1 INTRODUCTION

Determining fundamental stellar parameters – masses and radii – is very difficult because the stars are at (quite literally) astronomical distances. With the exception of a handful of nearby objects, we cannot resolve the physical size of stars. Instead, we see them as point sources of light and it is impossible to infer their properties directly. At the same time, knowing these parameters is the foundation of all stellar astrophysics: models of stellar structure and evolution hinge critically on their values (Kippenhahn et al., 2012).

If direct measurement is impossible, how do we get these fundamental stellar parameters? For the select few cases where we *can* resolve the stellar disk, we can use interferometry (Kervella et al., 2017). The stars that we can resolve are the Sun's nearest neighbors, so measuring their distance accurately by the triangulation method is tractable. The measurement of the radius then relies on the angular size provided by interferometry and the known triangulated distance. The measurement errors of interferometric radii are of the order of 5-10% (Torres et al., 2010).

Unfortunately, the accuracy of 5-10% is not good enough for stellar models. In order to truly anchor the evolutionary pathways, we need to get below 1-2%, otherwise we are not able to test *any* fine detail of the models. If, for example, the influence of heavy metal abundance on the predicted stellar luminosity causes a spread by a few percent, then interferometric radii cannot be used to adequately test this influence. This inadequacy is further augmented by the fact that we cannot obtain *any* mass measurements from such observations.

Fortunately, we can do better. Stars typically come in binary and multiple systems ($\sim$60%; Raghavan et al., 2010). Binary stars are systems of two stars orbiting about the mutual center of mass. Their motion is governed by the principal laws of Newtonian mechanics that have been understood for centuries, and depends exclusively on the masses of system components. In favorable circumstances where the orbital plane of a

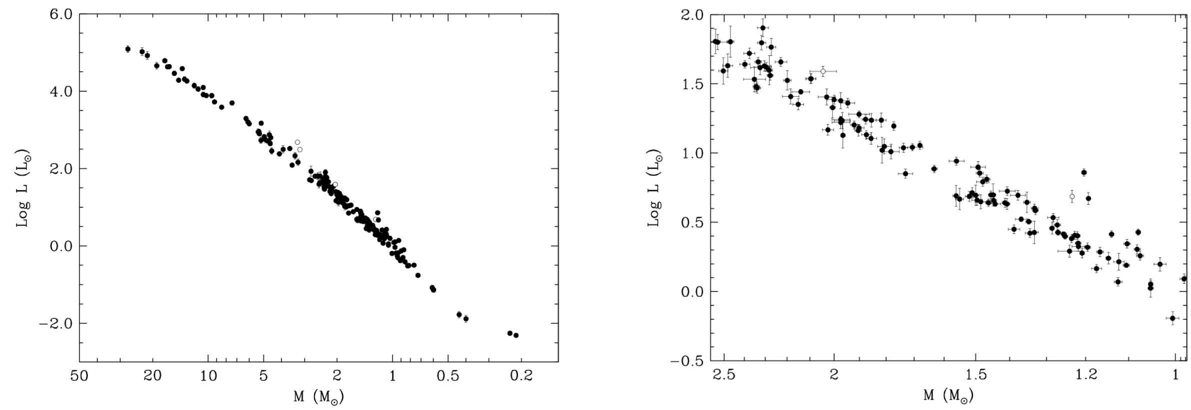

Figure 1: Mass-luminosity relationship derived from eclipsing binary data. The left panel depicts a full range of masses and luminosities, and the uncertainties are (typically) smaller than the size of the symbol. The right panel shows a zoomed-in range where dispersion in the mass-luminosity relationship is evident. Thanks to the small uncertainties from eclipsing binary models, we can conclude that the dispersion is caused by an independent physical phenomenon, in this case the abundance of heavier elements in stars (Torres et al., 2010).

binary star coincides with the line of sight (∼2% of all binary stars), the stars will pass in front of each other as they orbit around the center of mass, causing eclipses. These eclipses depend only on the aspect at which we view the binary star from Earth, and their shapes depend predominantly on the radii and luminosities of individual stars. If the stars are larger, the eclipses will be wider. If a brighter star is behind a fainter star, the eclipse will be deeper. Thus, eclipses serve as tell-tale evidence of the stellar radii and luminosities (Pickering, 1896). The amount of light as a function of time is called a *light curve*. Analyzing eclipsing binary (EB) star light curves provides us with a direct estimation of the component radii and luminosities. Add orbital motion to the mix and we get individual masses as well. Our group developed a de-facto standard for modeling EBs, PHOEBE (Prša et al., 2016), that enables researchers to derive fundamental stellar parameters from eclipsing binary observables to ∼1-2%. To follow up on the example above, Fig. 1 depicts a mass-luminosity diagram where the influence of heavy element abundance can be readily seen and studied.

While fundamental stellar parameters from EBs represent the state of the art, they are limited to the stellar components found in such systems. Astrophysicists are thus on the constant lookout for other types of objects that may provide masses and radii to sufficient accuracy for the models of stellar formation and evolution.

2 AN EMERGING FIELD OF ASTEROSEISMOLOGY

Asteroseismology is the study of internal structures of stars by way of seismic wave propagation observed in power spectra (Aerts et al., 2010). The field acquired its name by analogy with seismology: the study of earthquakes. The methodology is shared across the two fields.

Stars pulsate for many different reasons. They can be sustained by the so-called κ mechanism (Fleischer et al., 1995), where stellar interior opacity for radiative transfer of heat is a strong function of temperature. As the star expands, the blocking layer inside the star cools and becomes more opaque; energy is trapped and the star contracts. As it contracts, the blocking layer heats up and becomes less opaque, enabling energy to escape. Solar-like oscillators are driven by surface convection (Christensen-Dalsgaard & Daeppen, 1992), where the turbulent flow of fluids excites and dampens oscillations. Yet other types of pulsations are caused by convective blocking (Guzik & Kaye, 2000), where the inner edge of a convection zone is sharp and convection timescale is longer than the pulsation timescale, so perturbations grow into large, coherent pulsations.

Depending on the restoring force, pulsations in stars are either pressure (p) modes where the dominant restoring force is the pressure gradient, or gravity (g) modes where the dominant restoring force is buoyancy. Pressure modes are connected with acoustic waves that propagate through gas by compression and decompression, while gravity modes are connected with internal gravity waves that propagate through gas due to a varying buoyancy.

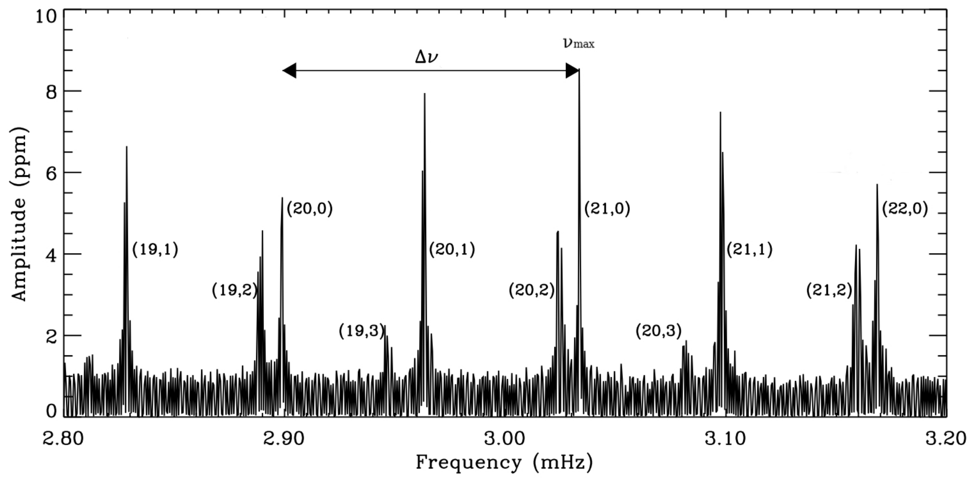

Figure 2: Small section of the solar amplitude spectrum showing (n, l) values for each mode. The large separation $\Delta\nu$ and maximum frequency ν_{max} are indicated. These can be used to infer the mass and the radius of the star using scaling relations. Adapted from Bedding & Kjeldsen (2003).

Pulsations in stars are described by a set of three wavenumbers: radial order n, longitudinal order m and non-radial degree l. Radial order gives the number of nodes between the center and the surface of the star; longitudinal order gives the number of longitudinal node lines; and non-radial degree gives the number of all (longitudinal and latitudinal) node lines. Thus, $l = 0$ modes are radial pulsations, $l = 1$ modes are dipole modes, $l = 2$ are quadrupole modes, etc.

A closer look at the amplitude spectrum reveals regular patterns (cf. Fig. 2). Modes with equal non-radial degree l and radial orders n that differ by 1 are separated by a fixed amount that we call large frequency separation and denote it with $\Delta\nu$. The frequency where the spectrum has the most power is denoted ν_{max}. The identification of the modes is done by comparing the observed power spectrum to theoretical predictions from pulsation codes such as GYRE (Townsend & Teitler, 2013).

These observables – $\Delta\nu$ and ν_{max} – can be directly related to the physical quantities by way of *scaling relations* (Huber et al., 2011):

$$\left(\frac{M}{M_\odot}\right) = \left(\frac{\nu_{\text{max}}}{\nu_{\text{max},\odot}}\right)^3 \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4} \left(\frac{T}{T_\odot}\right)^{3/2}, \tag{1}$$

$$\left(\frac{R}{R_\odot}\right) = \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)\left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2}\left(\frac{T}{T_\odot}\right)^{1/2}. \quad (2)$$

The surface temperatures that appear in these relations can be readily determined from either spectroscopy or from multi-color photometry, so they are straight-forward to obtain. The scaling relations, stemming from the theory of stellar interiors (Kippenhahn et al., 2012), open up a new possibility to obtain fundamental stellar parameters for any star that exhibits such pulsations. The question is, how accurately?

3 THE PROPOSED OBJECTIVE, AND ANTICIPATED SIGNIFICANT OUTCOMES

The number of pulsating stars in EBs is substantial. Kepler alone provided us with over 300 EBs with pulsating components, which constitutes more than 10% of the entire EB sample (Kirk et al., 2016, cf. Fig. 3). We propose to model these EBs using PHOEBE, obtain the masses and radii to 1-2%, compare them to the masses and radii obtained from asteroseismology, and both *validate* and *calibrate* scaling relations for these objects. As discussed before, no other type of object in astronomy can provide this level of validation.

The data-set is already available. The PI is chair of the *Kepler* EB working group and has full access to all data, including radial velocity follow-up for the determination of stellar masses. Significant outcomes of this project include a quantifiable test of the applicability of scaling relations to determine fundamental stellar parameters, and a set of gauge-quality parameters for these objects derived from the EB data.

To execute the project, we will use the in-house tool PHOEBE to model EB data. The project will proceed in the following steps: *(1)* select a subsample of 10 eclipsing binaries with the potential for the highest scientific yield, i.e. high signal-to-noise ratio; non-distorted components; highest $\Delta\nu$ and $\nu_{\max}$ accuracy (3 days); *(2)* gather all available *Kepler* data, follow-up spectroscopic data and any other auxiliary data (2 days); *(3)* model these binaries using PHOEBE to determine masses and radii of pulsating components (15

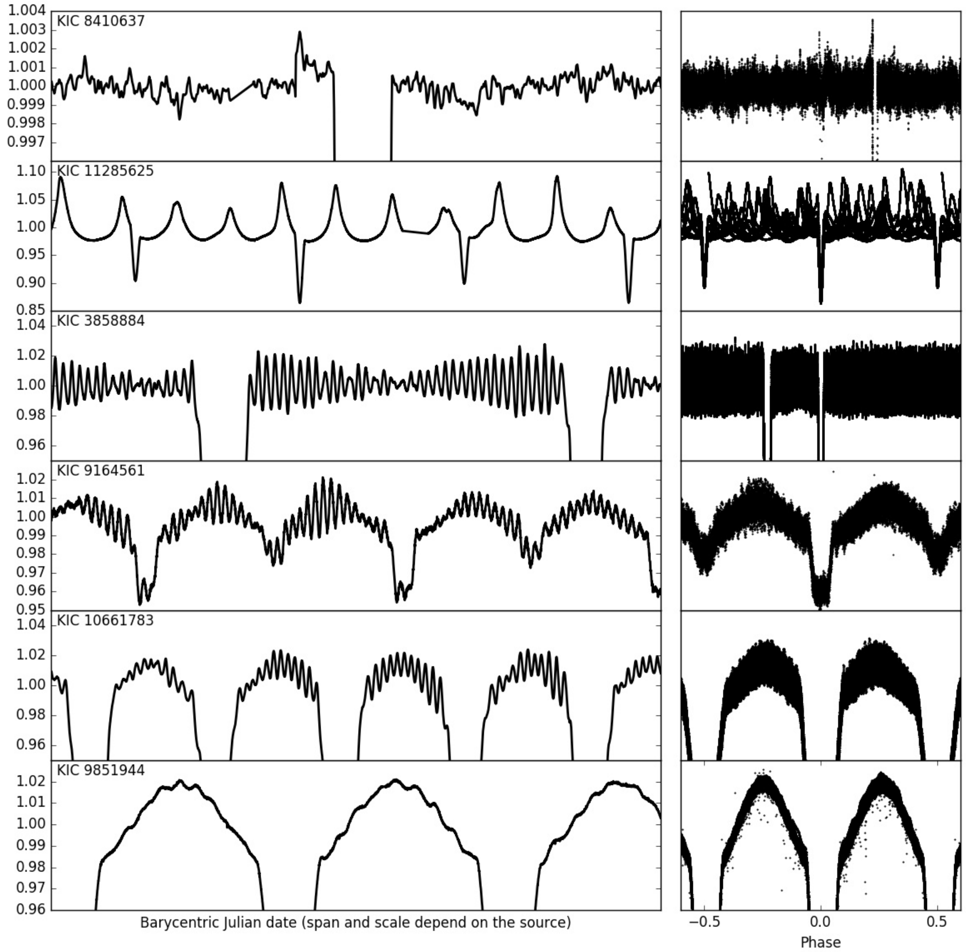

Figure 3: Light curves of several EBs with pulsating components. Left panels depict time sequences and right panels depict phase plots for each object, where time span and scale for time sequences has been chosen for each object individually to highlight the telling part of the light curve. The EBs contain: a red giant exhibiting solar-like oscillations (KIC 8410637), a γ Dor pulsator (KIC 11285625), tidally induced heartbeat star (KIC 3858884), a pre-He-WD pulsator (KIC 9164561), a δ Sct pulsator (KIC 10661783), and a hybrid δ Sct/γ Dor pulsator (KIC 9851944). All data are from the *Kepler* mission.

days); *(4)* compute the predicted masses and radii from scaling relations, and compare them to those determined from EBs (1 day); and *(5)* evaluate the precision of scaling relations and write a publication to disseminate these findings (5 days). The PI's field of expertise is modeling eclipsing binary stars, and this proposal opens a new research direction towards pulsating stars and towards proposals that bridge the two fields.

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