From Interacting Binaries to Exoplanets: Essential Modeling Tools
Proceedings IAU Symposium No. 282, 2011
Mercedes T. Richards & Ivan Hubeny, eds.

doi:10.1017/S1743921311026810

Techniques for Observing Binaries in Other Galaxies

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Abstract. I present an overview of the techniques used for detecting and following up binaries in nearby galaxies and present the current census of extragalactic binaries, with a focus on eclipsing systems. The motivation for looking in other galaxies is the use of eclipsing binaries as distance indicators and as probes of the most massive stars.

Keywords. binaries: eclipsing, binaries: spectroscopic, stars: distances, stars: fundamental parameters, Local Group

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1. Motivation

Eclipsing binaries are not only powerful tools for obtaining fundamental parameters of stars (Andersen 1991, Torres et al. 2010), but also the most accurate tools currently available for measuring masses and radii of massive stars and for probing the upper stellar mass limit. Double-lined spectroscopic binary systems exhibiting eclipses in their light curves provide accurate geometric measurements of the fundamental parameters of their component stars. Specifically, the light curve provides the orbital period, inclination, eccentricity, the fractional radii and flux ratio of the two stars. The radial velocity semi-amplitudes determine the mass ratio; the individual masses can be solved using Kepler's third law. Furthermore, by fitting synthetic spectra to the observed ones, one can infer the effective temperatures of the stars, solve for their luminosities and derive the distance (e.g. Bonanos *et al.* 2006). In the past two decades, many eclipsing binaries have been discovered in other galaxies and several of these have been subject to follow up studies, resulting in the measurement of their fundamental parameters. The main motivations for observing eclipsing binaries in other galaxies are to study massive stars and to obtain independent distances.

Massive stars are intrinsically rare compared to their lower mass counterparts, due to their shorter lifetimes and the steep initial mass function, which results in the formation of a smaller number of massive stars. Studying massive stars in the Galaxy is challenging, because they are located in the Galactic plane, where they reside in young massive clusters and usually near giant molecular clouds, and are therefore often heavily obscured by dust. Fig. 10 of Mauerhan *et al.* (2011) demonstrates the small fraction of the Milky Way surveyed for massive stars, by showing the locations of known Wolf-Rayet (WR) stars in the Galaxy. Although the total estimated number of WR stars in the Galaxy is 6500, there are only ~ 600 known and most are located within 5 kpc of the Sun, i.e. only $\sim 10\%$ of the Milky Way has been surveyed. This fraction is slowly increasing, with the recent availability of near-infrared and mid-infrared maps of the Galactic plane (obtained with *Spitzer*), which have been used both to identify new massive clusters (e.g. Davies *et al.* 2007) and massive evolved stars with nebulae (Gvaramadze *et al.* 2010, Wachter *et al.* 2010).

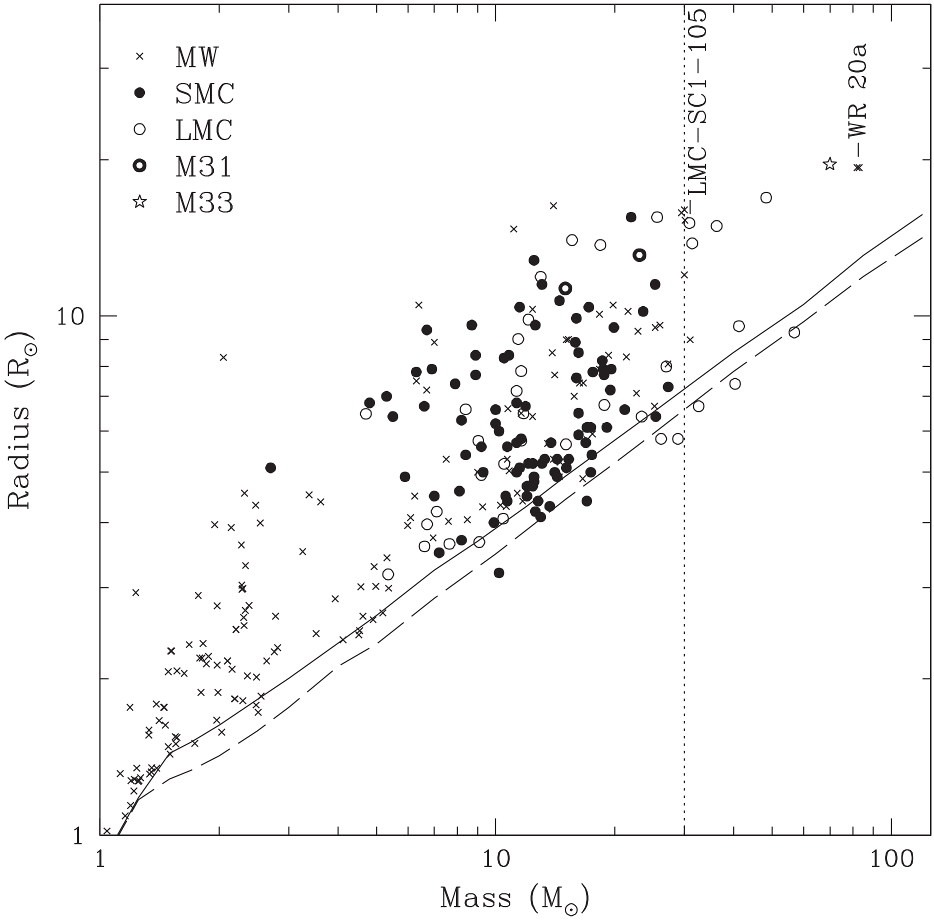

Figure 1. Mass and radius determinations of stars in eclipsing binaries, accurate to $\leqslant$ 10% and complete $\geqslant$ 30 M$_\odot$ (from Bonanos 2009). Since this compilation, measurements of only 2 more massive stars (Stroud *et al.* 2010) satisfy these accuracy requirements, bringing the total to 16.

Another reason why our knowledge of massive stars is incomplete is because their fundamental parameters are not well known, leaving formation and evolution models unconstrained. Masses and radii of massive stars measured from eclipsing binaries remain scarce. Bonanos (2009) compiled a list of the most massive stars accurately measured in eclipsing binary systems and found only 14 stars above 30 M$_\odot$ with mass and radius measurements accurate to 10% or better (see Figure 1). Since this compilation, measurements of only 2 more massive stars (Stroud *et al.* 2010) satisfy these accuracy requirements, bringing the total to 16. Therefore the need for accurate fundamental parameters of very massive stars at a range of metallicities and evolutionary phases remains of primary importance.

There are several advantages to studying massive stars in other galaxies, despite their greater distance from us. The low foreground extinction allows observations in the optical and ultraviolet, where the stars emit the most light, making possible their identification and study with smaller telescopes. The large metallicity range found in Local Group galaxies and beyond allows for a comparative study of the properties of massive stars as a function of metallicity (see e.g. Massey 2003), which is an important factor determining their fate. As variability studies become more widespread, eclipsing binaries are being identified in an increasing number of galaxies. Follow up studies of massive extragalactic systems is crucial to our understanding of massive star evolution.

Studying massive stars in other galaxies also offers the opportunity to obtain a complete census of eclipsing binaries and statistics on the binarity of whole populations of massive stars, a task that is currently impossible in our Galaxy. Specifically, obtaining the complete number of eclipsing systems in a galaxy down to a certain magnitude and within a certain period range will help constrain the binarity fraction of the higher mass population, which is near 50% among massive stars (Sana & Evans 2010).

Finally, another motivation for studying eclipsing binaries in other galaxies is that they are good distance indicators (Paczynski 1997), which can provide independent and accurate distances to Local Group galaxies. Given the radius and effective temperature of the component stars of the system, their luminosities (or absolute magnitude) can be calculated. Armed with both the absolute and apparent magnitude, and after correcting for extinction, one can obtain the distance.

2. Techniques

The most efficient techniques for observing eclipsing binaries in other galaxies, while not vastly different from galactic studies, include photometric variability studies with wide field CCDs and follow-up observations with multi-object spectrographs. Difference imaging or image subtraction (Alard & Lupton 1998, Alard 2000) is a technique widely used in extragalactic variability studies, given the crowded nature of the fields. Bonanos & Stanek (2003) demonstrated it to be a much more efficient method for detecting variables in crowded fields compared with traditional PSF-fitting photometry.

The discovery of extragalactic eclipsing binaries mainly comes from variability surveys of nearby galaxies with 1-2 meter telescopes, such as the DIRECT project (Stanek *et al.* 1998, Bonanos *et al.* 2003) that specifically aimed to discover eclipsing binaries in M31 and M33, or the Araucaria Project (e.g. Pietrzynski *et al.* 2002), which is surveying several nearby galaxies for RR Lyrae, Cepheids and eclipsing binaries to obtain accurate distances. Large numbers of extragalactic binaries have also resulted as side products of microlensing surveys, such as MACHO and OGLE, which have discovered thousands of eclipsing binaries in the Magellanic Clouds (see Derekas *et al.* 2007 and Faccioli *et al.* 2007 for MACHO results, and Wyrzykowski *et al.* 2003, Wyrzykowski *et al.* 2004 for OGLE-II results). Furthermore, the long time baseline of the OGLE project has resulted in the discovery of very long period systems or other rare systems, such as an eclipsing system containing a Cepheid (Pietrzynski *et al.* 2010).

Once the eclipsing binaries have been identified via photometric variability surveys, 6-10 meter class telescopes are needed for follow-up spectroscopic observations. Service mode observing (available e.g. at Gemini, VLT), targeting quadrature phases has been shown to be the most efficient way of obtaining spectroscopy for a small number of targets per galaxy (Gonzalez *et al.* 2005). When the number of targets is large (e.g. Hilditch *et al.* 2005), then multi-object spectrographs, such as FLAMES/VLT or 2dF/AAT, provide the most efficient follow up method. With the currently available telescopes, fundamental parameters of eclipsing binaries can be measured out to a distance limit of about 1 Mpc, as a resolving power $R \geqslant 3000$ and S/N$\geqslant$ 30 are necessary for early-type systems and targets typically have $V > 18$ mag.

Last but not least, several multi-epoch spectroscopic surveys have been undertaken to identify spectroscopic binaries (e.g. Foellmi *et al.* 2003), some of which are later found to be eclipsing systems as well (e.g. WR20a, Rauw *et al.* 2004, Bonanos *et al.* 2004).

Table 1. Census of Extragalactic Eclipsing Binaries.

Galaxy	**Distance**	**# of EBs**	**Source**
LMC	50 kpc	4634, 2580	MACHO, OGLE
SMC	60 kpc	1509, 1350	MACHO, OGLE
NGC 6822	460 kpc	3	Araucaria Project
IC 1613	730 kpc	1	Araucaria Project
M31	750 kpc	~ 500	DIRECT Project & Ribas *et al.* (2004)
M33	960 kpc	148	DIRECT Project
NGC 300	1.9 Mpc	1	Araucaria Project
NGC 2403	2.5 Mpc	1	Tammann & Sandage (1968)

The VLT-FLAMES Tarantula survey (Evans *et al.* 2011) is a recent example of such a multi-epoch spectroscopic survey, with the goal to identify massive binaries via radial velocity variations.

3. Eclipsing Binaries in Other Galaxies

Table 1 presents a census of known extragalactic eclipsing binaries. The first six galaxies are Local Group members, while NGC 300 is in the Sculptor group and NGC 2403 in the M81 group. The eclipsing binary in NGC 2403 was discovered by Tammann & Sandage (1968) and has a B magnitude of 22.

The large number of systems in the Magellanic Clouds is due to the MACHO and OGLE microlensing surveys. Faccioli *et al.* (2007) presented a catalog of MACHO eclipsing binaries, while Wyrzykowski *et al.* (2003) and Wyrzykowski *et al.* (2004) presented the catalogs from the OGLE survey. While some of these are bound to be foreground systems, most are indeed extragalactic. Note, there is some overlap between the catalogs. Moving farther out, the dwarf galaxy eclipsing systems in IC 1613 and NGC 6822 were discovered by the Araucaria project. Finally, the significant number of systems discovered in M31 and M33 is due to the dedicated searches by the DIRECT Project (e.g. Stanek *et al.* 1998) and Ribas *et al.* (2004).

The Local Group eclipsing binaries lend themselves as distance indicators and have been used as such so far to derive distances to the LMC, SMC, M31 and M33. Guinan *et al.* (1998), Ribas *et al.* (2002), Fitzpatrick *et al.* (2002), Fitzpatrick *et al.* (2003) have used early-B type systems to derive eclipsing binary distances to the LMC, while Pietrzynski *et al.* (2009) used a G-giant eclipsing system and Bonanos *et al.* (2011) an O-type eclipsing system. Most systems in the bar of the LMC are found to be at 50 kpc, however the distance to HV 5936 is discrepant, likely due to the 3-dimensional structure of the galaxy. In the SMC, Harries *et al.* (2003) and Hilditch *et al.* (2005) have obtained a distance modulus of 18.91 ± 0.03 mag by measuring 50 OGLE-II binaries with AAT/2dF spectrograph, while North *et al.* (2010) obtained a distance modulus of 19.11 ± 0.03 mag with 33 OGLE-II eclipsing binaries, using VLT/FLAMES. The discrepancy in the distance likely arises from systematic errors associated with lower resolution spectra from 2dF and the estimation of the extinction.

In M31, the eclipsing binary distances of Ribas *et al.* (2005, 772 ± 44 kpc or 24.44 ± 0.12 mag) and Vilardell *et al.* (2010, 724 ± 37 kpc or 24.30 ± 0.11 mag) are in agreement with each other. However, in M33, the long distance derived by Bonanos *et al.* (2006), 960 ± 54 kpc, was not in agreement with most measurements in the literature, and in particular with the HST Key Project measurement (Freedman *et al.* 2001), possibly because of the difficulty in estimating reddening with other methods. Nonetheless, the M33 result has pushed our current capabilities to the limit, measuring fundamental parameters of stars out to 1 Mpc. Overall, eclipsing binary distances are very valuable, because they provide independent distances, which can help evaluate the systematic errors associated with other widely used standard candles (e.g. Cepheids, RR Lyrae, tip of the red giant branch).

4. Future

The potential of eclipsing binaries for obtaining fundamental parameters of massive stars and independent distances to other galaxies is extremely promising. The ongoing OGLE project, now in its phase IV, is surveying even larger areas of the Magellanic Clouds and is bound to discover tens of thousands of eclipsing binaries. Furthermore, transient surveys such as Pan-STARRS and the Palomar Transient Factory, as well as asteroid surveys, such as the Catalina Sky Survey, and in the future, the Large Synoptic Sky Telescope will be including many nearby galaxies in their fields and monitoring them for long periods of time.

In conclusion, wide field surveys and multi object spectrographs are truly revolutionizing extragalactic binary studies. The rate of discovery of such systems is bound to increase and provide ample opportunity for studies of extragalactic massive stars, the determination of their distances, the binarity fraction and finally, statistics on binarity of various populations of stars in nearby galaxies.

Acknowledgements

The author gratefully acknowledges research support from the European Commission Framework Program Seven under the Marie Curie International Reintegration Grant PIRG04-GA-2008-239335, and travel support provided by an IAU Travel Grant.

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Discussion

R. Wilson: The way you find distances to eclipsing binaries is very good and logical (using complete optical light curves for most parameters and then the few infrared points for distance, thereby being relatively free of interstellar extinction dependence). However, now one can go a bit further, as the 2010 version of the WD program avoids the spherical star approximation previously used with the infrared points in the distance step. The program also gives options (process the optical and infrared data separately or together, or both ways) and assumes consistency. It is directly absolute, with fluxes in physical units and, since the program does most of the work, it makes the overall process very fast.