Binaries as Astrophysical Laboratories: Open Questions

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Abstract. Binary systems have long been recognized as the source of powerful astrophysical diagnostics. Among the many applications of binary stars, they have been used as probes of stellar structure and evolution (both of single and binary stars) in a broad range of masses, evolutionary stages, and chemical compositions, and as indicators of distance and time. With the numerous ongoing photometric surveys and upcoming space astrometry and photometry missions, the future of binaries looks bright. The various aspects of binaries as astrophysically useful laboratories are reviewed here, with emphasis on the currently open problems and research opportunities.

1. Introduction

Any star that belongs to a binary system becomes automatically more valuable. There are several characteristics that make stars orbiting each other especially noteworthy. For example, the orbital motion of a binary system makes it possible to directly determine the fundamental properties of the component stars to high accuracy. Stellar masses can be determined from radial velocities and/or direct astrometric measurements. Furthermore, if the binary system happens to have an orbital inclination close to 90 degrees, the components undergo mutual eclipses and the resulting light curve yields direct measurements of the stellar radii. The high-precision stellar properties from the analysis of binary stars constitute a very useful dataset to carry out stringent tests of stellar models. But also binaries have been successfully used as indicators of distance and time.

Binaries themselves are very interesting subjects of study. For example, tidal interactions or mass accretion alter the orbital properties and the evolution of stars in binary systems and provide valuable insight into the physical laws that govern those processes. In addition, binary systems can be associated with energetic phenomena such as cataclysmic binaries and X-ray binaries, and are the progenitors of objects of strong astrophysical interest such as novae, supernovae, gamma-ray bursters, etc. Calculations also indicate that double degenerate systems will be strong sources of gravitational waves, which is a new area of research that is bound to acquire great relevance.

In the era of surveys, binary systems with photometric variability (especially eclipsing binaries) are being reported by the thousands. But even larger numbers (millions) are expected in the next decade. Here I review some of the applications of binaries as astrophysical laboratories with special focus on the questions that
remain open in the different subjects. These open questions can equally be regarded as opportunities for research with well defined objectives.

2. Binaries as probes of stellar structure and evolution

The aim of stellar structure and evolution models is to produce a physically sound description of the interior of stars and thus a realistic picture of their evolution (as a function of the initial mass and chemical composition). Obviously, a direct view of the stellar interior is very difficult to obtain (except for measurements using asteroseismology) but theoretical models make predictions about the macroscopic properties of the stars, such as temperatures, masses, radii, densities, etc, that can be and need to be tested against observations. The comparison of model predictions with observations is more stringent when the number of free parameters is very small or null. Models will pass the test only if they are able to reproduce all of the observed stellar properties given the available constraints. Detached eclipsing binary stars, with their accurate determinations of their absolute dimensions, provide the best tests of stellar models (see, e.g., the thorough review by Andersen [1991]). The detached restriction is set to guarantee that the components of the binary system have evolved as single stars.

In this section, I review the comparison of binary star data with theoretical models. To do so, the section has been subdivided to cover high-mass and low-mass stars in the main sequence, which are subject to different physical mechanisms and thus have different issues. Also, this section addresses the use of binaries to study the extended atmospheres of cool stars (either evolved or in the main sequence), and briefly some of the open problems in a “new” and popular type of binary/multiple system: planetary systems.

2.1. High-mass stars

High-mass stars are very important for many astrophysical processes, e.g., emission of ionizing radiation, chemical evolution of the galaxy, energetic phenomena. Thus, a good characterization of their evolution off the zero-age main sequence (ZAMS) is of central importance to understand all subsequent processes. There are several physical mechanisms that acquire great relevance when modeling the evolution of high-mass stars. Convection parameters, rotation effects and mass loss are some of them. In particular, it is worth pointing out that our current theoretical description of convection is still rather crude and, although there have been advances in other directions (Canuto & Mazzitelli [1991]), the parametric and phenomenological mixing-length theory (Böhm-Vitense [1958]) is still widely used (e.g., Straka, Demarque, & Guenther [2005]). The main two parameters in the mixing-length theory are the mixing-length parameter, which is usually determined by comparison between the observed and predicted solar radius, and the convective overshoot parameter, which is more difficult to assess.

Convective overshoot in the stellar core basically modifies its size and has the observable effect of expanding the duration of the main sequence phase. The effect becomes more prominent with increasing mass of the star. Overshoot is often parameterized by the value $\alpha_{\text{ov}}$, which is the extension of the core size beyond the Schwarzschild boundary in units of the pressure scale height. A
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possible way to estimate the convective overshoot parameter is the study of the observational color-magnitude diagram of young clusters. Such studies (e.g., Prather & Demarque 1974; Maeder & Mermilliod 1981; Pols et al. 1998) have proved that convective overshoot is relevant and that the location of the terminal age main sequence of several young clusters is best described by a convective overshoot parameter \( \alpha_{ov} \) of about 0.25.

The high-accuracy stellar fundamental properties of detached eclipsing binaries were used by Andersen, Clausen, & Nordström (1990) to also place constraints on the amount of core overshoot. More recently, studies using larger samples of eclipsing binaries (Pols et al. 1997; Ribas et al. 2000a; Lastennet & Valls-Gabaud 2002) have confirmed the need for convective overshoot in the amount of \( \alpha_{ov} \sim 0.25 \) for stars of intermediate masses (1.5–3 M\(_{\odot}\)). However, two studies have further suggested the existence of an increase in the amount of core overshoot with stellar mass. Using binary systems with one or both component in an evolved stage (core helium burning phase), Schröder, Pols, & Eggleton (1997) found a value of \( \alpha_{ov} \sim 0.24 \) for 2.5-M\(_{\odot}\) stars slightly increasing to \( \sim 0.32 \) for 6.5-M\(_{\odot}\) stars. Ribas, Jordi, & Giménez (2000b) find that the overshooting parameter may increase up to \( \alpha_{ov} \sim 0.6 \) for stars of \( \sim 10–12 \) M\(_{\odot}\). This latter result is based on the analysis of the eclipsing binary V380 Cyg by Guinan et al. (2000) and it is worth reviewing the main points of the study here.

V380 Cyg may be the prototypical case of a stellar astrophysical laboratory. This eclipsing system is composed of two B-type stars of similar temperature but different evolutionary stages. The more massive component (\( M \sim 11 \) M\(_{\odot}\)) has a low surface gravity of \( \log g = 3.15 \) while the secondary component (\( M \sim 7 \) M\(_{\odot}\)) has barely left the ZAMS (\( \log g = 4.13 \)). The temperatures and metallicity of the system components could be determined to high accuracy from the fit of the spectral energy distribution in the UV/optical. The very unequal positions of the components in the HR diagram makes this system highly discriminant when testing the performance of evolutionary models. This fact is illustrated in Fig. which depicts a \( T_{\text{eff}} - \log g \) diagram with the components and evolutionary tracks (kindly computed by A. Claret using the prescriptions in Claret 1995) with different amounts of convective overshoot. As can be seen, the secondary component’s position is weakly influenced by overshooting and thus fixes the amount of helium in the models (which is treated as a free parameter). With the metallicity, helium abundance, \( \log g \) and \( T_{\text{eff}} \) of the primary component known, there are no degrees of freedom left in the comparison with models other than the value of the overshooting parameter. In this case, it is concluded that the physical properties of the primary are only reproduced for a high overshooting parameter of \( \alpha_{ov} \sim 0.6 \).

But V380 Cyg has the added value of being in an eccentric orbit and the existence of old timings makes it possible to measure an apsidal motion period of about 1500 yr. The rate of apsidal motion is directly related to the internal concentration of the star (i.e., ratio of mean to central density). Therefore, this provides a further independent check to stellar models since the amount of convective overshoot is correlated with the size of the stellar core and thus with the internal concentration of the star. As shown by Guinan et al. (2000), the apsidal motion test also suggests an overshooting parameter of \( \alpha_{ov} \sim 0.6 \).
A major step forward in the understanding of core overshoot came with the asteroseismological study of Aerts et al. (2003). The analysis of long time-series photometry of the 9 $M_\odot$ star HD 129929 led to the conclusion that the best match of the models to the observed frequencies occurs for an overshooting parameter of $\alpha_{ov} = 0.10 \pm 0.05$. How can the V380 Cyg result and this one, both apparently robust, be reconciled? No definitive answer is available yet. A possible clue could be the effect of stellar rotation. The primary component of V380 Cyg has a rotational velocity of about 100 km s$^{-1}$ while HD 129929 only rotates at 2 km s$^{-1}$. Rotation can have a similar effect to convective overshoot on the evolution of star in the sense that it alters the duration of the main sequence phase. The analysis of V380 Cyg is not able to discriminate between core overshoot and rotation. Thus, the conclusions can be reformulated to say that the observations indicate a larger convective core than predicted by the standard models by 0.6 times the pressure scale height. In view of the results for HD 129929, perhaps the extra core size has a small contribution from convective overshoot and a larger one from rotation.

In any case, most of the information on convective overshoot for massive stars hinges on the analysis of just two stars. High-mass eclipsing binaries with
evolved and unequal components will provide additional clues to help resolve the current issues and improve our theoretical modelling efforts.

2.2. Low-mass stars

A large fraction of the stars in the Galaxy have masses well below that of the Sun. In spite of the shear numbers, detailed investigations of the properties of low-mass stars have been hampered by their intrinsic faintness. The observation and study of low-mass stars is now experiencing a rapid development because of the increasing number of deep photometric surveys and the advent of powerful instrumentation able to obtain spectroscopy of these faint stars. But also renewed interest arises from one of the "hot topics" of this past decade: exoplanets. Low mass stars, brown dwarfs, and giant planets share many physical characteristics and their study and modeling is closely related.

Current stellar structure models of low mass stars have reached a high level sophistication and maturity (e.g., Chabrier & Baraffe 2000; Chabrier et al. 2005). However, theoretical progress has not been matched by observational developments because of the difficulty in obtaining accurate determinations of the physical properties of low-mass stars. The best source of such high-quality stellar properties comes from the analysis of double-lined EBs with detached components. For decades only two bona-fide EBs with M-type components were known: The member of the Castor multiple system YY Gem (Leung & Schneider 1978; Torres & Ribas 2002) and CM Dra (Lacy 1977; Metcalfe et al. 1996). Recently, Delfosse et al. (1999) reported the discovery of eclipses in the CU Cnc and Ribas (2003) carried out accurate determinations of the components' physical properties. Three additional new M-type EBs have been studied in detail. These are BW3 V38 (Maceroni & Montalbán 2004), TrES-Her0-07621 (Creevey et al. 2005), and GU Boo (López-Morales & Ribas 2005). Unfortunately, the quality of the available observations for BW3 V38 and TrES-Her0-07621 does not permit high-accuracy determinations of both masses and radii but GU Boo has well-determined physical properties that make it twin system of YY Gem.

Unfortunately, the number of known low-mass EB systems is still small because of the faintness of the stars and the often strong intrinsic variations due to magnetic activity. Another source of potentially accurate data is the observation of visual binaries and the direct measurement of the component radii using interferometry. Although there has been significant progress in this direction – and more is expected in the coming years, – the accuracy reached (Lane, Boden, & Kulkarni 2001; Ségransan et al. 2003) is not yet quite sufficient to place stringent constraints on the models. Fundamental properties of low-mass stars have also resulted from follow-up observations of OGLE transit candidates (Bouchy et al. 2005; Pont et al. 2003). However, the determinations are model-dependent to some extent and the accuracy is significantly lower than that resulting from double-lined EBs.

The best stellar data from double-lined EBs offer an excellent opportunity to carry out critical tests to evaluate the performance of low-mass stellar models. Such tests have been carried out by a number of authors in the past (Poppel 1997; Clausen et al. 1993; Torres & Ribas 2002; Ribas 2003), who have systematically pointed out a (rather serious) discrepancy between the stellar radii predicted by theory and the observations. Model calculations appear to
underestimate stellar radii by \( \sim 10\% \), which is a highly significant difference given the observational uncertainties. This is clearly illustrated in Fig. 2 which shows a mass-radius diagram for M-type EBs with accurate parameters \((\sigma < 3\%)\). Also included in the plot are the two K-type EBs V818 Tau (Torres & Ribas 2002) and RXJ0239.1-1028 (López-Morales et al., in prep.).

In addition to the radius discrepancy, other detailed comparisons have also shown that the stellar effective temperatures appear to be overestimated by \( \sim 5\% \). Complementary, the mass-luminosity plot (Delfosse et al. 2000) seems to be well reproduced by theoretical models (especially in the K-band, where the effect of starspots is small). All the evidence together seems to argue 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. The reason for such apparent coincidence is yet to be understood. A possible explanation for the discrepancy between models and observations may found in the effects of stellar activity, which close binaries experience strongly because they are forced to spin up in orbital synchronism. The larger radii and lower temperatures could be a reflex of such enhanced activity. Perhaps a significant spot areal coverage has the effect of lowering the overall photospheric
temperature, which the star compensates by increasing its radius to conserve the total radiative flux. A more detailed discussion is provided in Ribas (2005) and similar arguments have been used by Torres et al. (2005) to explain discrepancies observed in higher-mass stars.

The conclusion is that current models may only applicable to inactive stars, but this is a severe shortcoming since low-mass stars of relatively young ages are known to be very active. In any case, the discussion above illustrates that open problems still exist at the most basic levels, i.e., even in the description of the masses and radii of stars. More observations (leading to improved statistics) and further refinements in the theory of stellar interiors (including the effects of magnetic fields) will be needed to settle the current issues and achieve a full understanding of the properties of low mass stars of all ages.

2.3. Cool star atmospheres

There are certain evolutionary pathways that lead to binary systems with components of very unequal temperatures. This is the case of post-common envelope or post-mass transfer systems with a late-type star and a hot white dwarf or subdwarf. Especially interesting in terms of their astrophysical value are eclipsing systems such as the renowned Hyades binary V471 Tau (Nelson & Young 1970) or FF Aqr (Dworetsky et al. 1977). There are also detached eclipsing binary pairs, known as ζ Aur systems (e.g., Wright 1970), composed of a massive star that has evolved into a cool supergiant and a hot, less massive companion that still remains in the main sequence.

The study of these stars, with components in very different evolutionary stages and with large contrasts in temperature and radius, provides valuable information on stellar evolution and mass transfer. However, most of the interest in these systems has been driven by the possibility of using the hot component as a probe of the atmosphere and circumstellar environment of the cool companion. For example, International Ultraviolet Explorer spectra of the eclipse ingress and egress phases in V471 Tau were used by Guinan et al. (1986) to detect prominence-like structures in the atmosphere of the K-type component. In the case of ζ Aur systems, an illustration of their use to address questions related to mass loss in supergiant stars was provided by Che, Hempe, & Reimers (1983). Although it may seem that continued efforts for over two decades should have resolved all lingering issues, this is actually not the case. As discussed very recently by Harper et al. (2005), many aspects of the mechanisms responsible for mass loss in evolved supergiant stars are still poorly known, such as for example, the wind acceleration. Further studies of ζ Aur binary systems, in the UV, optical and radio domains, should help to shed new light on the currently open questions.

2.4. Planetary systems

Much interest has raised the discovery of exoplanets during the past decade. The quest for new planetary systems beyond our own is so appealing and has such social impact that is becoming one of the major goals of national funding agencies and the driving force of a large community of scientists. But seen in perspective, this “new” field is not much different from the “classical” binary studies in the sense that it uses the same techniques (radial velocity curves and
Figure 3. Mass-radius diagram of all currently known transiting exoplanets (filled circles) and the Solar System planets Jupiter and Saturn (open squares). Also represented are isodensity lines for various density values.

Using radial velocity and transit techniques, different groups have now reported some 170 planets (see the updated list at www.obspm.fr/planets). Much can be learned about planetary formation and evolution from the analysis of the distribution of planets as a function of different orbital and physical parameters with the increasing statistical significance of the sample (e.g., Marcy et al. 2005). For example, new concepts such as orbital migration have emerged in recent years to explain the presence of gaseous giant planets at close orbital distances. But a specially valuable source of information is that of transiting planets, in which case the actual mass (not just $M \sin i$) and the actual radius can be measured. A surprise came already with the first transiting planet reported (HD 209458 b; Charbonneau et al. 2000, Henry et al. 2000). The measured radius and mass resulted in a planet with a density significantly lower than that of Jupiter. Many models have been put forward to explain such large radius: irradiation from the host star (e.g., Chabrier et al. 2004), core size (e.g., Laughlin et al. 2005b), or tidal heating (Bodenheimer, Lin, & Mardling 2001; Bodenheimer, Laughlin, & Lin 2003). Although the latter explanation has been ruled out from observations of null orbital eccentricity (Deming et al. 2005; Laughlin et al. 2005a).

The sample of transiting exoplanets has now increased to 9 and the mass-radius diagram in Fig. 3 shows a large variety of planetary densities (differences of up to a factor of 3). This is surprising since the planets detected so far constitute a rather homogeneous group, with similar orbital distances, similar host
stars, etc. Different scenarios involving, irradiation, core sizes or evaporation are currently being investigated, but such dispersion in the intrinsic properties of otherwise quite similar planets still defies explanation.

3. **Binaries as distance and time indicators**

Besides providing tests of stellar models, binaries have also been successfully used as indicators. Most notably, visual binaries and eclipsing binaries have proved to yield reliable distances potentially accurate to a few percent. A particularly interesting case is when the binary system belongs to a larger structure, such as an open cluster or galaxy, and its distance can be used to estimate that of the host cluster or galaxy. On the other hand, the strict periodicity of the orbital motion of binary stars can be used to search for further orbiting companions via the light-travel time effect, a method much like the one used by O. Römer in 1676 to claim a finite value for the speed of light (see Sterken 2005, for a complete discussion).

3.1. **Distances**

Distances are crucial for a precise knowledge of the scales of the Universe and thus its structure and ultimate evolution. Since there is no single distance determination method that can cover from the Solar System to distant galaxies, the distance scale is built by concatenating a series of indicators in which each one is used to calibrate the next. Among the main rungs of this ladder are the Solar System, nearby stars and clusters, Local Group galaxies, and distant galaxies. Accurate distances to open clusters and Local Group galaxies are thus of central importance because the overall cosmic distance scale hinges on them. As shown here, binaries have made and will make significant contributions to this area.

Distance estimation using binaries can be approached in two distinct ways. In the case of visual binaries, the so-called method of the orbital parallax is based on comparing the angular size of the orbital semi-major axis observed from Earth with the true size measured by combining the elements from the orbital and the radial velocity curve solutions. Basically, it is equivalent to the classical trigonometric parallax method except for using the orbit of a binary system instead of the orbit of the Earth. The other approach is based on the fact that the intrinsic luminosities of the components of an eclipsing binary system can be determined directly from the analysis of the light and radial velocity curves and a temperature calibration. Then, comparison of the observed brightness with the intrinsic luminosity yields the distance via the inverse square law. These two distance determination concepts are further elaborated below.

The calculation of orbital parallaxes of visual binaries is a powerful and completely direct method to estimate distances (see the review by Quirrenbach 2001). The results do not rely on any calibration and thus are extremely robust. For the method to be applicable, both astrometric data and spectroscopic data are needed. This is, in fact, its main limitation, because the radial velocity amplitude decreases with increasing orbital semi-major axis, and vice-versa. The recent improvements in the accuracy of the astrometric (using speckle or interferometry) and radial velocity measurements makes it possible to apply the method to a large number of visual binaries and not just to a handful of nearby
ones. Current instrumental capabilities yield orbital parallaxes with accuracies <1% at distances of over 100 pc (to be compared with ~10% for Hipparcos trigonometric parallaxes).

The determination of orbital parallaxes by, e.g., Hummel et al. (1995) and Konacki & Land (2004) illustrate the capabilities of this method. Another particularly interesting example is that of the orbit of the Pleiades binary Atlas. As is well known, the release of the Hipparcos-based distance to the Pleiades of 118 pc (van Leeuwen 1999), which was some 10% lower than the “canonical” value of 132 pc from main sequence fitting (Pinsonneault et al. 1998), caused a major controversy (e.g., Paczyński 2004). Interestingly, it was the analysis of the visual binary Atlas in the cluster by Pan, Shao, & Kulkarni (2004) (later refined by Zwahlen et al. 2004) that opened the way to the resolution of the problem by obtaining a distance in agreement with the predictions of stellar models. A recent astrometric analysis by Soderblom et al. (2005) has indeed revealed a systematic difference between HST/FGS and Hipparcos parallaxes that could explain the discrepancy.

These are just a few selected examples of a method with great potential. As discussed by Pourbaix (2000) the use of visual binaries to estimate distances has been neglected in the past. However, the situation is due to change in the coming years with the launch of missions such as Gaia or SIM that will push the astrometric limits down to the micro-arcsecond domain. The prospects for Gaia are especially promising in the determination of distances to visual binaries because the mission will also obtain spectroscopic measurements from which radial velocities can be derived.

The second approach to distance determination using binaries relies on its particularity to yield the fundamental properties of the component stars. The procedure is direct and simple but it needs data from different sources. The combination of the light and radial velocity curves of eclipsing binaries yields the orbital and physical properties of the system. Then, an estimate of the stellar temperatures permits the calculation of the intrinsic luminosities and the distance follows by comparison with the observed brightness. There are two caveats worth mentioning. First, one needs to make sure that no systematic error is introduced when estimating the effective temperature, which is always based upon some type of calibration. There are several alternatives to determine reliable temperatures, such as atmosphere model fits the observed spectral energy distribution, empirical calibrations based on photometric indexes, or detailed spectral analyses. Second, interstellar extinction plays an important role and has to be corrected for. Clausen (2004) provides a general discussion with emphasis on the involved uncertainties.

It was long realized that eclipsing binaries can be used as powerful distance indicators (Gaposchkin 1940; de Vaucouleurs 1978; Paczyński 1996). However, the method did not receive much attention until the instrumental capabilities reached sufficient precision to permit detailed analyses of eclipsing binaries in the Magellanic Clouds (Guinan et al. 1998). The number of distance determinations of Large and Small Magellanic Cloud (LMC and SMC) binaries has increased in recent years (Fitzpatrick et al. 2002, 2003; Ribas et al. 2002; Harries, Hilditch, & Howarth 2003; Hilditch, Howarth, & Harries 2005), and more are expected shortly. Although it may seem that the longstanding
problem of the distance to the LMC and SMC is now resolved (Alves 2004), the scatter of the distance estimates to individual eclipsing binaries is larger than the expected error bars. This is discussed by Ribas (2004), who studies the possibility of a line-of-sight extension of the LMC. It is only with detailed analyses of further eclipsing binaries that the current issues can be settled. Extragalactic binary research is a rapidly developing discipline, with large numbers of new eclipsing binaries in Local Group galaxies being reported by several surveys. The recent first analyses of the faint eclipsing binaries in M31 (Ribas et al. 2005) and M33 (Bonanos et al. 2005), requiring the use of the most powerful instruments, constitute a clear example of the intense activity and interest in the field.

But eclipsing binaries are not only useful as distance indicators to Local Group galaxies. They can also be employed to estimate accurate distances to galactic clusters. A particularly relevant example is that of the Pleiades eclipsing binary HD 23642. Its analysis by Munari et al. (2004) and Southworth, Maxted, & Smalley (2004) has resulted in a distance estimation in excellent agreement with that from Atlas and from the cluster main sequence fitting. Many clusters in the Galaxy, which are key objects to our understanding of stellar evolution and a very important step in the distance ladder, should have eclipsing binaries that are still awaiting discovery and detailed analysis.

### 3.2. Clocks

The light-travel time effect (LTTE) in eclipsing binaries produces periodic variations in the mid-eclipse times with a very simple and direct physical meaning: The total path that the light has to travel varies periodically as the eclipsing pair moves around the barycenter of a wider triple system. In other words, the eclipses act as an accurate clock for detecting subtle variations in the distance to the object. This is analogous to the method used for discovering earth-sized objects around pulsars (Wolszczan & Frail 1992). The amplitude of the variation is proportional both to the mass and to the period of the third body, as well as to the sine of the orbital inclination. The analytical expressions that describe accurately the LTTE as a function of the orbital properties were first proposed by Irwin (1952). As discussed by Demircan (2000), nearly 60 eclipsing binaries show evidence for LTTEs.

Finding additional companions to an eclipsing binary system has limited interest unless the companion is a special kind of star. For example, the Timing analysis of the Hyades binary V471 Tau indicates a $\sim 30$ yr modulation with an amplitude of $\sim 140$ s. Such values are compatible with the perturbation from an object with a minimum mass of about $0.04 \ M_\odot$ (Guinan & Ribas 2001), which is in the brown dwarf realm. Another possibility is the combination of astrometric measurements and LTTE to resolve all the orbital and physical parameters of the third component. For example, this was done for Algol (Bachmann & Hershey 1975) and for R CMa (Ribas, Arenou, & Guinan 2002). However, this method will reach its full potential with the upcoming high-accuracy astrometric missions (such as Gaia and SIM). With timing accuracies of $\sim 10$ s for select eclipsing binaries with sharp eclipses, the detection of large planets ($\sim 10 \ M_\oplus$) in long-period orbits ($\sim 10–20$ yr) around eclipsing binaries will be a relatively easy task. The short-term astrometry will confirm the detections and yield the complete orbital solution and thus the actual mass
of the orbiting body. Finally, transiting planets are also prime candidates for LTTE studies. In this case, not only further orbiting planets can be discovered, but even moons around the transiting planet.

4. Binary star evolution

Besides providing useful tests to single star evolution models, the evolution of binary stars (in close, interacting systems) deserves attention in its own. Mass loss and mass transfer lead to evolutionary stages and stellar structures that would not be possible otherwise. The reader is referred to specialized literature on the subject (Chen & Han 2002; de Loore 2001; Taam & Sandquist 2000; Vanbeveren, De Loore, & Van Rensbergen 1998, and references therein). But also, the orbital evolution (i.e., circularization and synchronization) of binaries is directly related to the structure of the components. Orbital circularization is driven mostly by tidal dissipation. However, the actual dissipative mechanism in play is the matter of some controversy. Two competing theories (Zahn 1989; Tassoul 1989) predict rather different circularization and synchronization timescales. Observations are the only way to test which one of the approaches is indeed physically valid but no definitive conclusion have been reached yet (Claret, Gimenez, & Cunha 1993; Claret & Cunha 1997).

Interacting, close binaries are the progenitors of objects with strong astrophysical interest such as type Ia supernovae, novae, X-ray binaries, cataclysmic variables, microquasars, symbiotic stars, double degenerates, etc. Specific reviews on each of these object classes can be found in Hillebrandt & Niemeyer (2000), Shara (1993), Lewin, van Paradijs, & van den Heuvel (1995), Warner (2003), Mirabel & Rodríguez (1999), Corradi, Mikolajewska, & Mahoney (2003), Han (1998), and references therein. These objects, often related to energetic phenomena, are the subject of intense study today. An illustration of this is the strong interest raised by galactic microquasars, which are scaled-down versions of quasars in which the accretor is a stellar-mass compact object (neutron star or black hole) and the donor is a star that loses mass via Roche lobe overflow or stellar wind (Ribó 2005; Mirabel & Rodríguez 1999). Besides providing valuable information on accretion processes at smaller (temporal and spatial) scales than quasars, microquasars are the source of very high energy emissions (Paredes et al. 2000; Aharonian et al. 2005), but the mechanism by which such high energies can be attained has not been pinpointed yet (Romero 2005; Paredes 2005).

To conclude with this short overview of the interest of binaries by themselves, a point worth mentioning is the foreseen strong impact on gravitational wave astrophysics. This is a new window to astronomy that will experience a revolution with the increasing sophistication of the detectors and the launch of the space mission LISA. Binaries composed of compact objects such as white dwarfs, neutron stars and black holes, and the coalescence of the components of the binaries, are expected to be strong sources of gravitational radiation (Nelemans, Yungelson, & Portegies Zwart 2001). Furthermore, the shear number of double white dwarfs in the Galaxy is such that their gravitational wave radiation is anticipated to dominate the background and even limit the capabilities of the instrumentation (Evans et al. 1987). At this point, all expectations are
based upon theoretical calculations but many exciting results and new research opportunities are expected for the coming years with the dawn of observational gravitational wave astrophysics.

5. Binaries everywhere

We are living in the era of the photometric surveys. Many projects have produced huge amounts of photometric data and more are to come from those still ongoing. The ground-based projects EROS, MACHO, OGLE, STARE, ASAS, WASP, ROTSE, and the space missions COROT, Kepler, and Gaia are just a few examples. The resulting photometric datasets contain a wealth of information on stellar variability and, from this, many new binaries can be identified, mostly ellipsoidal and eclipsing binaries. Extensive catalogs of eclipsing binaries in the Galaxy and the Magellanic Clouds have already been compiled, greatly increasing (sometimes by orders of magnitude) the number of known systems.

But some criticisms should be made to hold back the possible euphoria when facing such bonanza of data. It has to be kept in mind that the majority of these surveys have not been designed for further exploitation of the resulting photometry. For example, in the case of eclipsing binaries, the light curves are usually in a single passband (two at most) and often undersampled. Also, complementary observations (either photometric or spectroscopic) may be needed to characterize the binary system. Survey data is of great use from a statistical point of view to study the distribution of, e.g., orbital periods, eccentricities, stellar radii, etc, as shown by, e.g., North & Zahn (2003). But caution must be exercised when carrying out detailed analyses. Particularly important when dealing with such large datasets are automatic light curve fitting schemes. Examples of automatic codes are the recent papers by Wyithe & Wilson (2001, 2002) and Devor (2005). Additionally, significant progress needs to be made in the modeling of fine effects in light curves (gravity brightening, limb darkening, reflection). Photometry with sub-millimag accuracy from upcoming space missions will certainly expose the shortcomings of our current theoretical description of light curves.

6. Conclusions

In this paper I have tried to present a brief overview of some of the areas in which binary stars (may) play an important role. The few aspects discussed here have been selected to illustrate that binaries can be very interesting as individuals but, more importantly, they can produce very valuable contributions to Astrophysics in general. Such astrophysical insight is central to make a research activity worthwhile. With binary stars one can address topics so diverse as the cosmic distance scale, stellar evolution, gravitational waves, which have been discussed here. But there are also many other aspects, like magnetic activity, plasma physics, variable stars in binaries, to name a few, that can also be studied. Some additional examples are given, e.g, in Guinan (1993) and the particular aspect of variable stars in binaries is addressed by Pigulski and Lampens in this volume. The binary world is rich both in variety and in value, and it offers plenty of exciting research opportunities.
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