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The New Era of Eclipsing Binary Research with Large Telescopes

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Abstract. The advent of larger telescopes and powerful instrumentation enables the exploration of new aspects of faint eclipsing binaries that are just now becoming accessible. An example of this are eclipsing binaries in Local Group galaxies such as the LMC, SMC, M31 and M33, whose study yields not only stellar properties of stars formed in different chemical environments (thus providing useful model tests) but also direct distance determinations to the host galaxies. In general this is also applicable to eclipsing binaries belonging to any stellar ensemble. Another example is the observation and study of eclipsing very-low mass stars, brown dwarfs and planets. Besides the need for large telescopes because of their faintness, these also benefit from improved observational capabilities in the infrared spectral windows. Here we discuss the prospects for eclipsing binary research using photometry and spectroscopy from large telescopes.

Keywords. binaries: eclipsing – stars: distances – stars: low-mass, brown dwarfs – stars: magnetic fields – distance scale

1. Introduction

Eclipsing binary (EB) research has made a strong impact on stellar astrophysics for over a century. The high-accuracy stellar properties that result from their study have greatly contributed to our understanding of stellar structure and evolution in a broad range of masses, evolutionary stages and chemical compositions. But, in addition, EBs have also played a role in many other aspects, such as close binary evolution, accretion physics, stellar atmospheres, etc (see Ribas 2006a for a review). For most of this research, observational data have been collected using small- to moderate-size telescopes because the EB systems studied are generally bright. In recent times, the increasing instrumental capabilities and telescope sizes have expanded the horizons to the study of faint EBs and made it possible to address new topics that had been beyond reach.

Classical EB work uses, in general, data in three different flavors: *1)* Multi-band time-series photometry in the form of light curves; *2)* Time-series spectroscopy to build a radial velocity curve; and *3)* Standard photometry or spectrophotometry. It is only from the combined analysis of these datasets that a full characterization of the EB system, including orbital and physical properties (M, R, L, $T_{\rm eff}$, $[Fe/H]$), is possible. In the case of time-series photometry, this was carried out mostly with photomultipliers until some 15 years ago, when CCDs became widely available and greatly increased the capabilities and efficiency of small telescopes. However, the accuracy reachable by CCDs was poorer than that of photoelectric detectors (typically 0.01–0.015 mag vs. a few mmag). This has remained true until recently, when the flawless cosmetics and improved stability of CCDs have greatly enhanced their performance. Also, sophisticated analysis techniques, such as optimal image subtraction (Alard & Lupton 1998), have made it possible for time-series CCD photometry to reach the 1 mmag level (see, e.g., Moutou *et al.* 2004).

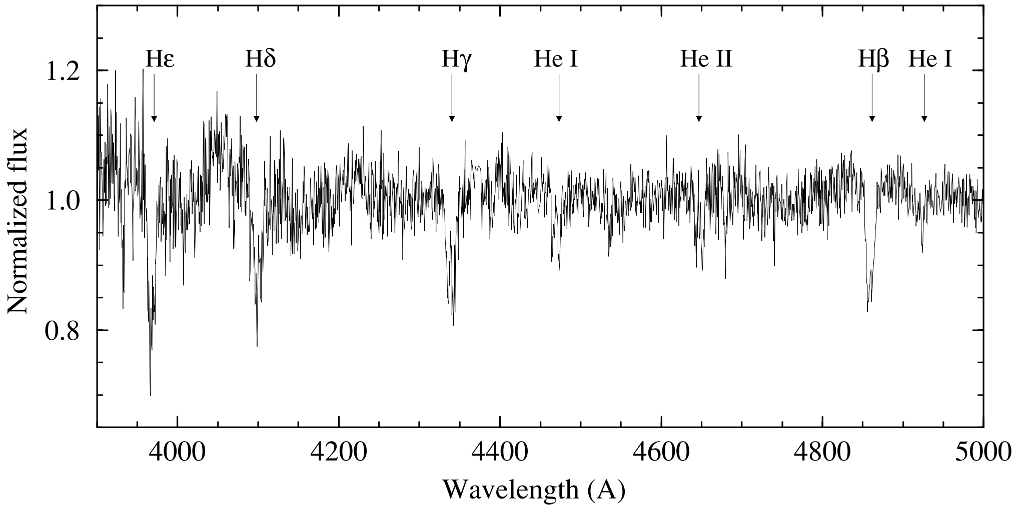

Figure 1. Spectrum of an EB target in M31 ($V = 19.3$ mag) obtained with the GMOS instrument of Gemini-N with a 1 hour integration. The average S/N of the spectrum is 15.

In general, EB photometry work is carried out with relatively small telescopes. To serve as a reference, good light curves of EBs of 14–15th mag can be obtained with a 1–1.5-m telescope, while 2.5–4-m telescopes can reach down to 19–20th mag. Obviously, these numbers depend on the length of the possible integrations and therefore on the orbital period of the binary. Much larger apertures are needed in the case of spectroscopy. Stars of 14–15th mag require 4–6-m telescopes and stars of 19–20th mag require today's largest 8–10-m telescopes, and even then, low spectral resolution has to be used to attain reasonable S/N values. The spectrum in Figure 1, obtained using a combination of a 8-m telescope (Gemini-N) and a high-throughput spectrograph (GMOS) illustrates this latter fact. A 1-hour exposure with a relatively low resolution of 3800 yielded a spectrum with a S/N of $\sim$15 for an EB target of visual magnitude 19.3.

In view of the numbers above, large telescopes are needed to study EBs in case these are intrinsically faint (such as low-mass stars or degenerates), are in highly absorbed lines of sight, are located at large distances or when there is some need for very high angular or time resolution. Also, it is true that new instrument developments and resources will be focused in years to come on large facilities. In spite of the strong competition, there are a number of EB projects that are being successful in obtaining precious large telescope time. In general, such success is related to the impact of the proposed research not only in understanding an individual object but in a broader area of Astrophysics. Studies making significant contributions to stellar structure and evolution, accretion physics or with cosmological implications stand the best chances. Also, it is important to point out that the instrumentation available in large telescope is not always perfectly suitable for stellar work (e.g., often only low resolution modes are available in spectrographs), a fact that requires adapting of the science goals and target selection to maximize the outcome.

Some examples of EB projects where the use of large telescopes make a difference will be discussed next. Basically, these are EBs in stellar ensembles (and, particularly, the Local Group galaxies) or EBs with components of very low mass, such as M-type stars, brown dwarfs or even planets.

2. Eclipsing Binaries in Stellar Ensembles

EBs provide simultaneous determinations of stellar masses and radii to an accuracy potentially better than a few percent, and these have been used for decades to better understand stellar structure and evolution (Pols *et al.* 1997; Ribas *et al.* 2000a). As a consequence of the full characterization of the system components, EBs provide determinations of the distances, which can be also as accurate as a few percent (see Clausen 2004 for a review). In case an EB system belongs to a stellar ensemble, its relevance is automatically enhanced. First, it provides much better and demanding tests of stellar models thanks to the age and chemical composition constraints, but also because of the added value of a distance measurement. Such stellar ensembles include open and globular clusters, star-forming regions, wide binaries, the Galactic bulge, and Local Group galaxies.

As discussed above, different datasets are needed to analyze EBs and, in particular, systems in stellar ensembles. Photometry requires arguably the larger investment of observing time, but can use relatively small telescopes. The single-target observing mode was the standard one until the mid/late 1990s, when the results of massive photometric surveys became available. Such surveys, consisting of calibrated time-series photometry, were designed to detect microlensing events and were focused on the Galactic bulge and the Large and Small Magellanic Clouds (LMC and SMC) (EROS: Grison *et al.* 1995; MACHO: Alcock *et al.* 1997; OGLE: Udalski *et al.* 1998, Wyrzykowski *et al.* 2003). But the legacy of the surveys goes beyond microlensing and they have provided phenomenal databases of photometry of variable stars, in particular EBs. As a result, the number of known EBs has increased ten-fold. However, it has to be noted that such observations were not tailored to be of use to EB research and therefore they have some shortcomings, most notably, the use of just one or two passbands. More recently, there have been specific surveys aimed at the detection of EBs in Local Group galaxies (Bonanos *et al.* 2003; Vilardell *et al.* 2006) and in a number of galactic open and globular clusters that have reported hundreds of new systems. It seems, therefore, that the availability of photometric data is not the limiting factor to the analysis of EBs in stellar ensembles.

The situation with spectroscopy is completely different. As we have mentioned before, the study of the faint targets detected by the microlensing surveys mostly requires large telescope time. This is certainly the bottleneck to a full determination of their properties, although new instrumentation with multi-object spectrographs are due to change the situation in the next several years. Note, however, that spectroscopy may not be the only way to extract scientifically valuable information from the survey EB data. Several groups (e.g., Tamuz *et al.* 2006; Devor & Charbonneau 2006) are developing codes for massive modeling of time-series photometry of EBs with very encouraging results.

Focusing on large telescopes, there are a number of examples illustrating their contribution to the characterization of EBs. Starting with Galactic systems, globular clusters pose very interesting cases to the study of their member EBs, from the point of view of distance and age determination and also to investigate stars formed in a very low metallicity environment. The CASE (Cluster AgeS Experiment) project illustrates the science case and the observational requirements of the study of EBs in globular clusters (see Kaluzny *et al.* 2005). Young open clusters also provide very interesting objects to analyze. Indeed, the the open cluster Westerlund 2 contains the Wolf-Rayet binary WR20a, whose component masses were determined to be 83 and 82 $M_{\odot}$ from spectroscopy using the NTT 3.5-m telescope and SOFI (Rauw *et al.* 2004). This binary holds the honor of being composed by the stars with the highest masses measured directly so far (Bonanos

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et al. 2004). Other stars are thought to have larger masses (such as the Pistol star or η Car), but these have been inferred through model comparisons.

A further step in distance leads to the Local Group galaxies. Our nearest neighbors, the LMC and SMC, with today several thousand EBs, have been the subject of spectroscopic studies for over a decade. Some of the brightest EBs can be measured spectroscopically with 1–2-m class telescopes (e.g., Niemela & Bassino 1994), but accurate work requires 3.5 to 4-m telescopes. This is the case of the LMC targets of Guinan *et al.* (1998), Fitzpatrick *et al.* (2002, 2003) and Ribas *et al.* (2002), whose magnitudes are between 14 and 15, and were observed with the 4-m Blanco telescope at CTIO. In contrast, the approach taken by Harris *et al.* (2003) and Hilditch *et al.* (2005) to study SMC EBs is quite different. They sacrificed spectral resolution but gained enormously in overall efficiency by using the 2dF spectrograph on the AAT 3.5-m telescope, which was indeed specially designed for Cosmology (galaxy redshifts). In this manner, the authors managed to measure radial velocity curves for a relatively large number of systems (50) with a quite modest investment of time.

The main driver behind studying EBs in Local Group galaxies has been the determination of the Cosmic Distance Scale. This was mainly motivated by the controversy in the late 1990s over the true distance to the LMC. Competing groups claimed distance values differing by over 20% (the so-called "long" and "short" distance scales) and this had direct consequences on the overall distance scale and, in particular, on the value of the Hubble constant, of clear cosmological implications. The analysis of EB systems permits the determination of the absolute radii of their components and also their temperatures, which, when combined with the fluxes observed from Earth, yield an accurate determination of the distance (e.g., Clausen 2004). The study of EBs, together with the improvement of other techniques, has helped to clear out the situation and converge towards an LMC distance value of 48.0–48.5 kpc (e.g., Macri et al. 2006), which is somewhat shorter than the canonical value of 50 kpc.

Recent further improvements in instrumental capabilities has allowed for the study of EBs in even more distant Local Group galaxies: M31 and M33. Photometric surveys with 2-m class telescopes (Bonanos *et al.* 2004; Vilardell *et al.* 2006) have provided hundreds of new EB systems in these galaxies. Spectroscopic studies, much more demanding for such objects of magnitudes 19–20, have also been carried out with success for two EB systems, one in M31 (Ribas *et al.* 2005) and one in M33 (Bonanos *et al.* 2006), using the GMOS instrument at the 8-m Gemini-N telescope. A more detailed discussion of EBs in Local Group galaxies and their implications to the Cosmic Distance Scale is provided by Bonanos (this volume). Challenges for the future include reaching to fainter magnitudes to avoid dealing with the hottest systems of each Local Group galaxy. As is well known, reliable determination of temperatures for the O- and early B-type stars is still an open issue. In the case of the LMC/SMC the solution is already in hand since late B-type EB pairs would have magnitudes of about 17–18 and these can be observed spectroscopically using 6–8-m class telescopes. The study of EBs with components of $\sim$15000-K, whose temperature scale is considerably better defined, will provide a final check of the current results and the ultimate determination of the distances to the Magellanic Clouds.

But Local Group EB systems are much more valuable than just accurate distance indicators. Decades of work has shown that EBs constitute excellent benchmarks to test stellar structure and evolution models. The extension of this to binaries in the Local Group, which have been formed in environments with a chemical history differing from that of the solar neighborhood, is the true legacy of the efforts to study these objects. A conspicuous example is the LMC EB HV 2274, which was used to assess the impact of convective overshoot in the evolution of high-mass stars with sub-solar metal abundance

(Ribas *et al.* 2000b). The same idea could be applied to SMC EBs. In this case, their metallicity is about 1/10th solar and could act as laboratories to study high-mass stars that existed long ago in our Galaxy before the enrichment of the interstellar medium. Research in this direction should become quite active in the near future once accurate stellar properties are available for a sizable sample of EBs in Local Group galaxies.

Finally, the Local Group galaxies are also home to some particular types of EB systems that have no counterparts in the Milky Way. This is the case of EBs with component stars of type Cepheid or RR Lyr. Such systems are truly "Rosetta stones" for stellar Astrophysics. On the one hand, they could provide a direct calibration of the most widely used extragalactic distance indicators. And, on the other hand, their study would yield the fundamental properties of these variable stars and thus constrain their structure and evolution. The MACHO and OGLE projects identified three EB systems in the LMC with Cepheid components (Welch *et al.* 1999; Udalski et al. 1999; Alcock *et al.* 2002). Unfortunately, none of the Cepheid components seems to be a fundamental mode pulsator, being overtone, W Vir and unclassified. Further analysis of their light curves (Lepischak *et al.* 2004) has helped to clarify the nature of some of the companions, while spectroscopic observations taken with HST – and currently under analysis (Guinan *et al.* 2005) – should provide better constraints on the fundamental properties of these systems. In addition, the OGLE team has identified three RR Lyrae variables that are members of EB systems (Soszynski *et al.* 2003). Close inspection reveals that probably only one of them is a true EB system with the other ones being likely blends. Surprisingly, little has been done to further study these important objects and exploit their potential.

3. Eclipsing Binaries with Low-Mass Components

The other end of the Main Sequence, i.e., the realm of very low mass stars, also profits very much from the use of large telescopes. In spite of being the most numerous stellar population in the Galaxy, the faintness of these stars hinders careful study. Recent efforts, both observational and theoretical, have greatly contributed to a better understanding of the individual and overall properties of low-mass stars (see Henry, this volume). However, it is still important to carry out stringent tests to stellar structure models by constraining the maximum number of observables. In one of such efforts, Torres & Ribas (2002) analyzed the M-type EB YY Gem (Castor C). Tight constraints on the age and chemical composition of the system could be obtained from their more massive companions Castor A and B. Coming as a surprise, the detailed comparison of the fundamental properties of the components with the predictions of state-of-the-art stellar models revealed very significant differences. Models predicted stellar radii some 10–20% smaller than observed and effective temperatures some 3–5% hotter.

Stemming from the results for YY Gem, the interest in the field has raised and a number of surveys and detailed studies have contributed to increasing the sample of EBs with low-mass components, with the ultimate goal being the improvement of the statistical significance of the possible differences between observation and theory. It is revealing to note that until 2002 the number of EBs with late-K and M-type components and well-determined physical properties was only 2, in 2003 came the third, the number had gone up to 6 in 2005 and we now have almost a dozen EBs with such low-mass components (and more keep coming). The reason for this increase, apart from the growing interest, has been the availability of larger telescopes and more powerful instrumentation. Most of these EB systems have visual magnitudes in the range 13–16 and even fainter. Currently, the faintest system studied, with a visual magnitude of 19.3, is a member of the open cluster NGC 1647 and might contain the star with the lowest mass in a double-lined EB

(Hebb *et al.* 2006). Because of this faintness, some of the resulting physical properties still lack sufficient accuracy to perform a critical test to stellar models, but continuing efforts will decrease the current error bars.

Interestingly, planetary transit searches have also contributed to research on low-mass EBs. Follow-up using the 8.2-m VLT of OGLE planetary transit candidates has uncovered a number of eclipsing systems consisting of main sequence F-G stars with M dwarf companions (Bouchy *et al.* 2005; Pont *et al.* 2005). Because of selection effects, their light curves have shallow and flat-bottom eclipses corresponding to the transit of the M-type star (the occultation not observable). Also, only the lines of the F-G components are visible in the spectra due to the large contrast. These restrictions imply that the masses and radii of the M-type stars have to be determined through different assumptions (some of which are model dependent). For the 11 objects studied thus far the resulting accuracies are in the range 5–20% and therefore do not provide very stringent tests on models.

So, where are we now with respect to the contrast between observation and theory? As a matter of fact, the new additions to the list of low-mass stars with accurately determined physical properties has done nothing but confirm the mismatch observed for YY Gem. The mass-radius plot now covers almost the entire realm of late-K and M-type stars (0.8–0.2 $M_\odot$), as shown in Figure 2. Represented are the mass and radius measurements for 22 components of EB stars, which are: 2MASS J05162881+2607387 A&B (Bayless & Orosz 2006), V818 Tau B (Torres & Ribas 2002), RXJ0239.1-1028 A&B (López-Morales & Shaw 2006), GU Boo A&B (López-Morales & Ribas 2005), YY Gem AB (Torres & Ribas 2002), NSVS01031772 A&B (López-Morales *et al.* 2006), UNSW-TR-2 A&B (Young et al. 2006), TrES-Her0-07621 A&B (Creevey *et al.* 2005), 2MASS J04463285+1901432 A&B (Hebb *et al.* 2006), BW3 V38 A&B (Maceroni & Montalbán 2004), CU Cnc A&B (Ribas 2003), and CM Dra A&B (Lacy 1977; Metcalfe *et al.* 1996).

As can be seen in Figure 2, stars tend to fall systematically above the theoretical line, leaving no doubt that a significant discrepancy exists between models and observations with regards to stellar radii. On average, the observed values are some 10% larger than those predicted by theory. Other detailed comparisons have also shown that the stellar effective temperatures appear to be overestimated by ∼5%. This, together with the good agreement in the mass-luminosity plot (see Henry, this volume), argues in favor of a scenario in which the stars have larger radius and cooler temperature than predicted by models but just in the right proportions to yield identical luminosities. A sensible hypothesis to explain the discrepancy is the effect of magnetic activity (Ribas 2006b). The close EB systems observed so far have orbital periods below 2.8 days and their components are forced to spin in orbital sync. The resulting high rotational velocities (10–60 km s^{-1}) give rise to a very efficient dynamo and thus enhance phenomena related to magnetic activity. The significant spot areal coverage observed in these eclipsing systems has the effect of lowering the overall photospheric temperature, which the star compensates by increasing its radius to conserve the total radiative flux. But also, the supposedly strong magnetic fields may change the heat transport efficiency in the stellar envelope and also alter the structure of the stars (Mullan & MacDonald 2001). Ongoing efforts, both observational and theoretical, are due to resolve this issue and yield a better understanding of these small but numerous stars.

Recently, EB research gave a further very important step down in mass. Stassun *et al.* (2006) reported the detection of a remarkable EB with brown dwarf components. The system is a member of the Orion Nebula star forming region and therefore has a very young age of about 1 Myr. Because of its youth, these 0.054 and 0.034-$M_\odot$ brown dwarfs have radii that are more akin to those of stars (0.67 and 0.51 $R_\odot$, respectively), which improves the chances for the occurrence of eclipses. Photometric observations of this system,

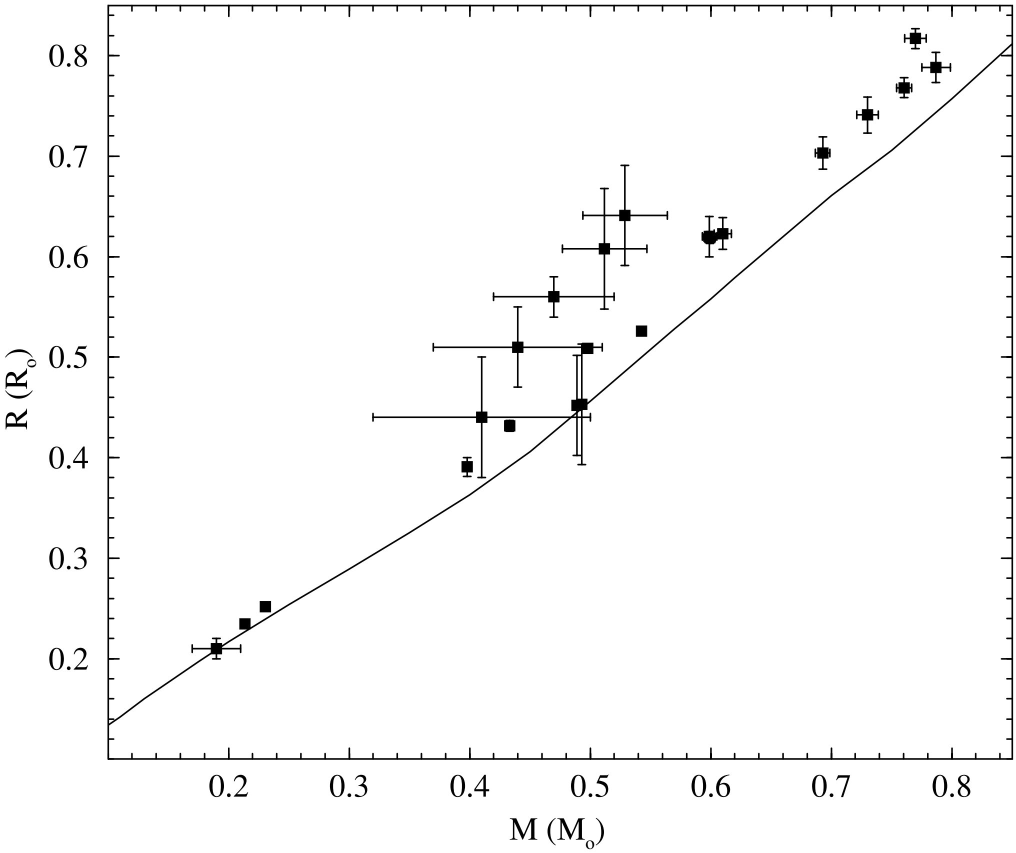

Figure 2. Mass-radius plot for EB stars with components of masses below 0.8 $M_\odot$. The solid line represents a theoretical 300 Myr isochrone calculated with the Baraffe *et al.* (1998) models.

with $V \approx 19.5$ mag, were carried out with 1-m class telescopes and the corresponding spectroscopy for radial velocities was obtained from the 8-m Gemini-S telescope. Detailed comparison of the observed properties with model predictions is still pending, but Stassun *et al.* (2006) find a reversed temperature ratio in the sense that the more massive component is also cooler. This would be a surprising result and in contradiction with theoretical expectations, but it still needs to be further confirmed.

Strictly speaking, transiting planets are just particular examples of EB systems and provide the final step down in mass. Some 12 planets have been found to date to transit the disk of their parent stars (see Bakos *et al.* 2007 for the full list). In all cases, confirmation of the planetary nature requires spectroscopic observations and these are obtained with the largest facilities available (8-10-m class telescopes). With their accurately measured masses and radii and the increasing statistical significance of the sample some surprises became evident. It was the first transiting exoplanet that already rose a red flag. Indeed, the mean density of the planet (which could be computed directly) turned out to be significantly smaller than that of Jupiter and in disagreement with the predictions of models. The additional 11 transiting planets detected have done nothing but confirm an unsuspected variety of physical properties in an otherwise quite homogeneous group of objects. The densities of the exoplanets detected cover values varying over a factor of 3 (see figure 6 in Bakos *et al.* 2007). Different scenarios involving irradiation, core sizes or evaporation are currently being investigated, but such dispersion in the intrinsic properties is still not understood.

4. Conclusions

Here we have shown several examples of studies related to EBs that require the use of large facilities. These were grouped in two classes, namely EBs in stellar ensembles, in which the faintness of the targets is due to the long distance, and EBs with low-mass components, in which the instrinsic low luminosity of the objects makes the use of large telescopes necessary. But there are other areas that will also have great importance. As opposed to the "classical" techniques discussed here, there are many aspects that are being and will be exploited, e.g., asteroseismology, Dopper tomography, high-precision/rapid photometry (e.g., eclipse mapping), interferometry (visual & spectroscopic binaries) and the opening of other windows such as the infrared. Some of these areas are discussed within this volume. It is also interesting to note that *all* examples shown here require the use of both large and small telescopes (spectroscopy vs. photometry). Thus, EB research constitutes a vivid example of the need to preserve also telescopes of smaller sizes to carry out high-quality and high-impact science.

The largest telescopes today are in the 10-m class but the next decade will witness the arrival of even larger telescopes in the 30–50-m range. The examples shown in this paper prove that EB research can be successful in competing against other scientific areas in obtaining large telescope time. The use of strong science cases, addressing topics of broad impact to Astrophysics and Cosmology, will ensure good prospects for research using EBs in an era in which most resources are likely to be put in large facilities.

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Discussion

Juan Manuel Echevarría: YY Gem is a milestone on the lower end of the M-R diagram. Since the models are not in agreement with the observations, can there be any room for error in the observations?

Ribas: The same disagreement between models and observations of YY Gem has also been found in all low-mass eclipsing binaries observed to date. In contrast, eclipsing binaries with components of higher mass are in good accord with the prediction of models. Since the techniques used to determine the masses and radii of the stars are independent of mass, systematic errors in the analysis could not explain the observed discrepancies.

Jonathan Devor: To skim the best candidates one can find (for followup) software such as MECI to measure the masses of EB's components.