The After SDSS-IV, Letter of Intent: Andrew Tkachenko on behalf of the KU Leuven Gaia/K2/TESS/PLATO2.0 team
(Institute of Astronomy, KU Leuven, Belgium)

Constraining the theories of stellar structure and evolution through observational studies of (massive) binary stars

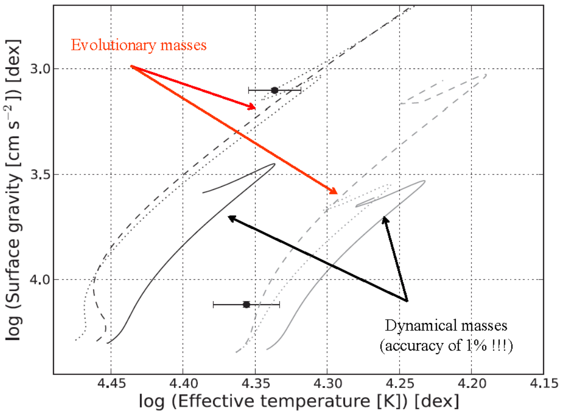

Fig. 1 Discrepancy between dynamical and theoretical masses in the V380 Cyg binary system. The primary component is more evolved and is associated with the lower log g value. The dashed and dotted tracks illustrate best fit evolutionary tracks obtained by varying mass and overshoot parameter, whereas the solid line refers to the tracks computed for dynamical masses and overshoot parameter of 0.2 (pressure scale height) typical for B-type stars.

State of the art. Asteroseismology is a powerful tool in modern astrophysics that allows us to "look" inside the stars and to study their interiors in great detail. Thanks to the fact that pulsating stars are found everywhere in the Hertzsprung-Russell (HR) diagram, asteroseismic studies become possible for stars over a large range in mass and ages. Despite the huge success of asteroseismology (largely driven by the launch of space missions such as MOST, CoRoT, and *Kepler*) in the past decade, it still remains a model-dependent research field, in which the model dependency is significantly larger for intermediate- and high-mass stars than for sun-like stars. Likely, binary stars provide us with the model-independent, dynamical measurements of masses and radii of their individual (often pulsating) stellar components. By studying different types of pulsating stars in binary systems, we have the unique opportunity of supplying the asteroseismic investigations with additional observational constraints (in terms of the dynamical masses and radii of stars), which naturally leads to the improvement of the current theories of stellar structure and evolution.

Massive stars (above ~5-6 solar masses) are the metal factories of the Universe, for which stellar evolution theory is least adequate. Despite the dominant impact of these objects on life cycles and on chemical enrichment of galaxies, massive stars were not sufficiently available in the fields of view of the above-mentioned space missions. Moreover, detailed chemical composition studies were performed for a limited number of massive binary stars with well-defined fundamental and orbital parameters. With this proposal, we will remedy the lack of the detections and detailed studies of massive binary stars. The two main issues addressed in the proposal are briefly outlined below.

Objectives. *Mass discrepancy* is one of the (major) problems that is currently pending a solution in the massive binary star research field. It stands for the difference between the stellar component masses inferred from binary dynamics (hereafter, dynamical masses), and those obtained from spectral characteristics of stars and evolutionary models (hereafter, theoretical masses). The V380 Cyg binary system is one of the best illustrations of the mass discrepancy observed in massive binary stars. Tkachenko et al. (2014, MNRAS, 438, 3093) found that the mass discrepancy exists for both components of this binary at the level of ~10% (for 11.4/7.0 solar masses primary/secondary), and the one for the primary cannot be explained by either the effects of rotation or significantly increased core overshoot, or a combination of both (see Fig. 1). However, in the literature studies dedicated to the analysis of massive binary stars, it is pointed out that the discrepancies between the dynamical and theoretical masses can be resolved by introducing unusually large values of the core overshoot parameter in the models of stellar structure and evolution (e.g., Guinan et al. 2000, ApJ, 544, 409). Such large values of core overshoot are not supported by asteroseismic studies of single stars in the same mass range. The mass discrepancy problem clearly points to some missing physical ingredients in stellar structure and evolution theory, as the dynamical masses of binaries are purely observational and model-independent values. Our ultimate goal is to reveal the shortcomings in the current theories of stellar structure and evolution to finally approach the solution of the mass discrepancy problem for massive stars.

Rotationally-induced mixing. A substantial enhancements of surface helium and nitrogen with the rotation rate of massive stars was theoretically predicted by Meyner & Maeder (2000, A&A, 361, 101) and Heger & Langer (2000, ApJ, 544, 1016). The authors explained the effect by rotationally-induced mixing that brings He and N to the surface of the star, alongside increasing its lifetime on the main-sequence. The surface nitrogen enrichment vs. projected rotational velocity ($v\sin i$) trend was observationally detected by Hunter et al. (2008, ApJ, 676, L29) who studied 135 single early B type stars in the Large Magellanic Could (LMC). The hydrogen core burning stars were found in three distinct groups as shown in Fig. 2. The stars of Group 1 are the most rapidly rotating objects in the sample showing mild surface nitrogen enrichment; the Group 2 objects are the slowly rotating stars with substantial enhancement of nitrogen abundances. Both groups of stars are in contradiction with the above-mentioned theoretical predictions. However, a large fraction of the analysed stars was found to follow the theoretically predicted trend of increasing surface nitrogen abundance

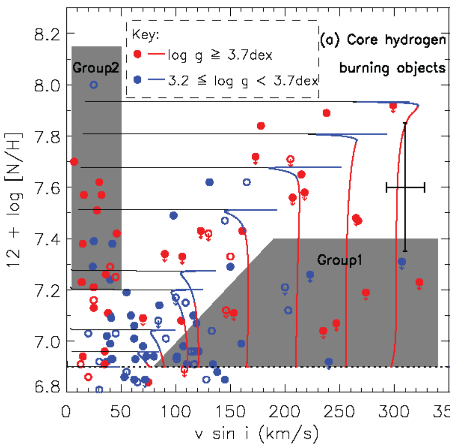

Fig. 2 Nitrogen abundance (12 + log[N/H]) vs. the *v*sin*i* for core hydrogen burning stars. The two groups of stars that do not follow the general trend are highlighted by shaded regions.

with *v*sin*i* (see Fig. 2). The observational trend found by Hunter et al. (2008) was subjected to a number of discussions in the community, where particularly Aerts et al (2014, ApJ, 781, 88) showed that neither the *v*sin*i* nor rotational frequency of a massive star have predictive power for the surface nitrogen abundance. Instead, there is a clear correlation between the effective temperature/the dominant acoustic oscillation mode of a star and atmospheric nitrogen abundance. With this project, we intend to measure atmospheric chemical compositions of eclipsing binary stars to verify the surface nitrogen abundance vs. *v*sin*i* trend predicted by the current theory and detected by Hunter et al. (2008) for single B-type stars. In our analysis, we will benefit from the precisely determined values of the surface gravity (from dynamical mass and radius) and the effective temperature (net result of the removed degeneracy between log *g* and T*eff*) of a star to measure individual abundances with the precision higher than the one typical for single stars in the same mass/spectral type range. We will confront our results to those of Hunter et al. (2008) and Aerts et al. (2014) to 1) check whether any of the announced correlations are found in our sample, and 2) see whether the differences in the results can be attributed to the effects of tides in binary stars.

Star samples, observations, and methodology. The goals will be achieved by providing homogeneous analyses of statistically significant samples of (pulsating) massive binary star systems. The star samples will be compiled using the objects studied in the literature as well as those observed/discovered with different ground-/space-based (photometric) instruments. The BRITE, K2, and TESS missions are the three main sources of precise space-based photometry as the massive stars are best represented in their fields of view (compared to e.g., the original *Kepler* mission and PLATO2.0). In total, about 100-150 binary systems will be characterized from combined spectroscopic and photometric data.

The ground- and space-based photometric data need to be complemented with medium- to high-resolution spectroscopic material obtained with ground-based facilities. The After SDSS-IV activity, with its specific focus on time-domain astronomy, is an ideal tool for collecting spectroscopic observational material required for the success of the proposed project. Since the project focuses mainly on bright binary stars, the desired signal-to-noise ratio (S/N) of ~100 per pixel can be obtained with 2m class telescopes. A certain instrument set-up is essential for the success of the proposed research: 1) medium- to high-resolution (30 000 and above) instrument is needed to resolve in detail spectral lines of our targets, in particular of the individual stellar components that are spinning synchronously with their intermediate-/long-period orbits. 2) The wavelength coverage should extend to the visible range (down to ~400 nm) where the majority of spectral lines of OB-type stars are found. Essentially, the ideal instrument set-up for the realization of our project is the wavelength range of current eBOSS/BOSS, but about twice the resolving power of APOGEE.

To reach the main goals of the project, a homogeneous analysis of all the selected stars will be performed. A semi-automated methodology was recently developed by us for the analysis of pulsating stars in binary systems, which includes three basic analysis steps. The three steps are: 1) *photometric analysis* (modelling the binarity signal with the aim to extract precise fundamental parameters of stars; the extraction of individual pulsation modes for further asteroseismic modelling), 2) *spectroscopic analysis* (spectral disentangling and interpretation of the obtained spectra to infer atmospheric parameters and chemical compositions of stars), 3) *statistical analysis* to identify the shortcomings in the current theories of stellar structure and evolution, to resolve the mass discrepancy problem, and to address the currently existing issues with theoretical predictions of the rotationally-induced mixing in massive stars.

Impact of the proposed research. The novelty of this project is situated in the fact that it will 1) provide a valuable test of the theoretical predictions for the rotationally-induced mixing in high-mass stars, 2) provide a solution for the existing mass discrepancy problem, thus allowing to improve the current theories of stellar structure and evolution for massive stars. All the data will be homogeneously reduced and analyzed, which will yield unbiased observational information on stellar fundamental and pulsation properties of stars, such as masses, radii, ages, spectral characteristics, frequencies and amplitudes of individual pulsation modes, etc.