The Ages of Stars
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Eclipsing binary stars as tests of stellar evolutionary models and stellar ages

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Abstract. Eclipsing binary stars provide highly accurate measurements of the fundamental physical properties of stars. They therefore serve as stringent tests of the predictions of evolutionary models upon which most stellar age determinations are based. Models generally perform very well in predicting coeval ages for eclipsing binaries with main-sequence components more massive than ≈1.2 M$_\odot$; relative ages are good to ∼5% or better in this mass regime. Low-mass main-sequence stars ($M < 0.8$ M$_\odot$) reveal large discrepancies in the model predicted ages, primarily due to magnetic activity in the observed stars that appears to inhibit convection and likely causes the radii to be 10–20% larger than predicted. In mass-radius diagrams these stars thus appear 50–90% older or younger than they really are. Aside from these activity-related effects, low-mass pre–main-sequence stars at ages ∼1 Myr can also show non-coevality of ∼30% due to star formation effects, however these effects are largely erased after ∼10 Myr.

Keywords. binaries: eclipsing, stars: activity, atmospheres, evolution, formation, fundamental parameters, low-mass, brown dwarfs

1. Introduction

Eclipsing binary stars are one of nature's best laboratories for determining the fundamental physical properties of stars and thus for testing the predictions of theoretical models. Detached, double-lined eclipsing binaries (hereafter EBs) yield direct and accurate measures of the masses, radii, surface gravities, temperatures, and luminosities of the two stars. These are measured directly via combined analysis of multi-band light curves and radial velocity measurements (Wilson & Devinney 1971; Prša & Zwitter 2005).

Knowledge of the distance to the EB is not required, and thus the physical properties of the stars can be measured with exquisite accuracy. As an example, Morales *et al.* (2008) have measured the component masses and radii of the low-mass EB CM Dra (Fig. 1) with an accuracy better than 0.5%, perhaps the most accurate measurements ever made for a low-mass EB. Similar accuracy has been achieved for the high mass β Aur (Southworth *et al.* 2007). Indeed, at this level of precision, a non-negligible contributor to the error budget is the uncertainty on Newton's gravitational constant (Torres & Ribas 2002).

Such high-quality measurements allow the predictions of theoretical models to be rigorously tested. For a main-sequence star of a given mass and metallicity, the radius is a monotonic function of age. Thus the models should assign the same age to the components of an EB (i.e., they should lie on a single model isochrone in, e.g., the M–R plane), assuming that the components formed from the same material at the same time. The apparent difference in age, $\Delta\tau$, of the two components is thus a direct measure of the error in the age calibration of the models. As we now discuss, the accuracy of the age

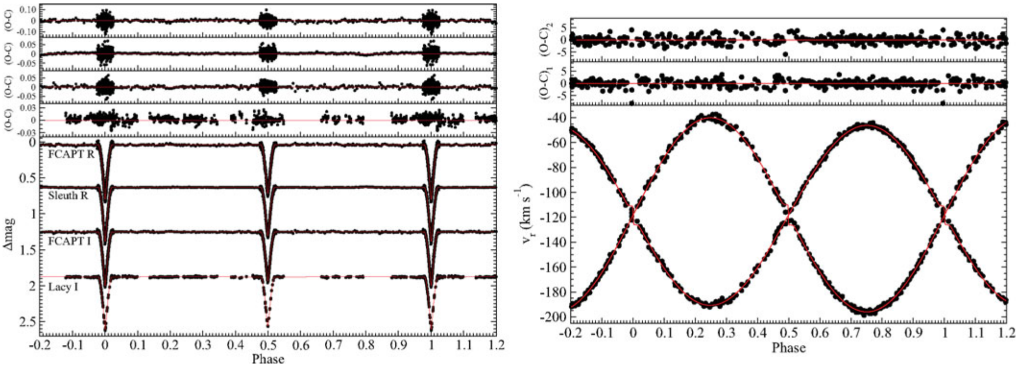

Figure 1. Simultaneous analysis of multi-band light curves (left) and radial velocities (right) of CM Dra by Morales *et al.* (2008). The resulting masses and radii of the stellar components are determined with an accuracy better than 0.5%.

calibration is principally a function of stellar mass, varying from ∼5% for $M > 1.2\ \mathrm{M}_\odot$, to ∼10% for $M \approx 1\ \mathrm{M}_\odot$, to 50–90% for $M < 0.8\ \mathrm{M}_\odot$ (see Table 1).

2. Accuracy of the stellar-age calibration as a function of stellar mass

2.1. *Massive stars ($M > 1.2\ M_\odot$)*

In general, theoretical models perform best in predicting coeval ages in main-sequence EBs with $\mathrm{M} > 1.2\ \mathrm{M}_\odot$. For example, Young & Arnett (2005) have performed a comprehensive re-analysis of the 20 EBs with $22 < \mathrm{M}/\mathrm{M}_\odot < 1.2$ that were included in the seminal review of Andersen (1991). Their TYCHO models incorporate updated abundances and, most importantly, improved treatment of interior-mixing physics such as core convective-overshooting. They find $\Delta\tau < 5\%$ for the typical case and $\Delta\tau < 10\%$ for all of the EBs in their sample.

This excellent performance of the models includes a few EBs near the terminal-age main sequence (TAMS), where the stars are evolving very rapidly toward the red-giant phase and for which any discrepancies in the models are amplified. For example, Fig. 2 shows the case of ξ Phe, a particularly challenging EB with a 2.6 $\mathrm{M}_\odot$ secondary and a 3.9 $\mathrm{M}_\odot$ primary that is leaving the main sequence. An *ad hoc* decrease in the metallicity

Table 1. Accuracy of stellar-age calibrations from eclipsing binaries.

Regime	Accuracy $\Delta\tau^\dagger$	Limiting Physics and/or Data	Exemplar(s)	Refs.
$\mathrm{M} > 1.2\ \mathrm{M}_\odot$	∼5%	modeling of core overshooting, mixing	ξ Phe	1
$\sim 1\ \mathrm{M}_\odot$	∼10%	modeling of convection, activity	CV Boo	2
$< 0.8\ \mathrm{M}_\odot$	50–90%	activity calibration, abundance measurements	V1174 Ori YY Gem V818 Tau V1061 Cyg	3 4 5 6
PMS stars, $\tau < 10$ Myr††	∼50%	star-formation effects (e.g. accretion history)	Par 1802	7

Notes:
[†] Apparent age difference of presumably coeval stellar components. [††] Convolved with mass-dependent effects.
[1] Young & Arnett (2005), [2] Torres *et al.* (2008), [3] Stassun *et al.* (2004), [4,5] Torres & Ribas (2002), [6] Torres *et al.* (2006), [7] Stassun *et al.* (2008)

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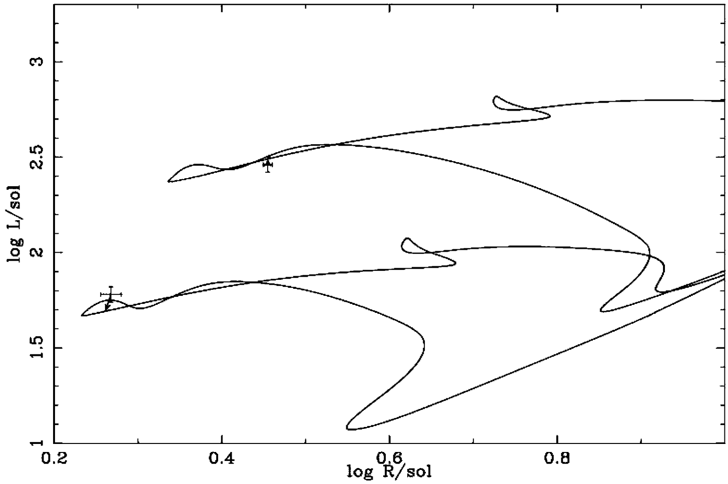

Figure 2. Theoretical evolutionary model fits to the components of the EB ξ Phe by Young & Arnett (2005). This massive, slightly evolved EB is a challenging case, yet even without *ad hoc* adjustments to the fitting parameters achieves $\Delta\tau \approx 3\%$.

of the secondary is required to improve the fit, but even without such an adjustment the fit to both components is marginally acceptable ($\chi^2_\nu \approx 4$) and has $\Delta\tau \approx 3\%$.

2.2. *Solar-mass stars ($M \approx 1\ M_\odot$)*

At masses of approximately 1 $M_\odot$, the theoretical models begin to show larger systematic discrepancies in the predicted ages. A good example is CV Boo, an old main-sequence EB with component masses of 1.03 and 0.97 $M_\odot$ (Torres *et al.* 2008). The primary shows evidence for having entered the H shell-burning stage, for which the predicted model age of 8 Gyr is in good agreement (Fig. 3). However, the secondary appears to be 25% older due to its radius being ~10% larger than predicted by the 8 Gyr isochrone. The oversized radius of the secondary is likely due to its magnetic activity (see §3).

Of course, the Sun is the only star for which an absolute age can be determined directly (e.g., chemical dating of meteorites). While the Sun's physical properties can be matched to better than 1% at the solar age by models that incorporate all of the observational constraints (including, e.g., helioseismology), the Sun's age cannot be predicted to better than ~7% if given only its observed mass, radius, temperature, and metallicity (Young & Arnett 2005). This is likely to be the best absolute accuracy that can be achieved with current models applied to EBs with a similar set of observational constraints.

2.3. *Low-mass stars ($\mathrm{M} < 0.8\mathrm{M}_\odot$)*

The past several years have seen rapid progress in the number of low-mass EBs that have been discovered and their components analyzed. A consistent finding among these studies is that the observed stellar radii are 10–20% larger than predicted by the models. For example, López-Morales (2007) and Ribas *et al.* (2008) have compiled the literature data for low-mass EBs with $0.2 < \mathrm{M}/\mathrm{M}_\odot < 0.8$. They find that in virtually all cases the theoretical main-sequence predicts radii smaller than those observed (Fig. 4). These oversized radii make the stars appear 50–90% older or younger than expected (depending on whether post– or pre–main-sequence models are used; see also Fig. 3).

Importantly, there are now several low-mass EBs for which there exist independent age constraints (e.g., YY Gem, V818 Tau, V1061 Cyg), and in these systems the same age discrepancies are verified (Fig. 5). A few EBs in young open clusters have also been

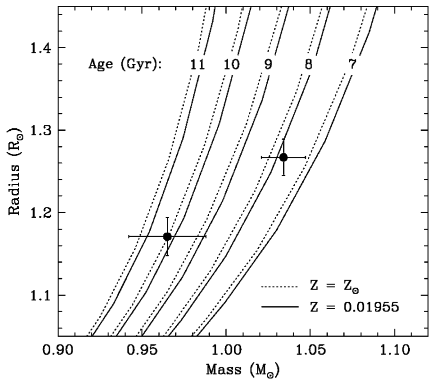

Figure 3. Theoretical evolutionary model fits to the components of the EB CV Boo by Torres *et al.* (2008). The active secondary of this solar-mass system is 10% larger than predicted by the 8 Gyr model isochrone, leading to a large age discrepancy, $\Delta\tau \approx 25\%$, between the components.

found (e.g. Hebb *et al.* 2006; Southworth *et al.* 2004), again verifying these trends. More EBs such as these with independent age determinations are very much needed.

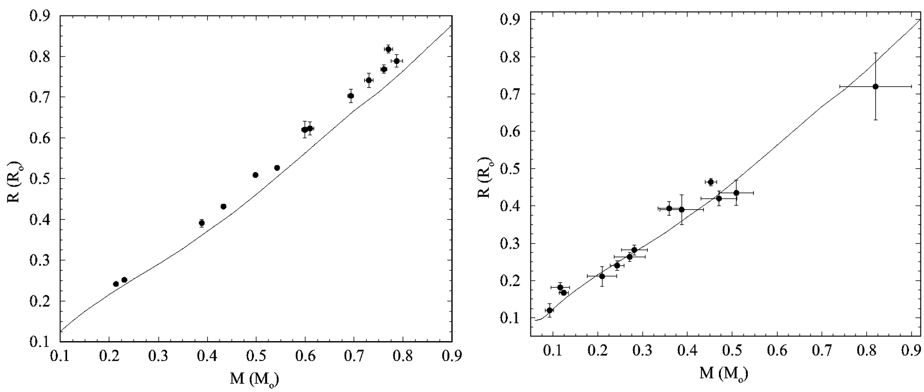

Figure 4. *Left:* Compilation of low-mass EB measurements, showing that the observed radii of these active stars are systematically larger, by 10–20%, than predicted. The solid line is a 1 Gyr isochrone from the models of Baraffe *et al.* (1998). *Right:* Same, but for single-lined EBs, which are effectively single stars from the standpoint of tidal effects which may induce activity. These inactive stars' radii agree much better with predictions. Note that the masses of single-lined EBs are model dependent and hence less accurate. Adapted from Ribas *et al.* (2008).

3. The effect of activity in low-mass stars

There is now very good evidence that the unexpectedly large radii of low-mass EBs is related directly or indirectly to magnetic activity on these stars. Several of the authors who published the original analyses of low-mass EBs had noted that the stars showing larger-than-predicted radii also show evidence for activity, in the form of Hα emission, X-rays, spot-modulated light curves, and other tracers.

More recently, López-Morales (2007) has demonstrated the relationship explicitly (Fig. 6). This is very good news, not only because it points clearly to an underlying cause for the observed oversized radii, but also because the tight correlation with X-ray luminosity suggests that this effect can be calibrated and the ages corrected. Indeed, single-lined EBs—which can be regarded as effectively single stars and which are thus

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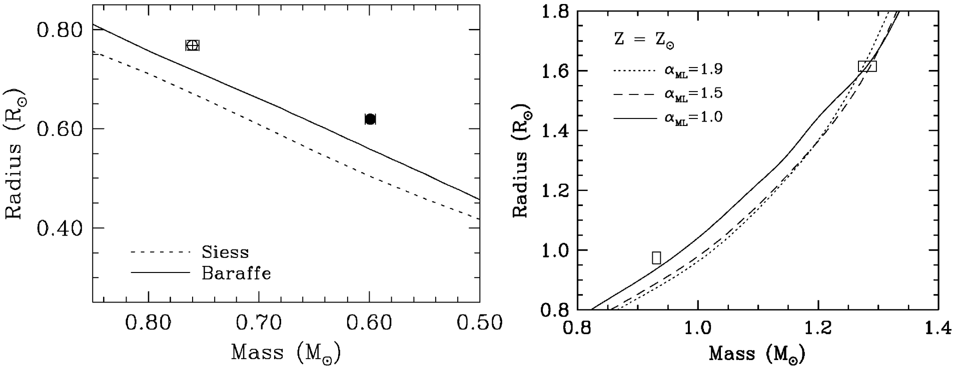

Figure 5. *Left:* Oversized radii are confirmed for the active, low-mass components of the EBs YY Gem (filled) and V818 Tau (open), for which independent age estimates have been made from their membership in young comoving groups. Adapted from Torres & Ribas (2002). *Right:* The components of V1061 Cyg are compared with isochrones from Baraffe *et al.* (1998) with different values of the convective mixing length, α. The oversized radius of the low-mass secondary requires suppressed convection (small value of α). Adapted from Torres *et al.* (2006).

less likely to have magnetic activity driven through interactions with a companion—do not show systematically oversized radii (Fig. 4, right).

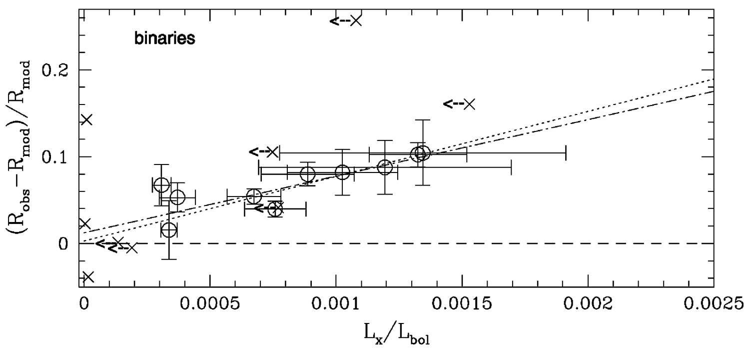

Figure 6. Correlation between X-ray luminosity and fractional discrepancy between measured and predicted radii for low-mass eclipsing binaries. Adapted from López-Morales (2007).

In addition, recent modeling that incorporates the effects of magnetically suppressed convection in low-mass stars due to magnetically active surfaces is now able to fit the observed oversized radii of active EBs extremely well (Fig. 7). In addition, these models simultaneously can explain the systematically low values of the effective temperatures of these stars.

In these new models, strong magnetic fields cause a suppression of convection near the surface. Heat flow to the surface is inhibited (by analogy to dark sunspots on the Sun), resulting in a decrease in the star's effective temperature. However, the star's overall luminosity is roughly fixed by internal processes far removed from the surface boundary condition, and thus the star's radius adjusts to a larger size in order to radiate the flux.

It should be stressed that at present these models use parametrizations of surface spots and of suppressed convection, in place of a full physical treatment of convection and surface fields. Even so, several additional lines of evidence corroborate this general picture. First, the observed properties of young, low-mass EBs are in general best fit by model isochrones with low convective efficiency, $\alpha \sim 1$ (e.g. Mathieu *et al.* 2007).

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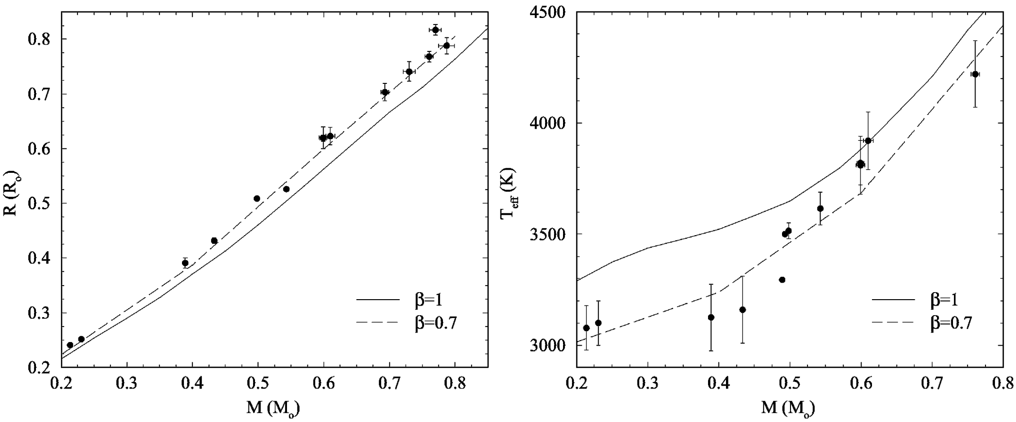

Figure 7. Model isochrones (Chabrier *et al.* 2007) incorporating activity in low-mass stars. *Left:* Oversized radii of active, low-mass EBs are well fit by a 1 Gyr isochrone from Baraffe *et al.* (1998) adopting a spot-covering fraction of 0.3 (i.e. 70% of the stellar surface is free of spots). *Right:* Same, but for effective temperature. Adapted from Ribas *et al.* (2008).

Second, the observed surface lithium abundances of young, low-mass EBs clearly indicate weak convective mixing (e.g. Stassun *et al.* 2004). Third, analyses of low-mass EBs have found that indeed the luminosities of the stars are in good agreement with the models even when the radii and temperatures are very discrepant. For example, in the brown-dwarf EB 2M0535–05 (Stassun *et al.* 2006), the brown dwarfs display ∼10% oversized radii, and the temperature of the very active primary (Reiners *et al.* 2007) has been so severely suppressed that it is in fact cooler than the lower-mass secondary. However, the luminosities remain in good agreement with model predictions for brown dwarfs at an age of ∼1 Myr (Stassun *et al.* 2007).

Finally, these findings have implications for low-mass stars more generally. First, because activity has the effect of decreasing the effective temperature but leaving the luminosity relatively unaffected, we can expect to see these stars scattered horizontally in the H-R diagram. Second, these effects will need to be taken into account when deriving ages from other means, such as age-activity relations and surface lithium abundances.

4. Star-formation effects at very young ages

Testing the accuracy of stellar evolutionary models via the $\Delta\tau$ test, as we have done above, assumes that EBs represent *coeval* systems of two stars that formed from the same material at the same time. Indeed, in many cases, this assumption of the coevality of EB components has been used to calibrate the various input parameters of the evolutionary tracks. For example, Young & Arnett (2005) have adjusted model parameters such as core overshooting, and have determined secondary stellar properties such as metallicities, on the basis of requiring that the evolutionary tracks yield the same model ages for the two stars of an EB. Similarly, Luhman (1999) has adjusted the temperature scale of young, low-mass stars on the basis of requiring that pre–main-sequence evolutionary tracks yield coeval ages for the components of pre–main-sequence binaries.

We now have evidence that, in at least some cases, the components of very young binaries may not in fact be strictly coeval. In particular, Par 1802 is a recently discovered EB in the Orion Nebula, with a mean age of ∼1 Myr, whose components are identical in mass to within 2% ($M_1 = M_2 = 0.41\ M_\odot$; Stassun *et al.* 2008). Having the same mass,

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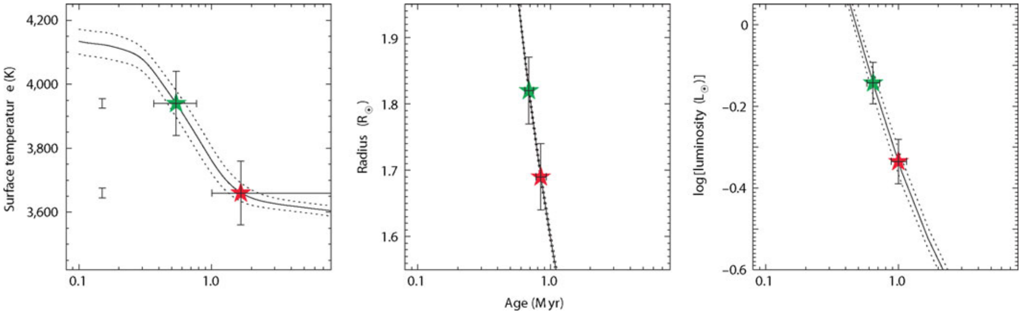

Figure 8. Comparison of physical properties of Par 1802 with theoretical predictions. In each panel, the solid line shows the predicted evolution of a 0.41 $M_\odot$ star from the models of D'Antona & Mazzitelli (1997). Dotted lines show the result of changing the stellar mass by the 0.015 $M_\odot$ uncertainty in the measured masses. Vertical error bars on the points represent the combination of measurement and systematic uncertainties. Horizontal error bars represent the range of ages for which the theoretical models are consistent with the measurements within the uncertainties (including systematic uncertainties). Note that the uncertainties in the temperatures, radii and luminosities are not independent between the two stars, because they are connected by precisely determined ratios; thus, for example, the primary star cannot be forced cooler while simultaneously forcing the secondary warmer. The nominal age of the Orion nebula cluster in which this EB is found is ~1 Myr. Adapted from Stassun *et al.* (2008).

these 'identical twin' stars are predicted by the models to have identical temperatures, radii, and luminosities. However, the components of Par 1802 are found to have different temperatures ($\Delta T \approx 300$K, or about 10%), radii that differ by 5%, and luminosities that differ by a factor of ~2 (Fig. 8). These surprising dissimilarities between the two stars can be interpreted as a difference in age of $\Delta\tau$~30%. It has been speculated that this age difference likely reflects differences in the star-formation history of the two stars, differences that may be specific to binary-star formation (Simon *et al.* (2009)).

Unfortunately, if such non-coevality turns out to be a common feature of young binaries, then Par 1802 suggests that using very young EBs to calibrate the evolutionary model ages may be limited to ~30% accuracy. Fortunately, these effects are largely erased after ~10 Myr. For example, Stempels *et al.* (2007) find that the components of ASAS J052821+0338.5, a solar-mass EB with an age of 12 Myr, are coeval to $\Delta\tau \sim 10\%$.

5. The future of eclipsing binaries with large surveys

The central importance of EBs for stellar-age determinations implies an ongoing need for precise and accurate EB data. As sky surveys are gaining on both precision and diversity, and since more and more medium size observatories are being refurbished into fully robotic telescopes, there is a "fire-hose" of photometric and spectroscopic data coming our way. Methods to reduce and analyze the data thus cannot rely on manual labor any longer; rather, automatic approaches must be devised to face the challenge of sheer data quantity. Pioneering efforts of automating the analysis of survey data by several groups, most notably Wyithe & Wilson (2001, 2002), Wyrzykowski *et al.* (2003), Devor (2005), and Tamuz *et al.* (2006). These are reviewed in Prša & Zwitter (2007).

A recent stab at automation is implemented within the Eclipsing Binaries via Artificial Intelligence project (EBAI; Prša *et al.* 2008). A back-propagating neural network is applied as a non-linear regression tool that maps EB light curves onto a subset of parameter space that is sensitive to photometric data. Its performance has been thoroughly tested on detached EB light curves (Fig. 9) and applied successfully to OGLE data. In a matter of seconds, the network is able to provide principal parameters of tens of thousands of EBs. The results that come from such an engine may be readily used to select those EBs that are most interesting for the studies of stellar formation and evolution. Given the number of surveys, we are talking thousands of interesting EBs! Since our understanding relies on these systems, such a disproportionate jump in data quantity will surely provide further insights and enhance the statistical significance of our results.

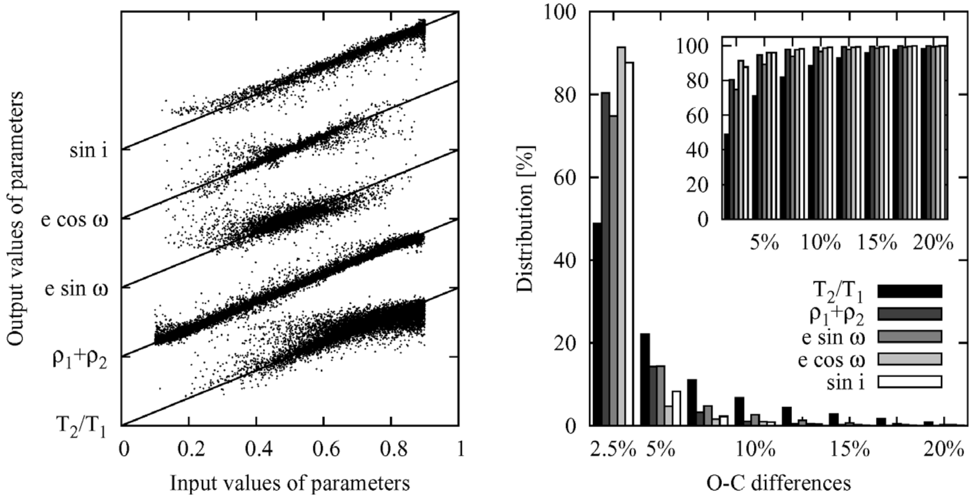

Figure 9. Neural-network recognition performance on 10,000 detached EB light curves. *Left:* comparison between input and output values of parameters. *Right:* distribution of differences (main panel) and their cumulative distribution (inset). Adapted from Prša *et al.* (2008).

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Discussion

E. Jensen: If the effects of stellar activity can be corrected for, what other effects are then the next most important for obtaining agreement between models and data?

K. Stassun: The next most important effect is metallicity. There are relatively few EBs for which a good, independent, metallicity constraint is available. In part this is because of the complexity of disentangling multiple-component spectra, but such techniques are improving. Another issue is that the surface abundances of many EBs may be complicated by rapid rotation and activity. In this respect, EBs that are associated with a cluster are ideal, as metallicities can be determined from the other stars.

M. Pinsonneault: Spot filling-factors can produce blocking at about the expected level, but one expects a smaller impact for fully convective stars. Is this observed?

K. Stassun: The recent models of Chabrier *et al.* (2007) indeed use large spot covering-fractions, but critically it is also important to invoke less efficient convection ($\alpha \sim 1$). Probably these effects are inter-related through the strong surface fields that drive activity. The observations do not support a strong dependence of the fractional radius discrepancy on mass; fully-convective stars (all the way down to the brown-dwarf eclipsing binary) show oversized radii of $\sim$10%. On the other hand, the degree of radius discrepancy does correlate very well with activity level.

L. Hillenbrand: You mentioned evidence for a 50% age spread in pre-MS binaries younger than 10 Myr. Can you give a "35 second" version of the evidence for this claim?

K. Stassun: Thank you for the excellent question. (I will give you your $20 for asking this question later.) The evidence is that in Par 1802 (a $\sim$1 Myr-old EB in Orion) the component stars have masses that are identical to about 2%, yet their temperatures differ by 10%, the radii differ by 5%, and the luminosities differ by 50%. These surprising differences can be explained if one component is a few times 10^5 yr older than its companion (see Stassun *et al.* 2008).

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