Classical Pulsators in Eclipsing Binary Systems

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We present a summary on a big advance in studies of classical pulsating stars in eclipsing binary systems. A discussion of properties of 6 Cepheids in 5 eclipsing binary systems is presented. The determination of precise and accurate stellar parameters for these Cepheids is very important for several fields of astrophysics. An update on a long term project on Galactic binary Cepheids has been presented at this conference by Gallenne et al. Soon, the interferometric orbits will be combined with radial velocities, and the orbital elements and masses for the studied Cepheids will be derived.

We also discuss the discovery of a new class of pulsating stars formed through mass exchange in binary systems. Such an evolutionary channel can produce stars which are very difficult to distinguish from classical pulsators. Recent studies on a candidate Type II Cepheid in eclipsing binary systems showed that this star is also a product of stellar evolution in binary systems. We can expect a few percent contamination from this class of pulsating stars in the catalogs of classical pulsators like Cepheids, RR Lyrae, etc.

Finally we highlight new, good candidates for RR Lyrae stars in binary systems. The dynamical mass (and other parameters too) determination for an RR Lyrae star has been awaited for a long time.

1 Introduction

Binary systems and pulsating stars are fundamental for many different fields of modern astrophysics. Eclipsing binaries offer a unique opportunity to measure precise and accurate basic stellar parameters like mass and radius (Torres et al., 2010). In well-detached double-lined systems, one can routinely reach even sub-percent precision. Moreover with eclipsing binaries, one can also determine limb darkening, age, helium content, and detect even very low mass companions.

Binaries are also excellent geometrical distance indicators. They provide two different ways to measure precise and accurate distances. The first method is based on spectroscopic and astrometric binaries. In such a case, the semimajor axis can be measured in physical units from spectroscopy and its projection on the sky from the astrometric orbit. Therefore, one can measure the distance in a purely geometrical way with a precision better than 1 % (Gallenne et al., 2016).

The distances to eclipsing binaries can be also measured using a very simple equation: $d(\mathrm{pc}) = 1.337 \times 10^{-5} \times r(\mathrm{km})/\phi(\mathrm{mas})$. The linear diameter ($r$) will come from an analysis of the light curve and spectroscopic orbit, while the angular diameter can be calculated from a surface brightness-color relation (e.g. Di Benedetto, 2005).

It is a decisive advantage of this method that its sources of uncertainty, including systematic errors, are known and can be accurately quantified due to the simplicity and empirical nature of this geometrical method (Pietrzyński et al., 2013).

Radially pulsating stars are also fundamental for distance measurements. Since the discovery of the Cepheid $P-L$ relation over a hundred years ago by Miss Leavitt, these stars have been widely used to measure cosmic distances on very different scales (e.g. Freedman et al., 2001; Pietrzyński et al., 2006) and have become, together with Type Ia supernovae, a basic tool to measure the Hubble constant (e.g. Riess et al., 2016). Other radially pulsating stars also have nicely defined $P - L$ relations, and some of them (e.g. RR Lyrae, Type II Cepheids) are very good distance indicators. Another way to use radially pulsating stars to measure distances is the Baade-Wesselink method (see, e.g. Storm, these proceedings). In this case, we determine the change of the linear diameter and angular diameter with the pulsational phase, and a simple linear relation gives us distance and mean radius. However due to pulsations, one needs to transform the observed radial velocities onto the pulsational velocities. In order to do that, a projection factor (p-factor; see Gallenne et al., Nardetto et al., these proceedings) has to be applied, and currently this is the main limitation of the precision of this method (some 7 %, see Storm, this conference). Apart from distances, pulsating stars provide very important information about stellar ages, stellar interiors, and stellar parameters through some relations (like period-mass-radius or period-age, see, e.g. Bono et al., 2001, 2005; Anderson et al., 2016).

Pulsating stars in eclipsing binaries are especially important. In such a case, we have an opportunity to apply different techniques and compare independent results. As a result, we can calibrate several widely used relations, like $P - L$, mass-radius, etc. Moreover we can also measure dynamical masses, limb darkening, and geometrical p-factors for pulsating stars. As a result, the studies of such objects provide very strong constraints on stellar evolution and pulsation theories (e.g. Cassisi & Salaris, 2011; Marconi et al., 2013).

2 Classical Pulsating Stars in Binaries

On average about 50 % of stars are in binary or multiple systems, so the binary systems are very frequently found in the sky. However due to several reasons, very few radially pulsating stars were detected in binary systems and in particular in eclipsing binary systems so far. In general, it is more complicated to detect a binary system with one of the components being a pulsating star because of the superposition of photometric and radial velocity variations. On the other hand, both components have to be very well detached in order to avoid mass exchange, which could prevent one or both components to become a classical radial pulsator. In particular, in the case of Cepheids, this condition implicates very long orbital periods of one year or more. This is a challenge to detect such long period eclipsing systems.

Below I will resume the current status of searches for and the analysis of radially pulsating stars (Classical and Type II Cepheids and RR Lyrae) in binary systems. I will also briefly discuss a new class of pulsating stars which can be formed in binary systems through mass exchange between its components and which can mimic very well the classical pulsators.

2.1 Classical Cepheids

Classical Cepheids are among the best known objects. However, there are still several problems related to these objects. One of them is the famous mass discrepancy problem: Cepheid masses predicted from stellar pulsation theory are smaller than masses derived from stellar evolution theory (e.g. Bono et al., 2006).

The frequency of binaries among bright Galactic Cepheids exceeds 50 %, while among the fainter ones an observational selection effect encumbers revealing binarity (Szabados et al., 2013). However all Galactic Cepheids detected in binary systems are SB1 non-eclipsing systems, which seriously limits their application to measure stellar parameters. All these systems are composed of Cepheids and an early type star located on the main sequence and have very long periods, typically of many years.

Gallenne et al. (2017) have been observing some of these stars interferometrically in order to measure the astrometric orbits. Once the interferometric orbits are ready and the radial velocity orbit for both components are measured (this is challenging due to very few broad lines of the secondary components), such systems together with *Gaia* parallaxes will provide accurate mass and distance determinations.

Cepheids in eclipsing SB2 binary systems are particularly interesting from the point of view of precise and accurate measurement of stellar parameters. However for many years no good candidates had been provided. The situation changed when the microlensing surveys like MACHO (e.g. Alcock et al., 2002) and OGLE (Udalski et al., 1992) started to provide a huge amount of high quality photometric data. In particular, the OGLE team provided a sample of very good candidates for Cepheids in eclipsing systems (Soszyński et al., 2017).

These objects were then very carefully studied in the course of the Araucaria project (Gieren et al., 2005). In 2010, we confirmed the first Cepheid in an eclipsing binary system (OGLE-LMC-CEP-0227) and measured its physical parameters including dynamical mass with a very good precision of $1 - 2\,\%$ (Pietrzyński et al., 2010). This measurement provided a strong evidence that pulsation theory correctly predicts the masses of classical Cepheids and motivated various refinements to stellar evolution calculations that bring the pulsation and evolutionary masses into agreement (e.g. Cassisi & Salaris, 2011; Neilson et al., 2011; Anderson et al., 2014). The next year, another Cepheid – OGLE-LMC-CEP-1812 – was confirmed to be a member of an eclipsing system (Pietrzyński et al., 2011). Recently we confirmed another 3 systems containing classical Cepheids: OGLE-LMC-CEP-1718 (Gieren et al., 2014), OGLE-LMC-CEP-2532 (Pilecki et al., 2015), and OGLE-LMC-CEP-4506 (Gieren et al., 2015). Therefore, our extended spectroscopic monitoring over some 10 years resulted in a confirmation of 5 systems in physical binary systems with Cepheid components.

Four of them are composed of a Cepheid and a helium burning giant star while one is composed of two Cepheids. These systems are very different from the Galactic systems with Cepheids where the secondary components are blue stars on the main sequence.

For all these Cepheids, we managed to measure their stellar parameters with a very good precision of about $1 - 3\,\%$. However in two cases, the secondary eclipses are not observed due to eccentricity and special orientation of the orbits, so we had to make some additional assumptions during our studies (e.g. Pilecki et al., 2015;

name OGLE-LMC-	P [days]	M [$M_\odot$]	R [$R_\odot$]	p	mode
CEP-0227	3.797086	4.15 ± 0.02	34.87 ± 0.12	1.21 ± 0.05	FU
CEP-1812	1.312903	3.76 ± 0.03	17.85 ± 0.13	1.26 ± 0.08	FU
CEP-2532	2.035349	3.98 ± 0.10	29.2 ± 1.4	-	FO
CEP-4506	2.987846	3.61 ± 0.03	28.5 ± 0.2	1.35 ± 0.09	FU
CEP-1718A	1.963663	4.27 ± 0.04	27.8 ± 1.2	-	FO
CEP-1718B	2.480917	4.22 ± 0.04	33.1 ± 1.3	-	FO

Table 1: Physical properties of 5 Cepheids in eclipsing systems

Gieren et al., 2014).

We also managed to measure the geometrical p-factors for three Cepheids. Table 1 summarises the obtained results (Pilecki et al., in preparation). Our empirical mass determinations are in a very good agreement with predictions from pulsational theory. We also show that the limb darkening coefficients for Cepheids are most probably much larger than expected (Pilecki et al., 2013).

The system which contains two classical Cepheids (OGLE-LMC-CEP-1718) provides very strong constraints on the evolutionary models (Pilecki et al., in preparation). However it is a challenge to analyze this system due to a superposition of pulsations from both components and orbital motion (eclipses). The OGLE-LMC-CEP-1812 system is also very interesting from the point of view of its evolutionary status (Pietrzyński et al., 2011). The secondary component is a less massive, smaller, and cooler, stable giant star, a configuration that is significantly different from the OGLE-LMC-CEP-0227 system (and other systems analyzed so far by our group, see Table 1) whose stable secondary giant has almost the same mass, and a slightly larger diameter than the Cepheid in that system. The configuration is also quite unusual from an evolutionary point of view because the system consists of two well-separated stars in a relatively short stage of common giant phase evolution, in spite of the large mass (and thus age) difference. To explain this discrepancy, Neilson et al. (2015) proposed a scenario that this Cepheid is a product of a stellar merger of two main sequence stars that has since evolved across the Hertzsprung gap of the HR diagram.

2.2 Type II Cepheids

Type II Cepheids (T2Cs) are widely recognized as a very good tool for studies of stellar evolution and structure and for measuring distances. These low-mass stars belong to the disc and halo populations. However, there are still several important problems in understanding the fundamental physics of these stars. According to Gingold (1976), the BL Her stars are evolving from the horizontal branch to the Asymptotic Giant Branch (AGB); the W Virginis stars are objects crossing the Cepheid instability strip during their evolution along the AGB towards higher effective temperatures; and the RV Tauri stars are objects that after their AGB phase are moving towards the white dwarf cooling sequence. However, some more recent evolutionary tracks (Pietrinferni et al., 2006) do not show these excursions, and the precise evolutionary state of T2Cs, especially of W Vir stars, remains unclear. The lack of knowledge of accurate masses for these stars, and their other physical parameters, does not presently allow us to provide strong constraints on their evolutionary and pulsational models.

Several good candidates for Type II Cepheids in eclipsing binaries were provided by microlensing projects (Soszyński et al., 2008). In the course of the Araucaria project, we performed extensive follow-up observations of several very good candidates. We confirmed that 6 systems are indeed physical binary systems. We finished analysis for one system: OGLE-LMC-T2CEP-098 (Pilecki et al., 2017). This star belongs to the peculiar W Vir group (Soszyński et al., 2008). Our obtained results show that the pulsating component is most probably a product of mass exchange in this binary system. This confirms that peculiar W Virginis may be Binary Evolution Pulsators (BEPs; see section 3). The p-factor derived for this object is of 1.30 ± 0.03 (Pilecki et al., 2017); similar to p-factors of classical Cepheids.

2.3 RR Lyrae

As Classical Cepheids and Type II Cepheids, RR Lyrae stars are also very powerful to trace stellar populations and measuring distances. TU UMa was the first candidate for an RR Lyrae in a binary system (Wade et al., 1999). A huge effort was dedicated to detect RR Lyrae in eclipsing binary systems. The first candidates provided by OGLE turned to be complicated blends (Prša et al., 2008). Another very good OGLE candidate turned out to be a completely different object (Pietrzyński et al., 2012). Therefore we still do not have confirmed RR Lyrae stars in eclipsing binaries. As the result we still do not have a precise empirical determination of stellar parameters of RR Lyrae stars. This is a very strong limitation since the theoretical prediction for RR Lyrae masses can differ even by 30 % (Barcza, 2003).

Recently Hajdu et al. (2015) provided a dozen of very good candidates for RR Lyrae stars in eclipsing binaries. They analysed the light-travel time effect in so-called observed minus calculated (O–C) diagrams constructed for 1952 fundamental-mode RR Lyrae stars having very high-quality photometry obtained by the OGLE project (Soszyński et al., 2016). The follow-up spectroscopic observations are being conducted by these authors (Hajdu et al. this conference). However, such observations are challenging due to relatively low amplitude radial velocity variations and very long orbital periods. Liška et al. (2016) extensively discussed and maintain an up-to-date list of candidates for binaries with an RR Lyrae component.

3 Binary Evolution Pulsators – BEPs

One of the candidates for RR Lyrae in an eclipsing binary system, OGLE-BLG-RRLYR-02792, was confirmed to be indeed the long awaited physical system containing an RR Lyrae star, which allows us to determine a dynamical mass for the variable star for the first time. However, combining these data with the OGLE photometric light curve, we measured a mass of $M_1 = 0.26\,\mathrm{M}_\odot$ and a radius of $R_1 = 4.2\,\mathrm{R}_\odot$ for the primary (RR Lyrae) component, and $M_2 = 1.7\,\mathrm{M}_\odot$ and $R_2 = 4.2\,\mathrm{R}_\odot$ for the secondary, non-pulsating component (Pietrzyński et al., 2012). Since RR Lyrae stars are widely believed to have masses in the range from 0.6 to $0.8\,\mathrm{M}_\odot$ our results are very unexpected. Moreover, if the pulsating component of OGLE-BLG-RRLYR-02792 is indeed an RR Lyrae star, the nature of the more massive, cooler ($T_2 = 0.68 T_1$) and by some 2 mag fainter secondary component would be very mysterious. Assuming a typical temperature for the RR Lyrae star of 6000 K, T_2 would be just 4100 K, which is much too cool for a giant star with $M_2 = 1.7\,\mathrm{M}_\odot$ (which should be close to 5000 K). However, the relatively short orbital period of 15 days suggests that mass exchange between both components should have occurred during the evolution of this system.

Therefore we calculated many models for Algol systems and found that a system with $M_1 = 1.4\,\mathrm{M}_\odot$ and $M_2 = 0.8\,\mathrm{M}_\odot$, and with an initial orbital period of 2.4 days, after 5.4 Gyrs should have changed into a system very similar to the observed one (e.g. $M_1 = 0.265\,\mathrm{M}_\odot$, $M_2 = 1.65\,\mathrm{M}_\odot$, and $P = 15.4$ days). We therefore conclude that the primary component of our system is most probably not a classical RR Lyrae star but rather a star with a partially degenerate helium core and a small hydrogen rich envelope (shell burning) that is crossing the main instability strip during its evolution to the region of the hot subdwarfs. Since such a star has a M/L ratio very similar to the M/L ratio of RR Lyrae stars, its light curve can perfectly mimic that of classical RR Lyrae stars. This is the reason why the OGLE team classified it as an RR Lyrae star from an analysis of its light curve Fourier parameters. Such objects should cross the main instability strip very fast, about 100 times faster than classical RR Lyrae stars, and therefore the OGLE photometry should allow us to measure the change of the pulsational period caused by the fast migration through the strip. Indeed, we measured dP/P of 8.4×10^{-6} days/year, which agrees very well (within a factor of 1.5) with the corresponding value estimated from the theoretical models. The secondary component, which was initially the less massive star, is now a typical red giant.

In general, Binary Evolution Pulsators (BEPs) can seriously affect an application of RR Lyrae to measure distances and ages. Pulsational properties of BEPs were studied in detail by Smolec et al. (2013). They showed that a resonant bump progression on the radial velocity curve can be used to distinguished such stars from RR Lyrae stars.

The evolution channel should produce not only RR Lyrae-like stars but also a whole range of peculiar low mass objects, which are not explained by the classical evolution models of single stars. Karczmarek et al. (2017) based on extended simulations showed that BEPs would contaminate genuine RR Lyrae and classical Cepheid variables at levels of 0.8 % and 5 %, respectively. Taking into account relevant detection limitations, they concluded that a majority of BEPs will remain undetected.

4 Summary

Over the last decade a very big advance has been achieved in detecting classical pulsating stars in eclipsing binaries. Microlensing projects like OGLE and MACHO provided a list of several dozens of very good candidates. Extended spectroscopic follow-up of OGLE candidates done in the course of the Araucaria project resulted in a confirmation of several Classical and Type II Cepheids as physical members of eclipsing binary systems. These studies provided the first precise and accurate measurements of the Cepheid dynamical masses, radii, p-factors, etc. However, the sample of stars is still quite small and populated by short period Cepheids only. Further studies of classical and Type II Cepheids sound very exciting and will shed more light on the physics of these objects. Interferometric studies of Galactic

Cepheids in binary systems are also very promising.

Spectroscopic studies revealed also a new class of pulsating stars that can mimic classical pulsators. They are very difficult to distinguish them from classical pulsators and can constitute a few percent of known Cepheids and RR Lyrae. Given the small percentage they do not seriously limit the application of classical pulsators as distance and age tracers.

A newly provided list of candidates of RR Lyrae stars in binaries sounds very optimistic. The empirical mass determination for RR Lyrae stars has been awaited for a long time.

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