# The Power of Eccentric Binaries

Milena Ratajczak[1], OGLE Collaboration and BRITE Team

1. Astronomical Observatory, University of Warsaw, Al. Ujazdowskie 4, 00–478 Warszawa, Poland

Eccentric binaries may serve as a tool for studying several astrophysical phenomena, like orbital dynamics and gravitational effects of stars on each other, including tidally induced pulsations. We hereby present the selection of eccentric ellipsoidal variable stars identified in the OGLE and BRITE data collections, whose nature we unveiled by tracking radial velocity changes around the periastron. The selection includes the most eccentric system with massive stars known to date, as well as an intriguing binary with a compact component from the Galactic bulge.

## 1 Introduction

Binary stars with eccentric orbits are widely used to study various astrophysical issues, e.g. gravitational interaction of stars or their orbital dynamics. They are also important for stellar evolution studies, for which precise determination of stellar parameters, especially masses, is required, thus the importance of eclipsing binaries (EB) with eccentric orbits is increasing. Another class of intriguing eccentric binaries are tidally distorted stars, called heartbeat (HB) systems. In the following paper we will focus on two examples of systems belonging to the aforementioned groups of eccentric binaries – EB and HB systems.

## 2 Eclipsing binaries in eccentric orbits

Figure 1 illustrates the eccentricity $e$ – orbital period $P$ relation for eccentric systems found among spectroscopic binaries (9th Catalogue of Spectroscopic Binaries – SB9; Pourbaix et al., 2004). Not surprisingly, there is a lack of short period systems with high eccentricity – it is expected their orbits tend to circularise at a rapid rate. Eccentric systems with long orbital period are thus useful tools to study timescales of circularisation, which is a consequence of energy loss in systems with small periastron separation.

We have found in BRIght Target Explorer (BRITE) (Weiss et al., 2014; Pablo et al., 2016) data an intriguing highly eccentric system, which revealed its eclipsing nature. Variability of N Sco (HD 148703, V = 4.23 mag) was also spotted in the long-term photometry from the Solar Mass Ejection Imager (SMEI) (Jackson et al., 2004), which enabled us to determine the orbital period of the system (P $\sim$ 223.9 d). Since the time between eclipses is only $\sim$ 3.5 d the system turned out to be highly eccentric with $e = 0.93$. We have performed spectroscopic campaign using both mid-res (BACHES, PUCHEROS, FIDEOS), as well as high-res (SALT/HRS) spectrographs to track radial velocity (RV) changes and detect spectral lines of the secondary component around the time of periastron (at the highest RVs separation). The analysis of the data yielded the masses of components of $\sim$ 7.5 and 3.9 $M_\odot$, and radii of $\sim$ 3.7 and 2.1 $R_\odot$, for the primary and secondary, respectively. N Sco components

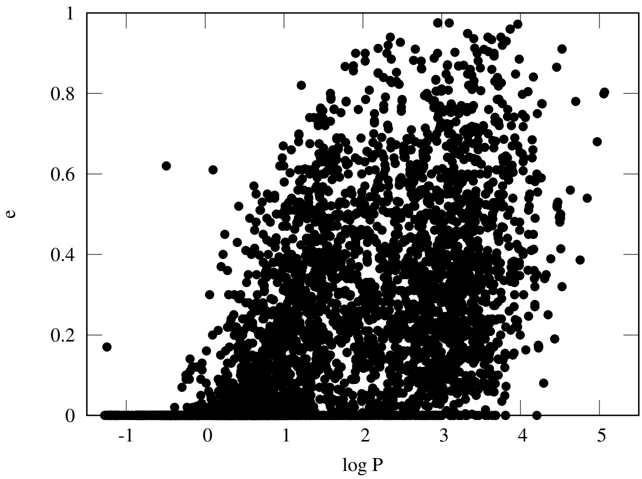


Fig. 1: Eccentricity – period relation for spectroscopic systems (from the SB9 catalogue).

are B-type stars with effective temperatures of 19 000 K and 12 800 K and the system is the most eccentric eclipsing binary with massive components found to date. The high eccentricity gives a new perspective on the issues of formation and evolution of such systems. More detailed analysis of N Sco is presented by Ratajczak & Pigulski (2018).

## 3 Heartbeat stars

Heartbeat stars (Thompson et al., 2012) are a class of eccentric binaries, which undergo tidal interactions at the periastron passage, causing stellar deformation and heating, and thus brightness variations. The light curves of such systems are characterised by an electrocardiogram-like signature. Tidal forces may also excite oscillations known as TEOs (tidally excited oscillations), which enable studying internal stellar structure via asteroseismology.

There are already more than 170 heartbeat systems known (Kirk et al., 2016)), most of which have been discovered by the Kepler mission (Koch et al., 2010). The vast majority of them are short-period low-mass stars with low-amplitude brightness changes (below 0.01 mag). Recent studies of HB stars (e.g. Pablo et al., 2017; Jayasinghe et al., 2019) have proved that this class of objects is much more diverse than expected and one can find among them both massive stars and high-amplitude brightness variation systems.

The shape of the flux variations of heartbeat systems depends on orbital inclination $i$, longitude of periastron $\omega$, and eccentricity $e$ of the system (Kumar et al., 1995), while the amplitude is related to the stellar masses and orbital separation at periastron. Because of these dependencies, the named parameters can, in principle, be derived from the light curves. Since this includes mass ratio of binary components, photometric mass estimations become possible even for objects without spectral lines (e.g. compact objects), like neutron stars (NSs) or even black holes (BHs). Therefore, high-amplitude eccentric HB systems can be very profitably searched for NSs and BHs in long-term photometric data sets, such as that collected

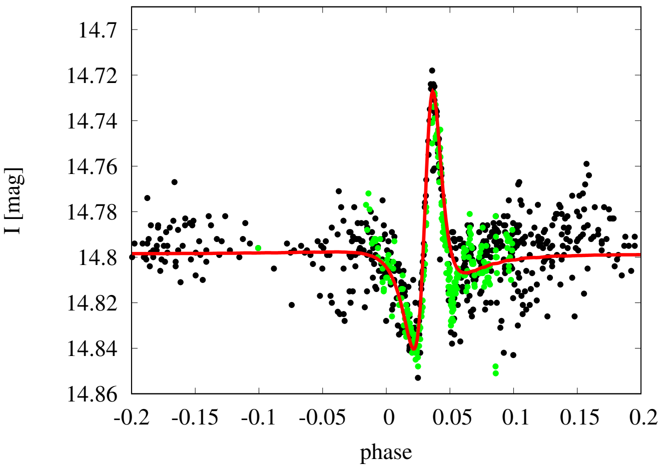


Fig. 2: OGLE I-band phased light curve of OHB-6312 with the best-fitting models (red line). Green points indicate data from the latest season.

by the Optical Gravitational Lensing Experiment (OGLE) project (Udalski et al., 2015).

Among OGLE collection of variable stars we have identified more than a hundred of objects showing heartbeat-like variations, both in the Galactic bulge, and in the Magellanic Clouds.

One of them is OGLE BLG-ELL-6312 ($V = 17.48\,\mathrm{mag}$, $I = 14.77\,\mathrm{mag}$, hereafter OH-B6312), which light curve (Fig. 2) resembles a heartbeat signal with a relatively large peak-to-peak variability of $\Delta I = 0.12\,\mathrm{mag}$. The orbital period of O-HB6312 is equal to $\sim 1079\,\mathrm{d}$, which makes it an HB system with the longest period known. Typically, heartbeat systems have much shorter orbital periods (Kirk et al., 2016), mostly shorter than 100 days. The pulse appearing in the light curve during the recent periastron started $\sim$ February 14th, 2019 and it lasted for about three months. The OGLE telescope followed the object photometrically with a higher-than-typical cadence to characterize the HB pulse in close detail. At the same time 6 mid-resolution (VLT/XSHOOTER) spectra were taken around the periastron passage to calculate RVs, which are crucial to determine spectroscopic orbit and parameters of the system components. Spectroscopic data revealed only one set of spectral lines (from one of the stellar components) and the rapid change of its RV (Fig. 3).

Using archival data in various passbands we have performed spectral energy distribution (SED) fitting. It occurred that the star which contributes most to the system brightness is a red giant of $T_{\mathrm{eff}} \sim 3\,400\,\mathrm{K}$. Preliminary combined modelling the OGLE $I$-band light curve and RVs with the PHOEBE code (Prša & Zwitter, 2005) resulted in the following orbital parameters: $e = 0.79$, $i = 55\,\mathrm{deg}$, $\omega = -28\,\mathrm{deg}$ and revealed that the most reliable solution (Fig. 2, 3) is that the system consists of a red giant of $\sim 1.8\,\mathrm{M}_{\odot}$ and a compact object of mass $\sim 3.9\,\mathrm{M}_{\odot}$, indicating an exceedingly massive neutron star or even a low-mass black hole.

A census of neutron star and black hole masses is critical to many aspects of astrophysics, from stellar evolution and mass-gap problem (e.g. Wyrzykowski & Mandel, 2019), to gravitational wave-emitting binary neutron star mergers (e.g.

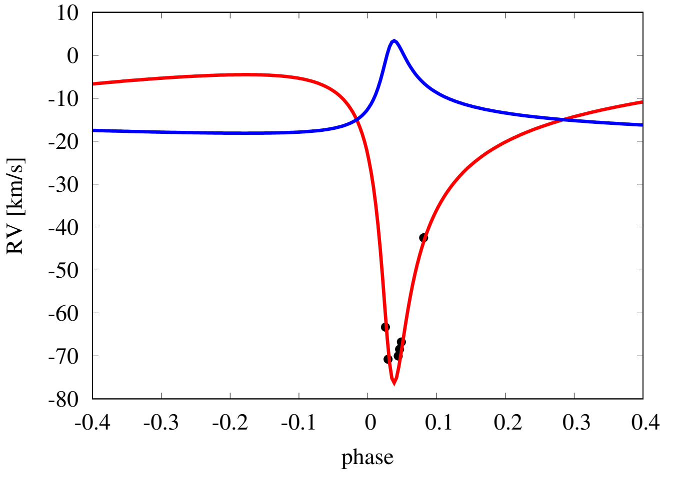


Fig. 3: Combined photometric and spectroscopic RV curves of both components of OHB-6312 derived from the same model as that used for the light curve above. Black points indicate the individual XSHOOTER RVs.

Smartt et al., 2017). Moreover, the mass function of neutron stars in binaries are the subject of intense study as they directly constrain the mechanism of core-collapse supernovae, and the physics of binary stars (Thompson et al., 2019). O-HB6312, for which the preliminary solution indicates its unseen companion lies in the mass gap, is therefore a unique system worth detailed investigation.

## 4 Summary

Eccentric binaries, both eclipsing systems, and heartbeat stars, are extremely useful tools to study various astrophysical phenomenon, among which one can list gravitational effects of stars on each other and orbital dynamics. The cases of N Sco and O-HB6312 are excellent examples of examination of these issues, which was possible by combining long-term photometric data from space and ground-based surveys with RVs from spectra taken around the periastron passage.

Further investigation of similar objects from the OGLE and BRITE collection is planned, which enriched by well-planned RV survey may bring more intriguing results.

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