True Mass-Luminosity Relation and Special Astrophysical Observatory Instruments

O. Malkov[1], A. Kniazev[2,3,4], V. Puzin[1], D. Kovaleva[1], and T. Burlakova[5]

[1] Institute of Astronomy, Russian Academy of Sciences, Moscow, Russia,
malkov@inasan.ru,
WWW home page: http://www.inasan.ru/~malkov
[2] South African Astronomical Observatory, Cape Town, South Africa
[3] Southern African Large Telescope, Cape Town, South Africa
[4] Sternberg Astronomical Institute, Lomonosov Moscow State University, Moscow, Russia
[5] Special Astrophysical Observatory, Russian Academy of Sciences, Nizhny Arkhyz, Russia

Abstract. We have started a project to study long-period massive eclipsing binaries in order to construct radial velocity curves and determine masses for the components. The results will be used to reconstruct the mass-luminosity relation (MLR), as the currently used MLR is presumably not correct for intermediate and high masses since it was constructed using double-lined eclipsing binaries, where the components are synchronized and consequently change each other's evolutionary path. Spectroscopic observations with SALT (SAAO), BTA (SAO) and Zeiss-2000 (TO) are described.

Keywords: stars: luminosity function, mass function; binaries: spectroscopic, eclipsing

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1 Introduction

The relationship between the mass of a star and its luminosity in the main sequence (mass-luminosity relation, MLR) is a fundamental law used in various fields of astrophysics. It is especially important for restoring the initial mass function (IMF) from the luminosity function of stars. An independent determination of the star's mass and its luminosity is possible only for components of binary systems of certain types. One of these types is orbital binaries (visual binaries with known orbital parameters and trigonometric parallax). These stars, as a rule, are wide pairs whose components do not interact with each other and in the evolutionary sense are similar to single stars. Another main source of independent mass determinations is eclipsing binaries with components on the main sequence, the spectrum of which shows the lines of both components (double-lined eclipsing binaries, DLEB). These are close pairs, the rotation of the components of which is synchronized by tidal interaction, and they evolve differently due to the slowdown of rotation. At the same time, in the mass region $M/M_{\odot} > 2.7$, MLR is based on data obtained for close DLEBs, and these data are applied to single stars. Apparently, such use of MLR is wrongful and can lead to systematically incorrect results.

2 Mass-Luminosity Relation of Rapid and Slow Rotators

The problem of determining the masses of the components of orbital binaries was discussed, for example, in the works of Docobo et al. (2016), Malkov et al. (2012), Fernandes et al. (1998). Henry (2004), Delfosse et al. (2000), Henry et al. (1999), Malkov et al. (1997) articles examine the problem of constructing MLR for low-mass stars. The exact parameters of DLEB stars and MLR based on them can be found, for example, in the works of Torres et al. (2010), Kovaleva (2001), Gorda & Svechnikov (1998), Andersen (1991), Popper (1980).

In order to combine these two MLRs (based on data on orbital binaries and DLEB stars), as well as to compare theoretical MLRs with empirical data, it was usually assumed by default that the components of separated close and wide binaries evolve equally.

However, comparing the radii of DLEB and single stars, Malkov (2003) found a noticeable difference between the observational parameters of the B0V - G0V DLEB components and single stars of similar spectral classes. This difference was confirmed by an analysis of independent studies published by other authors. Such difference also explains the disagreement of the published scales of the bolometric corrections.

The large radii and higher temperatures of the A-F components of DLEB stars can be explained by synchronization and the associated deceleration of rotation of such components in close systems. Another possible reason is the effect of observational selection: due to the non-sphericity of rotating stars, the values determined from observations depend on the orientation of their rotation axes; in this case, single stars are oriented randomly, and the components of eclipsing binaries are usually observed from the equator.

Then, in Malkov (2007), data were collected on the fundamental parameters of 19 components of long-period DLEBs. These stars, presumably, did not undergo rotation synchronization with the orbit period and, therefore, rotate quickly and evolve similarly to single stars. Only such data should be used to construct the relations (particularly, the mass-luminosity relations) for "isolated" stars in the mass range $M/M_{\odot} > 2.7$. The masses of components of other types of binary stars (orbital, resolved spectrally binary) rarely exceed this limit. Note that of the 19 components of DLEB stars mentioned above, only 13 have a mass exceeding 2.7 $M/M_{\odot}$. Our preliminary analysis shows that at least rapidly rotating stars of the late spectral subclasses B ($4.5 < M/M_{\odot} < 5.5$) exhibit slightly higher luminosities than the "standard" (based on data for slowly rotating stars) MLR predicted. Their radii, at the same time, exceed the radii of the components of short-period binaries, and the main sequence (MS) of these stars is shifted to the right relative to the MS of the components of close binaries. The lack of observational data makes it difficult to draw more definite conclusions. For the same reason, it is currently impossible to correctly assess the extent to which this can affect the IMF in the mass range $M > 2.7$ $M_{\odot}$: the available observational data for this mass range are too scarce. Information about the MLR (and other relations) of "isolated" stars should be obtained from dynamic determinations of the masses of the components of long-period massive eclipsing binary stars. Only after that it will be possible to revise the IMF for $M > 2.7$ $M_{\odot}$.

3 Selection of Objects and Observations

To construct the mass-luminosity relation of isolated stars long-period eclipsing B-A-F systems belonging to the main sequence are selected from the Catalog of Eclipsing Variables (CEV) catalog (Avvakumova et al. 2013; Avvakumova & Malkov 2014). These systems should also demonstrate the lines of both components in the spectrum. The selection uses additional information from the literature.

To obtain a radial velocity curve, we propose to carry out as minimum from five to ten spectroscopic observations for each of the targets, five observations for eclipsing binaries with circular orbits, and ten for pairs with non-circular orbits. Spectroscopic and photometric observations will be carried out in the northern and southern sky.

Spectroscopy of Southern Objects For observations of our object in the Southern hemisphere we constructed a sample of 42 eclipsing binary systems with periods larger than 15 days in the region of declinations δ from -75 till +10 available for observations with the High Resolution Èchelle Spectrograph (HRS, R=15000–65000; Bramall et al. 2012; Crause et al. 2014) at the 11-meter Southern African Large Telescope (SALT; O'Donoghue et al. 2006). Our plan was to use the Medium Resolution (MR) mode of this instrument with spectral resolution of

R$\sim$35000 covering spectral range 4000–8800 Å. In order to achieve the stated goals of the project we planned to reach an average signal-to-noise ratio (SNR) = 70-100 per pixel, since hot stars of temperature class B have only a few hydrogen and helium lines. We estimated the expected rotational velocities for the long-period eclipsing binary systems in the region of 10–50 km/s. Since the accuracy achieved in observations with MR mode is about 150-300 m/s, the use of MR mode seems reasonable. Obtained data should be reduced by the standard HRS MIDAS pipeline (Kniazev et al. 2019).

Spectroscopy of Northern Objects – SAO. At the 6-meter telescope BTA, we plan to conduct spectroscopic observations using recently designed high-resolution optical fiber-fed spectrograph (R=35000–100000). The spectrograph is capable of realizing planetary (several m/s) accuracies, and is ideal for use it in this task. From the year 2021 we expect the spectrograph to start operating in the trial operation mode and for scientific tasks. In the framework of the proposed study, a moderate spectral resolution mode of R=35000 will be used. In this mode, we expect characteristic accuracies of absolute radial velocity measurements in program stars of several tens of m/s. These accuracies are absolutely enough to implement program goals. In observations, the spectral range 4000 – 7000 A will be used, with an average SNR = 100 per pixel. As faint as 12 mag stars will be observed, and the exposure time for such stars (R=35000, SNR=100) will be 1 – 1.5 hour. The observed data will be reduced and analyzed using a pipeline based on the DECH package adopted for the reduction of the spectral data from the used fiber-fed echelle spectrograph.

Spectroscopy of Northern Objects – Terskol. The alpine Terskol peak observatory (TO) located at an altitude of 3150 m above sea level allows spectral observations in the range of 300 nm. The Zeiss-2000 telescope will be used as the main instrument for observing the program stars. The Zeiss-2000 telescope is equipped with a stationary èchelle spectrograph at the Coude focus (MAESTRO), which makes it possible to obtain spectra with a resolution R=50000, the radial velocity accuracy is about 1 km/sec. The operating range of the observed wavelengths is 3700-8000 A. The spectrograph characteristics meet the observation requirements stated in the program. A new suspended Cassegrain Focus Spectrograph (BACHES) is expected to be commissioned in 2021. The resolving power of the spectrograph is R=18000, which makes it possible to use it for observing weak objects inaccessible for observations on the MAESTRO spectrograph. An important feature of observations at the Zeiss-2000 telescope will be simultaneous spectral and photometric observations. Photometric observations can be carried out on a photometer mounted on a telescope guide (D =

200 mm). If necessary, the Zeiss-600 telescope will also be used for photometric observations. Spectral data processing will be carried out in DECH, MIDAS software packages. Photometric observations will be processed using the MaxIm DL program.

Photometric Observations. Photometric data for the studied objects are extracted from the literature and/or from the surveys ASAS, ASAS-SN, SuperWASP. For southern objects for which such data are not available, our application has been accepted for 50 hours at the 1-meter and 100 hours at the 40-cm LCO (Las Cumbres Observatory) telescopes. About 2000 photometric observations are made. It is also planned to submit applications for photometric observations to small robotic telescopes (mirror size 1 meter) of the South African Astronomical Observatory (SAAO). For photometric observations of northern objects, we plan to use a 60-cm telescope of the Ritchie-Chretien system of the Caucasus Mountain Observatory (KGO) SAI and the Zeiss-2000 telescope of the Terskol Observatory.

4 Pilot Results

First, we formed test sample for spectral observations with HRS/SALT and started our pilot project with SALT in 2017. This test sample and special software package FBS (Fitting Binary Stars) that was developed for the analysis of our spectral data are published in Kniazev et al. (2020). The radial velocity curves and the best-fit orbital elements for the two components of the FP Car binary system from the test sample are also presented.

Results of study of the long-period eclipsing binary star NN Del from the test sample are presented in Kniazev (2020). The constructed velocity curve is based on 19 spectra obtained between 2017 and 2019 years and covers all phases of the binary's orbit. The orbital period and eccentricity, as well as fundamental parameters of the components, were determined.

5 Conclusions

The immediate goal of the study is to obtain confirmation that massive ($M > 2.7$ $M_\odot$) fast-rotating stars do not satisfy the "standard" MLR (and other relations). This confirmation should be based on the analysis of high-quality spectroscopic and photometric observations of long-period eclipsing binaries of B-F spectral classes. Our observations and subsequent analysis will allow us to move towards building the true mass-luminosity relation, and, accordingly, to revise the IMF for stars with masses $M/M_\odot > 2.7$.

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