusion within that population. However, new insights from Feiden & Chaboyer (2013) (see their Fig. 3) show that the small amount of data available for eclipsing binaries are consistent with this explanation.

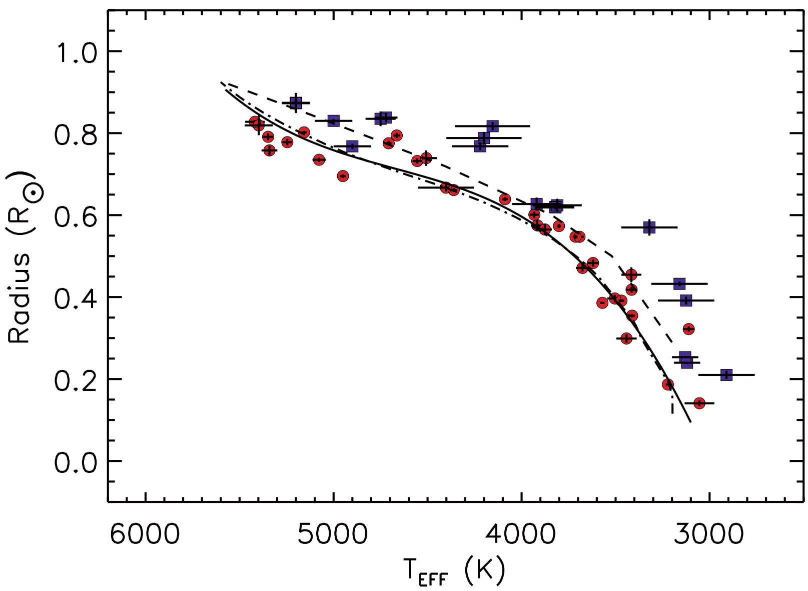

Fig. 3. Plot from Boyajian *et al.* (2012) showing stellar temperature *versus* radius for single stars (red) and detached eclipsing binaries (blue) and the 1-σ measurement errors. Also plotted is the fit to single star properties from Boyajian *et al.* (2012) (solid line), a Dartmouth 5 Gyr solar metallicity isochrone (dot-dashed line), and the tabulated "reference" values from Cox (2000) (dashed line). For details, see Boyajian *et al.* (2012).

5 A need for a new standard analysis: Binary star effective temperatures

As eloquently stated in the recent review by Torres *et al.* (2010): "It is an essentially impossible task to place all the [eclipsing binary] temperature determinations on a consistent – let alone correct – scale". We show in Figure 3 the consequences when careful calibration is not considered in the analysis of binary stars. As discussed in the previous section, the radii of both single and binary stars are offset compared to models, and thus even without a direct comparison, we may assume that their radii are equal. This makes the observed discrepancy of single and binary star parameters shown in Figure 3 entirely attributed to the erroneously derived binary star temperatures. These results impact the community's view of the "nominal" properties of stars as depicted in reference material (*e.g.*, in Allen's Astrophysical Quantities, Cox 2000, dashed line in Fig. 3), and clearly should be used with caution.

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