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)

Binary star astrophysics: towards empirical mass-luminosity relations for different metallicity values

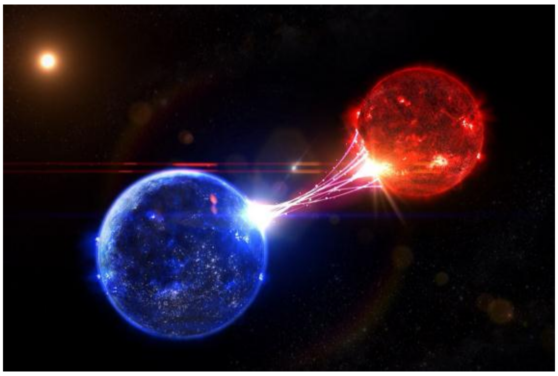

Fig. 1 An artist image of an interacting binary star system (taken from www.cozydark.com).

State of the art. Stellar evolution is well-understood on a global basis nowadays. The mass and initial chemical composition of a star are the key properties that define its evolution. All stars are formed from molecular clouds by means of gravitational collapse, and go through protostar (characterized by significant accretion of matter from its surrounding envelope) and pre-main-sequence (end of the main accretion phase; gravitational contraction is still the main energy source) phases of evolution until settling on the main-sequence (MS) when the nuclear hydrogen burning starts. As soon as all hydrogen has been exhausted in the core, depending on its initial mass, the star goes through the red giant or the supergiant phase of its evolution, to finally explode as a supernova or to expel its outer layers as planetary nebulae, leaving behind a compact stellar object (a black hole/neutron star or white dwarf).

While stellar physics and evolution are understood in these general terms, we lack important physical ingredients, despite extensive research during the past decades. Even our knowledge about the structure and age of stars in the core hydrogen burning phase is poor in terms of aspects such as the properties of internal rotation and angular momentum. Furthermore, mixing processes near the stellar core of intermediate- to high-mass stars in general play an important role in their evolution, as additional hydrogen is transported into the core, which significantly increases the lifetime of the stars on the MS. Understanding stellar evolution, which is largely driven by the processes occurring in the deep interiors of stars and by the dynamics in their atmospheric layers, is of major importance to understand the evolution of galaxies, chemical evolution of interstellar matter, details of star formation and death, formation and evolution of exoplanets, etc.

Objectives. The mass-luminosity relation (see Fig. 2 for a schematic representation) is an expression that relates the total amount of energy emitted by a star (luminosity) to its mass. The relation is essentially a power law where both luminosity and mass are expressed in the solar units, and the luminosity is given by the mass to the power of X (with X between 1 and 4). The value of X strongly depends on the mass range considered and is the largest/smallest for the low (mass range between ~0.4 and 2 solar masses) and high (above 20 solar masses) mass stars, respectively. The relation is empirically determined from the analysis of eclipsing binary stars and holds for the stars on the main-sequence.

The mass-luminosity relation is currently well-established for main-sequence stars found in the Milky Way, i.e. for certain metallicity value. However, one expects the relationship to be metallicity-dependent. Indeed, a star with the same mass but a lower metallicity is expected to have higher luminosity due to lower opacities and the radiation “freely” flowing to the stellar surface. The current LoI calls on using high-precision (space- and/or ground-based) photometry complemented by medium- to high-resolution spectroscopy, to study eclipsing binary stars in the Small (SMC) and Large Magellanic Clouds (LMC) with the ultimate goal of establishing empirical mass-luminosity relations for metallicities different from that of the Milky Way galaxy. The masses and the radii of the individual stellar components of eclipsing binary stars are determined with very high precision (up to 1-2 %) from basic binary dynamics, whereas the luminosity is derived from the radius of the star and its effective temperature inferred by “classical” spectroscopic methods. High accuracy in the determination of the effective is also achieved provided the degeneracy between the temperature and surface gravity of the star can be removed by fixing the latter to its dynamical value. The net result of the proposed research is two-fold: 1) empirical mass-luminosity relations for metallicity values of the SMC and LMC; 2) an efficient tool for the determination of precise, model-independent masses of stars provided their distances are known (e.g., from the Gaia mission). The latter is particular important in the view of the upcoming exoplanet search space missions such as TESS and PLATO2.0, which very much rely on precise fundamental parameters of host stars to measure the properties of exoplanets with high precision.

Star samples, observations, and methodology. The goals will be achieved by providing homogeneous analyses of statistically significant samples of binary systems found in the Magellanic Clouds and containing individual stellar components in large dynamical range of stellar masses. Statistically, more than 50% of stars are found in binary (or multiple) star systems. The star samples will be compiled from the objects studied in

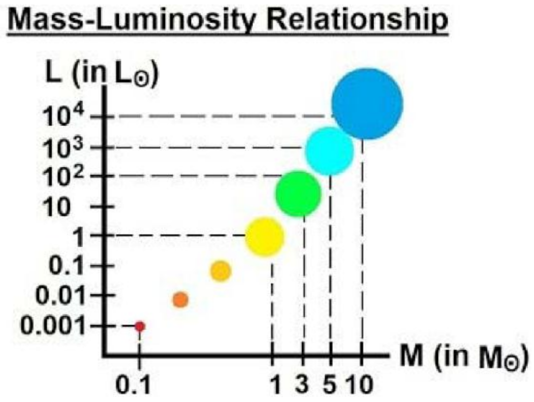

Fig. 2 Schematic representation of the mass-luminosity relation. Source: Astronomy – Ch. 17: The Nature of Stars: Mass-Luminosity Relationship

the literature and from the archives of different ground-based (photometric) instruments. The samples will also include the objects observed with the TESS mission, which is supposed to "look" at part of the Clouds. In total, about 200-300 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 the spectroscopic observational material required for the success of the proposed project. Provided the surface gravities of stars can be fixed to their dynamical values, the effective temperatures are then well-constrained from Balmer lines, even at intermediate signal-to-noise ratio (S/N) values (~50-60). No particularly high S/N is required for the determination of the radial velocities of stars (at least for those that show sufficient amount of lines in their spectra) either. Thus, 2m class telescopes are the ideal instruments for collecting spectroscopic information for our project. 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 slowly rotating solar-like pulsators and 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 OBAF-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 goal of establishing empirical mass-luminosity relations, a homogeneous analysis of all the selected stars will be performed. A semi-automated methodology was recently developed by us for the analysis of binary star 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), 2) *spectroscopic analysis* (spectral disentangling and interpretation of the obtained spectra to infer atmospheric parameters and chemical compositions of stars), 3) *statistical analysis* to establish empirical mass-luminosity relations for different metallicity values.

Impact of the proposed research. The novelty of this project is situated in the fact that it will 1) deliver a tool for the determination of basically model-independent masses of stars with known distances, 2) provide an independent check of the distances delivered by Gaia for stars in common with our sample, and 3) provide a valuable input for testing and improving the current theories of stellar structure and evolution, by means of asteroseismic methods complemented with high-precision, model-independent masses and radii of stars. All the data will be homogeneously reduced and analyzed, which will yield unbiased observational information on fundamental properties of stars, such as their masses, radii, spectral characteristics, etc. Due to similar dynamics with binary stars and due to the fact that the characterization of exoplanets requires a good knowledge about host stars in terms of their fundamental parameters, the proposed project is extremely important in the view of the upcoming exoplanet search missions, like TESS and PLATO2.0. The empirical mass-luminosity relations will also offer an independent verification of the masses inferred through asteroseismic methods for stars observed with the PLATO2.0 mission.