Contrib. Astron. Obs. Skalnaté Pleso **xx/x**, 1 – 7, (xxxx)
DOI: to be assigned later

Determining the physical parameters of eclipsing binaries from the B-Type Binaries Characterization programme (BBC) with PHOEBE

H. Willems

Max Planck Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany (E-mail: willems@mpia.de)

Received: November 15, 2024; Accepted: January 18, 2025

Abstract. Most massive stars, especially eclipsing binaries, offer a great opportunity to study their physical properties, yet they remain poorly understood. The objective of this work is to understand better the evolution and configuration of massive binaries. This is done by constraining the physical parameters of the eclipsing B-type binaries with the help of the `PHOEBE`, which have been observed spectroscopically and photometrically. From these values, the configuration of these systems is inferred, giving insight to the current state and past and future evolution.

Key words: eclipsing binaries – massive stars – 30 Doradus

1. Introduction

Most B-type stars are located in binaries or even multiple stellar systems (Offner et al., 2023). However, the evolution of massive stars, especially in binaries, has remained elusive. To enhance the understanding of these type of stars, they are studied in this work. The sample is located in the most active star-forming region of the local group, 30 Doradus (Fahrion & De Marchi, 2024), a nebula, where many massive stars are found, inside the Large Magellanic Cloud (LMC). The B-type Binaries Characterization programme (BBC; Villaseñor et al., 2021) is a multi-epoch spectroscopic campaign that followed 88 early B-type binaries inside 30 Doradus. With a radial velocity analysis, orbital solutions for 84 out of these systems were obtained - the largest homogeneous sample as of 2021. They included the semi-amplitude K_1 of the primary, the orbital eccentricity e, the period P and for double-lined spectroscopic binaries, the mass ratio q and the semi-amplitude of the secondary K_2. However, the inclination i remains an unknown parameter for determining the masses and the semi-major axis. This unknown can be measured by photometric observations of eclipsing binaries that have been carried out with the Optical Gravitational Lensing Experiment (OGLE; Pawlak et al., 2016).

Photometry also allows to get constraints of the effective temperatures $T_{\rm eff}$,

the equivalent radii R_{eq}. The period and eccentricity can be inferred from both types of observations.
With the combination of the existing spectroscopic analysis and the photometric analysis being carried out by this work, the aim is to accurately compute the physical parameters of the binaries and determine the orbital configuration of the system (i.e., detached, semi-detached or contact) can be found. This will allow us to strongly constrain the evolutionary history of the system as well as the probable future evolution.

2. OGLE data

OGLE is a multidecade photometric survey that became operational in its first phase (OGLE-I) in 1992 (Udalski et al., 1992) with a 1 m telescope, continuing with the second phase (OGLE-II) in 1996 when a 1.3 m telescope - both situated at Las Campanas observatory in Chile - dedicated to OGLE was used. The third phase with more technological upgrades started in 2003 (Udalski, 2003) (OGLE-III) and the current fourth phase (OGLE-IV) was initialized in 2010. In this work, data from OGLE-III and OGLE-IV is used to perform the analysis, making a total used baseline of 13 years with the two most recent phases until the paper Pawlak et al. (2016) was published.
OGLE was primarily inaugurated to detect gravitational micro-lensing events when exoplanets pass in front of their parent star. It can also detect exoplanets via transiting events.
OGLE-IV observed in the I band (from 700 to 900 nm) and the V band (from 500 to 600 nm) at a cadence of 1 to 3 days in the Magellanic systems (Udalski et al., 2015). 48605 systems in the Magellanic clouds have been classified as eclipsing binaries, of which 40204 are inside the LMC (Pawlak et al., 2016).

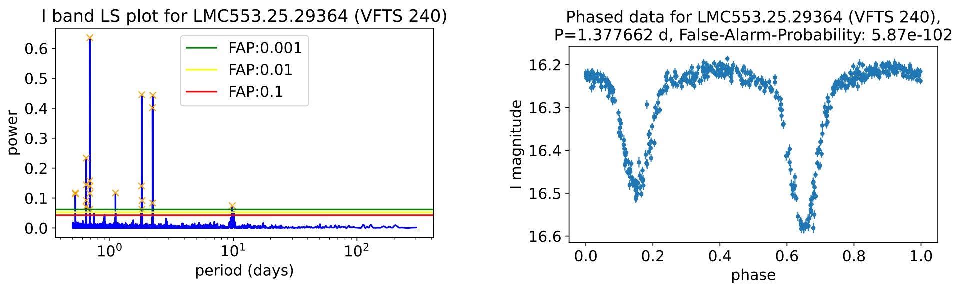
3. Methodology

The following procedure was applied for the analysis: The photometric period is determined first in order to phase-fold the data accordingly to make the eclipses visible. In order to achieve this, the OGLE data, which was available for 85 of them, was analysed through a Lomb-Scargle periodogram. The highest peaks were investigated to see the phase-folded data according to the period found. Eclipsing binaries can be identified using the phase-folded light curve, where `PHOEBE` v. 2.4.14 (Conroy et al., 2020) is used. Using initial values that are set to get close to the light curve, the `Nelder-Mead` is used to optimize the parameters, finding the best set that matches the light curve. Nelder-Mead is opted to find the point of minimal χ^2 in a multi-parameter space, resulting in the best fit to the light curve observations. Finally, `EMCEE` is used to get estimates of the parameter uncertainties. `EMCEE` is a sampler using the Markov Chain Monte

Carlo (MCMC) algorithm, sampling around the optimized values and returning their likelihoods.

3.1. Period determination

The first step in the analysis is to find the photometric period of the system. For that, a Lomb-Scargle (LS) periodogram (Lomb, 1976), (Scargle, 1982) is used. LS fits a set of sine curves to unevenly spaced data and finds the frequencies that reduce the χ^2 the most to find possible periodicities. The likelihood of a frequency matching the data is given by the power of the LS periodogram. In this work, the periods between 0.5 and 300 days with an oversampling factor of 2000 were analysed by the LS periodogram. For a few systems, the analysis was run again with a minimum frequency of 0.0002 (5000 days) to a maximum of 0.1 (10 days) because they showed periodicities from hundreds of days to a few years.



(a) Lomb-Scargle periodogram for VFTS240

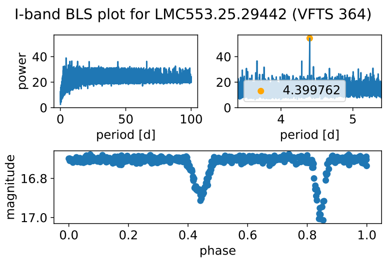
(b) Corresponding plot for the period of the eclipsing binary

Figure 1.: Lomb-Scargle periodogram for VFTS 240 with phased data to the best period

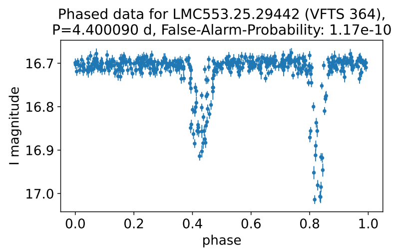
It can happen that the best period is not the one with the highest peak in the periodogram, making it necessary to check several periods. In most cases, the best period was twice the period of the highest LS power, as it can be seen in Fig. 1. This happens because at the highest LS power, the eclipses were positioned at the same phase and they have to be disentangled by multiplying the period by 2.

In a few other cases, when the eclipses are exceptionally sharp and narrow and have a non-sinusoidal shape, a different period-finding mechanism, the so called Box-Least-Squares (BLS; Collier Cameron et al., 2006), was applied to find the correct period. Box-Least Squares is mainly used in exoplanet transit detections, but it can also be used for eclipsing binaries. Contrary to Lomb-Scargle, the Box-Least Squares fits rectangular boxes to the light curve. VFTS

364 is a perfect example when it turned out to find the correct period. The top panels in Fig. 2a show the power at different periods where the top-right plot shows a refined search around the initial highest peak. Both searches were done with 50000 different periods within 0.1-100 days for the top left plot and 1 day around the highest peak for the top right plot.



(a) BLS plot for VFTS 364
top panels described in text



(b) Corresponding object with LS

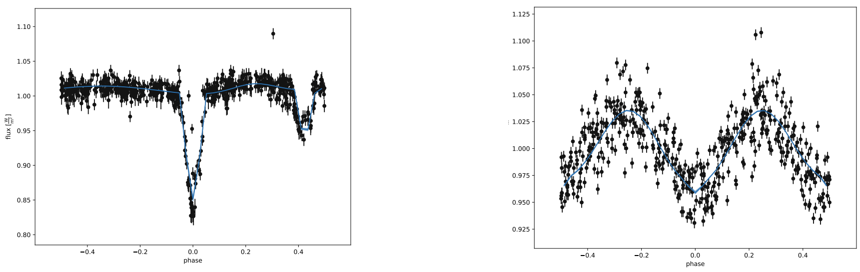
Figure 2.: Comparison between BLS and LS for VFTS364

A good period is defined as that the eclipses are well-defined and the data does not scatter in the eclipses. For example, the BLS plot for VFTS 364 in Fig. 2a shows a good period, while the period found through LS (Fig. 2b) is not good because the eclipses are not clearly enough resolved.
During the analysis of the light curves, 9 of them showed clear eclipses, 4 of them were ellipsoidal variables with higher amplitudes; 10 more showed low variations of the order of 0.02 magnitudes. 6 systems have long periodicities of longer than 100 days and one heartbeat star was in the sample. And 59 systems did not have good periods because for 50 of them, the light curve was fairly constant. 6 out of the 9 systems with no period showed no LS peak with a false-alarm probability of less than 0.1%. The remaining 3 objects did not have OGLE data available.

3.2. Modelling with PHOEBE

When a good period is found, `PHOEBE` can be used to get a model of the light curve of eclipsing binaries for its reproduction and the period becomes a fixed parameter. `PHOEBE` takes a set of orbital and stellar parameters as an input and it returns the light curve model, which can be overlaid with the observational data for comparison. While changing them, the impact of the parameters can be studied until a close agreement between the observations and the model is found. The initial temperatures were set to typical values of early B-type stars (around 20000 K).
When a good point in the parameter space is found, the values of the effective

temperatures, radii, the orbital inclination and for single-lined spectroscopic binaries, the mass ratio are further optimized with the help of `Nelder-Mead`. This fitting mechanism works with a χ^2 minimization of the model with the observational data and returns a set of optimized values. After about 150 to 250 iterations, the mechanism converges and the final set of values is the base to estimate the uncertainties with `emcee`. Emcee samples around a point in the parameter space and with trying the values, it obtains parameter uncertainties. In this analysis, the starting point are the parameters that are fitted through Nelder-Mead (effective temperatures, equivalent radii, the inclination; and for single-lined spectroscopic binaries, the mass ratio) and Gaussians around them were set for the sampler to investigate (e.g. 3000 K for the temperatures).
Figure 3 shows the final fits (blue lines) of an eclipsing system and an ellipsoidal system.



(a) VFTS 248 (b) VFTS 430

Figure 3.: `EMCEE` results for an eclipsing binary and an ellipsoidal variable

4. Looking for mass-transferring systems

The results from fitting the parameters via `Nelder-Mead` and `emcee` are used to plot them in an HRD with added isochrones to find out if both components are located on the same isochrone. Because the effective temperatures and the radii of the components were fitted, the result can be plotted on the HRD. With isochrones [1] plotted on the same HRD, the age of the systems can be estimated. From that plot, it can be referred to if the system has undergone a phase of mass transfer if the components are not located on the same isochrone. That is because mass transfer has happened and the change of mass heavily impacts the main sequence lifetime of stars. If the stars have evolved separately and have formed at the same time, they should be located on the same isochrone. An example for two systems can be found in Fig. 4 with two different isochrones. Both of the components of VFTS 364 are located close to the 10^6 year isochrone (Fig. 4), meaning that they have likely been evolving independently of each other.

[1] http://stev.oapd.inaf.it/cgi-bin/cmd

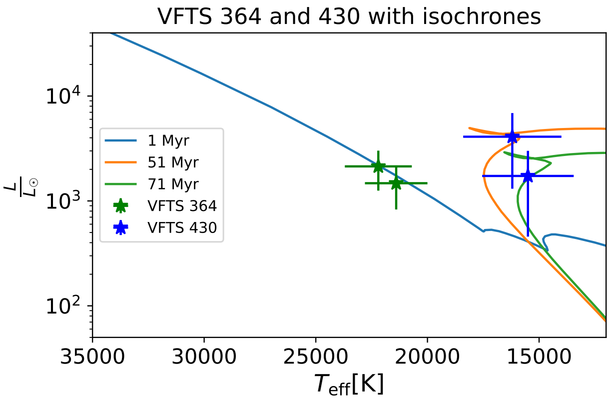


Figure 4.: VFTS 364 and 430 with two isochrones

It can be seen that the components of VFTS 364 lie on the 1 Myr isochrone. And for VFTS 430, the isochrone for the primary (51 Myr) does not lie on the secondary component. VFTS430's light curve shows no eclipses but ellipsoidal variability. This concludes that VFTS 430 is likely a mass-transferring system unlike VFTS 364 where both stars have evolved independently of each other.

5. Summary

The photometric analysis of 85 stars with OGLE data that also have spectroscopy available through BBC showed that 9 stars are eclipsing and 4 ellipsoidal variables were found. A more detailed analysis has been carried out for these systems except for the peculiar star VFTS 698 (Dunstall et al., 2012). Most of them are located on the same isochrone or close to it, making them evolve separately. For two of these twelve systems (VFTS 27, 430), a contact phase is likely because their components deviate more from the same isochrone. The periods for the eclipsing binaries ranged from 1.378 days for VFTS 240 to 12.945 days for VFTS 157.

6. Future work

In the future, this analysis should be carried out for more eclipsing binary systems, particularly in other regions of the sky. This is especially interesting in finding out a spatial dependency of the proportion of binary systems that have undergone a phase of mass transfer.

References

Collier Cameron, A., Pollacco, D., Street, R. A., et al., A fast hybrid algorithm for exoplanetary transit searches. 2006, *Monthly Notices of the Royal Astronomical Society*, **373**, 799, DOI: 10.1111/j.1365-2966.2006.11074.x

Conroy, K. E., Kochoska, A., Hey, D., et al., Physics of Eclipsing Binaries. V. General Framework for Solving the Inverse Problem. 2020, *The Astrophysical Journal Supplement*, **250**, 34, DOI: 10.3847/1538-4365/abb4e2

Dunstall, P. R., Fraser, M., Clark, J. S., et al., The VLT-FLAMES Tarantula Survey V: The peculiar B[e]-like supergiant, VFTS698, in 30 Doradus. 2012, *Astronomy & Astrophysics*, **542**, 1, DOI: 10.1051/0004-6361/201218872

Fahrion, K. & De Marchi, G., The hierarchical formation of 30 Doradus as seen by JWST. 2024, *Astronomy & Astrophysics*, **681**, A20, DOI: 10.1051/0004-6361/202348097

Lomb, N. R., Least-Squares Frequency Analysis of Unequally Spaced Data. 1976, *Astrophysics and Space Science*, **39**, 447, DOI: 10.1007/BF00648343

Offner, S. S. R., Moe, M., Kratter, K. M., et al., The Origin and Evolution of Multiple Star Systems. 2023, in Astronomical Society of the Pacific Conference Series, Vol. **534**, *Protostars and Planets VII*, ed. S. Inutsuka, Y. Aikawa, T. Muto, K. Tomida, & M. Tamura, 275

Pawlak, M., Soszyński, I., Udalski, A., et al., The OGLE Collection of Variable Stars. Eclipsing Binaries in the Magellanic System. 2016, *Acta Astronomica*, **66**, 421, DOI: 10.48550/arXiv.1612.06394

Scargle, J. D., Studies in astronomical time series analysis. II. Statistical aspects of spectral analysis of unevenly spaced data. 1982, *The Astrophysical Journal*, **263**, 835, DOI: 10.1086/160554

Udalski, A., The Optical Gravitational Lensing Experiment. Real Time Data Analysis Systems in the OGLE-III Survey. 2003, *Acta Astronomica*, **53**, 291, DOI: 10.48550/arXiv.astro-ph/0401123

Udalski, A., Szymanski, M., Kaluzny, J., Kubiak, M., & Mateo, M., The Optical Gravitational Lensing Experiment. 1992, *Acta Astronomica*, **42**, 253

Udalski, A., Szymański, M. K., & Szymański, G., OGLE-IV: Fourth Phase of the Optical Gravitational Lensing Experiment. 2015, *Acta Astronomica*, **65**, 1, DOI: 10.48550/arXiv.1504.05966

Villaseñor, J. I., Taylor, W. D., Evans, C. J., et al., The B-type binaries characterization programme I. Orbital solutions for the 30 Doradus population. 2021, *Monthly Notices of the Royal Astronomical Society*, **507**, 5348, DOI: 10.1093/mnras/stab2197