Ultraviolet Spectropolarimetry with Polstar: on the origin of rapidly rotating B stars

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ABSTRACT

The proposed MIDEX mission, Polstar, will provide high resolution UV spectroscopy and spectropolarimetry and offers a unique opportunity to study massive stars in this wavelength range with unprecedented detail. We demonstrate that these observations will provide critical new knowledge of several types of massive stars (specifically the B-emission stars and the Bn stars). We will determine accurate stellar parameters including their rotation rates and variation of surface temperature associated with stellar oblateness. Our work will allow us to detect binary companions and determine binary orbital properties. Binary population synthesis predictions will allow us to determine the fraction of these stars that are spun up due to binary interaction compared to single star evolution. These rapidly rotating stars have the potential to probe mass loss and the mixing of chemical elements which affects their evolution and ultimately the evolution of their surroundings.

Keywords: Ultraviolet astronomy (1736) — Ultraviolet telescopes (1743) — Space telescopes (1547) — Circumstellar disks (235) — Early-type emission stars (428) — Be stars (142) — Gamma Cassiopeiae stars (635) — O subdwarf stars (1138) — Multiple star evolution (2153) — Stellar rotation (1629) — Spectropolarimetry (1973) — Polarimeters (1277)

1. INTRODUCTION

B-emission or Be stars are formally defined by having observed emission in the hydrogen Balmer lines at some time. However, there are numerous physically different types of objects which meet this phenomenological description such as the Herbig Ae/Be stars, B[e] supergiants, B stars with strong magnetospheres, interacting binaries, etc (see Table 1 in Porter & Rivinius 2003). In what follows, one of the types of stars we consider are the “classical Be stars” (hereafter Be stars) which are non-supergiant B-type stars that have exhibited this type of emission at some time (Collins 1987). As the definition implies, these stars are variable and they have a range of timescales. They are distinguished by their rapid rotation which is thought to be less than critical (see Rivinius et al. (2013) and references therein). The gaseous...
circumstellar disks, when present, are formed from material ejected from the central star which slowly flows outward facilitated by viscosity commonly called the viscous decretion disk, VDD, and originally proposed by Lee et al. (1991). Currently, the VDD model, has been successful in reproducing observations over a range of wavelengths and with different observational techniques (see, for example, Haubois et al. (2014); Vieira et al. (2017); Rı́mulo et al. (2018); Klement et al. (2019); Ghoreyshi et al. (2021); Marr et al. (2021)). Mounting evidence suggests that the disks rotate in a Keplerian fashion (Rivinius et al. 2013). These disks are also geometrically thin as conclusively demonstrated in a study of seven Be star disks by Quirrenbach et al. (1997) using interferometry and spectropolarimetry. Radiative processes within these disks result in numerous observational effects including continuum and line emission, infrared and radio excess, linear polarization, and UV resonance features from wind-disk interaction, all of which are generally variable in time as the density and temperature profiles of the disk can evolve on timescales from hours to decades. The physical extent of these disks is a somewhat ambiguous quantity, since different observables probe different regions of the circumstellar environment. For instance, linear polarization and optical continuum emission are generally formed in the innermost disks (within a few stellar radii or less), while radio emission can arise from disk material out to several hundred stellar radii. For example, see figure 12 in Haubois et al. (2012), which shows the radial distances where the bulk of these observables are produced for an early Be disk model.

The exact mechanism(s) that result in the formation of the disk has been debated for decades. There is no doubt that rapid stellar rotation is a key ingredient by reducing the effective gravity in the equatorial region but it is generally believed that these stars are not rotating critically so another mechanism(s) must be acting to help launch material into orbit. This could be pulsations excited stochastically in the stellar core, which have a high amplitude thanks to the rapid rotation of the star, and transport angular momentum to the surface layers (for example, see Baade et al. 2016, 2018; Neiner et al. 2020 and references therein). Magnetic fields have been suggested as a possible mechanism to facilitate the release of material to form a disk (see Balona & Ozuyar 2020) but there are problems with this proposition as no large-scale field has been found for any Be star (see Wade et al. 2016 for efforts of the MiMes survey). Moreover, ud-Doula et al. (2018) showed that for a polar field strength above a few tens of Gauss, the magnetic field would disrupt the Keplerian disk, and so strong dipolar magnetic fields and Be disks are incompatible.

In this work, we also consider the Bn stars which have similar stellar properties as the Be stars (i.e. rapid rotation and span a wide range of spectral sub-types usually B7 to A2), but have never been observed to have a disk. The ‘n’ in ‘Bn’ indicates nebulous absorption lines (usually metals), which are widened due to high $v \sin i$ (Cochetti et al. 2020). Despite the name, the origin of these lines is now understood as being purely photospheric. Similar to the Be stars, it is not known how Bn stars acquired their present-day rapid rotation. Whatever (still unknown) physical mechanisms act in Be stars to create out-flowing disks must not (efficiently) operate in Bn stars (otherwise they would create disks and be known as Be stars). Alternatively, Bn stars might either exhibit emission sufficiently rarely or possess only quite tenuous disks that they have not, so far, been classified as Be stars. Regardless, studying the population of Bn stars is therefore important to understand the rotational evolution of massive stars at large, and also to elucidate the Be phenomenon – the actual physical mechanism that ejects mass and angular momentum, and that is either lacking or operating at small efficiencies in Bn stars.

Stellar rotation is important during main sequence (MS) evolution through potential mass loss and the mixing of chemical elements. It is also not clear how this rotation impacts post-MS stages. It is thought that Be stars may have achieved their rapid rotation from birth on the zero age main sequence (ZAMS) (Martayan et al. 2006), through single-star evolutionary processes (Georgy et al. 2013), via binary interactions (Pols et al. 1991), or by some combination of these. The decretion disks of Be stars transport angular momentum and mass out of the star, and are thus important for understanding the current and future evolution of these objects after they have acquired their rapid rotation. With time-series observations, the angular momentum and mass flux can be calculated, providing a unique probe of these evolutionary processes (Rí́mulo et al. 2018; Vieira et al. 2017) which can then be used to calibrate stellar evolution models (e.g. Granada et al. 2013).

A study by Oudmaijer & Parr (2010) found that approximately 30% of Be stars are found in binary systems which is essentially the same estimate as B stars. However, it has even been suggested that all Be stars are in binary systems (Kriz & Harmanec 1975). Yet, it is unknown what fraction of Be stars have close binary com-
panions\(^1\). Over the past decades, it has been suggested that binary interaction causes the spin-up of the Be star when an evolved companion donates material (van Bever & Vanbeveren 1997; Shao & Li 2014). Hastings et al. (2021) concluded that it is perhaps plausible for all Be stars to have been spun up by binary interaction. However, it is unclear if this is realized in nature given the somewhat extreme assumptions required (“an initial binary fraction very close to unity, a shallow initial mass function and very non-conservative mass transfer”).

In a different approach towards the same question, Bodensteiner et al. (2020) investigated the literature for 287 early-type Be stars and concluded that none of them have known main sequence companions in contrast to the large fraction of non-rapidly rotating B stars that do have main sequence companions. This finding also supports the idea that the binary channel is responsible for at least the majority of the rapidly rotating B stars. Even when a companion is not directly detected, its gravitational influence on the outer parts of the disk (causing disruption or truncation) can be measured. Analyzing the spectral energy distributions (SEDs) of 26 Be star out to the radio, Klement et al. (2019) found evidence for disk truncation in all 26 of the systems with sufficient data, in support of the hypothesis that a large majority of Be stars have been spun up by a companion. An additional method for indirectly inferring a companion is through disk oscillation modes in resonance with a binary orbit (i.e. \(m=2\) modes). These \(m=2\) modes are predicted by models (Panoglou et al. 2018; Cyr et al. 2020), and manifest in optical spectroscopy as periodic variations in emission line profile shape at the orbital period (e.g. Peters et al. 2008, 2016; Chojnowski et al. 2018). However, a comprehensive survey which can quantitatively determine these \(m=2\) modes has not been done, and is complicated by the general variability of the disks (often preventing any sort of “steady state” from being realized).

Finally, there are at most a few tens of Be stars where their binary status and their evolutionary journey to rapid rotation are fairly well known. These are the Be + subdwarf O star (sdO) binaries. In these binaries, the sdO star is the remnant core of an evolved star that has donated mass and angular momentum to the present-day Be primary, thus spinning it up. Such binaries are notoriously difficult to detect and classify, as the contribution in the optical flux from an sdO binary companion typically amounts to (perhaps significantly) less than a few percent owing to the much larger physical size of the Be star (Mourard et al. 2015).

Wang et al. (2018) examined IUE spectra of 264 Be stars and found 12 new candidate Be+sdO systems (using cross-correlation techniques) of which 9 were later confirmed using HST observations (Wang et al. 2021). As the known Be+sdO systems have spectral classes B0-B3, Wang et al. (2018) argue that there must be many Be+sdO systems that cannot be detected using existing observations and current techniques.

In contrast, there are also works that suggest the validity of single-star evolutionary channels to rapid rotation (Ekström et al. 2008; Granada et al. 2013), without the need to invoke binary evolution. van Bever & Vanbeveren (1997) determined that only \(\sim 5 - 20\%\) of Be stars can be formed through binary interactions, while Pols et al. (1991) determined that about half of the Be star population is the result of binary evolution. Analysis of the B and Be star populations of clusters seems incompatible with single-star evolution being the dominant channel for acquiring rapid rotation, yet may still be realized in some fraction of the Be stars (McSwain & Gies 2005). Based on the observed fraction of runaway stars in a large sample of Be stars, Boubert & Evans (2018) suggests that all Be stars could be products of binary mass transfer. In any case, the fraction of Be/Bn stars that have acquired their rapid rotation via binary interaction versus single-star evolution remains an open question.

Stellar evolution models for single stars have been developed that predict how rotation rate evolves over time, for a range of initial rotation rates (Eggenberger et al. 2008; Georgy et al. 2013). Consequently, accurately measuring the rotation rate – along with other physical parameters such as mass and radius – in both Be and Bn stars, constitutes a direct test of the feasibility of rapid rotation from single star formation scenarios.

We note that this paper is part of a series exploring ultraviolet spectroscopy and polarization in massive stars. For example, the paper entitled, “Ultraviolet Spectropolarimetry with Polstar: Massive Star Binary Colliding Winds” explores radiatively driven winds from massive stars using the light from the binary companion as a probe (St-Louis et al. 2021). In another work, “Ultraviolet Spectropolarimetry with Polstar: Mass Transfer and Loss in OB Interacting Binaries”, examines details about non-conservative mass loss in interacting binary systems in efforts to determine how much mass is lost to their environments (Peters et al. 2021). Binary interaction is also suggested as a pathway for magnetic stars in the paper “Ultraviolet Spectropolarimetry With Polstar: Hot Star Magnetospheres” (Shultz

\(^1\) “Close” here is taken to mean that binary interaction has or will have occurred at some point over the main sequence (MS) or post-MS evolution of one or both stars.
et al. 2021). Lastly, another investigation explores wind clumping and mass loss in massive stars in a paper entitled, “Ultraviolet Spectroscopy with Polstar: Clumping and Mass-loss Rate Corrections” (Gayley et al. 2021).

We further detail the motivation for our investigation in Section 2 and discuss the required observations, including our target list, in Section 3. Evolutionary considerations and potential results are described in Sections 4 and 5 respectively. The specific objective for this work is to test the prediction that the spin-up of massive main-sequence stars to form rapidly rotating star plus disk systems is caused by binary mass transfer, followed by rotational evolution due to core contraction and mass loss. To accomplish this objective we subdivide our results as follows: details and techniques about detecting binary companions and their orbits are provided in Subsection 5.1, how we model the sdO stars is presented in Subsection 5.2, how we determine rotational properties of the sample is outlined in Subsection 5.3, and disk physical properties are described in Subsection 5.4. We conclude in Section 6. Our target list is provided in Appendix A.

2. MOTIVATION

The purpose of this work is to demonstrate how UV polarization and spectroscopy can uniquely address fundamental questions regarding the most rapidly rotating massive stars. Understanding the origins of rapid rotation requires knowledge of the stellar (and binary) evolutionary history and the present-day rotation rates.

Figures 1 and 2 demonstrate the importance of accurate stellar rotation rates. Figure 1 shows for an early (B2) rapidly rotating star that the surface temperature varies substantially with increasing rotating and that near critical rotation results in a span of stellar effective temperature that covers the entire range for B stars.

Figure 2 shows the same spectral type (B2) rotating at 0.8 \(v_{\text{crit}}\). This Figure shows the oblate shape due to the rapid rotation. It also illustrates that depending on the viewing vantage point, the projected area of the star varies as well as the stellar surface temperature that can be seen. Given the star is the main energy source through its ionizing radiation, the requirement to obtain accurate rotation rates is important and has further implications for observables.

Polstar provides the capabilities for different (and generally complementary) observational strategies to determine certain properties of a large sample of Be/Bn stars and their circumstellar environments (discussed in Subsection 5.4).

Currently, the actual rotation rates are still contentious and the lack of firm rates means that we do...
not know actual stellar momentum rates. For example, in the work by Townsend et al. (2004), they argue that gravity darkening due to the oblate stellar surface has led to a systematic underestimate of stellar rotation rates. These rates are particularly important to stellar evolutionary models and the evolution of the stars themselves. For a large sample, UV linear polarization with Polstar will provide rotation rates with extremely high precision compared to conventional methods (e.g. optical spectral line fitting).

UV data will also allow the direct detection of companions. Indeed, the hot sdO companions of Be/Bn stars are to date virtually exclusively detected in the UV. This is primarily because although the intrinsic luminosity of sdO stars is relatively low, their flux peaks in the UV, which is a region rich with relatively narrow sdO absorption lines. This is due to a combination of factors, including the high Teff (hence a flux peaking in the UV) and low intrinsic luminosity (owing to a small size) of sdO stars. Another crucial factor that facilitates the detection of sdO companions is that they typically rotate much more slowly than their Be companions. In the Be+sdO systems studied by Wang et al. (2021) all sdOs except one (which had v sin i = 102 km s$^{-1}$) had v sin i < 40 km s$^{-1}$, while the Be stars all had v sin i > 250 km s$^{-1}$. These differences in rotational velocities are a direct consequence of binary mass transfer.

Furthermore, spectropolarimetry will provide information about the geometry, velocity, and inclination angle of the Be star disks, which can be used to determine the orbital inclination thus allowing masses to be determined.

High quality UV spectroscopy, spectropolarimetry, and continuum polarimetry of a large sample of rapidly rotating B stars thus has the potential to answer the question of the origin of rapid rotation by determining the fraction of such stars spun up by binary interaction versus those that have evolved as single stars.

During this investigation, we thus plan to determine the relative importance of the two main evolutionary channels (single-star versus binary interaction) by which hot stars acquire rapid rotation. In order to answer this question we also need to consider the incidence rates and properties of stripped binary companions to Be and Bn stars with UV spectroscopy. Precise stellar parameters of the rapidly rotating hot stars also need to be accurately determined as well as the distortions in geometry, surface gravity, and effective temperature on the stellar surface caused by rapid rotation. The similarities, differences, and evolutionary links between rapidly rotating stars that form disks versus those that do not also inform our study.

3. SAMPLE SELECTION AND PROPOSED OBSERVATIONS

3.1. The Be and Bn populations and sample selection

The Be phenomenon is found in stars between spectral types of approximately O9 through A0, but peaks around B2. The population of Bn stars is generally found to be between B5 and A2, but a small number of early-type Bn stars exist. In the Be stars, rotation rates over the entire population are on average $\geq 80\%$ of critical (Frémat et al. 2005), but with considerable spread such that Be stars as a class cannot be considered as critical rotators. The Bn stars roughly have the same rotation properties as Be stars when considered according to spectral sub-type (e.g. Cochetti et al. 2020).

While the Be star population has in common rapid rotation and the presence of a disk (at some point in their observational history), there is considerable diversity in the stellar pulsational properties (Labadie-Bartz et al. 2020) and the properties of the disks (Labadie-Bartz et al. 2018). The general trend among Be star disks is that disk mass and density decrease towards later spectral types (Vieira et al. 2017). The disks of mid- and late-type Be stars are often stable on timescales of years or decades. In contrast, the disks of early-type Be stars are much more prone to variability as a consequence of (sometimes highly) variable stellar mass ejection rates. Despite these trends, there is considerable diversity in disk strength and variability among early-type Be stars. For example, the disk of $\gamma$ Cas (B0.5Ve) has been built up at a relatively steady rate over a few decades and as of 2021 is relatively massive (Pollmann 2021). On the other hand, HD 49330 has the same spectral type as $\gamma$ Cas but is highly variable as the stellar mass ejection turns on and off over months/years (Huat et al. 2009).

Considering the diversity of Bn and especially Be stars, a comprehensive understanding of rapid rotation and the Be phenomenon (i.e. the creation of outflowing decretion disks via mechanical stellar mass ejection) and the ties to stellar evolution and angular momentum transport and loss requires studying the population of these stars. Lessons learned from a particular spectral sub-type or a small sample do not necessarily translate to the population at large.

Therefore, we have assembled a sample of 200 stars (140 Be, 60 Bn) that are representative of the general population. Histograms describing this sample are shown in Fig. 3 (spectral type) and Fig. 4 (V magnitude and UV flux). Fig. 4 also shows the expected SNR in channel 1 and 2 over the range in UV flux for the sample for 10 minute and 60 minute exposures.
This sample includes 19 of the so-called \( \gamma \) Cas analogues, which are a sub-class of Be stars (e.g. Nazé & Motch 2018). These systems emit a characteristic X-ray spectrum, but otherwise resemble perfectly typical Be stars. \( \gamma \) Cas analogues are only found among the early-type Be stars (\( \leq B3 \)). One class of scenarios to explain this peculiarity relies on the presence of evolved companions (Murakami et al. 1986; Postnov et al. 2017; Langer et al. 2020), but up to now, the presence of companions has been indirectly detected only for two cases (\( \gamma \) Cas and \( \pi \) Aqr) through the motion of the primary, Be, star and the nature of the companion remains debated. Polstar can address this question via direct detection and characterization (or upper limits) of any UV-luminous companions.

Also included are the 15 confirmed Be+sdO binaries (with direct detection of the sdO star in UV spectroscopy). These systems serve as a “ground truth” for sdO recovery and characterization. In the majority of these, only a few UV spectra of sufficient quality have been obtained, and additional observations are thus needed to sample the orbital period. Tight constraints on the stellar and orbital properties of these systems are expected.

3.2. Proposed UV observations

The Polstar mission is planned to have two observing modes, hereafter channel 1 and 2. In channel 1, UV spectroscopy is recorded at \( R \approx 30,000 \) from 122 nm to 200 nm. channel 2, with \( R \approx 100-1000 \) (higher at the FUV end), covers from 122 nm to 320 nm. A single observation in either channel always includes six sub-exposures that cycle through the waveplate positions, providing the information needed to extract the Stokes parameters (\( I, Q, U, V \)) and enabling spectropolarimetry. Further details are given in Scowen et al. (2021). Observations in both channel 1 and 2 can be leveraged to determine certain still-unknown properties of the Be and Bn populations.

The high-resolution farther-UV channel 1 observations are ideal for detecting and characterizing sdO binary companions to Be/Bn stars. The past binary interactions that have resulted in the present-day Be+sdO systems are fundamental in the evolution of these systems, and are the main reason the mass-gainer is rapidly rotating. However, only 15 Be+sdO systems have been confirmed, most of which are poorly characterized, limiting the current understanding regarding the prevalence of this evolutionary channel among the population at large.

Polstar (channel 1) is uniquely suited for conducting a UV spectroscopic survey of Be/Bn stars with sufficient precision, resolution, and cadence to detect hot sdO binary companions and determine the stellar properties and orbital parameters of the Be/Bn+sdO system. Towards this end, we propose \(~15\) UV spectroscopic observations of nearly each star in the target list. Each observation should have \( \text{SNR} \geq 300 \) for at least the brightest \(~1/3\) of the sample, and then with \( \text{SNR} \) decreasing towards the fainter end of the distribution (to conserve the total exposure time). The need to detect even the faintest sdO stars (with sufficient signal to character-
Figure 5. UV (left) and optical Hα (right) spectra of the Be+sdO binary φ Per. The broad features in this region of the UV spectra are from the photosphere of the rapidly-rotating B star, and the narrow lines originate in the sdO photosphere (with clear RV variability at the two plotted epochs). The sdO stars are brightest in the UV, and the abundance of (relatively narrow) lines renders this spectral region optimal for sdO detection and characterization. The sdO star in φ Per is perhaps ~5 – 20× brighter than typical (being in a short-lived bloated stage), but has qualitatively the same spectral features as other sdO stars. The Hα line traces a large volume of the disk (out to ~10 $R_\star$), with the line profile containing information about the disk size, density profile, kinematics, inclination angle, and any asymmetries (in some cases induced by the sdO companion). The HST data were downloaded from MAST (https://archive.stsci.edu/), and the Hα data from BeSS (http://basebe.obspm.fr).

4. EVOLUTIONARY CONSIDERATIONS

ize their properties) drives the need for high SNR (see Section 5.2 and Fig. 6). The number of observations is motivated by the need to sample the orbital period (i.e., to measure the orbital RVs of the sdO and Be/Bn stars). The cadence should be staggered so that orbital periods between ~1 – 10 months can be sampled. Most of the targets are not known to be binaries, but those that are have periods between ~30 – 200 days (excluding widely separated binaries which are not relevant in the context of binarity in stellar evolution).

Additionally, for each target a single long exposure should be taken in channel 2 of Polstar. The target polarization precision in this observing mode is ~2×10$^{-4}$. Polarization measurements of the continuum in this wavelength region can provide the necessary information to determine rotation rates, inclination, and (latitude-dependent) surface temperature and gravity (see Section 5.3 for further details). Unlike the aforementioned goal, time-series information is not needed. Since the Bn stars do not have disks, their channel 2 polarization signal will be purely photospheric. The Be stars may or may not have a disk during their channel 2 Polstar visit. However, since the polarimetric signatures of a disk and an oblate star have different features, it is expected that these components can be separated (see Sec. 5.3 and 5.4).

To complement the UV data, we will organize a specific watch of our targets in the context of existing monitoring networks. For example, the Be Star Spectra (BeSS) observing network and database (initialized and currently run by one of us, C.N.) involves dozens of active observers who specialize in Be star spectroscopy and regularly contribute to peer-reviewed scientific publications (e.g. Nazé et al. 2019; Richardson et al. 2021). This combination of professional and amateur facilities will allow us to get optical spectra preceding and during the Polstar mission. The flexibility of this network will allow for time-series optical spectra to coincide with the Polstar observations of our targets. This strategy is currently being employed to monitor Be stars simultaneously with, e.g., the TESS space photometry mission (Ricker et al. 2015), and is easily adaptable to Polstar. The visible spectra will allow us to consider the physical conditions in a larger volume of the gas, typically out to about 10 stellar radii. The Polstar data will reveal conditions on the stellar surface and near the central star (and potentially any interaction of disk material with a companion). In particular, it is useful to have the optical data to determine the global properties of the disk (or lack thereof) at a given Polstar epoch, especially since the disks are variable in general and may not exist at all at certain times. Additionally, this ground-based observing network can be used to trigger UV observations in the event of a sudden mass ejection episode. These events are inherently unpredictable, but at the earliest stages imprint certain characteristic signals in optical data, and can thus (with a short time lag) be captured with Polstar.
The origin of the Be phenomenon is still the subject of much debate. Is binarity essential for the Be phenomenon? Alternatively, what fraction of Be stars arise in binary systems in which binarity was essential to the formation of the Be star? Understanding the origin of Be stars is of course crucial for understanding their subsequent evolution.

Several studies have investigated whether Be stars can arise through single star evolution. A key process that can help facilitate the evolution of a young B star to a Be star arises because the maximum angular momentum a star can have (assuming rigid body rotation) decreases as the star evolves off the main sequence – a consequence of the shrinking core (Zhao & Fuller 2020). As a consequence the rotation rate of the evolving star may approach critical rotation when the material at the equator becomes unbound. Whether this actually occurs will depend on the efficiency of angular momentum transport and mass loss processes. Both of these are explicitly coupled to the rotation of the star. Two recent studies (Hastings et al. 2020; Zhao & Fuller 2020) have both concluded that, while Be stars can arise from single star evolution, mass transfer in binary systems is important for Be star production. While rotation near critical has often been taken to be associated with the Be phenomenon, statistical (e.g., Cranmer 2005) and interferometric studies indicate that this is not needed — many Be stars rotate at only 60 to 70% of breakup.

Some evolutionary insights into sdO/Be binary systems can be gleaned from the best studied system, $\phi$ Persei, that contains a Be star with a mass of $\sim 9.6 M_\odot$ and an sdO star with a mass of $\sim 1.2 M_\odot$ (Mourard et al. 2015). According to evolutionary calculations by Schootemeijer et al. (2018) the masses of the original stars were $7.2 \pm 0.4 M_\odot$ for the stripped (sdO) star and $3.8 \pm 0.4, M_\odot$ for the Be star. If not for mass transfer, both stars would have ended their lives as CO WDs. However, the mass of the Be star is now above $\sim 8 M_\odot$, and hence it will most likely end its life as a Type IIP core-collapse SN. The sdO star is very luminous for its mass, and must be He shell burning – a stage that lasts for less than 3% of the subdwarf’s lifetime.

In general, the evolution of a double star system depends fundamentally on the primary mass, the mass ratio, the orbital parameters, and the initial metallicity of the stars. Unfortunately, evolutionary calculations need to include numerous free parameters to facilitate the treatment of uncertain physical processes. The parameters govern (or set), for example, the efficiency of mass transfer, mass and angular momentum loss, the distribution of the kick velocity of any newly created neutron star, the minimum mass for a core collapse supernova, etc. The study of binary systems can provide crucial constraints on some of the parameters. For $\phi$ Persei, Schootemeijer et al. (2018) found that the system must have evolved with nearly-conservative mass transfer. Despite the complexities of binary evolution, crucial insights into their evolution can still be obtained from theoretical calculations.

In order to cover the large parameter space encompassed by binaries, and to test adopted parameters, an enormous number of models must be computed. For example, Zapartas et al. (2017) ran 3 million binary evolution calculations to investigate the late-time delay-time distribution of core-collapse SNe. Late-time SNe are those SNe that occur (in a coeval system) after all single stars more massive than $\sim 8 M_\odot$ have exploded. Such SNe can occur up to 200 Myrs after the last single star explosion, and their existence requires binary star systems in which mass transfer has occurred. The Zapartas et al. (2017) study also provides insights into the evolution of sdO+Be systems.

In sdO+Be binaries the initial evolution is, of course, governed by the transfer of most of the H envelope of the (initially) more massive primary star to the secondary star. The secondary is now the more massive Be star. Eventually the secondary will expand, and fill its Roche lobe, possibly triggering another phase of mass transfer and common-envelope evolution. Many different scenarios for the future evolution are possible – some are outlined below.

(1) Merger of the He subdwarf with the evolved secondary star after a common envelope phase, leading to a core-collapse SN. The merger process depends critically on the treatment of the common-envelope phase (Zapartas et al. 2017). When the common envelope is ejected the stars are less likely to merge. Significant progress towards 3D modeling of the common envelope phase is being made (e.g., Lau et al. 2021).

(2) Merger of the CO WD with the evolved secondary. The subsequent evolution is mass dependent, and uncertain. According to Zapartas et al. (2017) this may lead to a ONeMG core that may eventually collapse as a result of electron capture. Alternatively, the WD core could undergo a thermonuclear explosion inside a H-rich envelope. This could produce a Type Ia-CMS SN (e.g., SN2002ic, Hamuy et al. (2003)). A final possibility is that the core never obtains sufficient mass to undergo core collapse.

(3) The sdO star can evolve into a CO (or potentially a ONe) White Dwarf. The secondary star can explode as a Type II SN leaving. In most cases the neutron star will be ejected from the system, however in some case a WD + NS binary system will be formed.
5. POTENTIAL RESULTS

5.1. Determine the stellar and binary properties of the Be/Bn stars

5.1.1. The known Be+sdO population

High-resolution high-SNR UV spectroscopy is perhaps the best observational tool for the detection and characterization of hot small sdO companions to Be/Bn stars. To date there are 15 Be+sdO binaries where the sdO star has been directly detected (Gies et al. 1998; Peters et al. 2008, 2013, 2016; Wang et al. 2017, 2018, 2021).

The flux ratio at a given wavelength between an sdO and a Be star in a binary \( f_{sdO}/f_{Be} \) is a convenient parameter to determine the degree to which it is possible to de-convolve the composite spectrum as a function of SNR. Other stellar parameters \( T_{eff}, \log g, \text{and } v_{sini} \), plus binary motion, also have an effect. Thus, with a high-enough precision spectrum, these properties can be determined.

The Be+sdO system with the highest flux ratio, \( f_{sdO}/f_{Be} \approx 15\% \) (at \( \sim 150 \) nm), is \( \phi \) Per (Gies et al. 1998), where HST UV spectra reveal individual spectral features that are clearly seen to vary in RV (Fig. 5). However, the majority of the known Be+sdO binaries have lower flux ratios of approximately \( f_{sdO}/f_{Be} = 2.5\% - 10\% \) (Wang et al. 2021).

Other systems are known binaries (e.g. through SB1 orbital solutions for the Be star) but where no companion has been detected. For instance, an upper limit for the 203.5 d binary \( \gamma \) Cas (B0.5IVe, Nemravová et al. 2012) is approximately \( f_{sdO}/f_{Be} = 0.6\% \) at FUV wavelengths (Wang et al. 2017). Such binaries (with yet unseen companions) may also be found among the mid/late type B stars (e.g. \( 7 \) Vul, B5Ve, Harmanec et al. 2020). These and similar systems with known orbital periods are included in the target list, where Polstar observations can be scheduled to cover the orbital phases. There are additionally numerous systems where RV motion of a Be star and/or its disk has been detected, but that so far lack an orbital solution (e.g. Chojnowski et al. 2017). Thus, there are a large number of systems where binarity is suspected or known, but that are lacking in the observations needed to reveal the nature of the companion.

There are very few, if any, confirmed Bn+sdO binaries. This is generally consistent with the lack of directly-detected sdO stars in binaries with mid- and late-type Be stars (since Bn stars are typically of later spectral types). However, Bn stars are often less enthusiastically observed compared to the Be stars, and the scarcity of known hot sub-luminous companions (either sdO/B or pre-WD) to Bn stars (and also later-type Be stars) is likely in part due to a lack of data sufficient for the task of detecting these faint sources. For example, Regulus, a Bn star (B8IVn), was recently found to host a pre-WD companion (i.e. a low mass stripped core) in a 40 d orbit (Gies et al. 2020). The Regulus system likely has a similar binary evolution history as the Be+sdO binaries, yet has never been observed to build even a weak disk. With a flux ratio \( f_{sdO}/f_{Be} \approx 0.06\% \) in the visible, the UV flux from the pre-WD component of Regulus should be detectable in high-SNR channel 1 Polstar spectra.

5.1.2. Expanding the Be/Bn+sdO parameter space by pushing to higher contrast systems and larger numbers

The discovery of Be+sdO binaries has largely been driven by IUE UV spectroscopy (Wang et al. 2018). With these observations typically having low SNR (on the order of SNR\( \sim 10 \)), it is reasonable that the systems with relatively high values of \( f_{sdO}/f_{Be} \) were the first to be found. Although the known Be+sdO systems have \( f_{sdO}/f_{Be} \) of one to a few percent, it is necessary to acquire observations that can probe flux ratios smaller than this. For example, with IUE spectra of 6 Be stars known to be binaries, (Wang et al. 2017) derived upper limits on the flux contribution of any potential sdO companions to be \( \lesssim 1\% \) for five stars, and detected an sdO star in one (60 Cyg, B1Ve). Thus, observations that are sensitive to flux ratios of \( f_{sdO}/f_{Be} \lesssim 1\% \) (and even down to \( \sim 0.1\% \)) are a necessary step towards a better understanding of this population.

In a single Polstar channel 1 spectrum with \( R = 30,000 \) and \( \text{SNR} = 300 \), an sdO companion with a flux ratio as low as \( f_{sdO}/f_{Be} \approx 0.1\% \) may be detected (Fig. 6, middle panel). In systems with flux ratios of \( f_{sdO}/f_{Be} \gtrsim 0.5\% \), a single observation of SNR\( \sim 300 \) provides the means for a precise determination of the sdO properties (Fig. 6, top panel), and with multiple such observations the orbital properties can be determined. Then, with knowledge of the orbital RVs, each spectrum can be shifted to the sdO rest frame and co-added for perhaps a significant
increase in the precision with which the sdO properties are determined.

Since $f_{\text{sdO}}/f_{\text{Be}}$ is generally small, cross-correlations functions (CCFs) or similar techniques to maximize signal typically by combining information from many lines need to be employed for sdO detection and characterization in Be+sdO binaries. CCF techniques were used to find candidate Be+sdO binaries from IUE spectra (Wang et al. 2018), and later to confirm many of these candidates with higher quality HST spectra (Wang et al. 2021). Details of this technique can be found in the aforementioned works, and the method is also illustrated in Fig. 6. In brief, grids of model sdO spectra (varying the RV and the stellar parameters) are cross-correlated to the observed spectrum. The template that provides the best fit to the data then describes the stellar properties and velocity of the sdO star at each observed epoch.

To measure the orbital properties, multiple observations are needed to cover the orbital phase. In some cases, the orbital ephemerides are already known even when a companion has never been directly detected (e.g. π Aqr, γ Cas). However, in the general case where no specific prior information about a binary orbit is known, observations spread out over weeks and months are likely to sample a binary orbit. In the known Be binaries (both with and without detected sdO companions), orbital periods range between about 30 – 200 days.

With Polstar, we aim to observe a sample of $\sim 140$ Be and $\sim 60$ Bn stars $\sim 15$ times each with high-resolution ($R = 30,000$) UV spectroscopy. For the brightest $\sim 1/3$rd of the sample, each observation should have SNR $\gtrsim 300$ to enable precise measurements of the sdO properties and velocities at each epoch. In the remainder of the sample, a SNR of between $\sim 50 – 300$ can be achieved with reasonable exposure times, which in most cases should be sufficient to detect sdO companions. In these relatively lower SNR spectra, any detected sdO stars can still be characterized by stacking multiple observations, provided that some information about the RV motion of the sdO star can be extracted.

With Polstar, we can obtain not only the number of these objects with compact sdO-type companions, but also the orbital inclinations with polarization data mainly from disk scattering. In the majority of the known Be binaries with periods between $\sim 30 – 200$ d, the orbits are circular and co-planer with the rotation axis of the Be star (and thus also the Be star disk). When orbits are not aligned with the disk, tidal and radiative forces from the companion influence or warp the disk in characteristic ways, such that these misaligned cases can be additionally diagnosed through optical spectroscopy (e.g. Marr et al. 2021; Nemravová et al. 2010), and eccentricity can be determined from the RV measurements (especially of the sdO star) as in Peters et al. (2013). When combining the polarization-derived inclinations and the double-lined orbits, we obtain a distribution of the masses for both the Be/Bn stars and the companion sdO/WD stars. This will lead to powerful constraints for evolutionary pathways.

The combinations of channel 1 and channel 2 for our proposed targets are complementary for diagnosing the stellar properties of the Be/Bn stars. For instance, disentangling the B star rotation axis and its rotational velocity is enabled, since channel 1 spectroscopy and channel 2 spectro-polarimetry both constrain $v_{\text{sin}i}$ in different ways (see Sec. 5.3).

5.2. Model the spectra of sdO stars

Due to the high quality spectra obtained with Polstar, and multiple observations, we will be able to extract the
spectra for many of the sdO companions. This will in turn facilitate a direct analysis of the companion star using non-LTE radiative codes such as TLUSTY (Hubeny & Lanz 1995) and CMFGEN (Hillier & Miller 1998). Because of the narrow lines in sdO stars we should be able to obtain accurate spectra parameters and abundances, which help understand the past and future evolution of the system. Assuming observations with a signal-to-noise ratio of 1000, a sdO star with a flux of 10% (1%) of the Be star will (ignoring errors arising from disentangling the spectra) will have a signal-to-noise ratio of 100 (10).

Wang et al. (2021) used the height of the peak in the cross-correlation function to constrain the effective temperature of the sdO stars. They assumed a fixed gravity of 4.75, and estimated effective temperatures generally between 38,000 K and 45,000 K (one had $T_{\text{eff}} = 33800$ K) with an estimated error of 2500 K. For the cross-correlation analyses they used theoretical spectra computed with TLUSTY. One issue with the models (and O and B stars in general) is that UV lines list are incomplete/inaccurate, and hence lines are missing (if we use only lists with accurate wavelengths) or at the wrong location (if we also include lines with theoretical wavelengths). Our understanding of the UV should improve over the next few years through the ULYSES project and subsequent analyses. The ULYSES Project (https://ullyses.stsci.edu) devoted 1000 HST orbits to obtain a high quality UV spectral library of high and low mass stars.

There are several different methods available to extract individual spectra of the component stars in a binary system (e.g., Simon & Sturm 1994; González & Levato 2006; Binnenfeld et al. 2020; Quintero et al. 2020), although these have generally been designed to work in the optical, and they make assumption not necessarily applicable to UV analyses. For example, the algorithm of (Simon & Sturm 1994) works with rectified data, however the severe line blanketing in the UV makes it extremely difficult to rectify spectra. Some procedures suffer by convergences issues, although these can be addressed through modifications of the algorithm (e.g., Quintero et al. 2020). It is unclear however, how these procedures will work in the UV where the Fe forest causes severe line blending. Consequently we will need to test exist these algorithms, and as needed, develop modifications to improve their applicability to the UV, and to cases where the flux of the companion star is very much less than that of the Be star.

5.3. Model the rotational properties of the sample

Channel 1 spectroscopy will provide $v \sin(i)$ measurements for rapidly rotating stars (where $v$ is surface rotational velocity and $i$ is inclination of the stellar rotation axis to the line of sight). Combining Channel 2 continuum polarization will enable the inclination degeneracy to be overcome and the rotation rates of up to ~200 stars to be determined (150 Be, 50 Bn). The modelling process to determine rotation rate and inclination also furnishes determinations of effective temperature, $T_{\text{eff}}$, surface gravity, log($g$), and subsequently mass, $M$ and radius, $R$. Close to Polstar’s designed polarimetric precision of $2 \times 10^{-4}$ (0.02%) is needed to achieve a high degree of precision in this measurement.

As the rotation rate of a star increases the star becomes increasingly oblate. Under a Roche model, at critical rotation, the equatorial radius is 1.5 times larger than the polar radius (Maeder & Meynet 2015) – a value slightly modified by radiation pressure (Gagnier et al. 2019). Further, the temperature of the star varies with latitude, with the poles being hotter than the equatorial regions, which are said to be “gravity darkened” (Maeder & Meynet 2015; Gagnier et al. 2019).

Along with other fundamental parameters like temperature and luminosity, the rotation rate, $\omega/\omega_c$ – where $\omega$ is the angular rotational velocity, and the $\omega_c$ the critical angular velocity for break-up, probes a star’s evolutionary status. In particular, a comparison is facilitated with the rapidly-rotating stellar evolution models of Eggenberger et al. (2008); Georgy et al. (2013). These are single star models that simulate evolutionary tracks based on assumed initial mass and rotation rates, where deviation from the observations implies a binary merger.

Ordinarily, without prominent surface features, it is not possible to determine the rotational velocity of a rapidly spinning B- or A-type star. Spectroscopy can only reveal the projected velocity, from its nebulous spectral lines, in the form of $v \sin(i)$. Two methods exist for overcoming this restriction. With the addition of readily available astrometric and spectroscopic information, both facilitate comparison to evolutionary models.

The first method involves using interferometry to directly resolve the rotationally distorted shape of the stellar disk. Such an approach is intrinsically limited to the nearest stars. To date, several stars have had their rotational velocities measured in this way, only four of them have spectral types of A5 or earlier: Achernar (Domiciano de Souza et al. 2014), Regulus (Che et al. 2011), 51 Oph (Jamialahmadi et al. 2015) and Rasalhague (Zhao et al. 2009) – three of which are closer than 50 pc.

In the past five years a second approach using polarimetry has been demonstrated (Cotton et al. 2017;
Polarization from a hot stellar photosphere arises primarily as a result of electron scattering; it increases from the centre of the disc to the limb, to which its angle is tangential (Chandrasekhar 1946). All of the polarization vectors cancel out for a spherical star, but for a rapid rotator a net polarization is produced as a consequence of the different environments at the poles and equatorial regions (Harrington & Collins 1968).

The local polarization level depends on the ratio of scattering to absorption, and thus is larger for higher temperatures, and lower surface gravity. The net polarization further depends on rotation rate and the inclination to the line of sight. At visual wavelengths this polarization is small (Collins 1970; Sonneborn 1982; Cotton et al. 2017; Bailey et al. 2020). Within 100 pc of the Sun, the interstellar polarization level is similar to that induced by rotation in a B- or A-type dwarf star, but beyond, it is much larger and obfuscates the stellar intrinsic polarization.

The distance limitation imposed by interstellar polarization can be greatly alleviated by working in the UV. At UV wavelengths the net polarization is orders of magnitude larger than in the optical (Sonneborn 1982; Collins et al. 1991; Lewis et al. in preparation). Gravity darkening at the equator increasingly exacerbates the inequality in fluxes from the polar and equatorial regions shortward of the equatorial blackbody peak. The enhanced UV polarization is demonstrated for Regulus in Figure 7. Here, we can see that polarizations of up to $5 \times 10^{-3}$ are predicted for Polstar’s wavelength range and that this value is highly wavelength dependant. For more luminous stars, the polarization can be even higher – up to $10^{-1}$ or more for a giant with a spectral type later than A-type (Lewis et al. in preparation). Consequently Polstar will be able to exploit this phenomenon to determine rotational velocity for stars at much greater distances.

Four parameters contribute to the shape and magnitude of the observable polarization curve. Two of these are global parameters: rotation rate, $\omega/\omega_c$, and inclination, $i$. The other two – temperature and surface gravity – vary over the stellar disc, but can be parameterized as their values at a single surface location, the pole for instance (as $T_p$ and $\log(g_p)$), if a gravity darkening law is assumed along with a Roche model for the stellar shape. The classical law is that of von Zeipel (1924), but the ELR Law (Espinosa Lara & Rieutord 2011), which produces less gravity darkening, is preferred because it has been specifically designed to model rotating stars. With a known magnitude, distance and $v \sin (i)$, we can determine $T_p$ and $g_p$, if we assume $i$ and $\omega/\omega_c$.

Figure 7. The modelled surface flux, $F_\lambda$, in units of erg.cm$^{-2}$.s$^{-1}$.Å$^{-1}$ (a) and polarization (b) UV spectrum of Regulus. The polarization is given in fractional units on a log scale with the most negative $Q/I$ values (i.e. greatest polarization) at the bottom; the optical polarization of Regulus is at the level of a few $\times 10^{-5}$ (Cotton et al. 2017). Regulus has $\omega/\omega_c = 0.965$ and $i = 80^\circ$ (black); other inclinations are simulated (colours). The polarization is presented in terms of normalized $Q$ Stokes in the reference frame of the stellar rotation axis. In the UV the values are almost entirely negative in $Q/I$ – perpendicular to the rotation axis – with the largest negative values furthest into the UV. There is a marked difference in polarization with inclination – with $i \geq 20^\circ$ producing polarizations greater than $10^{-4}$ – but in all cases the absolute value of polarization increases approximately logarithmically with decreasing UV wavelength after the Balmer jump. The dashed blue vertical line represents 122 nm. The plot is based on a synspec/vlidort model using the parameters determined by Cotton et al. (2017). The models included the wavelength range from 100 to 400 nm and used the atomic UV line lists ‘gfFUV’ and ‘gfNUV’ acquired from the synspec website and originally computed by Kurucz & Bell (1999).
The methodology, then, is to construct a 2D parameter grid of assumed $i$ and $\omega/\omega_c$ values, where each point on the grid has a predicted polarization versus wavelength curve, which is then compared to observations (Cotton et al. 2017; Bailey et al. 2020; Lewis et al. in preparation). In this way, all four parameters are determined – $T_p$, $g_p$, $i$ and $\omega/\omega_c$. An inversion of Howarth & Smith (2001)’s method for determining distance can then also be used to determine mass, $M$, and make comparison to evolutionary models. It is for the purpose of discriminating between parameter grid models that the relatively high precision are required in spite of the very large polarizations predicted in the FUV, in particular. In the optical, with multi-band techniques, good outcomes are being achieved with a polarimetric precision one to two orders of magnitude smaller than the signal. Polstar’s limiting precision of $2 \times 10^{-4}$ achieves a similar ratio for the UV but with greater spectral resolution.

If the level of interstellar polarization is small or comparable to the intrinsic polarization, it can be simultaneously solved for, potentially with a loss of precision in the determination of stellar parameters (Bailey et al. 2020; Lewis 2019). However, supporting ground-based optical multi-band polarization measurements facilitate independent determination of the level of interstellar polarization. Standard techniques like use of field star polarization can be used to help characterize and remove the interstellar polarization component (see e.g. Wisniewski et al. 2003, 2006, 2007). Typically, in the optical the intrinsic polarization component will be small in comparison to the interstellar polarization for stars more distant than $\approx100$ pc; it can therefore be neglected to determine the interstellar polarization. Although the fine details of interstellar polarization in the UV is a matter of ongoing investigation (including for Polstar, for example, see the white paper entitled, ”Ultraviolet Spectropolarimetry with Polstar: Interstellar Medium Science” (Andersson et al. 2021)). In general interstellar polarization is well approximated by the Serkowski Law (Serkowski et al. 1975), which has only two or three parameters (Wilking et al. 1980; Whittet et al. 1992) – the wavelength of maximum polarization, $\lambda_{\text{max}}$, the maximum polarization, $p_{\text{max}}$, and sometimes a ‘constant’ $k$, where $\lambda_{\text{max}}$ is overwhelmingly observed to be at visual wavelengths (Wilking et al. 1982). Once these parameters are solved for, the Serkowski curve can be extrapolated into the optical accurately.

In practice, good measurements for magnitude across a wide wavelength range, and in the UV in particular, are desirable for precision in setting up the parameter grid (Cotton et al. 2017; Bailey et al. 2020). The UV spectra that will be obtained by Polstar are therefore an asset for this purpose, as well as for improving estimates of $v \sin(i)$. Thus, with only the addition of readily available Gaia parallaxes, Polstar becomes the ideal platform to facilitate measurements of rotation in the Bn stars in particular. For the Be stars, the often large polarizations produced by the emission disk are a complicating factor, but some portion of them will be diskless at the time of observation, which will easily facilitate the measurement. For stars in emission, the two components may still be able to be separated, as the UV wavelength dependence of polarization predicted for rapid rotation from the photosphere is different to that produced by scattering from the disk (Bjorkman et al. 1991).

5.4. Model the wind/disk properties of the sample stars

The spectropolarimetric observations obtained by Polstar will probe the circumstellar environment of Be/Bn stars, revealing details of their (polar) wind, disk geometry, and wind/disk interactions. Through detailed modeling of the resulting data, we will be able to place strong constraints on disk density in the innermost part of the disk and corresponding temperature profiles and interactions of any companion with the disk. Monte Carlo radiative transfer (MCRT) codes have been used extensively to study disks in Be stars (Wood et al. 1996a,b, 1997; Hoffman et al. 2003; Carciofi & Bjorkman 2006, 2008). In addition, recent MCRT simulations have investigated the optical and IR polarization produced by the wind structures around massive, mass-losing stars (Shrestha et al. 2018, 2021). MCRT methods are necessary for these scenarios because the high optical depths that often exist in Be disks give rise to multiple-scattering effects that modify the polarization beyond typical analytical results (Wood et al. 1996b; Shrestha et al. 2018). The Polstar team includes several MCRT experts who will extend these existing simulation techniques into the UV for comparison with Polstar data.

Wood et al. (1997) demonstrated the utility of a full-spectrum polarimetric model in analyzing the disk geometry of $\zeta$ Tau. Comparing the sizes of the polarization Balmer and Paschen jumps and the various continuum slopes in their model with polarimetric data from UV to IR allowed these authors to determine that the $\zeta$ Tau disk is geometrically thin ($\Delta \theta = 2.5^\circ$) and to constrain its origin (Fig. 8). Also, note in Fig. 8 at wavelengths short-ward of the Balmer jump in the UV spectral range, that the model predictions (thick line) are over-estimated compared to the observations (thin line) due to the presence of many UV metal lines which will provide diagnostics for the disk and stellar surface. The high-quality UV polarized spectra Polstar will ob-
tain will enable more detailed constraints on the geometry of disks and other CSM configurations (e.g., bipolar outflows; Schulte-Ladbeck et al. 1992), particularly when combined with sophisticated MCRT models taking into account non-LTE effects (Carciofi & Bjorkman 2006, 2008), line blanketing, and geometries more complex than simple 2D disks (Shrestha et al. 2018, 2021).

Obtaining spectropolarimetric data in the ultraviolet wavelength range will complement existing optical and IR polarimetric observations and allow us to probe the stellar surface and innermost part of the disk where material is potentially ejected and re-accreted. For example, Figure 9 shows an eccentric hole that has developed in a misaligned Be binary system. The interaction of the binary companion causes the particles in the disk to follow eccentric orbits resulting in re-accretion onto the stellar disk when the disk particles collide with the star (Suffak et al. 2021). By constraining the disk geometry, Polstar will be able to detect the effects of the binary companion on the disk such as these holes shown in Figure 9 predicted in misaligned systems. In fact, these features only appear in binary systems where the influence of the companion causes gas to orbit on eccentric paths which, in some cases, impact the stellar surface. For isolated Be stars, these cavities in the disk are not predicted. It is well documented that Be star disks empty from the inside, however, in single stars systems, as the gas accretes, gas moves inward from greater radial distance to fill the void. Interestingly, in misaligned binary systems, this phenomenon is predicted to occur even when the disk is building.

Figure 10 shows a simulation of a binary system where after a short time a disk has developed around the companion star from ejected material from the Be star. This means that if the material from an evolved companion initially caused the spin-up of the Be star, that the Be star can eventually donate some of this material back i.e., it is not lost to the system. This Figure also demonstrates that there may be opportunity to probe the interaction of the polar wind with the circumstellar material. The UV resonance lines will provide details about changes in mass outflow between visits to our targets to be investigate. Also, the UV lines Polstar obtains will potentially allow the interaction regions between the disk and winds to be mapped.

6. CONCLUSIONS

The Polstar mission is uniquely suited to addressing the fundamental questions regarding the rapidly rotating OB population. Our results using Polstar observations will be able to answer the questions related to the multiplicity of the Be/Bn stars. The discovery of a sample of companion sdO stars will constrain the multiplicity of these objects and the importance of past binary interactions for these stars. Polstar’s low-resolution UV spectropolarimetry serves as a precise probe of the surface gradients and asymmetries that arise from rapid rotation, and is an excellent observable from which to determine rotation rates. Having a large sample of Be/Bn stars with modeled disk and rotational properties (Sections 5.2 and 5.3), we can then answer questions as to the geometry of their orbits. With well-determined orbits for the primary stars, and reasonable orbits for the companions from the cross-correlation functions, we can then use the derived orbital/disk inclinations to determine the primary and secondary star masses.

With a distribution of stellar masses for both component stars, we will use models for binary populations to test the formation of the Be and Bn stars, such as the BPASS grids calculated by Eldridge et al. (2017) and Stanway & Eldridge (2018), and accessible through a python interface (Stevance et al. 2020). These types of comparisons are useful in that they provide the means to interpret the multiplicity fractions of the Be/Bn stars to enable the importance of past binary interactions for the formation of these unusual objects. These comparisons are only accessible through the high-quality spectropolarimetry of Polstar, which enables the determination of inclinations of these systems and promotes the discovery of the relatively faint companion sdO stars that seem increasingly common based on the results of Wang et al. (2018).
Figure 9. A 30 day, 60° simulation at 105 \( P_{\text{orb}} \). Left to right shows the \( x - y \), \( x - z \), and \( y - z \) planes. The primary and secondary star are represented by white circles, and the disc is coloured by its column density, indicated by the colour bars under each window. The scale bar in each window indicates the length of 10 primary stellar radii (\( R_\star \)) (Suffak et al. 2021).

Figure 10. Snapshots of the \( x\)-\( y \), \( x\)-\( z \), and \( y\)-\( z \) planes after 10 orbital periods of an equal-mass binary simulation with a circular 30 day orbital period and 60 degree misalignment angle, including the particle splitting feature. The stars are denoted by white circles, and the disk is coloured according to its column density, indicated by the colour bars below each panel. The scale bar in each window indicates the length of 10 primary stellar radii (Courtesy, Mark Suffak).
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Facilities:

Software: astropy (Astropy Collaboration et al. 2013, 2018)
**APPENDIX**

**A. TARGET LIST**

Table 1. Target list. The listed UV flux values (at 1500 Å and 2500 Å) are in units of erg/s/cm$^2$/Å×10$^{-10}$, and are estimated from IUE data whenever possible. If not observed by IUE, these flux values are interpolated based on the \( V_{mag} \) and the spectral type. The ‘Class’ column describes the type of system as follows. ‘sdO’ systems are confirmed Be+sdO binaries where the sdO stars has been directly detected. ‘gCas’ are the X-ray emitting \( \gamma \) Cas analogs. All ‘sdO’ and ‘gCas’ systems are also Be stars. The table is sorted by class, and then by \( V_{mag} \) within each class. Spectral types are from the literature. The ‘ch. 1 \( t_{exp} \)’ is the exposure time, in seconds, for one full Polstar observation (made up of six sub-exposures) and the corresponding SNR. The ‘ch. 2 \( t_{exp} \)’ is the exposure time needed in channel 2 to deliver the polarization precision given in the next column (‘ch. 2 prec.’).

| ID      | alt ID  | \( V_{mag} \) | Flux at 1500 Å (erg/s/cm$^2$/Å×10$^{-10}$) | Flux at 2500 Å | ch. 1 \( t_{exp} \) (s) | SNR | ch. 2 \( t_{exp} \) (s) | prec. \( \times 10^{-3} \) | ST | Class  |
|---------|---------|---------------|---------------------------------|---------------|---------------------|-----|---------------------|------------------|----|--------|
| HD 10516 | phi Per | 4.06         | 15.0                            | 5.5           | 190                 | 200 | 1498                | 0.20             | B1.5 | V:ce-shell sdO |
| HD 200120 | 59 Cyg | 4.75         | 11.0                            | 3.1           | 260                 | 200 | 2658                | 0.20             | B1.5Vnnne sdO |
| HD 41335 | HR 2142 | 5.21         | 4.0                             | 2.0           | 410                 | 150 | 3600                | 0.21             | B1.5IIV-Vnne sdO |
| HD 157042 | iota Ara | 5.25       | 4.0                             | 2.0           | 410                 | 150 | 3600                | 0.21             | B2Vnne sdO |
| HD 200310 | 60 Cyg | 5.43         | 5.0                             | 1.7           | 330                 | 150 | 3600                | 0.23             | B1Ve sdO |
| HD 137387 | kap01 Aps | 5.50     | 4.0                             | 1.6           | 410                 | 150 | 3600                | 0.24             | B2Vnpe sdO |
| HD 58978 | FY CMa | 5.56         | 6.0                             | 1.8           | 490                 | 200 | 3600                | 0.23             | B0.5I Ve sdO |
| HD 60855 | V378 Pup | 5.70      | 2.0                             | 0.9           | 830                 | 150 | 3600                | 0.32             | B2Ve sdO |
| HD 43544 | HR 2249 | 5.90         | 3.0                             | 1.1           | 550                 | 150 | 3600                | 0.29             | B2/B3Ve sdO |
| HD 194335 | V2119 Cyg | 5.90    | 3.0                             | 1.1           | 550                 | 150 | 3600                | 0.29             | B2IIIe sdO |
| HD 113120 | HD 113120 | 6.00  | 1.6                             | 0.7           | 1040                | 150 | 3600                | 0.36             | B2IV nVe sdO |
| HD 152478 | V846 Ara | 6.30      | 0.9                             | 0.4           | 820                 | 100 | 3600                | 0.51             | B3Vnpe sdO |
| HD 51354 | QY Gem | 7.20         | 0.6                             | 0.3           | 1230                | 100 | 3600                | 0.52             | B3ne sdO |
| HD 29441 | V1150 Tau | 7.60   | 0.3                             | 0.1           | 2460                | 100 | 3600                | 0.87             | B2.5VnVe sdO |
| HD 55606 | 9.04     | 0.1                             | 0.1                           | 1540          | 50                  | 3600 | 1.24               | 0.36             | B0.5VnmpVe sdO |
| HD 5394 | gamma Cas | 2.39  | 107.0                            | 39.0          | 60                  | 300 | 211                 | 0.20             | B0.5 Ivpe gCas |
| HD 212571 | pi Aqr | 4.60         | 10.0                            | 3.1           | 660                 | 300 | 2658                | 0.20             | B1 III-Ive gCas |
| HD 110432 | BD Cru | 5.31         | 1.2                             | 0.7           | 1887                | 175 | 3600                | 0.36             | B0.5IVe gCas |
| HD 44458 | FR CMa | 5.55         | 2.0                             | 0.9           | 1133                | 175 | 3600                | 0.32             | B1.5I Ve gCas |
| HD 120991 | V767 Cen | 6.10    | 1.2                             | 0.8           | 1887                | 175 | 3600                | 0.34             | B2Ve gCas |
| HD 45995 | 6.14     | 1.5                             | 0.9                           | 1507          | 175                 | 3600 | 0.32               | 0.32             | B1.5V nVe gCas |
| HD 183362 | 6.34     | 1.1                             | 0.5                           | 2060          | 175                 | 3600 | 0.43               | 0.33             | B3Ve gCas |
| HD 45314 | 6.64     | 0.6                             | 0.2                           | 1927          | 125                 | 3600 | 0.60               | 0.63             | O9:npe gCas |
| HD 157832 | V750 Ara | 6.66    | 0.6                             | 0.4           | 1927                | 125 | 3600                | 0.51             | B2ne gCas |
| HD 12882 | 7.62     | 0.2                             | 0.2                           | 7200          | 139                 | 3600 | 0.63               | 0.63             | B2.5III:n[e] gCas |
| HD 119682 | 7.90     | 0.2                             | 0.2                           | 7200          | 139                 | 3600 | 0.73               | 0.73             | B0Ve gCas |
| HD 220058 | 8.59     | 0.1                             | 0.1                           | 7200          | 99                  | 3600 | 1.01               | 0.07             | B2 gCas |
| BD+43 3913 | 8.91     | 0.2                             | 0.1                           | 7200          | 135                 | 3600 | 1.18               | 1.18             | B1.5V:nne gCas |
| HD 161103 | 9.13     | 0.2                             | 0.1                           | 7200          | 122                 | 3600 | 1.30               | 1.30             | B0.5III/IVe gCas |
| HD 162718 | 9.16     | 0.0                             | 0.0                           | 7200          | 68                  | 3600 | 2.25               | 2.25             | B3/5ne gCas |
| BD+47 3129 | 9.27     | 0.1                             | 0.0                           | 7200          | 115                 | 3600 | 1.38               | 1.38             | B0 gCas |
| HD 316568 | 9.66     | 0.1                             | 0.0                           | 7200          | 96                  | 3600 | 1.59               | 1.59             | B3 gCas |
| HD 90563 | 9.86     | 0.1                             | 0.0                           | 7200          | 87                  | 3600 | 1.75               | 1.75             | B2Ve gCas |
| HD 130437 | 10.04    | 0.1                             | 0.0                           | 7200          | 80                  | 3600 | 30.49              | 30.49            | B1Ve gCas |
| HD 10144 | Achernar | 0.46     | 26.0                            | 12.0           | 253                 | 300 | 687                 | 0.20             | B6Vpe Be |
| HD     | Name     | Magnitude | Distance | Radial Velocity | Proper Motion | Spectral Class | Type |
|--------|----------|-----------|----------|-----------------|--------------|----------------|------|
| 127972 | Eta Cen  | 2.31      | 92.0     | 35.0            | 67           | 300            | 0.20 | B2 Ve |
| 143275 | del Sco  | 2.32      | 70.0     | 30.0            | 93           | 300            | 0.20 | B0.3IV |
| 105435 | del Cen  | 2.52      | 55.0     | 23.0            | 120          | 300            | 0.20 | B2Vne |
| 23630  | Eta Tau  | 2.87      | 15.7     | 6.7             | 420          | 300            | 0.20 | B7 III |
| 58715  | beta CMi | 2.89      | 11.0     | 5.8             | 600          | 300            | 0.20 | B8 Ve |
| 37202  | Zeta Tau | 3.03      | 30.2     | 15.0            | 220          | 300            | 0.20 | B1 IV |
| 205021 | Bet Cep  | 3.23      | 35.3     | 12.9            | 187          | 300            | 0.20 | B0.5III |
| 56139  | 28 CMa   | 3.82      | 13.0     | 7.5             | 507          | 300            | 0.20 | B2.5Ve |
| 160014 | Omi Her  | 3.83      | 2.4      | 1.9             | 927          | 175            | 0.20 | B9.5III |
| 50013  | Kappa CMa| 3.89      | 28.9     | 10.0            | 227          | 300            | 0.20 | B1.5 Ve |
| 109387 | kap Dra  | 3.89      | 8.0      | 3.5             | 827          | 300            | 0.20 | B6III |
| 135734 | mu Lup   | 4.00      | 2.1      | 1.7             | 1087         | 175            | 0.20 | B8 Ve |
| 25940  | 48 Per   | 4.03      | 16.9     | 6.2             | 393          | 300            | 0.20 | B3 Ve |
| 45542  | nu Gem   | 4.14      | 6.0      | 2.6             | 1107         | 300            | 0.20 | B6IVe |
| 23480  | 23 Tau   | 4.18      | 4.7      | 2.0             | 980          | 250            | 0.20 | B6IV |
| 149630 | Sig Her  | 4.20      | 1.7      | 1.4             | 1300         | 175            | 0.20 | B9 Ve |
| 173948 | lam Pav  | 4.21      | 14.4     | 5.3             | 460          | 300            | 0.20 | B2Ve |
| 22192  | psi Per  | 4.23      | 5.5      | 2.2             | 1207         | 300            | 0.20 | B5 Ve |
| 6811   | Phi And  | 4.25      | 4.4      | 1.9             | 1047         | 250            | 0.20 | B5III |
| 33328  | Lam Eri  | 4.27      | 13.6     | 5.0             | 487          | 300            | 0.20 | B2III |
| 102776 | j Cen    | 4.31      | 13.1     | 4.8             | 507          | 300            | 0.20 | B3Ve |
| 5704   | gam Cir  | 4.35      | 4.0      | 1.7             | 1147         | 250            | 0.20 | B5IV |
| 20904  | ups Cyg  | 4.42      | 11.8     | 4.3             | 560          | 300            | 0.20 | B2Vne |
| 148184 | Chi Oph  | 4.43      | 11.7     | 4.3             | 567          | 300            | 0.20 | B2Vne |
| 63462  | Omi Pup  | 4.49      | 12.0     | 4.1             | 553          | 300            | 0.20 | B1IVe |
| 75311  | f Car    | 4.49      | 11.1     | 4.1             | 600          | 300            | 0.20 | B3Vne |
| 4180   | omi Cas  | 4.50      | 3.5      | 1.5             | 1320         | 250            | 0.20 | B5III |
| 198183 | lam Cyg  | 4.54      | 3.4      | 1.4             | 1367         | 250            | 0.20 | B5 Ve |
| 205637 | Eps Cap  | 4.55      | 10.5     | 3.8             | 633          | 300            | 0.20 | B3V |
| 37490  | Ome Ori  | 4.59      | 10.1     | 3.7             | 660          | 300            | 0.20 | B3Ve |
| 164284 | 66 Oph   | 4.60      | 7.0      | 2.3             | 947          | 300            | 0.20 | B2Ve |
| 112078 | lam Cru  | 4.60      | 10.0     | 3.7             | 667          | 300            | 0.20 | B3Vne |
| 78764  | E Car    | 4.65      | 6.0      | 3.5             | 1107         | 300            | 0.20 | B2IV |
| 56014  | 27 Cma   | 4.65      | 3.0      | 1.3             | 1513         | 250            | 0.20 | B4Ve |
| 57150  | ups01 Pup| 4.67      | 9.4      | 3.4             | 707          | 300            | 0.20 | B2V+B3IV |
| 209409 | omi Aqr  | 4.69      | 2.7      | 1.4             | 833          | 175            | 0.20 | B7IV |
| 192685 | QR Vul   | 4.75      | 8.7      | 3.2             | 760          | 300            | 0.20 | B3 Ve |
| 83953  | I Hya    | 4.66      | 2.8      | 1.2             | 820          | 175            | 0.20 | B5 V |
| 68980  | r Pup    | 4.77      | 8.6      | 3.1             | 773          | 300            | 0.20 | B1Ve |
| 158643 | 51 Oph   | 4.81      | 1.0      | 0.8             | 1160         | 125            | 0.20 | A0V |
| 92938  | V518 Car | 4.82      | 8.2      | 3.0             | 813          | 300            | 0.20 | B3Ve |
| 20336  | BK Cam   | 4.85      | 7.9      | 2.9             | 833          | 300            | 0.20 | B2.5Ve |
| 142983 | 48 Lib   | 4.87      | 3.5      | 1.0             | 1320         | 250            | 0.20 | B5III |
| 191610 | 28 Cyg   | 4.93      | 4.5      | 1.8             | 1027         | 250            | 0.20 | B2.5Ve |
| 35439  | 25 Ori   | 4.96      | 7.0      | 2.6             | 947          | 300            | 0.20 | B1Vne |
| HD   | Star Name | Type   | Mass | Age  | Temperature | Rotation | Spectral Class | Notes   |
|------|-----------|--------|------|------|-------------|----------|----------------|---------|
| 187811 | 12 Vul    |        | 5.96 | 0.2  | 3.0         | 0.2      | B2.5Ve         |         |
| 21076 | 31 Peg    |        | 5.09 | 0.3  | 3.0         | 0.3      | B2IV-Ve        |         |
| 24479 | HD 24479  |        | 5.04 | 0.0  | 3.0         | 0.0      | B9IV           |         |
| 124367 | V795 Cen  |        | 5.07 | 0.9  | 3.0         | 0.9      | B2Ve           |         |
| 32343 | 11 Cam    |        | 5.08 | 0.4  | 3.0         | 0.4      | B3            |         |
| 23686 | Pleione   |        | 5.10 | 0.6  | 3.0         | 0.6      | B8Ve           |         |
| 131492 | tet Cir   |        | 5.11 | 0.2  | 3.0         | 0.2      | B2IIIe         |         |
| 48917 | 10 Cma    |        | 5.17 | 0.2  | 3.0         | 0.2      | B2Ve           |         |
| 71510 | HD 3330   |        | 5.17 | 0.2  | 3.0         | 0.2      | B3IVe          |         |
| 203467 | 6 Cep     |        | 5.18 | 0.2  | 3.0         | 0.2      | B3IVe          |         |
| 189687 | 25 Cyg    |        | 5.19 | 0.2  | 3.0         | 0.2      | B3IVe          |         |
| 169985 | d Ser     |        | 5.32 | 0.4  | 3.0         | 0.4      | A0Vs+G:III     |         |
| 167128 | HR 6819   |        | 5.36 | 1.8  | 3.0         | 1.8      | B2Ve           |         |
| 142184 | HD 142184 |        | 5.40 | 1.8  | 3.0         | 1.8      | B2V            |         |
| 28497 | 228 Eri   |        | 5.41 | 2.0  | 3.0         | 2.0      | B2(V)Me        |         |
| 180968 | ES Vul    |        | 5.43 | 1.7  | 3.0         | 1.7      | B0.5IV         |         |
| 217050 | EW Lac    |        | 5.43 | 0.7  | 3.0         | 0.7      | B4IIIpe        |         |
| 58155 | NO Cma    |        | 5.43 | 1.7  | 3.0         | 1.7      | B3Ve           |         |
| 105521 | V817 Cen  |        | 5.50 | 1.6  | 3.0         | 1.6      | B3IVe          |         |
| 91120 | HD 91120  |        | 5.58 | 0.4  | 3.0         | 0.4      | B5/9IV/V       |         |
| 144   | 10 Cas    |        | 5.59 | 0.4  | 3.0         | 0.4      | B9IIIe         |         |
| 46860 | mu Pic    |        | 5.64 | 1.4  | 3.0         | 1.4      | B9Vne          |         |
| 49131 | HP Cma    |        | 5.68 | 1.4  | 3.0         | 1.4      | B1.5Vne        |         |
| 214168 | 8 Lac A   |        | 5.69 | 1.3  | 3.0         | 1.3      | B1Ve           |         |
| 36576 | 120 Tau   |        | 5.69 | 0.8  | 3.0         | 0.8      | B2IV-ve        |         |
| 23016 | 13 Tau    |        | 5.69 | 0.5  | 3.0         | 0.5      | B7Ve           |         |
| 169033 | HD 169033 |        | 5.70 | 0.5  | 3.0         | 0.5      | B5V            |         |
| 88661 | HR 4009   |        | 5.75 | 1.1  | 3.0         | 1.1      | B5Vne          |         |
| 142926 | 4 Her     |        | 5.75 | 0.3  | 3.0         | 0.3      | B9pe           |         |
| 72067 | HR 3356   |        | 5.81 | 1.2  | 3.0         | 1.2      | B2/3Ve         |         |
| 30076 | 56 Eri    |        | 5.81 | 1.2  | 3.0         | 1.2      | B2(V)me        |         |
| 66194 | V374 Car  |        | 5.81 | 1.2  | 3.0         | 1.2      | B3Vne          |         |
| 54309 | FV Cma    |        | 5.83 | 1.2  | 3.0         | 1.2      | B3Vne          |         |
| 208682 | HD 208682 |        | 5.86 | 1.1  | 3.0         | 1.1      | B2Ve           |         |
| 63215 | V392 Pup  |        | 5.87 | 0.4  | 3.0         | 0.4      | B5Ve           |         |
| 129954 | CO Cir    |        | 5.88 | 1.1  | 3.0         | 1.1      | B2Ve           |         |
| 149671 | etal TrA  |        | 5.88 | 0.4  | 3.0         | 0.4      | B7IVe          |         |
| 174237 | CX Dra    |        | 5.90 | 1.1  | 3.0         | 1.1      | B3+F5III       |         |
| 32991 | 105 Tau   |        | 5.92 | 1.1  | 3.0         | 1.1      | B2Ve           |         |
| 158220 | V862 Ara  |        | 5.98 | 0.4  | 3.0         | 0.4      | B7IIIe         |         |
| 185037 | 11 Cyg    |        | 6.03 | 0.3  | 3.0         | 0.3      | B8Vne          |         |
| 29866 | HD 29866  |        | 6.08 | 0.2  | 3.0         | 0.2      | B8V            |         |
| 183656 | V923 Aql  |        | 6.08 | 0.8  | 3.0         | 0.8      | B7III          |         |
| 23552 | HD 23552  |        | 6.14 | 0.2  | 3.0         | 0.2      | B8V            |         |
| 183537 | 7 Vul     |        | 6.33 | 0.3  | 3.0         | 0.3      | B5Vne          |         |
| 58050 | OT Gem    |        | 6.41 | 0.7  | 3.0         | 0.7      | B2Ve           |         |
| 65875 | HD 65875  |        | 6.59 | 0.6  | 3.0         | 0.6      | B2.5V          |         |
| 170235 | HD 170235 |        | 6.59 | 0.6  | 3.0         | 0.6      | B1Vne          |         |
| 24534 | X Per     |        | 6.72 | 0.2  | 3.0         | 0.2      | O9.5III        |         |
| 6226 | V442 And  |        | 6.82 | 0.3  | 3.0         | 0.3      | B2.5III        |         |
| Object   | Dist. | Mag. | Sp. Mag. | Disp. | Rad. Vel. | Rad. Dist. | Vel. Disp. | Type |
|----------|-------|------|----------|-------|-----------|------------|------------|------|
| HD 203699 | 6.86  | 1.2  | 0.5      | 1800  | 100       | 3600       | 0.45       | B2.5IVne Be |
| HD 162732 | 6.89  | 0.4  | 0.2      | 1900  | 100       | 3600       | 0.74       | B6IIImp,sh Be |
| HD 218393 | 6.92  | 1.2  | 0.4      | 1920  | 175       | 3600       | 0.46       | B3pe+K1III Be |
| HD 11606  | 7.02  | 1.1  | 0.4      | 2100  | 175       | 3600       | 0.48       | B2Vne Be |
| HD 17520  | 8.24  | 0.4  | 0.1      | 2100  | 100       | 3600       | 0.85       | O8V+O9:Ve Be |
| HD 87901  | 1.40  | 50.0 | 25.0     | 120   | 300       | 329        | 0.20       | B8IVn Bn |
| HD 169002 | 1.85  | 15.1 | 12.0     | 440   | 300       | 688        | 0.20       | B9IVp Bn |
| HD 135742 | 2.62  | 15.0 | 8.0      | 440   | 300       | 1030       | 0.20       | B8Vn Bn |
| HD 106490 | 2.75  | 54.9 | 25.0     | 120   | 300       | 410        | 0.20       | B3pe+K1III Be |
| HD 177724 | 2.99  | 5.3  | 4.2      | 1240  | 300       | 1968       | 0.20       | A0IV-Vm Bn |
| HD 136298 | 3.19  | 36.6 | 13.4     | 180   | 300       | 614        | 0.20       | B1.5IVn Bn |
| HD 143118 | 3.41  | 29.9 | 11.0     | 220   | 300       | 751        | 0.20       | B2.5IVn Bn |
| HD 177756 | 3.44  | 3.5  | 2.8      | 1300  | 250       | 2949       | 0.20       | B8.5V Bn |
| HD 125238 | 4.03  | 2.0  | 1.6      | 1100  | 175       | 3600       | 0.24       | B8/9IV Bn |
| HD 128345 | 4.05  | 16.6 | 6.1      | 400   | 300       | 1355       | 0.20       | B3/4IVn Bn |
| HD 144294 | 4.20  | 12.0 | 5.3      | 540   | 300       | 1548       | 0.20       | B2.5IVn Bn |
| HD 164577 | 4.43  | 1.4  | 1.1      | 1600  | 175       | 3600       | 0.29       | A0.5Vn Bn |
| HD 33802  | 4.45  | 1.4  | 1.1      | 1640  | 175       | 3600       | 0.29       | B7.5V Bn |
| HD 64503  | 4.47  | 11.2 | 4.1      | 580   | 300       | 2003       | 0.20       | B2Vn Bn |
| HD 22585  | 4.56  | 1.3  | 0.8      | 1740  | 175       | 3600       | 0.35       | B9IVn Bn |
| HD 142114 | 4.59  | 6.0  | 3.7      | 1100  | 300       | 2230       | 0.20       | B2.5Vn Bn |
| HD 144367 | 4.63  | 7.0  | 2.1      | 940   | 300       | 3600       | 0.21       | B1.5V Bn |
| HD 113703 | 4.69  | 2.9  | 1.3      | 760   | 175       | 3600       | 0.27       | B4Vn Bn |
| HD 24072  | 4.72  | 1.1  | 0.9      | 2100  | 175       | 3600       | 0.33       | B9.5V Bn |
| HD 176688 | 4.72  | 1.0  | 0.8      | 2260  | 175       | 3600       | 0.33       | B9.5V Bn |
| HD 93194  | 4.79  | 5.0  | 2.0      | 1320  | 300       | 3600       | 0.21       | B3/5Vn Bn |
| HD 108257 | 4.81  | 8.3  | 3.0      | 800   | 300       | 2726       | 0.20       | B3V Bn |
| HD 93607  | 4.85  | 2.5  | 1.1      | 880   | 175       | 3600       | 0.29       | B4Vn Bn |
| HD 15120  | 4.87  | 9.0  | 0.7      | 1220  | 125       | 3600       | 0.35       | A0V Bn |
| HD 32309  | 4.88  | 0.9  | 0.7      | 1240  | 125       | 3600       | 0.35       | B9V Bn |
| HD 18415  | 4.96  | 4.0  | 1.8      | 1140  | 250       | 3600       | 0.23       | B0.5III Bn |
| HD 42167  | 4.99  | 2.2  | 1.0      | 1020  | 175       | 3600       | 0.31       | B7III Bn |
| HD 184606 | 5.00  | 0.8  | 0.7      | 1380  | 125       | 3600       | 0.37       | B8III Bn |
| HD 43445  | 5.00  | 0.8  | 0.7      | 1380  | 125       | 3600       | 0.37       | B9V Bn |
| HD 181296 | 5.02  | 0.8  | 0.6      | 1400  | 125       | 3600       | 0.38       | A0V+M7/8V Bn |
| HD 20418  | 5.03  | 2.1  | 0.9      | 1040  | 175       | 3600       | 0.32       | B5V Bn |
| HD 196740 | 5.05  | 2.1  | 0.9      | 1060  | 175       | 3600       | 0.32       | B5IV Bn |
| HD 135240 | 5.09  | 6.4  | 2.3      | 1040  | 300       | 3532       | 0.20       | O8V Bn |
| HD 172777 | 5.11  | 0.8  | 0.6      | 1540  | 125       | 3600       | 0.39       | A0/1V Bn |
| HD 74753  | 5.16  | 3.0  | 2.2      | 1540  | 250       | 3600       | 0.20       | B1/2II/III Bn |
| HD 18331  | 5.16  | 0.7  | 0.6      | 1600  | 125       | 3600       | 0.40       | A1V Bn |
| HD 26793  | 5.22  | 0.6  | 0.5      | 1920  | 125       | 3600       | 0.41       | B9V Bn |
| HD 168905 | 5.23  | 5.6  | 2.1      | 1180  | 300       | 3600       | 0.21       | B3V Bn |
| HD 222847 | 5.24  | 0.7  | 0.5      | 1720  | 125       | 3600       | 0.42       | B9V Bn |
| HD 212710 | 5.26  | 0.6  | 0.5      | 1920  | 125       | 3600       | 0.42       | B9.5V Bn |
| HD       | HR     | V     | B     | T     | B-V  | Extinction Ratio | Spectral Type | Notes |
|----------|--------|-------|------|------|-----|------------------|---------------|-------|
| 34863    |        | 5.28  | 0.6  | 0.5  | 1800| 125 3600         | B7/8V         |       |
| 20809    | 1011   | 5.30  | 2.2  | 0.7  | 1020| 175 3600         | B5V           |       |
| 93540    | 4219   | 5.34  | 1.6  | 0.7  | 1400| 3600 3600        | B6Vn          |       |
| 107696   |        | 5.37  | 1.6  | 0.7  | 1420| 125 3600         | B7Vn          |       |
| 136849   | 50 Boo | 5.37  | 0.6  | 0.5  | 1960| 125 3600         | B9Vn          |       |
| 208321   |        | 5.44  | 0.6  | 0.4  | 2080| 125 3600         | A3V           |       |
| 19134    | 52 Ari | 5.47  | 1.4  | 0.6  | 1580| 3600 3600        | B9V           |       |
| 189395   |        | 5.50  | 0.5  | 0.4  | 2200| 125 3600         | B9V           |       |
| 35770    | 116 Tau| 5.51  | 0.5  | 0.4  | 2240| 125 3600         | B9.5V         |       |
| 560      | 34 Psc | 5.53  | 0.5  | 0.4  | 2300| 125 3600         | B9V           |       |
| 159358   |        | 5.54  | 0.5  | 0.4  | 2280| 125 3600         | B9V           |       |
| 21362    |        | 5.57  | 1.3  | 0.6  | 1720| 3600 3600        | B6V           |       |
| 209833   | 23 Peg | 5.70  | 0.4  | 0.3  | 1680| 3600 3600        | B9V           |       |
| 188293   | 57 Aql | 5.71  | 1.1  | 0.5  | 1960| 125 3600         | B7V           |       |
| 150745   | HR 6215| 5.73  | 3.5  | 1.3  | 1300| 3600 3600        | B2III/IV      |       |

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