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Searching for Be stars using multi-band photometry

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Abstract. Classical Be stars are a subset of main-sequence B stars that present viscous Keplerian decretion disks, responsible for their emission lines. There are several open questions regarding them. How do they become fast rotators? We know that in general, they are by far the fastest among non-degenerate stars. What is the role of metallicity in their evolution? How do they evolve during and past the main sequence? The goal of the MSc project here introduced is to use the S-PLUS survey alongside well-consolidated models of B and Be stars to search, identify and classify Be stars in different environments, mainly in the Galaxy and Magellanic Clouds. Using artificial populations, S-PLUS theoretical magnitudes can be synthesized in all used bandpasses, which will enable us to separate Be stars from the rest of the population. This will be crucial when analyzing real data.

Resumo. Estrelas Be clássicas são um subconjunto de estrelas B na sequência principal que apresentam discos de decréscimo viscosos Keplerianos, responsáveis pelas linhas de emissão destes objetos. Existem muitas questões em aberto sobre estes astros. Como se tornam rotadores rápidos? Sabemos que de longe, são as estrelas mais rápidas entre as não degeneradas. Qual o papel da metalicidade na evolução? Como evoluem durante e após a sequência principal? O objetivo do projeto de Mestrado aqui introduzido é utilizar o levantamento S-PLUS em conjunto de modelos bem consolidados de estrelas B e Be para procurar, identificar e classificar estrelas Be em diferentes ambientes, principalmente na Galáxia e nas Nuvens de Magalhães. Fazendo uso de populações artificiais, as magnitudes teóricas do S-PLUS podem ser sintetizadas em todas bandas do *survey*, o que nos permitirá separar estrelas Be do restante da população. Isto será crucial quando analisarmos dados reais.

Keywords. Stars: emission-line, Be – Hertzsprung-Russell and C-M diagrams

1. Introduction

The nature of Be stars, a subclass of main sequence B stars, remained elusive even after decades of active research. It is now understood that classical Be stars are mainly B type, non-supergiant stars with a rotation rate near the stellar critical limit, which have or had at some point emission lines in their spectrum due to a viscous decretion disk formed by material ejected from the star (Rivinius, Carciofi & Martayan 2013). The mechanism behind the mass ejection has been recently firmly established as due to non-radial pulsations (Baade et. al. 2016, 2018).

Be stars are perfect astrophysical laboratories to study the effects of fast rotation on the star's structure. Owing to fast rotation, close to or sometimes even at the critical limit, Be stars become flattened, leaving the stellar equator with weaker surface gravity, thus colder and fainter than the pole. Aside from important observational consequences of this gravity darkening, which makes Be stars seen pole on (edge on) to appear brighter and bluer (fainter and redder), fast rotation also strongly affects the stellar interior, leading to transport of matter and angular momentum from the core to the surface, as has been extensively studied by the group of the Geneva Observatory and their collaborators (Georgy et. al. 2013). However, recent results from a survey of the angular momentum loss rate by Be stars in the Small Magellanic Cloud (SMC) suggest that the state-of-the-art models of the Geneva group still falls short in explaining the inner structure of Be stars (Rímulo et. al. 2018).

Another distinguishing characteristic of Be stars is their photometric, spectroscopic and polarimetric variability, observed in a wide range of time scales, ranging from hours to decades. Short-term variability is generally associated with photospheric events (pulsation, mass-loss events), while larger timescales are related to processes occurring on the disk, such as its formation/dissipation (Haubois et. al. 2012), binary interactions (Panoglou et. al. 2016), and global density oscillations (Carciofi et. al. 2009).

Be stars are quite common, comprising about 10% to 50% of the B star content in a given population, depending on the metallicity (the larger the metallicity, the smaller the Be/(B+Be) fraction, see Sect. 7.2.2. of Rivinius et. al. 2013). Naturally, most of the known Be stars are in the Galaxy or nearby dwarf galaxies such as the Magellanic clouds (LMC and SMC; Rivinius et. al. 2013). Recently, Be star research has been extended to the Andromeda galaxy by Peters et. al. (2020), who used HST Hα emission survey to measure its Be star content. Important aspects concerning both galactic and extragalactic Be stars are their evolutionary status, internal structure, rotation rate, and Be incidence, which are all affected by their metallicity in complex ways (Georgy et. al. 2013). Therefore, studying Be stars in different metallicities is a matter of current interest, as it offers the opportunity to test present-day models of fast-spinning stars under different conditions.

Large-scale ground-based surveys, such as OGLE (Udalski, Kubiak & Szymanski 1997; Soszynski et. al. 2008) and more recently S-PLUS (Mendes de Oliveira et. al. 2019) offer the opportunity to accelerate Be star research in an exponential way. There are a handful of works in the literature that made use of photometric data to identify and classify Be stars from large surveys. One study for instance using MACHO data (Alcock et. al. 1997) was conducted by Keller et. al. (2012) for stars in the Galactic Bulge. These studies, however, used only broad-band data, which makes identification and classification of Be stars rather uncertain. Surveys with narrow bands centered at prominent emission lines such as Hα allow for a more precise characterization of the star and increase the chance of positive identifications (Peters et. al. 2020). This was also clearly demonstrated in cluster studies; for instance, McSwain & Gies (2005) used broad-band data in conjunction with Strömgren narrow-band measurements to investigate the Be star population of Galactic open clusters. Their study was only possible because the narrow-band Hα data allowed for a clear separation between the B and Be populations.

In the MSc project here introduced, the main goal is to conduct the most comprehensive search and classification of Be stars in the Galaxy and Magellanic Clouds yet done. We will use data of the S-PLUS survey (Mendes de Oliveira et. al. 2019), whose scope will allow studying Be stars in different environments (field stars, cluster stars, etc.) and for several different stellar populations (thin disk vs. thick disk, for instance). To reach this goal, we propose the following steps that are further detailed below:

1. Develop the ability to build stellar populations.
2. Use BeAtlas to obtain synthetic spectra for each star in the population and produce synthetic S-PLUS fluxes and colors.
3. Determine from the models what are the best diagnostic tools to identify and classify Be stars.
4. Use the developed tools to study a sample of the S-PLUS survey.

In Figure 1, we present a tiny flowchart containing the explained proposed steps above.

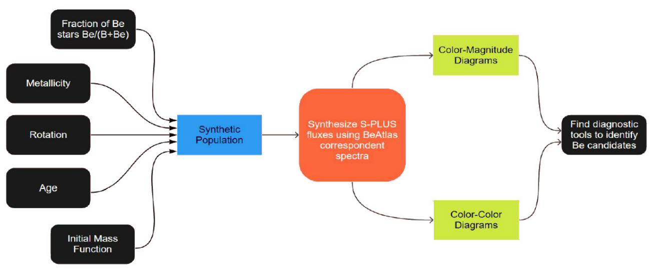

Figure 1. Flowchart explaining the previous proposed steps.

2. HDUST and the BeAtlas grid

BeAtlas (Mota 2019) is a grid of models of B and Be stars created using the HDUST code (Carciofi & Bjorkman 2006). It will provide the necessary models to develop the planned synthetic population of B and Be stars, allowing us to produce diagnostics based on the S-PLUS colors combinations to find Be stars in a variety of Galactic environments and in the Magellanic Clouds.

BeAtlas consists of two grids. The first (second) contains models without (with) a disk and they both cover a great number of values for many important system parameters. BeAtlas also considers different inclination angles (from 0 to 90 degrees), which is particularly important for rotating stars, as their SED is highly dependent on the viewing angle.

3. S-PLUS and estimates of possible candidates

The Southern Photometric Local Universe Survey (S-PLUS) is imaging more than 8000 squared degrees of the celestial sphere in 12 optical bands using a dedicated 80 cm robotic telescope, the T80-South, at the Cerro Tololo Inter-American Observatory, in Chile.

As detailed in Mendes de Oliveira et. al. (2019), the S-PLUS survey is divided into five sub-surveys: the Main Survey, the Ultra-Short Survey, the Variability Fields, the Galactic Survey (of great importance for this project in the future), and the Marble Field survey.

The filter system used in S-PLUS is the Javalambre 12-filter system, consisting of both broad-band and narrow-band filters. This filter-set is particularly well suited for this project, because the broad-band filters will allow probing the shape of spectral energy distribution (SED) in detail, including the Balmer and Paschen discontinuity, and the narrow band filter J0660, centered on Hα, will serve as a key diagnostic for line emission.

The survey PI, Dr. Claudia Mendes de Oliveira, in a private communication, indicated that the predicted number of stars to be observed after the end of the main survey is about 10 million objects, in an area of 8000 square degrees. We used the above number to obtain an estimate of 24 000 Be stars that will be observed by S-PLUS, assuming that 15% of B stars are Be stars (Rivinius et. al. 2013) and that Be stars are active (i.e., have a disk) 20% of their time (Figueiredo, A., priv. comm.).

4. Conclusions

There is a great expectation in our side to present interesting results up until the 16th S-PLUS meeting, in the end of this year. We mainly conclude that this project has the potential of increasing the number of Be stars currently known by one order of magnitude, using only the data from the S-PLUS survey. It is important to notice that the main Be spectra database existing today, BeSS database[1], contains about 2300 objects (Be, Herbig Ae/Be, and B[e] stars). This may seen like a small number in the epoch of multi-messenger astronomy, but this type of object (Classical Be stars) present complex variability, and there is a huge observational bias towards earlier types of B stars.

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