OBSERVATIONAL CONSTRAINTS FROM BINARY STARS ON STELLAR EVOLUTION MODELS

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Abstract. Accurate determinations of masses and radii in binary stars, along with estimates of the effective temperatures, metallicities, and other properties, have long been used to test models of stellar evolution. As might be expected, observational constraints are plentiful for main-sequence stars, although some problems with theory remain even in this regime. Models in other areas of the H-R diagram are considerably less well constrained, or not constrained at all. I summarize the status of the field, and provide examples of how accurate measurements can supply stringent tests of stellar theory, including aspects such as the treatment of convection. I call attention to the apparent failure of current models to match the properties of stars with masses of 1.1–1.7 $\text{M}_\odot$ that are near the point of central hydrogen exhaustion, possibly connected with the simplified treatment of convective core overshooting.

1 Introduction

Stellar evolution theory represents the backbone of much of modern Astrophysics. For decades astronomers have worked to gather observations of many different kinds to constrain and test various physical ingredients of the models, and to calibrate a number of free parameters. These include the helium abundance, mass loss rates, and convective quantities such as the mixing length parameter ($\alpha_{\text{ML}}$) and the amount of overshooting from the convective core ($\alpha_{\text{ov}}$). In the last decade or two, accurate observations have revealed several shortcomings in our knowledge of stellar physics. One example is the difficulty in reproducing the radii and effective temperatures of late-type stars, which are larger and cooler than predicted by current standard models (see, e.g., Torres\textsuperscript{2013a} and also the contribution by Greg Feiden in these Proceedings). Below I will describe another problem that is possibly related to the treatment of convection.

Perhaps one of the best known ways of constraining stellar evolution theory is by means of color-magnitude diagrams (CMDs) of star clusters, which have been

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compared extensively with model isochrones to infer other interesting properties of the clusters such as age, distance, or chemical composition. Comparisons like these are powerful probes of stellar physics, but are not without their difficulties. Contamination of the CMDs by field stars, or unresolved binaries, can complicate or bias the analysis, as can stellar variability and reddening. An additional source of uncertainty is the color-temperature transformations used to convert models from the theoretical plane to the observational plane. The technique of asteroseismology provides very different but highly complementary observational constraints, through the measurement of oscillation frequencies that give us access to properties of the stellar interiors. These are challenging measurements, however, which typically require high-precision, continuous, and long-term observations, and are generally best done in bright stars with luminosities similar to the Sun or higher. A third, important way to test models that is again complementary to the previous two is through the observation of detached binary systems, which enable the model-independent measurement of fundamental stellar properties such as the mass and radius, and also effective temperature, luminosity, etc. While simple in principle, this technique requires special configurations and is not always easy for all types of stars.

In this paper I will focus on how binary stars can help to test aspects of stellar evolution theory. It is useful to begin by reviewing the status of fundamental mass and radius determinations in eclipsing binaries, as recorded in the handful of “critical” reviews that have appeared in the literature. These are compilations that pay special attention not only to the formal precision of the measurements, but also to the quality of the data and the analysis, particularly regarding systematic errors. The first critical review by Popper (1967) listed only two systems with mass determinations (but no radii) having relative errors under 3%. A subsequent compilation by Popper (1980) increased this to 7 systems with masses and radii good to the same accuracy. Andersen (1991) brought the total to 45 systems, and Torres et al. (2010) more than doubled it, to 95 systems. The masses and radii for some of these systems, along with other measured properties, allow for very stringent tests of models, as illustrated in the latter two references. Here I will concentrate on the phenomenon of overshooting from the convective core.

2 Convective core overshooting: how binaries can help

Overshooting can be understood as mixing beyond the boundary of the convective core as given by the classical Schwarzschild (1906) criterion: rising convective elements “overshoot” into the radiative zone. There are a number of important consequences of overshooting that affect the later stages of evolution. Enhanced mixing prolongs core hydrogen burning by feeding more H-rich material into the core. This changes the ages predicted by models. Access to a larger hydrogen reservoir during the H-burning phase enhances the mass of the helium core left behind, and this alters the global characteristics of the giant phases. In particular, it shortens the shell H-burning phase, reduces the lifetime of the core He-burning phase, and affects the luminosities in the giant stages. The effect on the main
sequence portion of the evolutionary tracks in the H-R diagram is to extend the tracks toward cooler temperatures and higher luminosities, as illustrated, e.g., by Schröder et al. (1997). All giant phases occur at higher luminosities than they would without overshooting. For massive stars even the pre-main sequence (PMS) phases are affected, as shown by Marques et al. (2006): the evolutionary track for a 4 $M_\odot$ PMS star develops an extra loop near the zero-age main sequence that is completely absent if overshooting is not considered.

Even though there has been considerable progress in understanding turbulent convection, the sizes of convective cores in stars still cannot be predicted from first principles (VandenBerg et al. 2006). The most common approach in stellar evolution models is to parametrize the effect of overshooting in terms of a single variable representing the length of overshooting as a function of $H_p$, the local pressure scale height: $l_{ov} = \alpha_{ov} H_p$. This formulation is easy to implement, but the overshooting parameter $\alpha_{ov}$ must be calibrated using observations. This can be done in several ways. One is to use CMDs of clusters. In this approach one tries to match the detailed shape and extent of the “blue hook” region by adjusting $\alpha_{ov}$, as illustrated by Demarque et al. (2004). This method works quite well, though it is somewhat vulnerable to the uncertainties mentioned earlier. Another technique takes advantage of accurate measurements of the masses, radii, and temperatures of eclipsing binaries that are near the end of their main-sequence life. It is based on the premise that the likelihood of finding a random field star in the region of the H-R diagram corresponding to the shell H-burning phase is small, because evolution across this so-called “Hertzsprung gap” is very rapid. Therefore, if a star appears to be slightly beyond the point of hydrogen exhaustion as marked by an evolutionary track, it is usually possible to increase the amount of overshooting in the models so that the track “reaches out” to the star, bringing it onto a location still on the main sequence that is a priori much more likely. An example of this procedure is seen in the study of the eclipsing binary GX Gem by Lacy et al. (2008), shown in Figure 1. Caveats are that this procedure can be sensitive to errors in the measured temperatures, and that there is a certain amount of degeneracy with metallicity, if it is not known observationally for the system.

Typical values of $\alpha_{ov}$ are in the range 0.1–0.2. The treatment of overshooting in the transition region where stars begin to develop convective cores (approximately the mass range 1.1–1.7 $M_\odot$) is particularly difficult. The ways in which different models ramp up the overshooting from zero to some maximum value varies from model to model, but they are all rather arbitrary and therefore a source of concern. For example, in the Yonsei-Yale models (Yi et al. 2001) the overshooting parameter is increased in steps of 0.05 starting at some mass value $M_{\text{conv}}^{\text{crit}}$ at which stars develop cores, which is metallicity-dependent. It is then held constant at the value $\alpha_{ov} = 0.2$ for masses above $M_{\text{conv}}^{\text{crit}} + 0.2 M_\odot$ (Demarque et al. 2004). The Victoria-Regina models (VandenBerg et al. 2006) use a somewhat different prescription for overshooting that is equivalent to the single-parameter formalism used in the Yonsei-Yale models, and ramps up the strength of the overshootng in a smoother but different way, which also depends on metallicity.

A persistent question has been whether and exactly how $\alpha_{ov}$ depends on stel-
lar mass. Schröder et al. (1997) used accurate measurements for binary systems containing giant or supergiant primaries to estimate the degree of overshooting in the same way described above over the mass range 2–8 $M_\odot$, and concluded that $\alpha_{ov}$ increases from about 0.2 to 0.3 over this interval. A similar study by Ribas et al. (2000) used eight main-sequence eclipsing binaries with components ranging from 2 to 12 $M_\odot$, and also found a systematic increase in $\alpha_{ov}$, consistent with the previous results. However, the more recent study by Claret (2007) based on a larger number of main-sequence eclipsing binaries (13) with masses between 2 and 30 $M_\odot$ found a much shallower dependence of $\alpha_{ov}$ on mass that is also considerably more uncertain, so the question of the mass dependence of overshooting, if any, remains.

### 3 Constraints on overshooting from the eclipsing binary AQ Ser: indications of a new problem with stellar evolution models

Another illustration of how eclipsing binaries can help to calibrate models is provided by the F-star system AQ Ser, which has component masses of about 1.42 and 1.35 $M_\odot$, and relative errors smaller than 2% in both the masses and radii (Torres et al. 2013b). This is a highly evolved system presumably at the very end of its main-sequence phase, which makes it uniquely sensitive for testing convective core overshooting. A similar exercise as described earlier for GX Gem constrains $\alpha_{ov}$ to be between 0.2 and 0.3 (see Figure 2, left panels), using the Granada stellar evolution models by Claret (2004). However, the models are unable to match the well measured temperature difference between the components ($\Delta T_{\text{eff}} = 90 \pm 20$ K), even in sign: they predict the primary star to be hotter, while the observations indicate the reverse.

This discrepancy manifests itself in other ways, independently of the model con-
Fig. 2. Observations of the eclipsing binary AQ Ser compared with stellar evolution models (figure adapted from Torres et al. 2013b). Left: Mass tracks by Claret (2004) for the primary and secondary components, for a range of overshooting parameters. The best match is near $\alpha_{ov} = 0.3$ for $\text{[Fe/H]} = -0.20$. Top right: Isochrones from the models by VandenBerg et al. (2004), suggesting a satisfactory match for the same metallicity and an age of 2.9 Gyr. However, the predicted locations of the stars for the measured masses, indicated by the asterisks on the best-fit isochrone (solid line), are inconsistent with the observations. Bottom right: Radius and effective temperature as a function of mass, along with calculations from VandenBerg et al. (2004). The models predict a younger age for the primary star.
servations very well for an age of 2.9 Gyr at a metallicity of [Fe/H] = −0.20, and suggest the stars are slightly beyond the point of hydrogen exhaustion. However, the predicted location of the stars on this isochrone from their nominally measured masses, which is indicated with the asterisks, is very far from the actual locations marked by the filled circles and error bars. In other words, the models would predict a mass ratio much closer to unity (q = M2/M1 = 1.00083) than that measured spectroscopically (q = 1.054±0.011). The difference is highly significant, at nearly the 5-σ level. Yet another way to visualize the disagreement is presented in the lower-right panels of Figure 2, particularly in the diagram of radius versus mass. It is seen that the models predict the more massive primary star to be younger than the secondary, by about 0.3 Gyr (10%). Similar discrepancies in the same direction are obtained with the Yonsei-Yale and Granada models (0.45 Gyr and 0.5 Gyr, respectively). Experiments with several different trial values of [Fe/H] in which α_{ov} and also α_{ML} are allowed to vary independently for each star do not improve the age agreement, pointing to a fundamental problem with the models.

As it turns out, similar discrepancies have been reported by Clausen et al. (2010) for a handful similarly evolved F stars: GX Gem, V442 Cyg, BW Aqr, and BK Peg. All yield predicted ages for the primary stars that are younger than the secondaries, no matter which model is used. Two other systems showing the same anomaly have been identified more recently, although the problem was not noted in the original publications: CO And (Lacy et al. 2010) and BF Dra (Lacy et al. 2012).

A common property of these binary systems is that the components all have masses in the range of 1.1–1.7 M_☉, which is precisely where models ramp up the importance of overshooting, and they are all considerably evolved (i.e., near the end of the main-sequence phase). This is also the mass range in which stars transition from having their energy production dominated by the p-p cycle to the CNO cycle. Figure 3 displays all binary systems with well measured properties that have masses in the range indicated above. The shaded area represents the region of the blue hook, according to the Yonsei-Yale models, and an increase in α_{ov} would shift this region upwards. AQ Ser is seen to be the most evolved system in this regime, and is also the one showing the most pronounced discrepancy with theory.

Given that convective core overshooting has a direct impact on evolution timescales, especially for main-sequence stars in the more advanced stages, it is natural to suspect that the simplified treatment of this phenomenon in current stellar models has something to do with their failure to reproduce the observed properties of well-measured eclipsing binaries at a single age. However, from the experiments with AQ Ser described above, the explanation does not appear to be a simple difference in α_{ov} for the two components, and may be more complex. At the very least, it may involve a dependence of overshooting on the state of evolution, in addition to mass and metallicity.

This problem has not received much attention in the literature beyond the work of Clausen et al. (2010), and is a good example of the usefulness of accurate measurements of eclipsing binaries for testing our knowledge of stellar evolution.
Fig. 3. Masses and radii for all eclipsing binaries with accurately known parameters from Torres et al. (2010), supplemented with measurements for CO And (Lacy et al. 2010), BF Dra (Lacy et al. 2012), and AQ Ser (Torres et al. 2013b). The primary and secondary stars in each system are connected with a line. The shaded area corresponds to the blue hook region for solar metallicity, according to the Yonsei-Yale models. The dashed line above it represents the upper envelope of this region for a metallicity of Fe/H = −0.20 that is close to that of AQ Ser, and the dotted line at the bottom corresponds to the zero-age main sequence (ZAMS).

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