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Triennial Report of Division G Working Group on Active B Stars, 2018 - 2021

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1. Introduction

The Working Group on Active B Stars (WGABS, formerly Working Group on Be Stars) was re-established under IAU Commission No. 29 in 1979 to promote and stimulate research and international collaboration in the field of active B stars. The focus of the WG has increasingly shifted from Be stars to all types of active B stars including topics such as mass loss and accretion, pulsations, rotation, magnetic fields, and binarity, X-ray phenomena, fundamental parameters, and to promote collaboration and interaction between scientists specializing in these studies.

We have a well-developed website that is ready to serve our community†. We are also working to find an appropriate forum for a Newsletter, suitable for modern scientific communication.

The WGABS is open to all researchers interested in the field. Currently there are 107 members of WG Active B stars under Division G Stars and Stellar Physics.

Over the last decade, active B-type stars have emerged as laboratories for the examination of phenomena with a broad range of astrophysical applicability. The Keplerian decretion disks of classical Be stars are ideal test-beds for disk physics, insights from which can be applied to protoplantery disks and black hole accretion disks. Similarly, the magnetospheres of magnetic B-type stars share broad similarities with those of planets and ultracool dwarfs, making them ideal test-beds due to the relative ease with which they can be observed and characterized.

2. Developments within the past triennium

2.1. *Community efforts and meetings held in the reporting period*

In the reporting period, the active B star community engaged, among others, in the following activities.

- A workshop on "The γ Cas phenomenon in Be stars" was held in Strasbourg, Sep. 3rd–5th, 2018 to confront the different views put forward to explain their distinct properties.
- A conference called "Massive Stars and Supernovae" was held in honour of Nidia Morrell at the end of 2018 in Bariloche, Argentina. Although the meeting was not specifically dedicated to active B stars, it hosted numerous presentations on physical mechanisms affecting the evolution of massive stars and thus naturally attracted the attention of WGABS members.
- A "Stellar Magnetism and Spectropolarimetry" workshop in Thousand Oaks, California, held Dec. 10th-14th 2018, focused on the magnetic properties of massive stars (including B-type stars) and on topics ranging from magnetic characterization to binary interactions and circumstellar structures.

† http://activebstars.iag.usp.br/bstars/index.php

• "Stars and their variability, observed from space: Celebrating the 5th anniversary of BRITE-Constellation", a conference in Vienna, Aug. 19th-23rd, 2019, examined asteroseismology, rotational and wind variability, and magnetic phenomena.

• The "MOBSTER-1 virtual conference", held Jul. 12th-17th, 2020, was the inaugural conference of the MOBSTER (see Sect. 2.3.3) Collaboration and focused on five major themes: binarity; asteroseismology; magnetic characterization; evolution; and rotation, winds and outflows. A large cross-section of the field of massive stars was represented, and results enabled by *TESS* and other recent missions were presented.

• With the impending retirement of the Hubble Space Telescope, astronomy is poised to lose access to *high-dispersion ultraviolet spectroscopy*. A collaboration has formed to launch *PolStar*, a mid-sized UV spectropolarimeter that will offer high-S/N, high-resolution spectroscopy, low-resolution spectroscopy, and full-Stokes polarimetry (Scowen 2019; Scowen et al. 2019). The *PolStar* collaboration is moving forward with a MIDEX proposal, in competition with 5 other projects. A PolStar Science Meeting was held in virtual format on Mar. 15th-17th, 2021.

2.2. *Upcoming Events*

• "OBA Stars: Variability and Magnetic Fields", a hybrid virtual/in-person conference in St. Petersburg, will be held Apr. 26th-30th, 2021. The meeting will discuss the origin and evolution of magnetic fields in hot stars; associated phenomena such as chemical spots; instrumentation and observational techniques; magneto-asteroseismology; and will provide a forum for updates on results from large collaborations and space missions such as *Kepler*, *TESS*, *APOGEE*, *Gaia*, *BRITE*, etc.

• "IAUS 361: Massive Stars Near & Far", a virtual meeting to be held May 3rd-7th 2021, with an in-person conference scheduled for May 8th-13th, 2022. Originally scheduled for May 2020; postponed for obvious reasons. Amongst other topics, the conference will address rotation, mixing, pulsation, eruptions, and magnetic fields in hot stars.

• The "BeXRB2021" meeting, originally scheduled for July 27th–29th 2020 in Valencia, is now planned for July 26th–28th 2021. The conferences of Be/X-ray binaries have evolved into a series aiming at a comprehensive theoretical and observational coverage of Be/X-ray binaries and similar objects.

• The meeting entitled, "Hot Stars. Life with Circumstellar Matter", was to take place between July 19 and 24, 2020, in the city of Almaty, Kazakhstan but has now been postponed until 2022.

• There is a planned IAU Symposium entitled "Stellar Rotation: the portrait revealed by space missions and ground-based large surveys". The meeting is expected to be held in Natal, Brazil, from 5th to 9th December 2022.

2.3. *Scientific highlights*

New investigations reported in the literature reveal the study of active B stars as an active and productive area of research that is providing new scientific results. In this report we focus on four main topics discussed in the subsections below.

2.3.1. *Magnetic stars*

A population study of main sequence (MS) magnetic B-type stars by Shultz et al. (2019b), utilizing various high-resolution spectropolarimetric survey data (Alecian et al. 2015; Wade et al. 2016; Fossati et al. 2015; Schöller et al. 2017), found mass-dependent decrease in surface magnetic flux with age, validating an earlier examination based on incidence statistics (Fossati et al. 2016). This may point to a flux decay mechanism driven by subsurface convection zones (Jermyn & Cantiello 2020).

Weak magnetic fields in supergiant BA-type stars have been detected (Neiner et al. 2017; Martin et al. 2018); the high incidence of detection (as compared to the canonical 10% on the MS) may indicate that these are not fossil fields, but dynamo fields generated in subsurface convection zones.

The merger hypothesis for the origin of fossil magnetic fields (motivated by the similar 10% fractions of fossil fields and binary mergers) received support from magnetohydrodynamic simulations (Schneider et al. 2019). Alternatively, the low binary fraction may be a consequence of fossil field destruction by tidally induced pulsations (Vidal et al. 2019). Pre-MS surveys have shown that the magnetic incidence declines from 100% for convective stars to 10% immediately after the stars become fully radiative (Villebrun et al. 2019). Distinguishing between the merger and pre-MS dynamo scenarios is a high priority for future research.

Several novel magnetic B-type binary systems have been studied in detail (e.g. Shultz et al. 2018; González et al. 2018; Shultz et al. 2021a), including the first two magnetic eclipsing binaries (Kochukhov et al. 2018; Shultz et al. 2019c), one of which is an 'identical twin' system with equal mass components. The masses and radii of the components of the unique doubly magnetic B-type binary ϵ Lupi were directly measured using heartbeat variability detected in the *BRITE* light curve (Pablo et al. 2019).

Evolutionary models incorporating external and internal magnetic effects have been developed (e.g. Keszthelyi et al. 2019, 2020, 2021; Takahashi & Langer 2021). These have shown that the observed decrease in surface rotation with age (Shultz et al. 2019b) is consistent with magnetospheric braking (Keszthelyi et al. 2020), and further reproduce short-term cyclical rotational oscillations (Mikulášek et al. 2018; Shultz et al. 2019a) via internal Alfvén waves (Takahashi & Langer 2021).

Several pulsating magnetic B stars have been discovered in *Kepler* and *TESS* data (Bowman et al. 2018; Buysschaert et al. 2019; Shultz et al. 2021b), and the effects of magnetic fields on pulsational properties have been modelled (Prat et al. 2019).

Centrifugal breakout, analogous to magnetotail reconnection in planetary magnetospheres, is now known to govern mass balancing in centrifugal magnetospheres (Shultz et al. 2020; Owocki et al. 2020). Auroral maser emission has been reported around several stars (Das et al. 2018, 2019a,b; Leto et al. 2019, 2020a,b), increasing the known number of 'main sequence pulsars' from the previous population size of one (Trigilio et al. 2000). One star also shows indications of X-ray aurorae (Leto et al. 2020b).

Ultra-weak fields detected in A-type stars (e.g. Blazère et al. 2020) and photospheric spots inferred from the *BRITE* light curves of O-type stars (Ramiaramanantsoa et al. 2018) may indicate ubiquitous, small-scale magnetic fields generated by subsurface convection (Jermyn & Cantiello 2020). Prominences, flares, and spots due to small-scale magnetic fields have been suggested as an explanation for dips in the X-ray light curve of γ Cas (Smith & Lopes de Oliveira 2019), rotational modulation in the *Kepler* and *TESS* light curves of a large fraction of BA-type stars (Balona et al. 2019; Balona 2019), and possible flaring in the *TESS* light curves of Be stars (Balona & Ozuyar 2020a). However, claims of flares and rotational modulation in A-type stars have been challenged (Pedersen et al. 2017; Sikora et al. 2020). Flaring has been suggested as the ejection mechanism feeding the disks of Be stars (Balona & Ozuyar 2020b).

2.3.2. *Classical Be Stars*

The triennium saw two discoveries involving classical Be stars capture the public imagination with wide media coverage. The first was the detection of LB-1, a system proposed to harbour a (~ 70 $M_\odot$) black hole (BH; Liu et al. 2019), before the BH mass was revised to a lower value (Liu et al. 2020). The second was the suggestion that HR 6819 is a hierarchical triple with a stellar mass non-accreting BH, which would make it the closest BH to the Sun (Rivinius et al. 2020). Both have been called into question, and two competing models have emerged to explain the available observations of both LB-1 and HR 6819: (1) the systems are hierarchical triples with an outer Be star and an inner binary consisting of a B-type star and a BH (Rivinius et al. 2020) or (2) the systems are close binaries with a Be star and a low-mass binary interaction product with a B-type spectrum, which is in a very short-lived contraction phase on the path towards becoming a OB subdwarf (sdOB), just after the interaction ended (e.g. Shenar et al. 2020; Bodensteiner et al. 2020b; Gies & Wang 2020). Interferometric observations will be able to unambiguously distinguish between these models for both objects.

Binary interaction as a formation channel for classical Be stars has received further observational support by (1) new discoveries of Be+sdOB binaries from UV (Wang et al. 2018, 2021) and optical spectra (Chojnowski et al. 2018), (2) detection of a spectral energy distribution turndown among Be stars with radio data, suggesting truncated disks due to unseen companions (Klement et al. 2019), and (3) an apparent lack of main-sequence companions of early-type Be stars (Bodensteiner et al. 2020a).

Based on combined spectroscopic and photometric efforts, boosted by the increasing availability of high-quality space photometry (*K2*, *TESS*, *BRITE*), the unprecedented short cadence over long time spans has allowed us to catch numerous Be stars in outburst, facilitating study of star-disk interaction in much greater detail than was previously possible (e.g. Baade et al. 2018; Borre et al. 2020; Labadie-Bartz et al. 2021). Furthermore, analysis of space-based photometry has revealed that pulsation is ubiquitous among classical Be stars (Baade et al. 2016). A recent large survey based on hundreds of *TESS* lightcurves was conducted by Labadie-Bartz et al. (2020), the main outcomes of which were that frequency groups are ubiquitous in Be stars, and that these are causally linked to mass-loss episodes.

Recent results regarding observations of disk growth and dissipation in many Be stars also include new estimates for the viscosity parameter α in Be star disks (Rímulo et al. 2018; Ghoreyshi et al. 2021). and the first ever measurements of the rate of angular momentum loss $\dot{J}$ of the central star through the disk (Rímulo et al. 2018). These measurements are at odds with the predictions of evolutionary models that estimate $\dot{J}$ rates up to two orders of magnitude higher (Granada et al. 2013).

Interferometric and UV-spectroscopic studies to identify Be stars with evolved companions have also been undertaken, and an increasing number of γ Cas analogues (a group of X-ray active Be stars possibly linked to binarity) has been identified (Langer et al. 2020; Nazé et al. 2020).

Recently, modeling efforts focusing on viscous disk decretion (VDD) theory have expanded to follow disk evolution. Ghoreyshi et al. (2018) modeled the V-band light curve over several disk building and dissipation phases for the Be star ω CMa. This work was followed up by Ghoreyshi et al. (2021) by expanding the wavelength range from near UV through the mid-infrared, and to include spectroscopy and polarimetry. While finding qualitative agreement between their model and observations, with increasing wavelength the flux is over-predicted, possibly because the original work was constrained by observations produced within the disk nearest to the star. This points to the importance of using observations that are produced in different parts of the disk to ensure strong constraints over the entire disk volume. More recently, using archival photometry, spectroscopy, and polarimetry, Marr et al. (2021) modeled the evolution of the disk of the Be star 66 Oph as the Hα emission line became weaker and eventually went into absorption as the disk dissipated. This study showed that although the regions of the disk where Hα is produced dissipated, the excess radio emission required that 66 Oph's outermost disk be unaffected by the dissipation. If, on the one hand, these studies further illustrate the success of the VDD theory to explain Be star disks, on the other hand they also indicate we are a long way from having understood, or perhaps even identified, the main physical processes at play in the systems. These results on disk formation and dissipation provide new constraints on $\dot{J}$ rates. Understanding discrepancies between these rates determined from observations and those available in the literature, is a challenge for the next triennium.

2.3.3. *MOBSTER Collaboration*

The *Magnetic OB[A] Stars with* TESS*: probing their Evolutionary and Rotational properties* (MOBSTER) Collaboration (David-Uraz et al. 2019) was formed at the end of 2018 (at the *Stellar Magnetism and Spectropolarimetry* workshop in Thousand Oaks, see Sect. 2.1) to leverage the wealth of data acquired by the *TESS* mission to characterize known magnetic stars and use rotationally-modulated light curves as an indirect diagnostic of magnetism, allowing the identification of highly-probably magnetic candidates for spectropolarimetric follow-up. Currently, the collaboration has 56 members and has published 5 papers, and while it focuses on a larger portion of the HR diagram than this working group, most of its work so far has been on B-type stars, including the detection of a new magnetic B-type star (David-Uraz et al. 2021) and of a new magnetic companion to a known magnetic B-type star, which was also revealed to be a β Cep pulsator (Shultz et al. 2021b).

2.3.4. *Links to other Objects*

As mentioned above there is potential for active B stars to help understand other astrophysical objects. For example, a recent study by Cochetti et al. (2020) show that Bn and Be stars probably belong to the same population. The similarities found among Be and Bn stars deserve to be more deeply pursued. Cochetti et al. (2021) detected ^{12}CO in the classical Be star 12 Vul, suggesting a link between Be stars and other types of emission line stars.

2.4. *Challenges encountered*

The World Health Organization officially declared *COVID-19* as a pandemic on March 11, 2020. As a result, many large telescopes ceased operation, leading to cancelled or postponed observing programs; academic hiring freezes led to a marked decline in the number of tenure-track job openings; and conferences had to be either postponed or held in a virtual format. Mitigation strategies were put into place (including holding virtual scientific meetings and deliberately advantaging early-career scientists for equity).

The WGABS will work to ensure our executive and members consider these impacts when planning our future activities.

3. Key Points, Future Plans and Closing remarks

• Moving forward with *PolStar*: maintaining the capability to obtain high-resolution ultraviolet spectroscopy is a key priority. The perspective of ultraviolet spectropolarimetry is also attractive and enables novel science cases.

• Identifying and refining indirect diagnostics of massive star magnetism, as large spectropolarimetric surveys have effectively reached their magnitude limit (and ideally lobbying for high-resolution spectropolarimeters to be equipped on 8-10m class telescopes).

• Developing the next generation of magnetospheric models, able to self-consistently incorporate constraints from X-ray, ultraviolet, visible, and radio observations, will reveal stellar magnetospheres in unprecedented detail.

• Constraining the population of intermediate-distance, low-luminosity companions with high-contrast imaging techniques (e.g. long-baseline interferometry) will provide key insights into the developmental history of both classical Be stars and magnetic stars.

• Expanding both new and existing community archives holding classical Be star data to include as well other B stars with emission, in particular B[e] supergiants and magnetic B stars with emitting magnetospheres.

WGABS' main goal is to promote research and collaboration in the field of Active B-type stars. The phenomena that occur within the B-type stars are unique and different from those occurring in more massive O-type stars and our group, therefore, provides an important forum for researchers in this area. Furthermore, as noted in the introduction, the remarkable circumstellar phenomena displayed by active B-type stars provide astrophysical test-beds offering insights into processes relevant to the environments of planetary, protostellar, and compact objects. We expect the activities in this area to continue to ramp up.

We are currently asking for members who would be interested in serving on the executive to please reach out to us so that we can arrange a vote at the upcoming GA. Finally, while this report is meant to cover a broad selection of work and was compiled using contributions from WG members, it may not be exhaustive.

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