Constraining the Limits of the Magnetic Confinement-Rotation Diagram: An Analysis of Two B-type Systems Hosting Recently Discovered Extreme Centrifugal Magnetospheres

by

James Sikora

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Queen’s University
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Abstract

Following the detection in the late 70s of a strong magnetic field in the early B-type star $\sigma$ Ori E and, more recently with the results of the Magnetism In MassivE Stars (MiMeS) survey, an important and rare subclass of magnetic B-type stars has been emerging. Magnetic stars hosting so called “centrifugal magnetospheres” are characterized by rapid rotation and feature strong and broad emission lines in their spectra produced by a hot plasma co-rotating with the star well beyond the surface (at distances of several times the stellar radius). Since the first discovery of these properties in the magnetic B2Vp star $\sigma$ Ori E, the dense, rigidly-rotating circumstellar plasma has been understood as an accumulation of the star’s wind in regions of closed magnetic loops above the surface. These objects serve as unique laboratories for studying how the fast winds emitted by all B-type stars interact with magnetic fields in extreme environments. In this study, the properties of two rapidly rotating stars, HD 23478 and HD 35502, hosts to centrifugal magnetospheres and exhibiting strong emission in their spectra, are derived. Our results establish new upper limits on the magnetic confinement-rotation diagram – a diagnostic tool which is used to understand the magnetospheres of O- and B-type stars in a broader context.

The derived rapid rotation and strong magnetic fields imply that these two stars
occupy the most extreme region of the magnetic confinement-rotation diagram populated by known centrifugal magnetosphere-hosting stars such as σ Ori E and HR 5907.
Co-Authorship

This thesis presents results that have been published in other fora and represent collaborative efforts with other scientists.

Chapter 3 represents a modified version of an article published in the journal Monthly Notices of the Royal Astronomical Society (2015, 451, 1928-1938) by J. Sikora, G. A. Wade, D. A. Bohlender, C. Neiner, M. E. Oksala, M. Shultz, D. H. Cohen, A. ud-Doula, J. Grunhut, D. Monin, S. Owocki, V. Petit, T. Rivinius, and R. H. D. Townsend. I was the principal author of this work and was responsible for the large majority of the analysis, interpretation, and writing involved in the manuscript. My role in this paper was that I performed all the analysis involving the ESPaDOnS, NARVAL, and photometric observational data under the guidance of G. A. Wade. D. A. Bohlender and D. Monin provided longitudinal magnetic field measurements obtained using dimaPol. C. Neiner contributed the spectropolarimetric observations obtained using NARVAL. M. Shultz provided help verifying certain results. R. H. D. Townsend computed the Rigidly Rotating Magnetosphere model specific to the derived parameters. All of the co-authors also contributed comments and editing advice.

The analysis of HD 35502 presented in Chapter 4 uses data provided by C. Neiner
and E. Alecian obtained using NARVAL within the context of the Binarity and Magnetism in various classes of Stars (BinaMIcS) survey. D. A Bohlender and D. Monin provided spectra obtained at CFHT and DAO. I was also the principal author of the work presented in this chapter and carried out the majority of the analysis and associated interpretation.
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Chapter 1

Introduction

1.1 Stellar Magnetism

Given that a large fraction of the H, He, and metal atoms composing every star are either partially or completely ionized, it is natural that all stars exhibit magnetic fields on some scales. Whether or not these fields can be observed depends not only on technical limitations – i.e. the detection thresholds of modern polarimetric instruments – but also on the physical characteristics of the star’s magnetic activity. For instance, the complex and disorganized magnetic fields produced by the Sun tend to cancel out reducing the global strength in polarized light; therefore, such a field configuration may not be detectable in a distant, unresolved star. Despite this, widespread detections of magnetic fields of cool stars have been reported during the last decade (Donati et al., 2006b; Morin et al., 2008; Marsden et al., 2014), and now it appears likely that the majority of cool stars in the Milky Way host large-scale fields with strengths $\lesssim 3$ G (Donati & Landstreet, 2009).

On the other hand, magnetic fields in the hotter intermediate and high mass stars
(i.e. those with \( M \gtrsim 1.5 M_\odot \)) are rarely detected. Indeed, the incidence of fields observed in all O- and B-type stars is consistently reported to be \( \approx 10\% \) \cite{Landstreet1992}. More recently, this same 10\% incidence rate was reported by \cite{Grunhut2012} inferred from the Magnetism in Massive Stars (MiMeS) survey.

Along with the drastically different incidence rates, the magnetic fields observed in hot stars are typically found to exhibit much simpler structures than those of cooler stars. Specifically, they are generally not only coherent but are dominated by a dipole component that is stable on timescales at least on the order of decades \cite{Donati2009}. An important distinction between hot and cool star magnetism is that a well-determined correlation exists between the rotational periods of cooler stars and the strengths of their magnetic fields. That is, for stars having \( M \lesssim 1 M_\odot \), the mean large-scale field strengths increase with increasing rotational velocities \cite{Donati2009}. This result is consistent with a magnetic field that is generated by the turbulent motions of an ionized gas (otherwise known as dynamo processes) found within hot convective regions \cite{Brun2004, Browning2008}.

In order for a hot star’s magnetic field to be powered in a similar fashion to that of a cooler star, it must originate within a region dominated by convection. In O-, B-, and A-type stars, the temperatures outside the core are high enough that H is fully ionized resulting in energy transport that is dominated by radiation. However, in the core, the simultaneously high temperatures and densities allow convection to transport energy efficiently. It is only within the convective cores of hot stars where a sufficiently strong magnetic field could potentially be produced by a dynamo.
The possibility that this is indeed how the observed fields of magnetic hot stars are generated has been explored by various theorists (e.g. Charbonneau & MacGregor 2001; MacGregor & Cassinelli 2003); however, the main difficulty that is encountered is not in the generation of a sufficiently strong field but is rather related to the very long timescales required to transport the magnetic flux to the stellar surface. Alternatively, it has been proposed that the simple dipolar fields of massive stars are remnants from the initial formation of the star. In this scenario, the weak magnetic fields permeating the Galaxy (with strengths \( \sim 1 \mu \text{G} \), e.g. Heiles 1988; Frick et al. 2001) are amplified through flux conservation during the collapse of a giant molecular cloud. This leads to the formation of a star which hosts a so-called fossil field (e.g. Mestel 2012).

Currently, the theoretical evidence in support of long-life fossil stellar magnetism is relatively sparse. Several studies have demonstrated that either purely poloidal or purely toroidal field configurations in the radiative envelope of a star are inherently unstable (Tayler 1973; Wright 1973; Braithwaite 2006, 2007). However, a stable field may be obtained through a combination of toroidal and poloidal components (Braithwaite & Spruit 2004; Braithwaite 2006). These numerical magnetohydrodynamical simulations demonstrated that the magnetic fields evolve through various equilibrium states before settling into a non-axisymmetric configuration (Braithwaite 2008). More recently, Duez, Braithwaite & Mathis (2010); Duez & Mathis (2010) derived a family of axisymmetric field configurations that remained stable for many well-studied instabilities.

The recent theoretical demonstration that fossil fields may persist within the radiative envelopes of hot stars is particularly important given the strong observational
support of this hypothesis. Studies carried out by Bagnulo et al. (2006) and Landstreet et al. (2007) investigated the evolution of the magnetic fields of stars from the zero age main sequence (ZAMS) to the terminal age main sequence (TAMS). They found that the fields exist very early on in the star’s evolution (near or before the ZAMS) and that they dissipate approximately at a rate that what would be expected from flux conservation as the star’s radius expands near the TAMS. It is also well established that, unlike in cool Sun-like stars, the observed magnetic field strengths of hot stars do not scale with rotational periods and exhibit simple, primarily dipolar, field structures (Donati & Landstreet, 2009). An example of the typical magnetic field geometry of hot stars is shown in Fig. 1.1 as derived for σ Ori E by Oksala et al. (2015). According to recent MHD simulations of field relaxation, these are all properties one would expect from a residual magnetic field sustained from an earlier period during the star’s formation.

1.2 Emission in B-type Stars

Various emission features are often associated with the observed spectra of all hot stars. In the case of B-type stars, there exist several distinct mechanisms for producing emission lines in their observed spectra (described below). Given that both HD 23478 and HD 35502 are B stars which exhibit strong emission, it is important to distinguish between the known subclasses of emission-line stars in order to correctly interpret its origin.

One of the most basic manifestations of emission is a consequence of the dense stellar winds emitted by hot supergiants. All stars, including the Sun, emit winds having various velocities and densities throughout their lives; however, it has been
found that only the winds of O, B, and A stars having $L \gtrsim 10^4 L_\odot$ are directly observable in optical spectra (Abbott, 1979). This is possible through the identification of unique features in the star’s spectra known as P Cygni profiles. The mass loss rates associated with the radiatively driven stellar winds are sufficiently high to produce a relatively dense envelope of hot gas extending well beyond the star’s surface. As light emitted by the star passes through the gas that is located directly between the observer and the stellar disc, it is scattered and absorbed. Since the gas is moving towards the observer at typical terminal velocities exceeding $10^3 \text{ km s}^{-1}$, much of this absorption is strongly blue shifted. The diffuse wind that is located away from the
observer’s line of sight (i.e. projected on the sky beside the stellar disc) scatters and re-emits starlight. Similarly to the Doppler shifted absorption component, this emission is both blue shifted (from wind moving towards the observer, on the near side of the star) and red shifted (from wind moving away from the observer, on the far side of the star) (e.g. Kudritzki & Puls 2000). Therefore, an asymmetrical spectral feature is observed in various lines – particularly in Hα – that are easily identified from their characteristic profiles.

In contrast to the approximately spherical distribution of gas associated with stellar winds, the line emission observed in Classical Be stars is produced by a gaseous equatorial disk. Classical Be stars are rapidly rotating (exhibiting projected equatorial rotational velocities up to $v \sin i \sim 350\text{ km s}^{-1}$) B-type stars which host a Keplerian decretion disk (Rivinius, Carciofi & Martayan 2013). These stars can be classified as either emission-line or shell-line Be stars. Unlike shell-line stars, emission-line stars do not exhibit an absorption component but rather, all of the normalized flux associated with the Balmer lines (e.g. Hα) exceeded unity (Porter & Rivinius 2003).

Although the origin of the hot equatorial disk and the mechanism by which they are maintained is still unclear, several global properties of the central B stars have been identified. For instance, most Be stars are rapid rotators as characterized by the population’s average rotational period of approximately 70 – 80% of the critical period (i.e. the period at which the centrifugal force at the equator balances the gravitational force) (e.g. Porter 1996).

Herbig Ae/Be (HAeBe) stars are similar to Classical Be stars in that their abnormal spectral features are associated, in part, with equatorial disks. However, an HAeBe star’s disk is primarily composed of hot dust rather than a relatively diffuse
gas. They are pre-main sequence stars having masses between approximately 2 and 10 $M_\odot$. As a result of their locations within star-forming regions, they are enshrouded by gas that is heated by the central A or B star thereby producing emission lines in the observed spectra (Waters & Waelkens 1998). The dusty circumstellar matter associated with the star’s formation is similarly heated which adds a significant infrared flux contribution to the total spectral energy distribution.

Finally, another mechanism by which emission is produced in the spectra of B (and O) stars is through magnetic confinement of hot plasma. In this scenario, the emitted hot stellar wind is trapped by a strong, coherent magnetic field leading to the formation of a magnetosphere. Therefore, it is clear that despite the similar spectral properties which frequently motivate the classification of these stars as Be (or Oe), the origin of the observed emission differs from that of Classical Be stars. For instance, the clear rotational modulation of the emission strength is commonly associated with magnetically-confined winds (e.g. Landstreet & Borra 1978; Bohlender & Monin 2011; Grunhut et al. 2012). This is directly related to the fact that the strong dipole components of the magnetic fields of hot stars are often inclined with respect to the star’s rotation axis (see Section 2.2). While the gaseous disk is confined to the magnetic field’s equatorial plane, it is also forced to corotate with the star’s rotation. Therefore, if the magnetic axis is inclined relative to the star’s rotation axis, an observer will periodically be exposed to different configurations of the star-disk system. These can be approximately described by the Rigidly-rotating Magnetosphere (RRM) model which assumes that the magnetic field is undistorted by either the outflowing wind or the accumulating plasma (Townsend & Owocki 2005).
1.3 Dynamical vs. Centrifugal Magnetospheres

As a better understanding of certain astrophysical objects or phenomena is acquired over time, initially devised classification schemes are often subdivided. This is also true of the magnetically-confined winds discussed in Section 1.2. In this case, the magnetospheres (i.e. the regions of ionized gas located within the closed loops of a star’s magnetic field) of O and B stars are classified as either dynamical or centrifugal (Petit et al., 2013) based on the dominant physical properties that contribute to their global structure and characteristics.

Before describing dynamical and centrifugal magnetospheres and how they differ, it is useful to be familiar with the parameters which are inherent to their definitions. The more important of the two is the Alfvén radius ($R_A$). It is used to define the point within which the energy density of the magnetic field dominates over the kinetic energy density of the wind. $R_A$ is relatively difficult to compute because of its dependence on the wind confinement parameter defined as

$$\eta_* \equiv \frac{B_{eq}^2 R_*^2}{\dot{M}_{B=0} V_\infty}$$  \hspace{1cm} (1.1)

where $B_{eq}$ is the magnetic field strength at the magnetic equator (located at a distance of $R_*$ from the star’s center), $V_\infty$ is the terminal velocity of the wind, and $\dot{M}_{B=0}$ is the mass-loss rate in the absence of a magnetic field (ud-Doula & Owocki, 2002). $R_A$ within the plane of the magnetic equator can then be estimated using $\eta_*$ as a scaling relation which, assuming the magnetic field is dominated by a dipole component, is given by

$$\frac{R_A}{R_*} \approx 0.3 + (\eta_* + 0.25)^{1/4}$$  \hspace{1cm} (1.2)
as derived by ud-Doula, Owocki & Townsend (2008). The second more basic parameter is the Kepler corotation radius ($R_K$). It defines the point at which the inward gravitational pull is exactly balanced by the outwardly directed centrifugal force associated with the star’s rotational velocity. This is given by

$$R_K \equiv \left( \frac{GM}{\Omega^2} \right)^{1/3} \quad (1.3)$$

where $M$ is the mass of the star and $\Omega$ is its frequency of rotation. With the Kepler corotation radius and the Alfvén radius of a star specified, classifying its magnetosphere as either dynamical or centrifugal is simply a matter of computing $R_A/R_K$ (Petit et al., 2013).

Stars hosting dynamical magnetospheres (DMs) are those for which $R_A/R_K < 1$. Since the plasma is corotating with the star, a value of $R_A/R_K < 1$ implies that the centrifugal force acting on the wind dominates over the magnetic pressure. Thus, in this regime, the bulk of the wind that accumulates in the magnetosphere will eventually fall back onto the surface of the star. The implication for the observation of stars hosting DMs is that the confined plasma will accumulate only over the relatively short dynamical timescales (i.e. $t_{dyn}^2 \approx R^3/GM$, Hansen, Kawaler & Trimble, 2004). One expects their magnetospheric plasma densities to be relatively low, and therefore one would not expect to find many of these stars exhibiting Balmer line emission unless their mass-loss rates are particularly high (Shultz et al., 2014).

Stars hosting centrifugal magnetospheres (CMs) are those for which $R_A/R_K \geq 1$. In this case, the corotation of the wind is enforced beyond $R_K$. Plasma in the region where $R_K < r < R_A$ is subject to a net centrifugal force that is larger than the local gravitational force. This supports the plasma against infall. Therefore the wind tends
to accumulate in the region between $R_K$ and $R_A$, thereby producing Hα emission. A diagram depicting both the CM and DM scenarios is shown in Fig. 1.2 which appears in Fig. 2 of Petit et al. (2013). Additionally, a number of the CM hosting B-type stars are also known to be luminous X-ray sources ($L_X \propto \dot{M}^{1.4}$ where $L_X$ is the X-ray luminosity, Nazé et al. 2014). This is likely caused by the hot wind being directed along the dipolar magnetic field lines and colliding near the magnetic equator producing strong shocks. Magnetohydrodynamic simulations suggest that these shocks, and thus, the emitted $L_X$, may be enhanced by unusually strong mass-loss rates (Townsend, Owocki & ud-Doula 2007).

Based on the compilation of 54 magnetic B-type stars, Petit et al. (2013) demonstrated that at least 39 (i.e. $\gtrsim 70\%$) host CMs. Furthermore, when the 4 Herbig Be stars in their sample are neglected, only 26% of the B stars in the sample are known to exhibit Hα emission with all but one hosting a CM. More recently, Shultz et al. (2014) suggested that detectable Hα emission is limited to those stars having $R_A/R_K \gtrsim 10$. Thus, while the reason that only this particular subset of B stars is able to accumulate a dense plasma is currently unknown, it is clear that both the volume of the magnetosphere and the star’s rotational period likely play a critical role. The magnetic confinement-rotation (MCR) diagram published by Petit et al. (2013) is shown in Fig. 1.3.

The distribution of stars across the MCR diagram is such that approximately 72 per cent of all known magnetic B-type stars host centrifugal magnetospheres; if those stars which potentially host CMs based on their unconstrained $R_K$ and $R_A$ parameters are also considered, the population increases to nearly 94 per cent. Moreover, it is evident from Fig. 1.3 that the number of magnetic stars sharply decreases for
Figure 1.2: A diagram depicting the DM and CM regimes (Petit et al., 2013). The vertical blue line corresponds to $R_A$ (the extent of the magnetic field’s confinement of the wind) while the vertical black line corresponds to $R_K$ (the point at which the local gravitational force balances the centrifugal force).
Figure 1.3: The magnetic confinement-rotation diagram published by Petit et al. (2013). The diagonal line corresponds to \( R_A = R_K \) which defines the boundary between the centrifugal \( (R_K/R_A > 1) \) and the dynamical \( (R_K/R_A < 1) \) regimes. The indices refer to each of the 64 O- and B-type stars included in their study. The star \( \sigma \) Ori E, discussed in Section 1.4, corresponds to number 31 located at \( R_K = 2.1 R_* \) and \( R_A = 31 R_* \) (circled in red).
$R_A \gtrsim 20 \, R_\star$ and $R_K \gtrsim 4 \, R_\star$.

### 1.4 σ Ori E: A Prototypical CM Host

One of the first stars to be suspected of hosting a CM is σ Ori E. However, before being recognized as a prototypical CM host, interest in this specific star began with the discovery of its chemical peculiarities. Following the discovery of its enhanced He abundance (Greenstein & Wallerstein, 1958), σ Ori E became the first member of the class of He-rich stars (Osmer & Peterson, 1974). Since then, magnetic fields have been detected in the majority of these He-rich stars (e.g. Borra & Landstreet, 1979; Bohlender et al., 1987). These results confirmed speculation that this class of stars is analogous to the chemically peculiar Ap stars, all of which are magnetic (e.g. Babcock, 1947, 1958; Aurière et al., 2007).

Before its magnetic field had been detected, observations of σ Ori E indicated that several of its observational properties tended to vary periodically. The depths of the Hα absorption line measured with respect to the continuum were found to fluctuate from a minimum of 25% (maximum emission) to a maximum of 74% (minimum emission) (Walborn, 1974). Although, at the time, the detection of emission is not unusual for B-type stars, the variation in the strength of σ Ori E’s Hα emission was a previously undocumented phenomenon. Moreover, photometric observations revealed maximum brightness variations of approximately 0.16 mag in the $u$ band (at an effective wavelength of $\approx 3500$ Å) (Walborn & Hesser, 1976). A period analysis performed on the photometric and Hα equivalent width measurements suggested that both phenomena varied over a 1.19 d period. Although these discoveries prompted a discussion (e.g. Hesser, Walborn & Ugarte, 1976; Kemp & Herman, 1977) on whether
or not they might be related in some way to the oblique rotator model (ORM, see Section 2.2), the nature of σ Ori E remained unclear.

The discovery of σ Ori E’s strong magnetic field by [Landstreet & Borra 1978] allowed for a new interpretation of this star’s variability. The magnetic field was found to have a dipolar strength of $B_d > 10 \text{ kG}$ which was derived based on the ORM using multiple longitudinal field measurements ($-0.9 \lesssim \langle B_z \rangle \lesssim 2.8 \text{ kG}$). These measurements were later confirmed with follow-up observations carried out by [Bohlender et al. 1987]. With an inferred $\langle B_z \rangle$ period of 1.19 d, it was suggested that the similarly variable brightness and emission strengths are produced by a magnetically confined plasma corotating with the star’s rotation. Based on these results along with the $R_A = 31 R_\star$ and $R_K = 2.1 R_\star$ later calculated by [Petit et al. 2013], σ Ori E became known as the first and most well-studied star to host a CM. Its location on the MCR diagram is shown in Fig. 1.3.

The stars located near σ Ori E on the MCR diagram essentially all exhibit similar behaviour. The range of Kepler radii associated with all of the magnetic B-type stars is primarily a result of the distribution of rotational periods; therefore, it is clear that those neighbouring stars are all relatively rapid rotators exhibiting $P_{\text{rot}} \sim 1 \text{ d}$. Moreover, these stars all have large dipole magnetic field strengths of approximately $5 - 25 \text{ kG}$. Aside from two other instances (HD 35912 and HD 35298), this region of the MCR diagram is populated by stars exhibiting clear Hα emission in their spectra.

As a result of the relatively small number of strongly emitting stars known to host CMs, the current theoretical framework remains largely untested. In order to fully understand the physical mechanisms governing these systems and, more generally, all magnetic stars, a larger sample size containing systems exhibiting a greater variety
of properties needs to be obtained. This will not only facilitate the testing of various theoretical models, but will also benefit statistical studies such as that currently being carried out by Shultz et al. (2014).

1.5 HD 23478 & HD 35502

HD 23478 was one of two rapidly rotating stars identified as potential CM hosts based on infrared observations from the Apache Point Observatory Galactic Evolution Experiment survey (Eikenberry et al., 2014). These observations revealed strong and broad emission exhibited by all of the observed H lines (Brackett series). Following this discovery, 12 Stokes $V$ observations were obtained by Sikora et al. (2015) using the ESPaDOnS and NARVAL instruments along with 11 medium-resolution Stokes $V$ spectra using dimaPol operated at the Dominion Astronomical Observatory. The primary goal of obtaining these spectropolarimetric observations was to confirm whether or not the star was indeed magnetic. Such a confirmation was expected to yield properties similar to that of $\sigma$ Ori E.

HD 35502 was initially discovered to exhibit relatively broad shell-lines in its spectrum by Abt & Hunter (1962). Nearly two decades later, the first magnetic detections were obtained resulting in several longitudinal field measurements of $\langle B_z \rangle \sim 1.5$ kG being reported (Borra, 1981). Although these results suggested that HD 35502 hosted a CM, more precise measurements were required in order to constrain its magnetic strength and geometry. Furthermore, no definitive rotational period had been reported prior to this study which is a crucial aspect of accurately characterizing the star’s magnetospheric properties.

The purpose of this study is to investigate the physical, rotational, and magnetic
properties of these two stars. In doing so, their positions on the magnetic confinement-
rotation diagram will be derived which will allow them to be studied in the context
of the broader population of magnetic stars.

This study confirms HD 23478 and HD 35502 as two new members of the rare
class of stars hosting CMs and, in particular, the subset of those which are known
to exhibit Hα emission. In Chapter 2 the relevant analytical and observational
methods and principles employed throughout this study are described. Chapters 3
and 4 describe the various physical properties of these two stars and how they were
derived including their effective temperatures, surface gravities, masses, rotational
periods, and magnetospheric characteristics. The results of this work along with the
future goals for this research are summarized in Chapter 5.
Chapter 2

Observational & Analytical Principles

2.1 Calculating Basic Astrophysical Parameters

A number of basic physical parameters used in the field of stellar astronomy and astrophysics are calculated throughout this study. One of the most important, and historically, one of the most difficult to determine, is the distance to astronomical objects. In the case of stars within the Milky Way, distances are often determined by precisely measuring the annual trigonometric parallax (i.e., the angle by which an object appears to move with respect to the most distant stars as the Earth revolves around the Sun). Until sufficient data are obtained using the recently launched Gaia space observatory (Dec. 19, 2013), stellar astronomers will continue to rely on astrometric measurements obtained using HiPParCoS, a space observatory operated from 1989 to 1993. During this time, HiPParCoS was used to derive the distances \( d = 1/p \) where \( d \) is the object’s distance in pc and \( p \) is the measured parallax angle.
in arcseconds) of approximately 118,000 stars \cite{Perryman97}.

With the distance to an object known, one can derive its absolute magnitude which depends on the object’s emitted luminosity. It is defined as the apparent magnitude that would be measured at a distance of 10 pc from the object. It can be determined by measuring the object’s apparent magnitude and using the simple relation given by

\[ M = m - 5 \log d + 5 \]  \hspace{1cm} (2.1)

where \( m \) and \( M \) are the object’s apparent and absolute magnitudes in a particular filter and \( d \) is the object’s distance in pc \cite{Carroll07}. Since most astronomical objects emit radiation over a very wide range of wavelengths, one is typically interested in knowing its bolometric magnitude (\( M_{\text{bol}} \)) which corresponds to the absolute magnitude integrated over this full wavelength range. In order to do this, we generally use bolometric corrections (\( BC = M_{\text{bol}} - M_V \) where \( M_V \) corresponds to the absolute magnitude in the visual band) which are calculated from empirically derived calibrations.

The luminosity, \( L \), of a star is typically calculated using one of two methods. The first method depends on \( M_{\text{bol}} \) and is given by

\[ L = 10^{-0.4(M_{\text{bol}} - M_{\text{bol,\odot}})} \]  \hspace{1cm} (2.2)

where \( M_{\text{bol,\odot}} \) is the absolute bolometric magnitude of the Sun. The second approach can be used if the radius (\( R \)) and effective temperature (\( T_{\text{eff}} \)) are known. In this case, the star is considered to be a spherical blackbody (i.e. an object which absorbs all
incident radiation) and the luminosity is derived using the Stefan-Boltzmann law:

\[ L = 4\pi R^2 \sigma T_{\text{eff}}^4 \]  

(2.3)

where \( \sigma = 5.67 \times 10^{-5} \text{ g s}^{-3} \text{ K}^{-4} \). Since the spectral energy distributions produced by most stars are well approximated, to first order, by the spectrum associated with a blackbody of a given temperature, both of these methods for calculating \( L \) generally yield similar results.

### 2.2 Measuring Stellar Magnetic Fields

The first extraterrestrial magnetic field to be discovered and directly measured was found emanating from the surface of the Sun in sunspots \((B \approx 1 - 3 \text{ kG})\) (Hale, 1908). Nearly forty years passed before a similar detection was made in another star (Babcock, 1947) which hosted a field with a strength \( \sim 1 \text{ kG} \). However, before advancements in observational techniques allowed for direct measurements to be more easily obtained, a number of indirect indicators of magnetic activity on stars other than the Sun were developed. For instance, it is now well understood that relatively cool spots like those found on the Sun can be detected on other stars through rotationally modulated variations in the observed brightness (e.g. Mullan, 1979; Pettersen, 1980; Hall, Henry & Sowell, 1990). Similarly, UV, X-ray, and optical emission produced in the chromospheres and coronae of Sun-like stars is known to be produced by hot plasma that is confined and channeled by a star’s magnetic field (e.g. Schrijver, Mewe & Walter, 1984; Baliunas et al., 1995; Reiners & Basri, 2007). In certain instances, the properties of stars (e.g. rapid rotation) and their environments (e.g.
obscuring dust) prevent even the highly sensitive modern instruments from obtaining direct measurements. While these indirect methods may not yield precise information about the field’s strength and geometry, they can be used to definitively detect the presence of magnetic field.

The primary technique for directly measuring stellar magnetic fields is based on the process of atomic energy level splitting known as the Zeeman effect. It is a quantum mechanical process in which an electron energy level of an atom or molecule that is embedded within a magnetic field is split. Therefore, any electron transitions involving such a split energy level yields multiple spectral lines (absorption or emission) where, in the absence of a magnetic field, only a single line would be observed.

Although the magnetic field can be inferred directly from observations of spectral line splitting, this typically requires relatively large field strengths. Depending primarily on the impact of various non-magnetic broadening parameters (e.g. rotational, thermal, and macroturbulent broadening), line splitting may only be detected in stars exhibiting magnetic fields with $B_z \gtrsim 5 \text{ kG}$ (Donati & Landstreet, 2009). Another means of inferring the field strength from Zeeman splitting is through observations of polarized spectra. The primary advantage of this approach is that only the polarized Zeeman signatures produce a signal; the typically strong line broadening effects apparent in the unpolarized spectra do not influence the polarized intensity (Reiners, 2012).

The various polarization components are commonly referred to using the Stokes parameters where Stokes $I$ corresponds to the unpolarized intensity, Stokes $V$ is the circularly polarized intensity, and the two linearly polarized intensities are referred to as the Stokes $Q$ and $U$ components. Using measurements of the Stokes $I$ and $V$
parameters, the surface-averaged longitudinal field, $\langle B_z \rangle$, is given in units of G by

$$\langle B_z \rangle = -2.14 \times 10^{11} \frac{\int vV(v) \, dv}{\lambda z c \int [I_c - I(v)] \, dv},$$

(2.4)

where $v = c \Delta \lambda / \lambda$ is the velocity with respect to the line rest wavelength, $\lambda$, in nm, $z$ is the effective Landé factor, and $I_c$ is the unpolarized continuum intensity [Donati et al. 1997; Wade et al. 2000]. Clearly, measuring a single component of the magnetic field is insufficient to reconstruct the structure of the global field unless certain assumptions are made about its structure (e.g. the field is dominated by a dipole component). Moreover, stars exhibiting complex fields such as those typically found in cooler stars may not be detected in certain components (i.e. parallel or perpendicular to the line-of-sight) as a result of anti-parallel components on the surface. In these cases, Stokes $Q$ and $U$ intensities may also be obtained in order to infer the transverse field component. An example of Zeeman signatures observed in Stokes $V$ is shown in Fig. 2.1.

For hot and massive magnetic stars such as the B-type main sequence stars examined in this study, the fields are typically dominated by a stable dipole component (see Section 1.1). In the specific case that the axis of symmetry of the dipole is inclined by an angle $\beta$ (known as the obliquity) with respect to the star’s axis of rotation (Stibbs 1950), the polar strength of this dipole component at the stellar surface, $B_d$, may be estimated. This derivation forms the basis of the Oblique Rotator Model (ORM) (Stibbs 1950; Preston 1967) which attempts to explain the periodic variations in $\langle B_z \rangle$ that are commonly detected from hot stars (e.g. Landstreet & Borra).
Figure 2.1: An example of the Stokes $I$ (bottom, black) and $V$ (top, red) parameters obtained from the A5p main sequence star, HD 188041. The blue middle curve corresponds to the diagnostic null which contains no polarized signal and can therefore be used to verify the significance of the Stokes $V$ Zeeman signatures. The null and Stokes $V$ measurements have been shifted vertically by 1.05 and 1.36, respectively.

$B_d$ is then given by

$$B_d = 20 \frac{3 - u}{15 + u} \langle B_z \rangle_{\text{max}}$$  \hspace{1cm} (2.5)$$

where $u$ is the limb-darkening coefficient and $\langle B_z \rangle_{\text{max}}$ is the maximum inferred $\langle B_z \rangle$ ([Preston, 1967]). The ORM also yields the obliquity as given by

$$\beta = \cot^{-1} \left[ \frac{1 + r}{1 - r} \tan i \right]$$  \hspace{1cm} (2.6)$$
Figure 2.2: A diagram depicting the Oblique Rotator Model taken from Rauw et al. (2001). The star’s axis of rotation is indicated by the vertical black line. The dotted line indicates the magnetic axis which is inclined with respect to the rotational axis by an angle \( \theta \).

where \( r \equiv \langle B_z \rangle_{\text{min}} / \langle B_z \rangle_{\text{max}} \) and \( i \) is the inclination angle of the rotation axis relative to the line of sight of the observer. A diagram depicting the ORM is shown in Fig. 2.2

2.3 Observational Instruments & Data Reduction

One significant advantage of measuring stellar magnetic fields using the Zeeman effect is its use of relatively simple observations. As discussed in Section 2.2, this primarily involves the measurement of stellar radiation in polarized light that is dispersed by a spectrograph such that the Stokes \( Q \), \( U \), or \( V \) parameters are obtained as a function of wavelength. This process is carried out through the use of spectropolarimeters of which there are currently several operating at various telescopes worldwide.
Both HD 23478 and HD 35502 were observed using the twin spectropolarimeters ESPaDOnS and NARVAL installed at the Canada France Hawai‘i Telescope (CFHT) and the Télémètre Bernard Lyot (TBL), respectively. These instruments have a resolving power of \( R \gtrsim 65000 \) (which specifies the wavelength resolution, \( \Delta \lambda \), through \( R \equiv \lambda/\Delta \lambda \)) and are optimized to obtain spectra across a wavelength range of approximately 3600 – 10000 Å (Donati et al., 2006a). ESPaDOnS and NARVAL essentially consist of two components: a cross-dispersed échelle spectrograph which allows for wide wavelength coverage and a polarimeter which splits the incoming light into its polarized constituents\(^1\).

The light collected by the telescope’s primary mirror is first sent to the polarimeter mounted at the Cassegrain focus. This instrument contains a Bowen-Walraven image slicer which splits the beam and, in conjunction with a Wollaston prism, yields two orthogonally polarized beams. Three Fresnel rhombs are used to rotate the polarization plane associated with these beams: one fixed quarter-wave rhomb and two rotatable half-wave rhombs.

Four subexposures are normally acquired for any single polarized Stokes parameter observation. All of these subexposures are obtained with the Fresnel rhombs rotated at various angles about the optical axis with respect to one another. Two exposures (each consisting of two spectra) are obtained in order to simultaneously yield orthogonally polarized intensities: the first frame consists of the source’s linearly polarized (along north/south and east/west axes) light while the second frame consists of the oppositely circularly polarized (left and right) light. The various Stokes parameters

\[\text{for more details and images of ESPaDOnS, see: http://www.ast.obs-mip.fr/projets/espadons/espadons.html}\]
parameters are then obtained by adding together various combinations of the measurements. For instance, the (unpolarized) Stokes $I$ intensity is obtained by adding together the two linearly polarized spectra while the Stokes $V$ intensity is obtained by adding together the two circularly polarized spectra. Once the desired polarized beams are obtained, they are directed towards the spectrograph, located in a Coudé room below the telescope, through fibre optic cables.

Upon entering the spectrograph, the light transmitted from the polarimeter is reflected off of a parabolic collimating mirror. The resulting parallel beam is then directed towards the primary component of ESPaDOnS’s and NARVAL’s spectrograph: the échelle grating. This is essentially a plane of long, narrow, and evenly spaced reflective grooves which disperse the light into its constituent wavelengths. These particular gratings are 200x400 mm in size and have 79 adjacent grooves per mm (Donati et al., 2006a). Unlike ordinary reflection gratings, échelle gratings are designed to produce very high numbers of multiple overlapping spectral orders. Once these orders are separated using a cross-disperser (i.e. a prism), the full potential of this style of grating is realized: the full optical spectrum of an astronomical object can be captured on a CCD in a single exposure (Gray, 2005).

The final reduced spectrum requires several calibration exposures which are used to remove instrumental biases, determine the orientation of the spectrograph’s slit, or determine the corresponding wavelength of each pixel along the recorded spectrum. The bias frame is used to measure the zero level offset of the CCD before an observation is carried out. A flat-field frame is an exposure of an evenly illuminated plane which reveals variations in the sensitivities inherent to each pixel on the CCD. In the case of ESPaDOnS, the flat-fields are obtained by recording the spectrum produced
by a combination of filters and tungsten lamps which yield an evenly illuminated spectrum across all spectral orders. In order to accurately determine the orientation of the slit, light emitted by a flat field lamp – which produces uniform illumination – is transmitted through a Fabry-Perot interferometer. This yields a spectrum of regularly spaced lines which trace both the projected shape and alignment of the slit onto the CCD. The bias, flat-field, and Fabry-Perot frames are generally obtained at the beginning of each night. This process may be carried out again at the end of the night in order to account for any variations with temperature or other observing conditions. Wavelength calibration is carried out using an arc lamp emitting a known spectrum (e.g. thorium spectrum) that is placed within the polarimeter. With all of the spectral lines produced by the arc lamp catalogued, the wavelengths of each pixel can be determined by using the linear dispersion relation associated with the spectrograph (i.e. \( \frac{d\lambda}{dx} \) where \( x \) is the distance along the CCD) \cite{Gray2005}. An example of the flat field exposure and wavelength calibration spectrum obtained using ESPaDOnS is shown in Fig. 2.3.

After the polarized spectrum, or rather its CCD image, is obtained by the instrument, the data must be reduced into a useable format. This involves multiple steps such as wavelength calibration, noise reduction, and processing of the polarized spectra. The first step is to translate the 2D image into a 1D spectrum by determining a polynomial fit to the shape of each order and to the projected slit where the light enters the spectrograph. The ThAr comparison spectrum is then extracted from the CCD image and is used to determine the wavelength associated with each pixel. This process involves the automatic identification of \( \sim 10^2 - 10^3 \) spectral lines of the ThAr spectrum. With the 2D fitting functions and the pixel-wavelength relations
determined, the individual spectral orders of each exposure are extracted where each data point corresponds to a velocity resolution of 1.8 km s\(^{-1}\). This process is carried out autonomously using the Libre-ESprIT reduction software (Donati et al., 1997).

Once the individual subexposures are reduced, it is a simple matter of subtracting the bias and dividing by the bias and flat frame intensity measurements, from the scientific frame (i.e. the intended observation). The Earth’s velocity (both the orbital and rotational components) is then calculated based on the observatory’s coordinates and the Heliocentric Julian Date (HJD) so that any Doppler shift resulting from this motion can be compensated for in the final spectrum.

Along with spectropolarimetric observations, unpolarized spectra of HD 35502 were obtained using the FEROS instrument operated by the European Southern Observatory (ESO). Similar to the spectrographs incorporated into ESPaDOnS and NARVAL, FEROS uses an échelle grating which yields high resolution spectra (\(R = 48\,000\)) over a wavelength range of 3 600 – 9 200 Å (Kaufer et al., 1999). Although
the general reduction procedure is similar to that implemented by Libre-ESpRIT, certain differences in the instruments and their configurations must be taken into account. For instance, the beam of light collected by the telescope is sent to the spectrograph via two fibre optic cables and are subsequently split using a double image slicer. In this configuration, the shape of each spectral order is well defined which allows the fitting of the spectral orders to be carried out accurately and easily. Moreover, the function relating the wavelengths of the calibration spectrum (i.e. the ThArNe spectrum) to the CCD pixels is given by a single expression which includes the order number as a parameter (Kaufer et al., 2000).

2.4 Least-Squares Deconvolution

The method of measuring a star’s magnetic field using polarized Zeeman signatures typically requires very high precision. The amplitudes of these signatures are often on the order of 0.1% of the continuum thus requiring large signal-to-noise ratios (SNRs) of $\text{SNR} \sim 10^4$ in order to be detected (Donati, Semel & Rees, 1992; Donati et al., 1997). One method of dramatically improving the SNRs of a stellar Zeeman signature is by essentially combining the signals obtained from many individual spectral lines. This is known as the Least-Squares Deconvolution (LSD) cross-correlation analysis and has become an indispensable tool in the study of stellar magnetism.

LSD is based on several assumptions which allow a single, representative disc-integrated Zeeman signature to be extracted from multiple spectral lines. Firstly, it is assumed that the shape of each Zeeman signature is approximately independent of the wavelength (i.e. the same for each spectral line) and only scales in amplitude. This requirement suggests that certain lines exhibiting abnormal profiles should be
excluded from the analysis such as the Balmer lines which are typically very broad (Donati et al., 1997). Secondly, the derivation assumes that the strength of the longitudinal field being measured is weak such that the line broadening produced by the Zeeman signature is significantly less than that associated with thermal broadening (Kochukhov, Makaganiuk & Piskunov, 2010).

Before the analysis can be carried out, a line mask encoding several properties of the spectral lines to be included in the LSD must be compiled. These properties include the wavelengths, Landé factors, and line depths and are obtained from the Vienna Atomic Line Database (VALD) (Kupka et al., 2000). In order to generate accurate Stokes $V$ and $I$ profiles, it is crucial to remove all spectral lines which are coincident with atmospheric absorption features (tellurics) along with those lines exhibiting anomalous profiles. The longitudinal magnetic field can then be calculated from the LSD profiles using Equation 2.4. For spectra obtained using NARVAL and ESPaDOnS, the effective Landé factor and wavelength are generally chosen to be $z = 1.2$ and $\lambda = 500$ nm. An example of an LSD profile associated with a strong longitudinal field of $1.03 \pm 0.02$ kG is shown in Fig. 2.4.

## 2.5 Model Atmospheres & Synthetic Spectra

Two grids of model atmospheres were used throughout this research. One of the primary differences between these grids relates to the assumption of local thermodynamic equilibrium (LTE). Adopting this assumption allows for various simplifications in the calculations to be made. For instance, under LTE, the mean free path of the particles composing the atmosphere are small and thus, the thermodynamic properties of the gas are determined locally (Gray, 2005). Furthermore, a gas that is
Figure 2.4: An example of the Stokes $I$ (bottom, black) and $V$ (top, red) LSD profiles obtained from the A5p main sequence star, HD 188041. As in Fig. 2.1 the blue line is the diagnostic null. The Stokes $V$ and $I$ LSD profiles are associated with a longitudinal field strength of $1.03 \pm 0.02$ kG.

considered to be in LTE obeys the well known Saha-Boltzmann relation which allows the distribution of ionization and excitation states to be calculated relatively simply.

A commonly used grid of LTE atmospheric models were generated using the ATLAS codes originally developed by Kurucz (1979). These models have undergone continuous development since. In this study, the ATLAS9 (Kurucz 1993) models are used which were most recently updated by Castelli & Kurucz (2004). The latest grid uses comprehensive opacity distribution functions (ODFs) which are used to describe how absorption by various elements and molecules is calculated (Howarth 2011).

Although accurate for a wide range of effective temperatures and densities, the
LTE assumption does have limits beyond which it is no longer valid. The deviations from LTE are generally most apparent in detailed analyses of strong absorption lines. For example, Mihalas (1972) demonstrated that the central depth of the H$\alpha$ Balmer line associated with a 19 000 K, log $g = 4.0$ (cgs) model differs between the LTE and non-LTE cases by a factor of 2. Therefore, in addition to the synthetic spectra generated from ATLAS9 atmospheric models, we also used the non-LTE TLUSTY models produced by Lanz & Hubeny (2007).

The importance of obtaining accurate model atmospheres cannot be overstated. However, it is ultimately through the fitting of directly observable properites (e.g. stellar spectra and spectral energy distributions) that estimates of important physical parameters are derived. For instance, the effective temperatures and surface gravities of all of the stars discussed in this research were inferred in this fashion. Several grids of models, each involving various assumptions and input parameters, were used in these analyses.

We adopted two grids of synthetic SEDs in this study: one based on the LTE ATLAS9 atmospheric models (Howarth 2011) along with one generated from the non-LTE TLUSTY models (Lanz & Hubeny 2007). The latter synthetic SEDs form the BSTAR2006 grid, an extension of the original OSTAR2002 grid, for effective temperatures ranging from 15 000 – 30 000 K across the UV (900 – 3 200Å) and visible (3 200 – 10 000Å) bandwidths. An analogous collection of high resolution normalized models (i.e. model spectra) was also used to compare with the observed visible spectra of HD 23478. These models were generated using the IDL program SYNPNLOT which serves as a wrapper for the SYNSPEC utility – meaning that it is an interface between the user and original program – published by Hubeny & Lanz (2011).
CHAPTER 2. OBSERVATIONAL & ANALYTICAL PRINCIPLES

Figure 2.5: The spectrum of the A0V star HD 115735 (black) is compared with a $T_{\text{eff}} = 11$ kK, log $g = 3.7$ (cgs) synth$_3$ model spectrum (red). The synthetic spectrum has been convolved with a Gaussian function in order to account for the instrumental broadening inherent to the observed spectrum. Rotational broadening has been applied using an adopted value of $v \sin i = 110$ km s$^{-1}$.

Finally, a grid of LTE model spectra was generated using synth$_3$ (Kochukhov 2007) and applied to the analysis of HD 35502. These models use ATLAS9 atmospheres (Kurucz 1993) in conjunction with atomic line data obtained from VALD (Kupka et al. 2000). An example of a stellar spectrum compared with a synth$_3$ model spectrum is shown in Fig. 2.5.

2.6 Measuring Equivalent Widths

One of the simplest analyses that can be applied to stellar spectra is the measurement of equivalent widths (EWs). An EW is the width of a hypothetical spectral line that has the same area (i.e. absorbing wavelength by intensity region) of an observed line.
Figure 2.6: A diagram depicting the equivalent width of a spectral absorption line taken from [Stahler & Palla (2008)]. \( W_\lambda \) is the equivalent width that would be measured by integrating across the line between the regions where \( F_\lambda = F_0 \). The shaded region indicates the area of a hypothetical line that is entirely saturated and exhibiting a width of \( W_\lambda \).

but is entirely saturated. Its measurement can be used to detect and characterize any variability in a line profile which may be produced by various phenomena. For example, isolated regions of enhanced chemical abundances are often observed on the surfaces of rotating stars. These chemical spots are detected in stellar spectra as rotationally modulated distortions in the line profiles associated with specific elements. The classical EW is given by

\[
EW = \int \left( 1 - \frac{I(\lambda)}{I_c} \right) d\lambda
\]  

(2.7)

where \( I(\lambda) \) is the intensity, \( I_c \) is the continuum intensity, and the integration is carried out across the full width of the line [Gray (2005)]. A diagram showing how the equivalent width relates to the associated spectral line is shown in Fig. 2.6.
Although the calculation of an EW is straightforward, estimating the associated uncertainty ($\sigma_{\text{EW}}$) is somewhat ambiguous as is evident from the various derivations that can be found in the literature (Chalabaev & Maillard, 1983; Sembach & Savage, 1992; Jones, Tycner & Smith, 2011). This is likely a result of the fact that two significant sources of error must be considered: (1) that associated with the noise inherent in all observations, and (2) the error related to the determination of the continuum. Depending on the observational SNR, the widths and depths of the spectral line, and the value of the EW, the significance of these two contributions may vary. In this study, two methods are used to calculate $\sigma_{\text{EW}}$.

The first method is the statistical approach derived by Vollmann & Eversberg (2006). It uses the mean value theorem to yield an approximate relation for the EW in terms of the mean intensity, $\bar{I}$, and the mean continuum intensity, $\bar{I}_c$, across the spectral line. A general expression for $\sigma_{\text{EW}}$ is then obtained from the variance of the first order Taylor expansion of $\text{EW}(\bar{I}, \bar{I}_c)$. After defining the contributions to $\sigma_{\text{EW}}$ from $\sigma_I$ and $\sigma_{I_c}$, the analysis yields the relatively simple result given by

$$\sigma_{\text{EW}} = \sqrt{1 + \frac{\bar{I}_c}{\bar{I}} \frac{(\Delta \lambda - \text{EW})}{\text{SNR}}} \quad (2.8)$$

where $\Delta \lambda$ is the width of the line at the continuum.

The second method of estimating equivalent width uncertainties that was used in this study was the technique known as bootstrapping (Efron, 1979). The simple procedure involves repeatedly carrying out a particular calculation, which is based on an empirical data set (e.g. in this case, calculating an equivalent width), after randomly resampling the original data set. Specifically, at the beginning of each iteration, a number of randomly selected data points are replaced by different values
taken from the set at random. After several thousand iterations, depending on the size of the data set, a distribution of the calculated parameter is obtained. The uncertainties are then chosen based on the width of this distribution (Wall & Jenkins 2003). For instance, by fitting a Gaussian function to the distribution, the resulting standard deviation may be adopted.

2.7 Markov Chain Monte Carlo Algorithm

It is often the case that the most reliable means of deriving various properties of a physical system is through comparisons with numerical models. This is true throughout many scientific fields; therefore, it is not surprising that there exists a wide range of analytical techniques with varying levels of sophistication for carrying out such an analysis.

One modelling challenge that was overcome in this study was that of fitting synthetic spectral energy distributions (SEDs) to observed photometry (see Sections 3.3.1 and 4.3.2). Two different SED fitting routines were adopted in the analysis of HD 23478 and HD 35502. The first method involved a computationally expensive $\chi^2$ minimization routine in which a large grid of models were systematically compared with the data using

$$\chi^2 \equiv \sum_{i=1}^{N} \frac{(F_i - F_{\text{syn}})^2}{\sigma_{F_i}^2}$$

(2.9)

where $F_i$ and $\sigma_{F_i}$ are the $i^{\text{th}}$ observed flux and associated uncertainty while $F_{\text{syn}}$ is the model flux. Once a $\chi^2$ value was determined for each model, the optimal set of fitting parameters could easily be identified and their associated uncertainties could be derived from the marginalized $\chi^2$ distributions. Given the low number of free
parameters (i.e. \( T_{\text{eff}} \), and \( \log g \)), this brute force approach was able to be carried out in a reasonable amount of time. However, the same could not be said of HD 35502’s SED fitting analysis which required a minimum of 6 free parameters: \( T_{\text{eff}} \), \( \log g \), and the radius, \( R \), of two model SEDs (in this case, \( R \) is required in order to correctly scale the contributions from each model to the total flux).

The brute force method applied to HD 23478 was found to be highly impractical as a result of HD 35502’s relatively large number of free parameters. We instead opted to employ a Markov Chain Monte Carlo (MCMC) algorithm. Not only is this approach substantially more efficient, it is also relatively simple to implement and provides a convenient means of identifying degenerate solutions. The MCMC analysis is based on Bayesian statistics in the sense that it attempts to determine a best-fitting solution by maximizing a likelihood function – the probability of obtaining a data set given a set of parameters \citep{Wall2003}. This is carried out by evaluating the fit yielded by randomly selected parameters drawn from a prior probability. If the likelihood function increases in response to a change in parameters, this new solution is adopted; otherwise, the previous solution is maintained. The algorithm also includes a random mechanism that will occasionally cause a poorer fitting solution to be adopted. This helps to prevent the routine from getting stuck on solutions which may yield a maximum likelihood locally but not globally.

After approximately \( 10^4 - 10^6 \) iterations, a successful MCMC routine will yield a posterior probability function indicating the best-fitting solution along with any degenerate solutions that exhibit a comparable quality-of-fit. When applied to HD 35502’s SED fitting analysis, the MCMC algorithm was capable of completing \( 10^6 \) iterations in approximately 5 min (as compared to the \( \sim 1 \) hr runtime of the \( \chi^2 \) minimization
routine).
Chapter 3

HD 23478

3.1 Introduction

Upon the first detection of its magnetic field, the strong, broad, and variable Hα emission line of the main sequence B2 star σ Ori E was suggested to be a natural consequence of a plasma co-rotating with the star well beyond its surface (Landstreet & Borra, 1978). Since then, a significant number (≳ 13) of magnetic mid- to early-B stars (i.e. those having $T_{\text{eff}} < 25$ kK) exhibiting Hα emission were discovered (Brown, Shore & Sonneborn, 1985; Shore et al., 1990). These stars are of particular interest because they provide a unique means of probing the mass-loss and stellar winds of B-type stars. While the strength of the magnetic field likely plays an important role in determining if a magnetic B star exhibits Hα emission, the key distinction between the stars with emission and those without is rotation – the emission line stars are all rapid rotators having rotational periods $\lesssim 1.5$ d (Petit et al., 2013).
These correlations between rotation and the presence of Hα emission can be understood in a general framework in which the magnetospheres of massive stars are classified as either dynamic magnetospheres (DM) or centrifugal magnetospheres (CM) based on the ability of the field to confine the wind and the degree of criticality of the stellar rotation. ud-Doula & Owocki (2002), Petit et al. (2013), Petit et al. (2013), and more recently Shultz et al. (2014), demonstrate that stars like σ Ori E are those with the largest magnetospheric volumes: those with the largest Alfvén radii combined with the smallest Kepler radii. Shultz et al. (2014) estimated that Hα emission is never observed for typical magnetic B stars with $R_A/R_K \lesssim 10$, while it is frequently observed in the spectra of stars with ratios above this threshold.

Recently, Eikenberry et al. (2014) identified two emission line B stars from near-infrared (nIR) spectra obtained during the Apache Point Observatory Galactic Evolution Experiment (APOGEE) survey: HD 345439 and HD 23478. They found that both stars exhibited strong and broad emission at all nIR H lines along with relatively large projected rotational velocities of $\approx 270$ and $125$ km s$^{-1}$, respectively. Although lacking any information about their magnetic fields, Eikenberry et al. (2014) concluded that the similarities between these stars and σ Ori E provided reasonable evidence for a magnetospheric origin of the observed nIR emission.

The principal aim of the present study is to search for the presence of a magnetic field in the brightest of these two stars (HD 23478), and to test the hypothesis of Eikenberry et al. (2014) that it is similar to σ Ori E in that it also belongs to the more general class of Hα emitting CM stars. In Section 3.2 we describe the spectropolarimetric observations used in this study. In Section 3.3 we estimate the physical
parameters of HD 23478 using photometric data from the literature along with newly-acquired high-resolution spectroscopy. We then analyze in Section 3.4 variability in HiPParCoS epoch photometry in an attempt to infer the star’s rotational period. In Section 3.5 we compute the longitudinal magnetic field and search for its variability. In Section 3.6 we discuss the spectral line emission and variability. In Section 3.7 we derive the stellar magnetospheric parameters.

3.2 Observations

3.2.1 High-resolution spectropolarimetry

HD 23478 was observed during eight nights between Aug. 2014 and Jan. 2015 using the ESPaDOnS and Narval spectropolarimeters installed at the Canada-France-Hawaii Telescope (CFHT) and Télescope Bernard Lyot (TBL), respectively. Both instruments have a resolving power of $R \simeq 65,000$ acquiring spectra in circularly polarized light spanning the visible range of $3,600 – 10,000 \text{Å}$. The Heliocentric Julian Dates (HJDs), exposure times, and signal-to-noise ratios (SNRs) of these observations are listed in Table 3.1.

Each circular polarization observation consists of four subexposures which the Libre-ESpRIT pipeline (Donati et al., 1997) automatically reduces yielding the final Stokes $I$ and $V$ spectra. The majority of the observations (10 out of 12) were obtained with ESPaDOnS using a total exposure time of 560 s. The remaining two observations were obtained with Narval during a single night using a total exposure time of 1200 s.
Table 3.1: Observations of HD 23478 obtained with ESPaDOnS and Narval. The phases are calculated using Eqn. \(3.1\). SNRs per \(1.8 \text{ km s}^{-1}\) spectral pixel are reported at 5400 Å. The three rightmost columns list the longitudinal magnetic field measurements obtained from H\(\beta\) and LSD profiles generated from a He+metal line mask along with the detection status according to the criteria of Donati et al. (1997): definite detection (DD), marginal detection (MD), and no detection (ND) (see Section 3.5).

<table>
<thead>
<tr>
<th>HJD</th>
<th>Phase</th>
<th>Total Exp. Time (s)</th>
<th>SNR (pix(^{-1}))</th>
<th>Instrument</th>
<th>(\langle B_z \rangle_{H\beta}) (kG)</th>
<th>(\langle B_z \rangle_{\text{He+metal}}) (kG)</th>
<th>Detection Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>2456884.116</td>
<td>0.304</td>
<td>560</td>
<td>473</td>
<td>ESPaDOnS</td>
<td>(-1.52 \pm 0.27)</td>
<td>(-1.98 \pm 0.25)</td>
<td>DD</td>
</tr>
<tr>
<td>2456908.146</td>
<td>0.194</td>
<td>560</td>
<td>500</td>
<td>ESPaDOnS</td>
<td>(-1.68 \pm 0.24)</td>
<td>(-2.15 \pm 0.22)</td>
<td>DD</td>
</tr>
<tr>
<td>2456909.134</td>
<td>0.135</td>
<td>560</td>
<td>381</td>
<td>ESPaDOnS</td>
<td>(-1.42 \pm 0.32)</td>
<td>(-2.33 \pm 0.29)</td>
<td>DD</td>
</tr>
<tr>
<td>2456909.144</td>
<td>0.145</td>
<td>560</td>
<td>346</td>
<td>ESPaDOnS</td>
<td>(-1.89 \pm 0.29)</td>
<td>(-2.26 \pm 0.26)</td>
<td>DD</td>
</tr>
<tr>
<td>2456925.512</td>
<td>0.736</td>
<td>1200</td>
<td>402</td>
<td>Narval</td>
<td>(-2.19 \pm 0.37)</td>
<td>(-1.98 \pm 0.36)</td>
<td>MD</td>
</tr>
<tr>
<td>2456925.691</td>
<td>0.907</td>
<td>1200</td>
<td>291</td>
<td>Narval</td>
<td>(-2.32 \pm 0.28)</td>
<td>(-2.49 \pm 0.30)</td>
<td>DD</td>
</tr>
<tr>
<td>2456962.025</td>
<td>0.517</td>
<td>560</td>
<td>409</td>
<td>ESPaDOnS</td>
<td>(-0.95 \pm 0.34)</td>
<td>(-1.93 \pm 0.26)</td>
<td>DD</td>
</tr>
<tr>
<td>2456969.837</td>
<td>0.101</td>
<td>560</td>
<td>409</td>
<td>ESPaDOnS</td>
<td>(-2.13 \pm 0.31)</td>
<td>(-2.44 \pm 0.27)</td>
<td>DD</td>
</tr>
<tr>
<td>2456972.833</td>
<td>0.813</td>
<td>560</td>
<td>353</td>
<td>ESPaDOnS</td>
<td>(-1.94 \pm 0.39)</td>
<td>(-2.52 \pm 0.37)</td>
<td>MD</td>
</tr>
<tr>
<td>2456972.843</td>
<td>0.822</td>
<td>560</td>
<td>352</td>
<td>ESPaDOnS</td>
<td>(-2.98 \pm 0.41)</td>
<td>(-2.84 \pm 0.37)</td>
<td>MD</td>
</tr>
<tr>
<td>2456973.099</td>
<td>0.066</td>
<td>560</td>
<td>497</td>
<td>ESPaDOnS</td>
<td>(-2.05 \pm 0.27)</td>
<td>(-2.11 \pm 0.22)</td>
<td>DD</td>
</tr>
<tr>
<td>2457034.695</td>
<td>0.740</td>
<td>560</td>
<td>461</td>
<td>ESPaDOnS</td>
<td>(-1.63 \pm 0.29)</td>
<td>(-1.99 \pm 0.27)</td>
<td>MD</td>
</tr>
</tbody>
</table>
Table 3.2: Observations of HD 23478 obtained with dimaPol. The phases are calculated using Eqn. (3.1) and the magnetic field measurements correspond to the longitudinal field derived from H\(\beta\) Stokes \(V\) observations.

<table>
<thead>
<tr>
<th>HJD</th>
<th>Phase</th>
<th>Total Exp. Time [s]</th>
<th>SNR [pix(^{-1})]</th>
<th>(\langle B_z \rangle_{H\beta}) [kG]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2456680.700</td>
<td>0.537</td>
<td>5400</td>
<td>300</td>
<td>(-1.78 \pm 0.56)</td>
</tr>
<tr>
<td>2456681.630</td>
<td>0.422</td>
<td>3000</td>
<td>250</td>
<td>(-0.92 \pm 0.72)</td>
</tr>
<tr>
<td>2456963.734</td>
<td>0.146</td>
<td>3000</td>
<td>440</td>
<td>(-1.62 \pm 0.27)</td>
</tr>
<tr>
<td>2456971.888</td>
<td>0.911</td>
<td>4800</td>
<td>400</td>
<td>(-2.88 \pm 0.36)</td>
</tr>
<tr>
<td>2456972.802</td>
<td>0.782</td>
<td>4800</td>
<td>520</td>
<td>(-1.82 \pm 0.26)</td>
</tr>
<tr>
<td>2456973.758</td>
<td>0.693</td>
<td>4800</td>
<td>430</td>
<td>(-1.29 \pm 0.41)</td>
</tr>
<tr>
<td>2456974.846</td>
<td>0.731</td>
<td>4800</td>
<td>410</td>
<td>(-1.37 \pm 0.38)</td>
</tr>
<tr>
<td>2456976.032</td>
<td>0.859</td>
<td>4800</td>
<td>400</td>
<td>(-2.08 \pm 0.29)</td>
</tr>
<tr>
<td>2456991.962</td>
<td>0.033</td>
<td>4800</td>
<td>480</td>
<td>(-1.95 \pm 0.30)</td>
</tr>
<tr>
<td>2456992.711</td>
<td>0.748</td>
<td>4800</td>
<td>310</td>
<td>(-1.86 \pm 0.49)</td>
</tr>
<tr>
<td>2457085.723</td>
<td>0.347</td>
<td>4800</td>
<td>550</td>
<td>(-1.11 \pm 0.33)</td>
</tr>
</tbody>
</table>

### 3.2.2 Medium resolution H\(\beta\) spectropolarimetry

Eleven spectropolarimetric observations were also obtained using the dimaPol medium resolution spectropolarimeter located at the Dominion Astronomical Observatory (DAO) from Jan. 2014 to March 2015. The instrument has a resolving power of \(R \approx 10,000\) and is optimized to acquire spectra over a wavelength range of \(4700 - 5300\AA\) (Monin et al. 2012). The HJDs, exposure times, SNRs, and longitudinal magnetic field measurements derived from H\(\beta\) Stokes \(V\) profiles are listed in Table 3.2.
3.3 Physical Parameters

3.3.1 SED fitting

Photometry spanning a wide range of wavelengths is available for HD 23478 thereby providing a means of constraining both the effective temperature and surface gravity. These observations include narrow-band Johnson $UBV$ (Anderson & Francis, 2012), 2MASS $JHKs$ (Cutri et al., 2003), and TD1 ultraviolet (Thompson et al., 1978) photometric measurements. Short (SWP imager: 1150 – 1975 Å) and long (LWP imager: 1900 – 3125 Å) wavelength ultraviolet broadband measurements were also recorded by the International Ultraviolet Explorer (IUE). The high-resolution ($\delta\lambda = 0.1$ Å) IUE data were rebinned at $\delta\lambda = 3$ Å using the prescription of Solano (1998) in order to increase the SNR per pixel. All of the observed magnitudes were converted to physical fluxes using published zero points for Johnson and 2MASS filters (Bessell, 1979; Cohen, Wheaton & Megeath, 2003); both TD1 and IUE measurements were obtained in the appropriate units of ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$. Dereddening was applied using the method of Cardelli, Clayton & Mathis (1989) using a typical total-to-selective extinction ratio of $R(V) \equiv A(V)/E(B-V) = 3.1$.

The photometric observations were compared with the non-local thermodynamic equilibrium (NLTE) TLUSTY BSTAR2006 synthetic energy distribution (SED) grid (Lanz & Hubeny, 2007) for effective temperatures $T_{\text{eff}}$ ranging from 15 – 30 kK and surface gravities log $g$ (cgs) from 3 – 4.75. The published grid has $T_{\text{eff}}$ and log $g$ resolutions of 1000 K and 0.25, respectively, that were linearly interpolated to a finer grid of 250 K and 0.05 resolution. Solar abundances and a 2 km s$^{-1}$ turbulence velocity were assumed for the model grid. The NLTE model SEDs have a resolution
\[ \geq 0.002 \text{ Å} \] – much higher than the rebinned IUE observations. We reduced the resolution of the model spectra by convolving with a Gaussian profile assuming a resolving power of \( R = (1150 \text{ Å})/(3 \text{ Å}) \approx 380 \) to match the 3 Å IUE bin-width at \( \lambda = 1150 \text{ Å} \). Theoretical monochromatic fluxes were calculated by convolving Johnson \( UBV \) and 2MASS \( JHKs \) transmission functions \cite{Landolt_Uomoto_2007, Cohen_Wheaton_Megath_2003} with the unbroadened model spectra.

The best fitting NLTE model, shown in Fig. 3.1, was found to have an effective temperature, surface gravity, and colour excess of \( T_{\text{eff}} = 22.00 \text{ kK}, \log g = 4.60 \text{ (cgs)}, \) and \( E(B-V) = 0.35 \) yielding a reduced \( \chi^2 \) value of 1.70. The monochromatic fluxes were found to be adequately reproduced by a wide range of \( T_{\text{eff}}, \log g, \) and \( E(B-V) \) values. Changes in the surface gravity of each model SED were found to primarily affect the depths of the absorption lines, resulting in minimal changes in the calculated monochromatic fluxes. The IUE spectra provided the greatest constraint on the fitting parameters. In particular, we found relatively large discrepancies between the IUE LWP spectra and the model SEDs having \( T_{\text{eff}} \lesssim 20 \text{ kK} \) and \( T_{\text{eff}} \gtrsim 24 \text{ kK} \) at \( 2,000 \lesssim \lambda \lesssim 2,500 \text{ Å} \). This is clearly a consequence of the respectively lower and higher values of the required extinction associated with these models. In Fig. 3.2, we show the LWP spectrum dereddened in order to fit models of 18, 20, 22, and 24 kK. The \( 2,000 - 2,500 \text{ Å} \) region shows growing discrepancies for the lower and higher temperatures. This leads us to prefer \( T_{\text{eff}} = 22 \text{ kK} \) based on the SED fitting.

### 3.3.2 Spectral line fitting

Spectral line fitting can provide a further constraint on \( T_{\text{eff}} \) and \( \log g \) through comparisons between the obtained ESPaDOnS and Narval spectra and synthetic model
Figure 3.1: Top: Comparing the IUE spectra (solid blue) and narrow-band fluxes (red points) with the best-fitting TLUSTY model (dashed black) convolved by a Gaussian profile to match the rebinned IUE resolution. Bottom: Theoretical $U$, $B$, and $V$ fluxes (black crosses) were calculated by convolving the unbroated TLUSTY models (solid black) with the filter’s associated transmission functions.

 grids. We found that HD 23478’s metallic line spectrum was not suitable for tuning the atmospheric parameters due to a number of characteristics. The strongest metal lines have shallow depths of less than 10% of the continuum with only 3 lines deeper than 5%. This difficulty was alleviated to some extent by using averaged spectra thereby increasing the SNR by a factor of $\approx 3.5$. That is, by binning the observed intensities, the depths of the lines relative to the noise was increased.
We also noticed that many line profiles were distorted. Sharp asymmetric features having depths $\lesssim 10\%$ of the continuum are prevalent in many spectral orders (Fig. 3.3). These were identified as diffuse interstellar bands (DIBs) by conferring with Hobbs et al. (2008, 2009) and by directly comparing the spectra of HD 23478 and ζ Oph, a star which is well known to exhibit strong DIBs (e.g. Walker, Bohlender & Krelowski 2000).

In addition to the DIB features, many metal lines show peculiar strengths and
Table 3.3: Stellar parameters of HD 23478.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sp. Type</td>
<td>B3IV</td>
</tr>
<tr>
<td>( \pi ) [mas]</td>
<td>4.99 ± 0.62</td>
</tr>
<tr>
<td>( d ) [pc]</td>
<td>200^{+29}_{-22}</td>
</tr>
<tr>
<td>Photometric</td>
<td></td>
</tr>
<tr>
<td>( V ) [mag]</td>
<td>6.67^{+0.01}_{-0.07}</td>
</tr>
<tr>
<td>( E(B-V) ) [mag]</td>
<td>0.30^{+0.05}_{-0.04}</td>
</tr>
<tr>
<td>( BC ) [mag]</td>
<td>-1.97^{+0.24}_{-0.22}</td>
</tr>
<tr>
<td>( M_V ) [mag]</td>
<td>-0.77^{+0.26}_{-0.36}</td>
</tr>
<tr>
<td>( M_{bol} ) [mag]</td>
<td>-2.74^{+0.51}_{-0.58}</td>
</tr>
<tr>
<td>Physical</td>
<td></td>
</tr>
<tr>
<td>( T_{eff} ) [kK]</td>
<td>20 ± 2</td>
</tr>
<tr>
<td>( \log(g) ) [cgs]</td>
<td>4.2 ± 0.2</td>
</tr>
<tr>
<td>( v \sin i ) [km s(^{-1})]</td>
<td>140 ± 10</td>
</tr>
<tr>
<td>( \log L/L_{\odot} )</td>
<td>3.0 ± 0.2</td>
</tr>
<tr>
<td>( M/M_{\odot} )</td>
<td>6.1^{+0.8}_{-0.7}</td>
</tr>
<tr>
<td>( R/R_{\odot} )</td>
<td>2.7^{+1.6}_{-0.9}</td>
</tr>
<tr>
<td>( \tau_{age} ) [Myr]</td>
<td>3^{+37}_{-1}</td>
</tr>
<tr>
<td>( P_{rot} ) [d]</td>
<td>1.0498 ± 0.0004</td>
</tr>
<tr>
<td>( v_r ) [km s(^{-1})]</td>
<td>17 ± 5</td>
</tr>
</tbody>
</table>

Table references: 1Blaauw & van Albada (1963), 2van Leeuwen (2007), 3Syfert, Hardie & Grenchik (1960), 4Harris (1956).

distorted profiles, likely due to non-solar surface abundances and nonuniform distributions of the abundances of these elements. As a consequence, modelling the metallic spectrum to constrain the atmospheric parameters would require a detailed analysis which is outside the scope of this work. Therefore we opted to model the Balmer lines to provide further constraints on \( T_{eff} \) and \( \log g \) because they are more weakly influenced by abundance non-uniformities. Specifically, H\( \gamma \) and H\( \delta \) were chosen because
Figure 3.3: Comparisons between two DIBs found in the spectra of HD 23478 and ζ Oph.

of their relative insensitivity to emission (as compared to Hα) and because they are not directly adjacent to other strong absorption features thus reducing normalization errors.

We relied primarily upon spectral models calculated using SYNPLOT, the IDL wrapper for SYNSPEC [Hubeny & Lanz, 2011], along with NLTE TLUSTY model atmospheres [Lanz & Hubeny, 2007]. The grid was linearly interpolated such that a finer resolution of $\delta T_{\text{eff}} = 250$ K and $\delta \log g = 0.1$ (cgs) was obtained. The synthetic spectra were then convolved with a Gaussian profile associated with the characteristic $R = 65,000$ resolving power of the ESPaDOnS and Narval spectropolarimeters, corresponding to a velocity resolution of $\delta v \approx 4.6 \text{ km s}^{-1}$. It is noted that changes in the He abundance can affect the wings of the Balmer lines [Leone & Manfre, 1997]. When calculating the NLTE H line profiles, we use the minimum He abundance of $[\text{He}/\text{H}] = -0.58$ required to fit a sample of averaged He i lines (where $[\text{He}/\text{H}]_{\odot} = -1.01$; Grevesse, Noels & Sauval, 1996).
As shown in Fig. 3.4, the best effective temperature according to the SED fitting (22 kK) reproduces the Balmer line wings reasonably well with log \( g = 4.4 \). However, the core depths are seriously underestimated by the model. By reducing \( T_{\text{eff}} \), good agreement between the observed and computed wings and core is achieved for \( T_{\text{eff}} = 18 \) kK and \( \log g = 4.0 \).

We therefore find that the Balmer lines and SED yield different solutions to the atmospheric parameters. Based on our analysis, we conclude that the effective temperature of HD 23478 is likely in the range 18 – 22 kK and its surface gravity between 4.0 and 4.5. Further refinement of these parameters will require a more detailed future analysis.

The colour excess of \( E(B-V) = 0.30^{+0.05}_{-0.04} \) inferred for the \( T_{\text{eff}} = 20 \pm 2 \) kK range is in agreement with both the 0.28 and 0.34 values reported (without consideration of uncertainties) by Voshchinnikov et al. (2012) and Beeckmans & Hubert-Delplace (1980). For \( T_{\text{eff}} = 22 \) kK however, a slightly higher \( E(B-V) = 0.35 \) is required. As was expected, \( T_{\text{eff}} \) was indeed found to be closely coupled with the colour excess.

**Rotational broadening**

To estimate the rotational broadening, we compared observed phase-averaged He and metal profiles with synthetic profiles computed assuming \( T_{\text{eff}} = 22 \) kK. We adjusted the projected rotational velocity, \( v \sin i \), as well as the abundance of each element in order to obtain a reasonable fit to the line profiles. Generally, a \( v \sin i \) of 140 ± 10 km s\(^{-1}\) yielded the best overall fit to the line profiles (consistent with that of Eikenberry et al. 2014). Fits to selected lines for several \( v \sin i \) values are shown in Fig. 3.5. The inclusion of either macroturbulent or microturbulent broadening
Figure 3.4: Comparisons between TLUSTY models (blue) and the averaged observed spectrum (black) for \( \text{H} \delta \) (left) and \( \text{H} \gamma \) (right). The bottom frames show the residuals between the observations and the synthetic spectra (\( F_{\text{obs}} - F_{\text{syn}} \)).
Figure 3.5: $T_{\text{eff}} = 22\,\text{kK}$ and $\log g = 4.4$ TLUSTY models with a range of $v \sin i$ values compared with the averaged observed spectrum (black). The abundances of each element were adjusted in order to yield the best overall fit to the synthetic spectra. DIBs in both the Si $\text{ii}$ $\lambda 5056$ and Fe $\text{ii}$ $\lambda 5169$ lines are visible at 5055 Å and 5170.5 Å.
did not significantly improve the fits. The distorted shapes of many line profiles are apparent. We also note the remarkably poor fit to the He i λ4471 line. This discrepancy cannot be relieved by changing $T_{\text{eff}}$ or $\log g$. It is reproduced in a number of other He i lines. We suspect that it is a consequence of stratification of He in the atmosphere of this star (e.g. Bohlender, 1989; Farthmann et al., 1994).

### 3.3.3 Hertzsprung-Russell Diagram

The mass and age of HD 23478 were estimated by comparing its location on the Hertzsprung Russell diagram (HRD) with theoretical isochrones and evolutionary tracks.

The luminosity of HD 23478 required to determine its location on the HRD was calculated using the de-reddened visual magnitude of $V = 5.62^{+0.01}_{-0.07}$ mag where the color excess of $E(B-V) = 0.30$ discussed in Section 3.3.2 was used. The calculation of the absolute visual magnitude, $M_V$, required a bolometric correction which was approximated by the temperature and surface gravity relation by Nieva (2013) applicable to stars with $15.8 \leq T_{\text{eff}} \leq 34.0$ kK. The luminosity was then found to be $L = 1.0^{+0.7}_{-0.4} \times 10^3 L_\odot$ where the primary contributions to the uncertainty are from the temperature (through the $BC$ calibration) and parallax (i.e. the distance). The temperature of $T_{\text{eff}} = 20 \pm 2$ kK yielded by the SED fitting was used in the final HRD placement.

The comparisons used Geneva model grids of isochrones ranging in stellar age from 3.16 Myr to 12.9 Gyr generated by Ekström et al. (2012). The associated grid of evolution tracks contains models ranging in mass from 0.8 to $120 M_\odot$; both the isochrone and evolution grids assume a solar metallicity of $Z = 0.014$. An identical
resolution, $Z = Z_\odot$ grid which included rotational effects for a star having $v/v_{\text{crit}} = 0.4$ (Georgy et al., 2013a) was also used in the analysis. However, the comparisons between the derived mass and radius of HD 23478 using both the rotating and non-rotating model grids yielded negligible differences of less than 5%.

The position of HD 23478 on the HRD is shown in Fig. 3.6 where the nearby stellar evolution tracks are shown as dotted black lines and the main sequence masses are indicated by black ‘plus’ symbols. The isochrones (indicated by red dotted lines), log $L$, and log $T_{\text{eff}}$ imply a range in the estimated age and radius for the star of $\tau = 3^{+37}_{-1}$ Myr and $R = 2.8^{+1.3}_{-0.2} R_\odot$, respectively. Likewise, the main sequence mass of HD 23478 is estimated to be $M = 6.1^{+0.8}_{-0.7} M_\odot$. A similar radius of $R = 2.7^{+1.6}_{-0.9} R_\odot$ is derived from $L$ and $T_{\text{eff}}$ using the Stefan-Boltzmann law; we adopt this value because of its larger uncertainty. We note that these mass and radius estimates imply a surface gravity of log $g = 4.3^{+0.5}_{-0.4}$ which is consistent with the value derived from the spectral line fitting procedure described in Section 3.3.2.

### 3.4 Rotational period

The HiPParCos Epoch Photometry catalogue (Perryman et al., 1997) contains 75 measurements of HD 23478 spanning a time period of three years with minimum and maximum time separations of approximately 20 minutes and 174 days, respectively. The measurements are therefore sufficient for detecting photometric variability across a wide range of time scales associated with, for example, stellar rotation. All of the uncertainties are reported to be between 0.005 and 0.011 magnitudes with a mean value of 0.007. Out of the 75 observations, three report the presence of anomalous
Figure 3.6: The position of HD 23478 is indicated by the black diamond. The evolutionary tracks (black dotted-dashed lines) and isochrones (red dotted lines) assume a non-rotating star of solar metallicity (Ekström et al., 2012).

measurements between the FAST and NDAC Data Reduction Consortia. Furthermore, one observation reports a magnitude that is $2.7\langle \sigma_{H_p} \rangle$ larger than $\langle H_p \rangle$ and is likely an outlier. The exclusion of any of the flagged or outlying data points had an insignificant effect on the estimated rotational period with a maximal deviation of $\Delta P < 5\text{s}$. 
The period of the Epoch Photometry observations was found by assuming a sinusoidal fit and calculating the reduced $\chi^2$ distribution for periods ranging from 0 to 5 days with a resolution of $\delta P \sim 5$ sec. This yielded a range of minimal-$\chi^2$ solutions with the global minimum having a reduced $\chi^2$ value of $\chi^2_{\text{red}} = 0.85$, occurring at a period of $P_{\text{rot}} = 1.0498 \, \text{d}$. The HiPParCoS measurements phased at this best-fitting period are shown in Fig. 3.7 along with a subsample of the full periodogram centered on $P_{\text{rot}} = 1.0498 \, \text{d}$.

Assuming a $3\sigma$ confidence limit corresponding to an uncertainty of $\delta P = 0.0004 \, \text{d}$, we find that only one other period has a $\chi^2$ value below this threshold at $P = 1.02454 \, \text{d}$ where the $\chi^2$ peak is shown in Fig. 3.7 (bottom) bounded by the dashed dark blue lines. The 1.02454 d period does not result in a better fit compared with the 1.0498 d period; moreover, a similar analysis has previously been applied to ground-based photometry resulting in a photometric period of 1.0499 d (for which no uncertainty is reported) (Jerzykiewicz, 1993). We therefore adopt the 1.0498 d period along with the ephemeris

$$JD = 2448700.606 \pm 1.0498(4) \cdot E$$

(3.1)

where the reference JD (2448700.606) corresponds to the epoch of $H_p$ maximum.

When phased with this ephemeris, the $H_p$ data exhibit a roughly sinusoidal variation with a full amplitude of 0.015 mag and extrema located at phases of $0.00 \pm 0.05$ and $0.50 \pm 0.05$.

As discussed by Jerzykiewicz (1993), several possibilities exist for the origin of the 1.0498 d photometric period. Slowly pulsating B stars typically have periods $\sim 0.5 - 5.0 \, \text{d}$ and can be conclusively identified by the presence of multiperiodicity (Waelkens, 1991). Jerzykiewicz (1993) noted that $g$-mode pulsations could potentially explain
Figure 3.7: Top: HiParCoS Epoch Photometry phased with a period of 1.0498d. Bottom: A subsample of the full reduced $\chi^2$ versus period centered on the period of the best fitting sinusoid. The 1.0498d minimal-$\chi^2$ solution is bounded by the dashed dark blue lines. The dashed light blue lines ($P_{\text{rot}} = 1.02454\, \text{d}$) indicate the only other $\chi^2$ peak falling below our chosen 3$\sigma$ threshold.

the observed variability. Another explanation is that HD 23478 is an eclipsing binary with a dimmer, less-massive companion for which no spectral signature is found. Jerzykiewicz (1993) rejected this possibility arguing that radial velocity variations $\gtrsim 80\, \text{km s}^{-1}$ would be exhibited in this scenario. The observations analyzed here do not exhibit any variations $\geq 5\, \text{km s}^{-1}$.

Assuming that the photometric variations are instead caused by rotational modulation, the inclination angle of the stellar rotation axis, $i$, can be inferred from
the projected rotational velocity, \( v \sin i = 140 \pm 10 \text{ km s}^{-1} \), and the stellar radius, \( R = 2.7^{+1.6}_{-0.9} R_{\odot} \), resulting in an inclination of \( i = 69^{+21}_{-10} \degree \); the uncertainty is propagated from the 3\( \sigma \) value of \( \delta P_{\text{rot}} = 0.0004 \text{ d} \) and estimated errors in \( R \) and \( v \sin i \).

These values imply a stellar rotational velocity of \( v = 150^{+30}_{-20} \text{ km s}^{-1} \) which is consistent with typical values for B stars \( \text{[McNally, 1965]} \). Therefore, in agreement with \( \text{[Jerzykiewicz, 1993]} \), we conclude that the observed HiPParCoS photometric variations are mostly likely generated by the star’s rotation.

### 3.5 Magnetic Field

The longitudinal magnetic field, \( \langle B_z \rangle \), is measured through Zeeman signatures in the circularly polarized Stokes \( V \) spectrum. In order to maximize the SNR in these observations, the Least Squares Deconvolution (LSD) cross-correlation procedure \( \text{[Donati et al., 1997]} \) \( \text{[Kochukhov, Makaganiuk & Piskunov, 2010]} \) was applied to all ESPaDOnS and Narval spectra. The LSD line masks are constructed using spectral line lists associated with a specified surface gravity, effective temperature, detection threshold (i.e. the central depth of the weakest lines included in the mask), and microturbulence (\( v_{\text{mic}} \)) obtained from the Vienna Atomic Line Database (VALD2) \( \text{[Piskunov et al., 1995]} \). In the case of HD 23478, a detection threshold of 0.01 and \( v_{\text{mic}} = 0 \) were used.

Terrestrial atmospheric absorption appears as deep, narrow telluric lines in the Stokes \( I \) LSD profiles that can significantly affect the value of \( \langle B_z \rangle \); therefore, any lines near spectral regions where tellurics were present were removed.

\( \langle B_z \rangle \) measurements are known to vary to some extent depending on which element’s atomic absorption lines are used to analyze the Zeeman signatures (e.g. \( \text{Pyper} \)).
Several LSD line masks were therefore created in order to better evaluate the strength and variability of the inferred field – one which contained only He lines, one in which both H and He lines were removed leaving only absorption due to metals, and one containing both He and metal lines.

For each line mask, we adopted normalization values of the wavelength, Landé factor, and line depth of 500 nm, 1.2, and 0.2, respectively. Both the pure He and pure metal line masks yielded results similar to the combined He+metal line mask. This latter mask resulted in the smallest uncertainties. Examples of the Stokes $V$ and $I$, and of the $N$ (circularly polarized intensity, total intensity, and null diagnostic) LSD profiles obtained using the He+metal line mask at 3 phases are shown in Fig. 3.8. The profiles corresponding to phases of 0.140 and 0.817 were obtained by combining two consecutive measurements resulting in a moderately increased SNR.

The three LSD profiles shown in Fig. 3.8 demonstrate that no strong variability is observed in the He and metal line Zeeman signatures. We also computed the longitudinal magnetic field from each LSD profile using Eqn. (1) of Wade et al. (2000) where an integration range of $v \in (-140, 170) \text{ km s}^{-1}$ was used. The values of $\langle B_z \rangle$ derived from the He+metal mask are reported in Table 3.1. We phased these measurements according to the photometric period of Eqn. (3.1). The phased longitudinal field measurements calculated using the He+metal ($\langle B_z \rangle_{\text{He+metal}}$) LSD line mask are shown in Fig. 3.9.

Measurements of the longitudinal field were also determined using the core of the H$\beta$ line. As with the measurements obtained from LSD profiles, the first moment method was applied. We integrated the ESPaDOnS and Narval Stokes $V$ and $I$
Figure 3.8: Examples of He+metal LSD profiles at 3 phases showing Zeeman signatures in Stokes $V$ (top, red), along with associated Stokes $I$ (bottom, black) and diagnostic null (middle, blue) profiles. Vertical dotted lines indicate the integration range.
Figure 3.9: Longitudinal magnetic field measurements phased according to Eqn. 3.1. The curves correspond to the best-fitting sinusoids. Top: $\langle B_z \rangle$ values derived using He+metal LSD line profiles. Bottom: $\langle B_z \rangle$ values derived from H$\beta$ Stokes V observations. Black circles correspond to measurements obtained by Narval and ESPaDOnS while red diamonds are those obtained with dimaPol.

Profiles across the full core, from $-200$ to $220$ km s$^{-1}$. Stokes $I$ was normalized to the spectral flux computed from the 10 pixels located immediately outside the integration range. The process used to calculate the DAO longitudinal field measurements is outlined in Monin et al. (2012). The ESPaDOnS and Narval measurements are listed in Table 3.1 and the DAO measurements are listed in Table 3.2.

The phased H$\beta$ longitudinal measurements ($\langle B_z \rangle_{H\beta}$) show a somewhat larger amplitude variation of $0.6 \pm 0.1$ kG compared with the $0.3 \pm 0.1$ kG amplitude obtained from the He+metal LSD profiles (Fig. 3.9).
Table 3.4: Calculated values of various parameters associated with the magnetosphere of HD 23478 as derived from He+metal LSD profiles and H\(\beta\). For those values dependent on \(B_d\), which diverges as \(\beta \rightarrow 0^\circ\) and \(i \rightarrow 90^\circ\), only lower limits are provided.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>He+metals(_{LSD})</th>
<th>H(\beta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i [\text{deg}])</td>
<td>69(^{+21}_{-10})</td>
<td></td>
</tr>
<tr>
<td>(\dot{M}<em>{B=0} [\times 10^{-10} M</em>\odot \text{ yr}^{-1}])</td>
<td>2.0(^{+0.8}_{-0.4})</td>
<td></td>
</tr>
<tr>
<td>(V_\infty [\times 10^3 \text{ km s}^{-1}])</td>
<td>1.2(^{+0.4}_{-0.3})</td>
<td></td>
</tr>
<tr>
<td>(R_K [R_\ast])</td>
<td>2.9(^{+1.7}_{-1.2})</td>
<td></td>
</tr>
<tr>
<td>(\beta [\text{deg}])</td>
<td>3(-3)</td>
<td>8 (\pm) 8</td>
</tr>
<tr>
<td>(B_d [\text{kG}])</td>
<td>(\geq 12.0)</td>
<td>(\geq 9.5)</td>
</tr>
<tr>
<td>(\eta_\ast)</td>
<td>(\geq 2.1 \times 10^5)</td>
<td>(\geq 1.3 \times 10^5)</td>
</tr>
<tr>
<td>(R_A [R_\ast])</td>
<td>(\geq 21.3)</td>
<td>(\geq 19.0)</td>
</tr>
<tr>
<td>(R_A/R_K)</td>
<td>(\geq 4.6)</td>
<td>(\geq 4.1)</td>
</tr>
</tbody>
</table>

While the sinusoidal fits to the two \(\langle B_z \rangle\) data sets appear to reproduce the phased measurements reasonably well, only the variability observed in \(\langle B_z \rangle_{H\beta}\) is statistically significant. Furthermore, the phases of the extrema of the sinusoidal fits \((0.4 - 0.5\) and \(0.9 - 1.0\) with uncertainties of about 0.05) are in agreement amongst the two curves. This suggests that the marginal detections of \(\langle B_z \rangle_{\text{He+metal}}\) variations are in fact real.

In the context of the Oblique Rotator Model (ORM), periodic variations in \(\langle B_z \rangle\) can be understood to be due to the rotation of a star having a dipolar magnetic field component with an axis of symmetry that is inclined from the rotational axis by an angle \(\beta\) \cite{Stibbs1950}. Assuming that HD 23478’s magnetic field is characterized by an important dipole component, as typically observed in hot stars, the weak variability observed in the \(\langle B_z \rangle\) measurements shown in Fig. 3.9 implies an obliquity angle
of $\beta \approx 0^\circ$. Other explanations for the weak longitudinal field variability can be excluded based on the inferred rotational period and observed spectral properties. For instance, regardless of the value of $\beta$, no variations in $\langle B_z \rangle$ would be apparent if $i = 0^\circ$; however, this is inconsistent with the $i = 69_{-10}^{+21}^\circ$ calculated in Section 3.4. Weak variability would also be observed if the star’s rotational period is on the order of the observing timescale of $\tau_{\text{obs}} \gtrsim 30$ d. This is inconsistent with HD 23478’s inferred 1.0498 d rotational period and relatively large $v \sin i$.

In the ORM, the obliquity angle is derived from $i$ along with the best sinusoidal fit to the $\langle B_z \rangle$ measurements, given by $\langle B_z \rangle = B_0 + B_1 \sin 2\pi(\phi - \phi_0)$, using the relation given in Eqn. 3 of [Preston (1967)]. A least-squares analysis yielded the fit to $\langle B_z \rangle_{\text{He+metal}}$ shown in Fig. 3.9 described by the parameters $B_0 = -2.1 \pm 0.1$ kG, $B_1 = 0.3 \pm 0.1$ kG, and $\phi_0 = -0.3 \pm 0.4$ where the uncertainties correspond to 1σ confidence. Applying Eqn. 3 of [Preston (1967)] with the inclination angle derived above and $r = 0.77 \pm 0.12$ (Eqn. 2 of [Preston (1967)]) results in an obliquity of $\beta = 3_{-3}^{+4}^\circ$. A similar value of $8 \pm 8^\circ$ was found for $\langle B_z \rangle_{\text{H}\beta}$.

With the inclination and obliquity angles known, the polar strength of the surface dipole component of the magnetic field can be estimated using the method of [Preston (1967)]. For this calculation, we use a maximum longitudinal field magnitude of $|\langle B_z \rangle_{\text{max}}| = 2.4 \pm 0.2$ kG as given by the sinusoidal fit to $\langle B_z \rangle_{\text{He+metal}}$ and a limb-darkening coefficient determined by linearly interpolating the values associated with the TLUSTY model atmosphere grid yielding a value of $u = 0.398$ for the $T_{\text{eff}} = 20$ kK, $\log g = 4.2$ model [Daszyńska-Daszkiewicz & Szewczuk, 2011]. This yields a dipole field strength of $B_d \geq 12.0$ kG where no upper limit is provided due to the divergence of the dipole field as $\beta \to 0^\circ$ and $i \to 90^\circ$. A relatively small difference in the lower
limit of $B_d$ was found (9.5 kG) using the combined Narval, ESPaDOnS, and DAO $\langle B_z \rangle_{\text{H}\beta}$ values. The results of the magnetic analysis are summarized in Table 3.4.

We note that an upper limit on the dipole field strength may be estimated based on the fact that Zeeman splitting is not observed in the spectral lines themselves. However, given the high $v \sin i$ of the star, those constraints are not likely to be very helpful. Moreover, the field strength may be better constrained by generating synthetic Stokes $V$ profiles (e.g. Petit & Wade 2012). On the other hand, its utility would likely be hampered by the weak variability of the Stokes $V$ profiles. Such an analysis is beyond the scope of this work but could be carried out in the future using a more extensive and higher SNR spectropolarimetric data set.

### 3.6 Emission and Variability

HD 23478 was originally identified as a potential CM star based on the large degree of emission occurring at all near-infrared H lines (Eikenberry et al. 2014). As expected, the most significant emission detected in the visible observations presented here occurs at the H$\alpha$ line. Fig. 3.10 shows the minimum and maximum emission observed at phases of 0.740 and 0.516 and visible at all phases forming a double peak with a separation of approximately $\pm 480$ km s$^{-1}$. The large Doppler shifted velocities of the peaks are more than 3 times the star’s projected rotational velocity of $v \sin i = 140 \pm 10$ km s$^{-1}$ (indicated by the dotted vertical lines in Fig. 3.10). If we assume that this emission is produced by gas bound in corotation with the star, this implies the presence of an emitting plasma at $R \gtrsim 3R_\star$.

Although H$\alpha$ presents the largest emission throughout the observed spectra, it varies relatively weakly (in comparison to $\sigma$ Ori E, for example) over the 1.0498 d
Figure 3.10: Maximum Hα emission (solid dark blue), as observed at a phase of 0.740, forms a double-horned peak separated by a velocity of ±480 km s\(^{-1}\) well beyond the stellar surface indicated by the vertical dotted black lines at \(v \sin i = ±140 \text{ km s}^{-1}\). Minimum Hα (solid light blue) observed at a phase of 0.516. The dashed black curve is the \(T_{\text{eff}} = 22 \text{ kK, log } g = 4.4\) TLUSTY model spectrum discussed in Section 3.3.2.

Photometric period. This is demonstrated by the equivalent width (EW) measurements shown in Fig. 3.11 and the overplotted line profiles shown in Fig. 3.12. Similar to the ORM interpretation of a sinusoidally varying longitudinal magnetic field, the continuous and strong emission of CM stars is also expected to be rotationally modulated (e.g. Oksala et al., 2012). We find that the Hα EWs vary coherently when phased by the 1.0498 d period and is therefore consistent with this interpretation.

The clearest example of HD 23478's spectral variability is found in He line EW measurements as demonstrated by He i \(\lambda4713\) and He i \(\lambda5876\) shown in Fig. 3.11. While low SNRs and sparse phase coverage prevent an independent determination
of $P_{\text{rot}}$ from these EW variations, our observations are in agreement with a 1.0498 d period. Furthermore, $\text{H}\alpha$ and the He lines do not vary coherently when phased by the other candidate 1.02454 d rotational period discussed in Section 3.4. This provides further evidence in support of a 1.0498 d rotational period.

The maximum and minimum $\text{H}\alpha$ EWs occur at phases $0.39 \pm 0.05$ and $0.89 \pm 0.05$, respectively. These values are approximately in phase with both the HiPParCoS photometry and the $\langle B_z \rangle$ measurements. The He I $\lambda 5876$ and He I $\lambda 4713$ EW measurements are in mutual agreement and have maximum and minimum values at $0.76 \pm 0.06$ and $0.26 \pm 0.06$. They are shifted in phase relative to $H_p$ and $\langle B_z \rangle$ by $0.24 \pm 0.08$, i.e. one-quarter of one cycle.
Figure 3.12: Overlaid line profiles associated with the EWs shown in Fig. 3.11 from each of the 12 measurements. Significant variability was found in all identified He I lines.

3.7 Magnetosphere

The defining characteristic of CM stars aside from the often present strong and broad emission lines is their large ratio of the Alfvén radius to the Kepler co-rotation radius (Petit et al., 2013). The Kepler radius defines the point at which a rigidly rotating star’s gravitational force is balanced by the outward centrifugal force. Based on HD 23478’s inferred mass and rotational period, we calculate a Kepler radius of $R_K = 2.9^{+1.7}_{-1.2} R_\odot$. The Alfvén radius ($R_A$) can be estimated from the wind confinement parameter ($\eta_*$) which depends on the equatorial magnetic field magnitude ($B_{eq}$), the stellar radius, mass-loss rate in the absence of a magnetic field ($\dot{M}_{B=0}$), and terminal
wind speed \( V_\infty \) as derived by \( \text{ud-Doula, Owocki & Townsend} \) (2008). Following the treatment carried out by \( \text{Petit et al.} \) (2013), we calculated \( \eta_* \) using the calibration for \( \dot{M}_{B=0} \) derived by \( \text{Vink, de Koter & Lamers} \) (2000) with \( V_\infty = 1.3V_{\text{esc}} \) for a \( T_{\text{eff}} = 20 \text{ kK} \) star.

Assuming the \( B_d \) values calculated in Section 3.5, we derived \( \eta_* \) and \( R_A \) based on the He+metal and H\( \beta \) analyses and find the results to be consistent. The larger uncertainties on the H\( \beta \) measurements yielded the lowest minimum \( \eta_* \) and \( R_A \) at \( 1.3 \times 10^5 \) and \( 19.0 \, R_\odot \), respectively. With a Kepler radius of \( R_K = 2.9^{+1.7}_{-1.2} \, R_\odot \), we obtain a ratio of \( R_A/R_K = 13.3 \) (with a lower limit of 4.6) thereby placing HD 23478 well within the CM star regime (i.e. those with \( R_A/R_K > 1 \)). The full range of magnetospheric parameters calculated from \( \langle B_{\text{He+metal}} \rangle \) and \( \langle B_{\text{H}\beta} \rangle \) are listed in Table 3.4.

In the context of all known CM stars, the estimated Kepler and Alfvén radii place HD 23478 within a region of the magnetic confinement diagram – Fig. 3 of \( \text{Petit et al.} \) (2013) – populated by approximately 12 mid to early B-type stars. Six of these are reported to exhibit H\( \alpha \) emission and only one from this subset – HD 142990 – has a rotational period shorter than that of HD 23478 \( \text{Bychkov, Bychkova & Madej} \) (2005). The lowest reported dipolar magnetic field strengths of these 12 CM stars is HD 176582’s \( B_p \geq 7.0 \text{ kG} \), a Bp star that exhibits comparatively weaker H\( \alpha \) emission \( \text{Bohlender & Monin} \) (2011).

We note that HD 23478 exhibits similar physical and spectral properties to the well-studied B2Vp star \( \sigma \) Ori E. \( \sigma \) Ori E has a comparable effective temperature of \( 23\pm1 \text{ kK} \) \( \text{Groote & Hunger} \) (1982) and its rotational period and projected rotational velocity differ from HD 23478 by as little as 13% and 6%, respectively \( \text{Townsend} \).
et al., 2010). Hα EW measurements of σ Ori E show stronger variability ∼ 3 Å (Oksala et al., 2012) compared with the ΔEW_Hα ∼ 1 Å derived for HD 23478. In terms of the empirical $R_A/R_K \gtrsim 10$ limit noted by Shultz et al. (2014) for the occurrence of Hα emission in CM-hosting stars, these differences in emission properties are consistent with σ Ori E’s likely higher $R_K/R_A$ of approximately 15 (Petit et al., 2013).

Comparisons with the rigidly-rotating magnetosphere (RRM) model\(^1\) (Townsend & Owocki, 2005) suggest that the photometric variability of HD 23478 may be caused by variable occultation of the stellar disc by the magnetosphere. In this scenario, the plasma forms a circumstellar disk in the magnetic equatorial plane. A non-zero obliquity may then allow the plasma to periodically eclipse the stellar disk resulting in an observed dimming of the star.

The Hα emission and unsigned longitudinal field ($|\langle B_z \rangle|$) associated with an $i = 70^\circ$ and $\beta = 10^\circ$ RRM model are predicted to be in phase; this is consistent with our analysis of HD 23478. This supports our interpretation of the emission and its variability as due to magnetically confined plasma in a CM. On the other hand, the model also predicts a maximum photometric brightness at the phase of maximum $|\langle B_z \rangle|$, whereas we observe roughly the opposite. Therefore, the periodic dimming of the star is likely not related to magnetospheric occultation.

Photometric variability may be observed if chemical spots are present on the star’s surface, which serve to redistribute the star’s flux into the UV (e.g. Peterson, 1970; Krtiˇ cka et al., 2013, 2015). The variable He line profiles introduced in Section 3.6 provide evidence for He spots on the surface of the star. However, the He EWs do not vary in phase with $H_p$ but are instead shifted by one quarter of a cycle. Thus,

\(^1\) for a visualization, see: www.astro.wisc.edu/~townsend/static.php?ref=rrm-movies
He spots are also not able to fully account for the observed $H_p$ variations. On the other hand, spots of other elements (in particular Si and Fe) may well also contribute. Such an investigation would be a useful element of a future, more detailed study of HD 23478.
Chapter 4

HD 35502

4.1 Introduction

Magnetic B-type stars exhibiting strong emission (e.g. \( \sigma \) Ori E, HD 142184, HD 182180, Landstreet & Borra 1978, Grunhut et al. 2012, Rivinius et al. 2013) serve as important diagnostic evidence for understanding how stellar winds interact with magnetic fields. Models such as the Rigidly-rotating Magnetosphere (Townsend & Owocki 2005) have provided a reasonably accurate description of these systems; however, detailed comparisons with observations of \( \sigma \) Ori E have uncovered important discrepancies which require explanations (Oksala et al. 2012, 2015). Shultz et al. (2014) also suggest that the predictions of the centrifugal breakout model (Ud-Doula, Townsend & Owocki 2006), which describes the leakage of plasma from a stellar magnetosphere, are inconsistent with the observed densities.

Although these tests of the current theoretical framework provide useful information, their conclusions are based on a relatively small number of case studies. However, these numbers have been expanding with the recent confirmation of HD 23478’s
centrifugal magnetosphere (CM) (Sikora et al., 2015; Hubrig et al., 2015) as well as the candidate CM-host, HD 345439 (Hubrig et al., 2015). The latest addition to this particular subset of magnetic B-type stars, HD 35502, is the focus of this thesis.

Over the past 60 years, the nature of HD 35502 has been redefined in various ways. Located within the Orion OB1 association (likely within the OB1a subgroup, Landstreet et al., 2007), it was initially identified as a B5V star (Sharpless, 1952; Crawford, 1958). Higher resolution spectra later obtained by Abt & Hunter (1962) revealed both narrow and broad spectral lines, the latter of which being evident from the author’s adopted $v \sin i$ of 290 km s$^{-1}$. Moreover, He i lines were reported to be relatively weak; an analysis of early-type stars found within OriOB1 carried out by Nissen (1976) demonstrated that HD 35502’s He abundance was approximately half that of the nearby chemically normal field stars. These results motivated its eventual reclassification as a B5IVsnp star (Abt & Levato, 1977).

HD 35502’s magnetic field was first detected by Borra (1981) and later confirmed by subsequent studies (Bychkov, Bychkova & Madej, 2005; Glagolevskij et al., 2010). Since then, it has been suggested that some of the unusual features apparent in its spectrum may be related to this strong field. In this paper, we use high-resolution spectra to provide a new interpretation of HD 35502 as a spectroscopic trinary system whose primary component is a magnetic B-type star hosting a centrifugally supported magnetosphere.

In Section 4.2, we discuss both the polarized and unpolarized spectroscopic observations used in this study. Section 4.3 focuses on our derivation of some of the physical parameters of the system including its orbital configuration, along with the
effective temperatures, surface gravities, masses, radii, and projected rotational velocities of the three stellar components. The various analytical methods used to derive these parameters are described such as the modelling of spectroscopic and photometric data. In Section 4.4, the longitudinal magnetic field measurements of HD 35502’s primary component are derived. In Sections 4.5 and 4.6 we discuss the variability observed from the system as well as our interpretation of its origin. In Section 4.7, we derive various parameters associated with the B star’s magnetic field geometry and magnetosphere.

4.2 Observations

4.2.1 ESPaDOnS & Narval Spectropolarimetry

Spectropolarimetric observations of HD 35502 were obtained over the course of 5 years during the MiMeS (Wade et al., 2009) and BinaMiS (Neiner & Alecian, 2013) surveys. Ten Stokes $V$ measurements were taken using the high-resolution ($R \simeq 65000$) spectropolarimeter ESPaDOnS installed at the Canada-France-Hawaii Telescope over a wavelength range of approximately 3600 – 10000Å. Three of these observations exhibited signal-to-noise ratios (SNRs) $\lesssim 100$ and were removed from the analysis. Twenty Stokes $V$ observations were also obtained with the twin instrument Narval installed at the Télescope Bernard Lyot (TBL). These observations were reduced using the LIBRE-ESPRIT pipeline (Donati et al., 1997) yielding final Stokes $I$ and $V$ spectra. The Heliocentric Julian Dates (HJDs), total exposure times, and SNRs are listed in Table 4.1.
4.2.2 FEROS Spectroscopy

Thirty-two unpolarized spectra were acquired from Dec. 30, 2013 to Jan. 3, 2014 using the spectrograph FEROS installed at the European Southern Observatory (ESO). The instrument has a resolving power of \( R = 48 000 \) across a wavelength range of \( 3600 \text{ Å} - 9200 \text{ Å} \) \cite{Kaufer1999}. Uncertainties in the measured intensities were estimated from the root mean square (RMS) of the continuum intensity at multiple points throughout each spectrum \cite{Wade2012}. The HJDs, total exposure times, and SNRs are listed in Table \ref{table:4.2}.

4.2.3 H\( \alpha \) Spectroscopy

A total of 144 spectroscopic observations of H\( \alpha \) covering various wavelengths from approximately \( 6300 \text{ Å} - 6800 \text{ Å} \) are also used in this study. 130 of these observations were obtained at the Dominion Astronomical Observatory (DAO) from Nov. 26, 1991 to Feb. 4, 2012. The remaining 14 observations were obtained at CFHT from Nov. 21, 1991 to Oct. 3, 1995.

4.3 Physical parameters

Based on the high-resolution spectra obtained of HD 35502, three distinct sets of spectral lines are apparent: the strong and broad lines associated with a hot star and two nearly identical components attributable to two cooler stars, the latter of which are observed to change positions significantly. Based on HD 35502’s reported spectral type, the bright, dominant component is presumed to be a hot B5IVsnp star \cite{Abt1977}; the weaker components are presumed to be two cooler A-type stars.
Table 4.1: ESPaDOnS and Narval spectropolarimetric observations. SNRs per 1.8 km s$^{-1}$ pixel are reported at 5400 Å. The two right-most columns indicate the longitudinal magnetic field calculated using the He+metal line mask (see Section 4.4) along with the associated detection status: definite detection (DD), moderate detection (MD), and no detection (ND) as outlined by Donati et al. (1997).

<table>
<thead>
<tr>
<th>HJD</th>
<th>Total Exp. Time (s)</th>
<th>SNR (pix$^{-1}$)</th>
<th>Instrument</th>
<th>$\langle B_z \rangle_{\text{He+metal}}$ (kG)</th>
<th>Detection Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>2454702.138</td>
<td>1800</td>
<td>677</td>
<td>ESPaDOnS</td>
<td>0.12 ± 0.25</td>
<td>DD</td>
</tr>
<tr>
<td>2455849.677</td>
<td>3600</td>
<td>662</td>
<td>Narval</td>
<td>0.60 ± 0.26</td>
<td>DD</td>
</tr>
<tr>
<td>2455893.623</td>
<td>3600</td>
<td>522</td>
<td>Narval</td>
<td>-4.33 ± 0.33</td>
<td>DD</td>
</tr>
<tr>
<td>2455910.518</td>
<td>3600</td>
<td>263</td>
<td>Narval</td>
<td>-2.06 ± 0.63</td>
<td>DD</td>
</tr>
<tr>
<td>2455934.528</td>
<td>3600</td>
<td>587</td>
<td>Narval</td>
<td>-3.68 ± 0.30</td>
<td>DD</td>
</tr>
<tr>
<td>2455936.534</td>
<td>3600</td>
<td>472</td>
<td>Narval</td>
<td>-4.04 ± 0.55</td>
<td>DD</td>
</tr>
<tr>
<td>2455938.525</td>
<td>3600</td>
<td>564</td>
<td>Narval</td>
<td>0.36 ± 0.32</td>
<td>ND</td>
</tr>
<tr>
<td>2455944.500</td>
<td>3600</td>
<td>494</td>
<td>Narval</td>
<td>0.60 ± 0.37</td>
<td>ND</td>
</tr>
<tr>
<td>2455949.429</td>
<td>3600</td>
<td>545</td>
<td>Narval</td>
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<td>DD</td>
</tr>
<tr>
<td>2455950.472</td>
<td>3600</td>
<td>478</td>
<td>Narval</td>
<td>0.07 ± 0.37</td>
<td>ND</td>
</tr>
<tr>
<td>2455951.471</td>
<td>3600</td>
<td>431</td>
<td>Narval</td>
<td>-1.61 ± 0.38</td>
<td>DD</td>
</tr>
<tr>
<td>2455966.376</td>
<td>3600</td>
<td>550</td>
<td>Narval</td>
<td>-4.65 ± 0.46</td>
<td>DD</td>
</tr>
<tr>
<td>2455998.332</td>
<td>3600</td>
<td>397</td>
<td>Narval</td>
<td>0.00 ± 0.45</td>
<td>ND</td>
</tr>
<tr>
<td>2455999.362</td>
<td>3600</td>
<td>402</td>
<td>Narval</td>
<td>-2.93 ± 0.41</td>
<td>DD</td>
</tr>
<tr>
<td>2456001.309</td>
<td>3600</td>
<td>523</td>
<td>Narval</td>
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<td>DD</td>
</tr>
<tr>
<td>2456003.329</td>
<td>3600</td>
<td>528</td>
<td>Narval</td>
<td>-0.11 ± 0.41</td>
<td>DD</td>
</tr>
<tr>
<td>2456202.665</td>
<td>3600</td>
<td>604</td>
<td>Narval</td>
<td>-4.31 ± 0.29</td>
<td>DD</td>
</tr>
<tr>
<td>2456205.618</td>
<td>3600</td>
<td>494</td>
<td>Narval</td>
<td>0.02 ± 0.36</td>
<td>DD</td>
</tr>
<tr>
<td>2456224.646</td>
<td>3600</td>
<td>450</td>
<td>Narval</td>
<td>-0.46 ± 0.47</td>
<td>ND</td>
</tr>
<tr>
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<td>3600</td>
<td>505</td>
<td>Narval</td>
<td>-2.68 ± 0.48</td>
<td>DD</td>
</tr>
<tr>
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<td>710</td>
<td>ESPaDOnS</td>
<td>-2.25 ± 0.26</td>
<td>DD</td>
</tr>
<tr>
<td>2456295.787</td>
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<td>190</td>
<td>ESPaDOnS</td>
<td>-4.32 ± 1.19</td>
<td>ND</td>
</tr>
<tr>
<td>2456295.808</td>
<td>1600</td>
<td>231</td>
<td>ESPaDOnS</td>
<td>-4.69 ± 0.87</td>
<td>MD</td>
</tr>
<tr>
<td>2456556.002</td>
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<td>ESPaDOnS</td>
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<td>DD</td>
</tr>
<tr>
<td>2456557.140</td>
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<td>670</td>
<td>ESPaDOnS</td>
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<td>DD</td>
</tr>
<tr>
<td>2456560.077</td>
<td>1600</td>
<td>612</td>
<td>ESPaDOnS</td>
<td>0.68 ± 0.34</td>
<td>ND</td>
</tr>
</tbody>
</table>
Table 4.2: Unpolarized spectra obtained using FEROS. The phase is calculated using Eqn. 4.2. The SNRs listed in column 4 are estimated from the RMS of the continuum near $\lambda = 5400 \text{Å}$. 

<table>
<thead>
<tr>
<th>HJD</th>
<th>Phase</th>
<th>Total Exp.</th>
<th>RMS SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Time (s)</td>
<td></td>
</tr>
<tr>
<td>2456656.568</td>
<td>0.534</td>
<td>100</td>
<td>271</td>
</tr>
<tr>
<td>2456656.609</td>
<td>0.582</td>
<td>100</td>
<td>315</td>
</tr>
<tr>
<td>2456658.535</td>
<td>0.838</td>
<td>100</td>
<td>262</td>
</tr>
<tr>
<td>2456658.542</td>
<td>0.846</td>
<td>100</td>
<td>145</td>
</tr>
<tr>
<td>2456658.679</td>
<td>0.006</td>
<td>100</td>
<td>215</td>
</tr>
<tr>
<td>2456658.683</td>
<td>0.010</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>2456658.686</td>
<td>0.015</td>
<td>100</td>
<td>195</td>
</tr>
<tr>
<td>2456658.690</td>
<td>0.019</td>
<td>100</td>
<td>178</td>
</tr>
<tr>
<td>2456658.694</td>
<td>0.024</td>
<td>100</td>
<td>215</td>
</tr>
<tr>
<td>2456658.698</td>
<td>0.028</td>
<td>100</td>
<td>248</td>
</tr>
<tr>
<td>2456658.701</td>
<td>0.032</td>
<td>100</td>
<td>219</td>
</tr>
<tr>
<td>2456658.702</td>
<td>0.033</td>
<td>100</td>
<td>181</td>
</tr>
<tr>
<td>2456658.709</td>
<td>0.041</td>
<td>100</td>
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</tr>
<tr>
<td>2456658.713</td>
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<td>2456658.763</td>
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<td>252</td>
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<td>2456659.628</td>
<td>0.117</td>
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<td>0.169</td>
<td>100</td>
<td>222</td>
</tr>
<tr>
<td>2456659.677</td>
<td>0.175</td>
<td>100</td>
<td>284</td>
</tr>
<tr>
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<td>0.180</td>
<td>100</td>
<td>233</td>
</tr>
<tr>
<td>2456659.685</td>
<td>0.185</td>
<td>100</td>
<td>209</td>
</tr>
<tr>
<td>2456659.689</td>
<td>0.189</td>
<td>100</td>
<td>299</td>
</tr>
<tr>
<td>2456659.693</td>
<td>0.194</td>
<td>100</td>
<td>245</td>
</tr>
<tr>
<td>2456659.697</td>
<td>0.198</td>
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<td>310</td>
</tr>
<tr>
<td>2456659.700</td>
<td>0.203</td>
<td>100</td>
<td>240</td>
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<tr>
<td>2456659.704</td>
<td>0.207</td>
<td>100</td>
<td>222</td>
</tr>
<tr>
<td>2456659.708</td>
<td>0.211</td>
<td>100</td>
<td>231</td>
</tr>
<tr>
<td>2456659.746</td>
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<td>100</td>
<td>300</td>
</tr>
<tr>
<td>2456660.614</td>
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<td>249</td>
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<tr>
<td>2456660.653</td>
<td>0.319</td>
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<td>276</td>
</tr>
<tr>
<td>2456660.724</td>
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<td>2456660.763</td>
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<tr>
<td>2456660.801</td>
<td>0.492</td>
<td>100</td>
<td>250</td>
</tr>
</tbody>
</table>
based on the presence of Fe II lines and the absence of Fe III lines.

Some of the B star lines (the He I lines, in particular) appear to exhibit intrinsic variability. Such features are commonly found in magnetic He peculiar stars (e.g. Borra, Landstreet & Thompson [1983] Bolton et al. [1998] Shultz et al. [2015]).

### 4.3.1 Orbital solution

The radial velocity ($v_r$) of the central B star in each observation was determined using spectral lines for which no significant contribution from the two A stars was apparent. Various He I lines were considered; however, non-negligible variability resulted in significant systematic errors. C II $\lambda$4267, on the other hand, was found to be both relatively strong (with a depth of 10 per cent of the continuum) and non-variable. Radial velocities calculated by fitting a Gaussian to this line yielded the most precise values. The uncertainties were estimated through a bootstrapping analysis in which a subsample of the normalized flux (in this case, the normalized flux associated with C II $\lambda$4267) is replaced by data points randomly selected from the full sample. The fitting routine is then repeated on this new data set for a chosen number of iterations and a probability distribution is obtained for each fitting parameter. The Gaussian fitting routine was carried out for 500 iterations in which 61 per cent of the normalized intensity measurements were replaced; a $3\sigma$ standard deviation was then chosen from the resulting distribution. The average B star $v_r$ was found to be $20 \pm 4$ km s$^{-1}$; no significant $v_r$ variability was detected from the 62 observations.

The relatively sharp spectral lines of the two A stars allowed radial velocities to be determined with a significantly higher precision than those of the B star. They were calculated from Stokes I profiles produced using the Least Squares Deconvolution
(LSD) method (Donati et al., 1997; Kochukhov, Makaganiuk & Piskunov, 2010). The LSD line mask used to carry out the procedure was compiled using data taken from the Vienna Atomic Line Database (VALD) (Kupka et al., 2000). In order to isolate the A stars from the dominant B star component in the Stokes I LSD profiles, we used a line list associated with an 8000 K star having a surface gravity of log $g = 4.0$ and a microturbulence of $v_t = 0$. Several line masks were used to generate various LSD profiles including one in which both the A and B star components are evident as shown in Fig. 4.1. The radial velocities were then determined by simultaneously fitting two Gaussians to the sharp components of the Stokes I profiles. The $v_r$ errors were estimated using a 500 iteration bootstrapping analysis. The values were found to range from $-30.4$ to $78.6$ km s$^{-1}$ with an average uncertainty of 0.8 km s$^{-1}$.

The similar amplitudes of the two A star $v_r$ variations ($|v_r - v_{r,sys}| \approx 55$ km s$^{-1}$ where $v_{r,sys}$ is the mean $v_r$ of both A stars) suggests that their orbital periods, $P_{orb}$, are approximately equal. Adopting this assumption greatly simplifies the determination of $P_{orb}$; however, the problem of consistently distinguishing between the two nearly identical spectral components remains. This was overcome by further assuming that the A star $v_r$ variations were purely sinusoidal and described by

$$v_{r,i}(t) = C_0 + C_{1,i} \sin \left(2\pi t / P_{orb} + \phi_0\right)$$

with $C_{1,1} = -C_{1,2}$ where the subscript $i$ indicates the 1$^\text{st}$ or 2$^\text{nd}$ A star. We then applied the following procedure:

1. define a grid of possible orbital periods;

2. define an amplitude and phase shift of the radial velocity variations based on the
Figure 4.1: ESPaDOnS, Narval, and FEROS Stokes $I$ profiles generated such that the three spectral components are emphasized. The observations are phased by the A star orbital period of 5.6686(2) d. The vertical dashed black lines indicate the surface of the B star located at $v = \pm v \sin i = \pm 75$ km s$^{-1}$. The dashed black sinusoids correspond to the fits obtained for $v_r$ of the two A stars.
maximum observed $v_r$ separation;

3. for every period, determine which sinusoidal model the blue and red shifted spectral lines must be associated with in order to minimize the residuals.

The two components in each observation were then identified using whichever period returned the minimal residual fit. A traditional period fitting routine (e.g. Lomb-Scargle) could then be applied to the $v_r$ time series of each star separately thereby yielding more precise periods, amplitudes, and phase shifts for each model.

We chose a grid of periods ranging from 0.1 to 10 d in increments of $10^{-5}$ d ($\sim$ 1 s). The amplitude and phase shift were defined by the maximum $v_r$ separation of 109 km s$^{-1}$ (i.e. phase 0.073 in Fig. 4.2 where this phase corresponds to the phase of the B star’s maximum longitudinal magnetic field derived in Section 4.4). The amplitudes associated with the two A star $v_r$ models were then found to be $56.1 \pm 0.4$ km s$^{-1}$ and $53.0 \pm 0.6$ km s$^{-1}$ where the uncertainties correspond to 3$\sigma$. The best-fitting periods of the two components were found to be 5.6685(1) d and 5.6688(2) d with 3$\sigma$ uncertainties.

The short and similar orbital periods obtained from our analysis suggest that the two A stars form a synchronized binary sytem orbiting about the central B star rather than the alternative hierarchical configuration. We therefore adopt the mean period of $P_{\text{orb}} = 5.6686(2)$ d. Fig. 4.2 shows the radial velocities of the A stars phased by this period. The sinusoidal fits demonstrate that the orbits of the A stars are nearly circular. Based on the best-fitting sinusoidal models recalculated using the adopted period, the $v_r$ amplitudes of $52.9 \pm 0.6$ km s$^{-1}$ and $-55.8 \pm 0.4$ km s$^{-1}$ imply a mass ratio of $M_{A_1}/M_{A_2} = 1.05 \pm 0.03$. The systemic velocity of the two A stars ($v_{r,\text{sys}}$) was found to have a median value of 25 km s$^{-1}$ with a median absolute deviation of
CHAPTER 4. HD 35502

Figure 4.2: Top: The sinusoidal fits to the radial velocities of the two A stars phased by a period of 5.6686 d. Bottom: The reduced \( \chi^2 \) distribution yielded by the period fitting routine applied to one of the A stars. The 5.6686 d period is indicated by the red arrow.

1 km s\(^{-1}\). Comparing with the average B star \( v_r \) of 20 ± 4 km s\(^{-1}\) and noting that no significant variability in the \( v_{r,sys} \) was detected over the 5.3 year observing period implies a very long orbital period of the A binary about the B star. A lower limit for this period is derived in Section 4.3.2.

4.3.2 SED fitting

Photometric fluxes of HD 35502 have been measured throughout the UV, visible, and near infrared spectral regions thereby allowing the temperatures and radii of the three stellar components to be constrained. Ultraviolet measurements were previously obtained at four wavelengths – 1565 Å, 1965 Å, 2365 Å, and 2749 Å – by the S2/68...
instrument on board the TD1 satellite (Thompson et al., 1978). Photometry spanning the visible spectrum were taken from the Geneva Observatory’s catalogue of U, B, V, B1, B2, V1, and G filters (Rufener 1981). Additionally, infrared observations catalogued by 2MASS (J, H, and Ks filters) (Skrutskie et al., 2006) and WISE (W1 and W2 filters) (Wright et al., 2010) were used. The reported Geneva, 2MASS, and WISE magnitudes were converted to the flux units of ergs/\(s\cdot cm^2\cdot \AA\) using the zero points reported by Rufener & Nicolet (1988), Cohen, Wheaton & Megeath (2003), and Wright et al. (2010).

The reported photometric measurements of HD 35502 include the contributions from each of the three stellar components. This renders an SED fitting analysis particularly susceptible to degenerate solutions; however, speckle interferometry measurements obtained by Balega et al. (2012) provide additional photometric constraints on the system. Using filters centered on 5500 \(\AA\) and 8000 \(\AA\), they detected two sources exhibiting magnitude differences of 1.45 \(\pm\) 0.02 and 1.21 \(\pm\) 0.02, respectively. The sources were reported to have angular separations of 69 \(\pm\) 1 mas and 68 \(\pm\) 1 mas in the two filters. The speckle companion is also identified in observations obtained by Horch et al. (2001) with a consistent angular separation of \(\rho < 59\) mas.

In conjunction with the distance to HD 35502, the angular separations may be used to determine the associated linear separation. Using \(d = 430 \pm 120\) pc inferred from the 2.35 \(\pm\) 0.68 mas parallax (van Leeuwen 2007) yields a projected linear separation of 29 \(\pm\) 8 AU. The minimum orbital period between the B star and the A star binary system can then be approximated by assuming upper limit masses of 8 \(M_\odot\) and 3 \(M_\odot\) for the B and A stars, respectively (lower masses are derived in Section 4.7). This implies an orbital period of \(P_{\text{orb}} \gtrsim 60\) yrs which is consistent with the fact that no
significant variations were detected in either the B star radial velocities or the A star binary’s systemic radial velocity.

The observed photometry was fit using ATLAS9 synthetic spectral energy distributions (SEDs) generated from the atmospheric models of \cite{Castelli2004}. The grid consists of models with effective temperatures ranging from $3.5 - 50.0$ kK and surface gravities spanning $\log g = 0.5 - 5.0$ (cgs) as described in detail by \cite{Howarth2011}. This grid was linearly interpolated in order to produce models with a uniform temperature and surface gravity resolution of 125 kK and 0.01 dex for $T_{\text{eff}} = 5 - 25$ kK and $\log g = 3.0 - 4.75$ (cgs). All of the SEDs were then convolved with the transmission functions associated with each of the narrow band filters: TD1 UV \cite{Carnochan1982}, Geneva \cite{Rufener1988}, 2MASS \cite{Cohen2003}, and WISE \cite{Wright2010}.

Modelling the photometry of unresolved multi-star systems using synthetic SEDs requires a large number of fitting parameters and therefore the solution is expected to be highly degenerate. The contribution to the total flux from each of the three stellar components depends on, among other factors, their effective temperatures, surface gravities, and radii. In order to reduce the number of solutions, we adopted a solar metallicity ($Z_{\odot} = 0.014$) and a microturbulence velocity of $v_t = 0$. The high-resolution spectra of HD 35502 obtained by Narval, ESPaDOnS, and FEROS suggest that the two cooler A star components are approximately identical in terms of their $T_{\text{eff}}$, $\log g$, and line-broadening parameters (see Section 4.3.3). If we assume that the two A stars contribute identically to the SED, this reduces the number of independent models required in the fitting routine from three to two thereby resulting in a total of six free parameters: $T_{\text{eff}}$, $\log g$, and the stellar radius, $R$, for both the B star and
the (identical) A stars.

The effective temperature of a star inferred from fitting model SEDs to photometry is expected to be highly correlated with the colour excess, $E(B - V)$. Given HD 35502’s probable location within the Orion OB1a cluster (Landstreet et al., 2007), the extinction caused by the presence of gas and dust is expected to be significant. Indeed, Sharpless (1952) and Lee (1968) report values (without uncertainties) of $E(B - V)$ of 0.13 and 0.14, respectively. We used the method of Cardelli, Clayton & Mathis (1989) with an adopted total selective extinction of $R(V) = 3.1$ in order to deredden the observed photometry. Small differences in the resulting best-fitting parameters of < 3 per cent were found by using an $E(B - V)$ of 0.13 or 0.14. Although we investigated how our analysis was affected by varying the colour excess from 0.0 – 0.2, the final effective temperatures are reported by assuming $E(B - V) = 0.14$.

We found that a Markov Chain Monte Carlo (MCMC) fitting routine provided a suitable means of determining the most probable solution while simultaneously revealing any significant degeneracies. This was carried out by evaluating the likelihood function yielded by a set of randomly selected fitting parameters drawn from a prior probability (e.g. see Wall & Jenkins, 2003). For each iteration, the derived likelihood is compared with that produced by the previous iteration. If a new solution is found to yield a higher quality of fit (higher likelihood), these parameters are adopted, otherwise, the previous solution is maintained. In order to broadly sample the solution space, the MCMC algorithm is designed to adopt poorer fitting solutions at random intervals thereby preventing a local (but not global) maximum likelihood from being returned.

Uniform prior probability distributions were defined for $T_{\text{eff}}$, $\log g$, and $R$ where the
Figure 4.3a: Marginalized posterior probability distributions returned by the MCMC algorithm that was applied to the SED fitting. Each frame demonstrates the correlations that are apparent between various parameters while the vertical and horizontal blue lines indicate the value of each parameter associated with the maximum likelihood solution (i.e. $T_B$, $T_A$, $R_B$, and $R_A$). The contours approximately correspond to $1 - 3\sigma$ confidence regions in increments of $0.5\sigma$; $\sigma_{T_B}$, $\sigma_{T_A}$, $\sigma_{R_B}$, and $\sigma_{R_A}$ indicate the value of each parameter’s $1\sigma$ region.

The most probable effective temperatures for the B and A star models were found to be $T_B = 18.4$ kK, $\sigma_{T_B} = 0.6$ kK, $R_B = 3.0$ $R_{\odot}$, $\sigma_{R_B} = 0.1$ $R_{\odot}$, $T_A = 8.9$ kK, $\sigma_{T_A} = 0.3$ kK, $R_A = 2.1$ $R_{\odot}$, and $\sigma_{R_A} = 0.1$ $R_{\odot}$.

The latter was constrained within $1.0 - 10.0 R_{\odot}$. The two speckle observations (Balega et al., 2012) were then included in the total prior probability as monochromatic flux ratios (i.e. magnitude differences) at 5500 Å and 8000 Å. We assumed that the reported 0.02 mag uncertainties correspond to $1\sigma$ significance. The marginalized posterior probability distributions produced after $10^6$ iterations in the Markov Chain are shown in Fig. 4.3a.

The most probable effective temperatures for the B and A star models were found
Figure 4.3b: Comparisons between the observed photometry (red points) and the model SEDs. The dashed blue and dot-dashed black curves correspond to the model SEDs of the composite A star components (i.e. $2F_A(\lambda)$) and the B star, respectively. The black crosses indicate the flux obtained by convolving the model SED with the transmission function of the associated filter.

to be $18.4 \pm 1.2$ kK and $8.9 \pm 0.6$ kK, respectively, where the uncertainties correspond to the 93rd percentile (approximately $2\sigma$). The fitting parameters used to derive the stellar radii, $R_B$ and $R_A$, depend on the distance to HD 35502 (i.e. as a scaling factor given by $R_*^2/d^2$). Although the posterior probability distributions for $R_B$ and $R_A$ both yield $2\sigma$ uncertainties of $0.2 R_\odot$, the consideration of the relatively large distance uncertainty ($d = 430 \pm 120$ pc) implies values of $\delta R_B = 0.9 R_\odot$ and $\delta R_A = 0.6 R_\odot$. The most probable radii and their uncertainties found from the MCMC analysis are then given by $R_B = 3.0 \pm 0.9 R_\odot$ and $R_A = 2.1 \pm 0.6 R_\odot$. The analysis was insensitive to changes in $\log g$ as indicated by an essentially flat posterior probability distribution;
therefore, no definitive surface gravity can be reported. Comparisons between the observed photometry and the best-fitting model are shown in Fig. \[4.3b\] where we have adopted $\log g = 4.3$ for both the A and B models as derived in Section \[4.3.3\].

The model B star flux ($F_B$) and the model binary A star flux ($2F_A$) can be used to verify our initial assumption that the two components detected in the speckle observations do indeed correspond to the central B star and the A star binary system. The models can be compared with the speckle observations by calculating the flux ratios, $2F_A(\lambda)/F_B(\lambda)$, at the speckle observation wavelengths. Both $F_A(\lambda)$ and $F_B(\lambda)$ are integrated over wavelength intervals of 200 Å and 1000 Å (i.e. the FWHM of the filters used by Balega et al., 2012) centered at 5500 Å and 8000 Å, respectively. We then obtain magnitude differences of $\Delta m_{\text{syn}}(5500 \, \text{Å}) = 1.46$ and $\Delta m_{\text{syn}}(8000 \, \text{Å}) = 1.23$. These values yield a negligible discrepancy with the speckle observations of 1 per cent at $\lambda = 5500 \, \text{Å}$ and 2 per cent at $\lambda = 8000 \, \text{Å}$.

### 4.3.3 Spectral line fitting

Various properties of HD 35502’s three stellar components may be estimated through comparisons with synthetic spectra (e.g. the surface gravity, line broadening characteristics, etc.). We carried this out using local thermodynamic equilibrium (LTE) models generated with SYNTH3 [Kochukhov, 2007]. The code computes disc-integrated spectra using spectral line data provided by VALD [Kupka et al., 2000] obtained using an extract stellar request for a specified effective temperature, surface gravity, and turbulence velocity in conjunction with ATLAS9 atmospheric models [Kurucz, 1993]. The synthetic spectra can then be convolved with the appropriate functions in order to account for instrumental and rotational broadening effects.
Table 4.3: Stellar parameters of HD 35502.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sp. Type</td>
<td>B5IVsnp</td>
</tr>
<tr>
<td>$\pi$ (mas)</td>
<td>$2.35 \pm 0.68$</td>
</tr>
<tr>
<td>$d$ (pc)</td>
<td>$430 \pm 120$</td>
</tr>
<tr>
<td>Photometric</td>
<td></td>
</tr>
<tr>
<td>$V$ (mag)</td>
<td>$7.331 \pm 0.004$</td>
</tr>
<tr>
<td>$E(B-V)$ (mag)</td>
<td>$0.14$</td>
</tr>
<tr>
<td>B Star Parameters</td>
<td></td>
</tr>
<tr>
<td>$T_{\text{eff}}$ (kK)</td>
<td>$18.4 \pm 0.6$</td>
</tr>
<tr>
<td>log($g$) (cgs)</td>
<td>$4.3 \pm 0.2$</td>
</tr>
<tr>
<td>$v \sin i$ (km s$^{-1}$)</td>
<td>$75 \pm 5$</td>
</tr>
<tr>
<td>log $L/L_\odot$</td>
<td>$3.0^{+0.4}_{-0.5}$</td>
</tr>
<tr>
<td>$M/M_\odot$</td>
<td>$5.7^{+0.7}_{-0.5}$</td>
</tr>
<tr>
<td>$R_p/R_\odot$</td>
<td>$3.0^{+1.1}_{-0.4}$</td>
</tr>
<tr>
<td>$\tau_{\text{age}}$ (Myr)</td>
<td>$20^{+20}_{-17}$</td>
</tr>
<tr>
<td>$P_{\text{rot}}$ (d)</td>
<td>$0.85380(4)$</td>
</tr>
<tr>
<td>A Star Parameters</td>
<td></td>
</tr>
<tr>
<td>$T_{\text{eff}}$ (kK)</td>
<td>$8.9 \pm 0.3$</td>
</tr>
<tr>
<td>log($g$) (cgs)</td>
<td>$4.3 \pm 0.3$</td>
</tr>
<tr>
<td>$v \sin i$ (km s$^{-1}$)</td>
<td>$12 \pm 2$</td>
</tr>
<tr>
<td>log $L/L_\odot$</td>
<td>$1.4^{+0.4}_{-0.5}$</td>
</tr>
<tr>
<td>$M/M_\odot$</td>
<td>$2.1^{+0.4}_{-0.3}$</td>
</tr>
<tr>
<td>$R/R_\odot$</td>
<td>$2.1 \pm 0.6$</td>
</tr>
<tr>
<td>$\tau_{\text{age}}$ (Myr)</td>
<td>$&lt; 630$</td>
</tr>
</tbody>
</table>

The ESPaDOnS, Narval, and FEROS observations were normalized using a series of polynomial fits to the continuum. The relatively shallow (≈ 5 per cent of the continuum) and narrow lines produced by the two A stars made the spectral line modelling inherently uncertain. For instance, the typical root mean square continuum intensity near the A stars’ Mg\textsc{i} λ4703 lines was found to be approximately 14 per cent of the line depth. Thus, the SNRs of the majority of the A star lines were relatively low. This was mitigated to some extent by binning the observed spectra with a bin width of ≈ 0.03 Å (i.e. 2 pixels). In order to account for the instrumental profile of the ESPaDOnS and Narval observations, the synthetic spectra were convolved assuming a resolving power of \( R = 65000 \); similarly, the FEROS spectra were fit after convolving the synthetic spectra assuming \( R = 48000 \).

The quality of fit yielded by the total normalized synthetic flux depends not only on \( T_{\text{eff}} \) of the three models but also on their (relative) luminosities. Without well constrained luminosities (\( L(\lambda) \)), the effective temperatures could not be reliably estimated. Therefore, we adopted the 18.4 kK and 8.9 kK values associated with the B and two A stars obtained from the SED fitting (Section 4.3.2). Moreover, we assumed that the luminosities of the two A stars are equal thereby reducing the number of degrees of freedom in the spectral analysis.

With \( T_{\text{eff}} \) specified, the stellar luminosities can be estimated through various methods. For instance, the un-normalized spectra generated by synth3 may be used or the wavelength independent luminosity (\( L \propto T_{\text{eff}}^4 R^2 \)) may be adopted along with the radii found from the SED fitting in Section 4.3.2. However, we found that the best results were obtained by letting the luminosity ratio of the B and A star models, \( L_B/L_A \), be a free parameter and subsequently finding the minimum \( \chi^2 \) fit for a given
surface gravity ($\log g$) and rotational broadening ($v \sin i$). This was carried out using the observed spectra for which the two A stars were most widely separated in wavelength (phase 0.073 in Fig. 4.2) in the wavelength range of 4200 – 4300 Å. This region was chosen because of the presence of the strong and non-variable C II line produced by the B star along with many A star lines of various elements (e.g. Fe, Ti, Cr, Mn). Most importantly, this wavelength range is free of B star lines exhibiting obvious chemical abundance anomalies and variability such as those observed from He. A subsample of this region containing C II$\lambda 4267$ is shown in Fig. 4.6.

$log g$ and $v \sin i$ of HD 35502’s three components were then fit iteratively using various B and A star lines while recalculating the best-fitting $L_B/L_A$ for every change in the parameters. As a result of the presumed chemical peculiarities and line variability of the B star (see Section 4.5) and the limited number of lines, $\log g_B$ could not be reliably constrained using He or metal lines (e.g. Mg I and Mg II). Instead, we relied upon the wings of the strong and broad Balmer lines. In particular, H$\beta$, H$\gamma$, and H$\delta$ exhibited no significant variability which allowed for accurate continuum normalization. Several metal lines were used to constrain $v_B \sin i$ such as C II$\lambda 4267$, S II$\lambda 5640$, and Fe II$\lambda 5780$. $\log g_B$ and $v_B \sin i$ were found to be $4.3 \pm 0.1$ (cgs) and $75 \pm 5$ km s$^{-1}$, respectively. Examples of the best-fitting model spectra are shown in Fig. 4.4; the adopted range in $v_B \sin i$ is shown in Fig. 4.6.

The surface gravity and rotational broadening of the two A stars were fit simultaneously using several Fe and Mg lines. Their best-fitting $\log g$ and $v \sin i$ values were found to be $4.3 \pm 0.3$ (cgs) and $12 \pm 2$ km s$^{-1}$, respectively. Two examples of the modelled A star lines are shown in Fig. 4.5.
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Figure 4.4: Comparisons between the best-fitting synthetic (red) and observed (black) H lines, H\(\gamma\) (left) and H\(\beta\) (right). The filled blue region indicates the total uncertainty associated with log\(g_B\) and log\(g_A\).

Figure 4.5: Comparisons between best-fitting model (dark blue) and observed (black) Fe \textsc{ii} and Mg \textsc{i} lines used to constrain the surface gravity and rotational broadening of the two A stars; the light blue curves indicate the \(v_A\sin i\) and log\(g_A\) uncertainties. The phase corresponds to the maximum observed separation between the two binary components (see Fig. 4.5).
4.3.4 Hertzsprung-Russell Diagram

The masses, ages, and polar radii of HD 35502’s three stellar components may be estimated by comparing their positions on the Hertzsprung-Russell diagram (HRD) with theoretical isochrones.

Two approaches were used to determine the B star’s temperature and luminosity. The first method used \( T_{\text{eff}} = 16.3 \pm 0.6 \) kK obtained from the single star SED fitting routine. The associated luminosity was then determined by calculating the absolute bolometric magnitude, \( M_{\text{bol}} \), from the absolute visual magnitude and the bolometric correction. Based on the colour excess of \( E(B-V) = 0.14 \), we calculated a dereddened visual magnitude of \( V = 6.28 \pm 0.02 \) for the system. The bolometric correction was estimated to be \( BC = -1.49^{+0.13}_{-0.12} \) based on the calibration for effective temperatures ranging from 15.8 – 34.0 kK by Nieva (2013). Using the distance of 430 ± 120 pc
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derived from the reported parallax of $2.35 \pm 0.68 \text{mas}$ (van Leeuwen 2007), we obtain $\log L/L_\odot = 3.0 \pm 0.3$.

The second approach used the $18.4 \pm 0.6 \text{kK}$ effective temperature and $3.0 \pm 0.9 R_\odot$ radius derived from the three star SED fit in Section 4.3.2. The Stefan-Boltzmann law then yields a luminosity of $\log L/L_\odot = 3.0^{+0.4}_{-0.5}$. Similarly, the position of the A stars on the HRD can be identified using $T_{\text{eff}} = 8.9 \pm 0.3 \text{kK}$ and $R_A = 2.1 \pm 0.6 R_\odot$. We calculate an A star luminosity of $\log L/L_\odot = 1.4^{+0.4}_{-0.5}$. The HRD positions of the B and A stars using this second approach are shown in Fig. 4.7.

The masses ($M$) and polar radii ($R_p$) associated with a given $T_{\text{eff}}$ and $\log L/L_\odot$ were determined using a grid of Geneva model isochrones generated by Ekström et al. (2012). The grid consists of ages ranging from $3.16 \text{Myr}$ to $12.9 \text{Gyr}$ for masses of $0.8 - 120 M_\odot$. The turbulence velocity was fixed at $v_t = 0.0 \text{km s}^{-1}$ and a solar metallicity of $Z = 0.014$ was assumed. In the case of HD 35502’s central B star, the ratio of the angular velocity to the critical angular velocity, $\Omega/\Omega_c$, is known to be significant based on the $0.85380(4) \text{d}$ rotational period (see Section 4.6). Its position on the HRD was therefore compared against several additional grids calculated using $\Omega/\Omega_c = 0.4 - 0.9$ in increments of 0.1 (Georgy et al. 2013b). While no significant difference in the inferred $M$ was apparent (i.e. $< 4 \text{per cent}$), $R_p$ was found to decrease by as much as 15 per cent.

In order to select the most accurate grid of isochrones and thus, the most accurate $R_p$, $\Omega/\Omega_c$ must first be estimated. Since $\Omega_c$ depends on both the mass and polar radius, it was calculated using the parameters derived from each grid of isochrones. Using $P_{\text{rot}}$ inferred in Section 4.6 to determine $\Omega$, a range of $\Omega/\Omega_c$ values were found. The appropriate grid was then chosen based on whichever $\Omega/\Omega_c$ most closely agreed
with the $\Omega/\Omega_c$ associated with the isochrone grid. For the single star SED fit (i.e. $T_{\text{eff},B} = 16.3 \pm 0.6 \, \text{kK}$), a calculated $\Omega/\Omega_c$ of 0.72 yielded the best agreement; we found $R_p = 3.5^{+1.3}_{-0.8} \, R_\odot$ and $M = 5.5 \pm 0.5 \, M_\odot$ using the $\Omega/\Omega_c = 0.7$ isochrones. A lower $\Omega/\Omega_c$ of 0.53 was calculated for the three star SED fit (i.e. $T_{\text{eff},B} = 18.4 \pm 0.6 \, \text{kK}$) using $R_p = 2.8^{+1.4}_{-0.2} \, R_\odot$ and $M = 5.5^{+0.8}_{-0.7} \, M_\odot$ inferred from the $\Omega/\Omega_c = 0.5$ grid.

The two A star’s $M$ and $R_p$ were inferred using the $\Omega/\Omega_c = 0.0$ isochrone grid.
The results derived from the three star SED fit (i.e. \( T_{\text{eff},A} = 8.9 \pm 0.3 \text{kK} \)) were used yielding \( R_p = 2.0^{+1.4}_{-0.6} R_\odot \) and \( M = 2.1^{+0.4}_{-0.3} M_\odot \).

### 4.4 Magnetic field

Zeeman signatures produced by the magnetic field of HD 35502’s B star were detected in the circularly polarized (Stokes \( V \)) ESPaDOnS and Narval observations. The SNRs of these signatures were enhanced using the LSD procedure discussed in Section 4.3.1 [Donati et al., 1997; Kochukhov, Makaganiuk & Piskunov, 2010]. A master line mask containing He and metal lines was generated using data obtained from VALD [Kupka et al., 2000] with a specified \( T_{\text{eff}}, \log g, \) and \( v_t \) of 26 kK, 4.0 (cgs), and 0 km s\(^{-1}\), respectively. Removing all of the remaining A star lines from this mask effectively isolated the B star allowing its longitudinal field to be accurately determined. All Balmer lines were also removed along with any regions affected by atmospheric absorption (i.e. telluric lines). Several single element line masks were subsequently generated from this He+metal mask by retaining specific chemical elements such as He, C, Si, Fe, and Mg. Clearly, the magnitudes of \( \langle B_z \rangle \) derived using different elements will be affected by the star’s chemical abundances. Therefore, our analysis also includes measurements obtained using H lines which do not typically exhibit non-solar abundances or non-homogeneous surface distributions (i.e. chemical spots). A H mask was generated for which the strongly emissive H lines (e.g. H\( \alpha \)) were removed. The mask contained 4 H \( \text{i} \) lines: H \( \text{i} \lambda 3970 \), H \( \text{i} \lambda 4102 \), H \( \text{i} \lambda 4340 \), and H \( \text{i} \lambda 4861 \). An example of the Stokes \( I \) and \( V \) LSD profiles along with the associated diagnostic null generated using a He+metal line mask is shown in Fig. 4.8.

\( \langle B_z \rangle \) was inferred from each of the Stokes \( I \) and \( V \) LSD profiles using equation
(1) of Wade et al. (2000). We used a wavelength of 500 nm with a Landé factor of 1.2 for the He and metal mask measurements and a Landé factor of unity for the H mask measurements. For every LSD profile generated using the various line masks, we subtracted the Doppler shift of the B star produced by its radial velocity of approximately 20 km s\(^{-1}\). The Stokes \(I\) and \(V\) profiles were then normalized to the continuum intensity at \(v = -100\) km s\(^{-1}\) where the Stokes \(V\) Zeeman signature is no longer apparent. An integration range of \(v \in [-100, 100]\) km s\(^{-1}\) was then used in the calculation of \(\langle B_z \rangle\) for each of the LSD profiles constructed from He or metal lines. For \(\langle B_z \rangle\)\(_H\), we normalized to the intensity outside the Doppler core of the Balmer lines at \(v = -400\) km s\(^{-1}\); a wider integration range of \(v \in [-400, 400]\) km s\(^{-1}\) was then adopted. The \(\langle B_z \rangle\) values calculated using the He+metal line mask (\(\langle B_z \rangle\)\(_{\text{He+metal}}\)) are listed in Table 4.1 with the status of their detections as outlined by Donati et al. (1997).

The periods of each set of \(\langle B_z \rangle\) measurements calculated from the various line masks were found by first assuming a sinusoidal fit (i.e. \(\langle B_z \rangle = B_0 + B_1 \sin 2\pi t / P\) where the period is given by \(P\) and \(t\) is the observation’s HJD). A \(\chi^2\) distribution was then generated using periods ranging from 0.1 to 10.0 d in increments of approximately 1 s. All of the resulting best-fitting periods were found to be \(\lesssim 0.9\) d with associated reduced \(\chi^2\) values ranging from 0.1 – 0.9. Two of the \(\langle B_z \rangle\) sets (\(\langle B_z \rangle\)\(_N\) and \(\langle B_z \rangle\)\(_O\)) yielded periods of \(\approx 0.1\) d; however, the variability of these measurements exhibited the lowest statistical significance as a result of the relatively large uncertainties. \(\langle B_z \rangle\) obtained using the He, He+metal, C, Si, Fe, and H line masks all yielded periods of \(\approx 0.8538\) d. Only \(\langle B_z \rangle\)\(_{\text{Fe}}\) was found to have more than one period within a 3\(\sigma\) \(\chi^2\) interval of the best solution. Adopting this 0.8538 d period for all of the \(\langle B_z \rangle\)
measurements, the uncertainties of the fitting parameters ($B_0$, $B_1$, and the phase shift, $\phi_0$) were then estimated using a 1000 iteration bootstrapping analysis. Fig. 4.9 shows the phased $\langle B_z \rangle$ measurements derived from the H, He+metal, He, C, Si, and Fe line masks.

The periodic variability of $\langle B_z \rangle$ can be explained, in part, as a consequence of a stable magnetic field configuration. If we assume that the field is dominated by a dipole component, the sinusoidal variations in $\langle B_z \rangle$ imply that the dipole’s axis of symmetry is inclined by an angle (i.e. obliquity, $\beta$) with respect to the star’s rotational axis. This interpretation, first described by Stibbs (1950), is known as the Oblique Rotator Model (ORM). It provides a useful framework for describing various
properties of both the star and its magnetic field. For instance, the ORM postulates that \( \langle B_z \rangle \) is modulated by the star’s rotation thereby allowing an additional means of estimating the rotational period, \( P_{\text{rot}} \), (see Section 4.6). Moreover, the orientation of the magnetic field’s dipole with respect to the rotational axis’ inclination angle \( (i) \) can be derived; the strong variations shown in Fig. 4.9 suggest that \( i + \beta \approx 90^\circ \).

Under the assumptions of the ORM, \( \beta \) can be calculated from equation (3) of Preston (1967) which depends on \( r \equiv |\langle B_z \rangle|_{\text{min}}/|\langle B_z \rangle|_{\text{max}} \) and the inclination angle, \( i \). The latter of these dependencies can be determined using \( P_{\text{rot}} = 0.85380(4) \) d derived in Section 4.6, \( v \sin i = 75 \pm 5 \) km s\(^{-1}\) derived in Section 4.3.3, and \( R_{\text{eq}} = 3.1^{+1.8}_{-0.4} R_\odot \) derived in Section 4.7. We obtain a value of \( i = 24^{+6}_{-10}^\circ \). \( r \) is determined from the sinusoidal fitting parameters \( B_0 = -1.5 \pm 0.1 \) kG and \( B_1 = 1.7 \pm 0.1 \) kG for which 3\( \sigma \)}
Table 4.4: Obliquity angles ($\beta$) and magnetic field magnitudes of HD 35502’s dipolar components. Each set of longitudinal measurements derived using different LSD line masks yields consistent results.

<table>
<thead>
<tr>
<th>Line Mask</th>
<th>$\beta$ (°)</th>
<th>$B_d$ (kG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>$63^{+13}_{-11}$</td>
<td>$14^{+10}_{-3}$</td>
</tr>
<tr>
<td>He+metal</td>
<td>$62^{+14}_{-12}$</td>
<td>$23^{+17}_{-5}$</td>
</tr>
<tr>
<td>He</td>
<td>$64^{+12}_{-15}$</td>
<td>$23^{+20}_{-6}$</td>
</tr>
<tr>
<td>C</td>
<td>$59^{+17}_{-20}$</td>
<td>$24^{+21}_{-8}$</td>
</tr>
<tr>
<td>Si</td>
<td>$55^{+19}_{-17}$</td>
<td>$16^{+9}_{-3}$</td>
</tr>
<tr>
<td>Fe</td>
<td>$38^{+38}_{-32}$</td>
<td>$10^{+11}_{-5}$</td>
</tr>
</tbody>
</table>

uncertainties have been chosen; we then obtain $r = 0.06^{+0.08}_{-0.05}$. Finally, the obliquity angle is found to be $\beta = 63^{+13}_{-11}$°.

In addition to the obliquity, the strength of the magnetic field’s dipole component, $B_d$, can be calculated by inverting equation (1) of Preston (1967) and letting $t = 0$ correspond to $\langle B_z \rangle_{\text{max}}$. We used a linear limb darkening constant that was averaged over the values associated with the $U$, $B$, $V$, $R$, and $I$ bandpasses derived by van Hamme (1993). These specific filters were selected because of the approximate equivalent bandwidth of the ESPaDOnS and Narval wavelength range. A value of $u = 0.264$ was obtained after interpolating the published table for an effective temperature and surface gravity of 18.4 kK and 4.5 (cgs). $i$, $\beta$, and $u$ then yield $B_d = 14^{+10}_{-3}$ kG. Similar obliquity angles and dipolar field strengths are derived from $\langle B_z \rangle_{\text{H}}$, $\langle B_z \rangle_{\text{He}}$, $\langle B_z \rangle_{\text{C}}$, $\langle B_z \rangle_{\text{Si}}$, and $\langle B_z \rangle_{\text{Fe}}$. These values are listed in Table 4.4.
4.5 Emission and variability

Hot magnetic B-type stars are commonly found to exhibit spectral line variability either as a result of chemical spots (e.g. Yakunin et al., [2015]; Kochukhov et al., [2015]) or from the presence of a hot plasma beyond the stellar surface (e.g. Landstreet & Borra, 1978). Furthermore, photometric variability correlated with both of these phenomena as well as with strong, coherent magnetic fields has been previously reported (e.g. Shore et al., 1990; Oksala et al., 2010).

The HiPParCoS Epoch Photometry catalogue (Perryman et al., 1997) contains 98 observations of HD 35502 which were obtained over a period of 3.1 yrs. 3 of these measurements have multiple quality flags that were reported and were therefore removed from our analysis. The remaining measurements have an average magnitude of 7.331, a standard deviation of 0.011, and an average uncertainty of 0.009 mag. The period searching routine described in Section 4.4 was applied to the data resulting in a best-fitting period of $P_{\text{best}} = 0.8630(2)$ d with a reduced $\chi^2$ of $\chi^2_{\text{red}} = 0.97$. Multiple peaks were found in the $\chi^2$ distribution having $\Delta \chi^2 < 3\sigma$ where $\Delta \chi^2 \equiv \chi^2(P) - \chi^2(P_{\text{best}})$. A period of $0.8540(3)$ d – consistent with the majority of the periods derived from the $\langle B_z \rangle$ data sets – was found to yield the second highest quality of fit having $\chi^2_{\text{red}} = 1.05$. Comparing the sinusoidal fits associated with the 0.8630 and 0.8540 d periods with a constant model demonstrates that the variability is statistically significant. Fig. 4.10 shows the sinusoidal fit of the HiPParCoS magnitudes, $H_p$, obtained when phased by the 0.85380 d period.

The variability of the spectral lines associated with HD 35502’s central B star are most easily detected by calculating equivalent widths (EWs). We carried this out for a number lines for which no absorption produced by the two A stars was
Figure 4.10: Top: HiPParCoS observations phased by a period of 0.85380 d. Bottom: The $\chi^2$ distribution for the sinusoidal fit. Multiple peaks were found below the adopted $3\sigma$ $\chi^2$ confidence interval threshold which ranged from $\approx 0.85 - 1.23$ d.

This included H I, He I, C II, Si III, and N II lines. The EWs of the He and metal lines were calculated using integration ranges of $[-100, 100]$ km s$^{-1}$. Wider integration ranges of $[-600, 600]$ km s$^{-1}$ were adopted for H$\alpha$, H$\beta$, and H$\gamma$. The EWs for the majority of these lines were calculated by unambiguously normalizing to the continuum just outside the chosen integration ranges. In order to ensure consistent normalization amongst the Balmer line observations and to properly characterize the
Figure 4.11: Left: Dynamic spectra of various H i, He i, C ii, Si iii and N ii lines. A low-pass filter has been applied to the spectrum for aesthetic purposes. Each set of observations are compared with the average spectrum (dashed red). Right: Measured equivalent widths associated with the lines shown in the dynamic spectra plots. All of the measurements are phased by the B star’s rotational period of 0.85380 d.
emission occurring within 500 km s\(^{-1}\) of the line, the continuum flux was calculated at \(|v| \gtrsim 700\) km s\(^{-1}\). Therefore, only the differences in the Balmer line EWs rather than the absolute values are accurate. The uncertainties in the EW measurements were estimated using a bootstrapping analysis with 1000 iterations.

Each set of EWs were fit to sinusoids and various best-fitting periods were derived using the method previously applied to both the HiPParCoS photometry and the \(<B_z>\) measurements. EW variability was detected in many of the investigated lines with varying degrees of significance. The strongest variability was measured from H\(\alpha\) which yielded a minimum \(\chi^2\) solution at 0.853807(3). The amplitude of the associated sinusoidal fit was found to be 23.5 \(\pm\) 0.9 Å where the uncertainty corresponds to 3\(\sigma\). Similar variability – both in terms of the phase of maximum emission and the best-fitting period – was also detected in H\(\beta\) although, at a much lower amplitude of 5.1 \(\pm\) 0.9 Å.

Strong variability was also detected from all measured He \(\text{i}\) EWs which yielded best-fitting periods of \(\approx 0.8538\) d. For instance, the highest quality of fit found for He \(\text{i}\lambda 4713\) had a 0.85377(3) d period with an amplitude of 2.4 \(\pm\) 0.2 Å. Significantly weaker EW variability was detected from C \(\Pi\lambda 4267\) and Si \(\text{III}\lambda 4553\); however, no single best-fitting period was found for either of these two lines or for N \(\Pi\lambda 4643\) and H\(\gamma\). The EWs of all of these lines, phased by a period of 0.85380 d (see Eqn. 4.2), are shown in Fig. 4.11 along with their associated dynamic spectra. A similar plot of H\(\alpha\) is shown in Fig. 4.12.

Figures 4.11 and 4.12 demonstrate that the sinusoidal fits to the He \(\text{i}\lambda 4713\) and H\(\alpha\) EWs are in anti-phase: their minimum values occur at phases of 0.5 \(\pm\) 0.1 and 0.98 \(\pm\) 0.06, respectively. This suggests that the sources of line variability for these
two lines are independent. While the Hα (and to a lesser extent, Hβ) variability is undoubtedly produced by a plasma located beyond the stellar surface, the most probable explanation for the He I variability is the presence of He spots. Moreover, the epoch of maximum He I absorption is in phase with the maximum magnitude of the longitudinal field measurements. Assuming that the star’s magnetic field consists of a strong dipole component as discussed in Section 4.4, this suggests that the distribution of He is more concentrated near the field’s negative pole. Enhanced He abundances on the surfaces of magnetic Bp stars have been commonly reported to coincide with both the magnetic equator and magnetic poles (e.g. Bohlender & Monin, 2011; Grunhut et al., 2012; Rivinius et al., 2013; Oksala et al., 2015).

Only weak features can be discerned in the Stokes I and V LSD profiles generated using the single element $T_{\text{eff}} = 26$ kK, log $g = 4.0$ (cgs) line masks discussed in Section 4.4. While it is clear that the two cooler A stars do not contribute significantly to the He and C profiles, their narrow signatures are apparent in both the Si and Fe profiles along with the cores of the H profiles.

4.6 Rotational period

As demonstrated in Sections 4.3.1, 4.4, and 4.5, HD 35502 exhibits periodic variability in several distinct observables. Understanding which of these parameters (e.g. longitudinal field measurements, epoch photometry, and equivalent widths) are rotationally modulated is crucial in order to accurately characterize the central B star’s magnetic field and magnetosphere.

In the context of the ORM discussed in Section 4.4, consistently variable ⟨$B_z$⟩ measurements indicate the presence of a stable magnetic field configuration. This
Figure 4.12: *Top:* Dynamic spectra of the normalized Hα flux with respect to the model flux \( F_{\text{mod}} \) generated in Section 4.3.3. A low-pass filter has been applied to the spectrum in order to minimize the A star contributions and tellurics. *Bottom:* Measured equivalent widths of Hα using ESPaDOnS, Narval, FEROS, and DAO observations. Both the EWs and dynamic spectra are phased by the B star’s rotational period of 0.85380 d. The vertical dashed lines indicate the approximate velocity of maximum emission at \( v = \pm 300 \text{ km s}^{-1} \).
Figure 4.13: H, He+metal, He, C, Si, and Fe Stokes I and V LSD profiles generated from a $T_{\text{eff}} = 26$ kK, $\log g = 4.0$ (cgs) line mask. The profiles are all phased by a period of 0.85380 d.
suggests that the phased $\langle B_z \rangle$ measurements shown in Fig. 4.9 are indeed modulated by the star’s rotation. Moreover, the winds emitted by strongly magnetic B-type stars have been known to become confined within the magnetic equatorial plane (assuming an axisymmetric configuration). In this case, line emission (in particular, in H lines such as Hα) will be observed to vary in strength over the rotational period. Depending on the obliquity and inclination angles, the same phenomenon can also produce photometric variability. Specifically, if the configuration of $i$ and $\beta$ is such that the surface of the star is partially obscured, a periodic dimming will be observed. The fact that the phased HiPParCoS photometric measurements exhibit a maximum brightness at a phase of $0.6 \pm 0.2$ (i.e. approximately in phase with the minimum Hα emission) is inconsistent with this interpretation. The observed variability in $H_p$ may instead by produced by stable chemical spots redistributing flux (e.g. Peterson, 1970) and thus, also be used to infer the rotational period. However, the low amplitude of the sinusoidal fit to $H_p$ ($0.008 \pm 0.003$ mag) shown in Fig. 4.10 does not provide substantial evidence for either explanation. Moreover, the subtle variations cannot rule out non-rotationally modulated sources of brightening such as that caused by pulsations.

Along with the Balmer line emission, line variability produced by the presence of chemical spots can be used to infer $P_{\text{rot}}$. In the case of HD 35502, the variable He 1 EWs yield the strongest evidence for spots that are stable over a period $\gtrsim 5$ yrs (i.e. the period over which ESPaDOnS, Narval, and FEROS observations were obtained). Therefore, the He 1 EWs are most likely rotationally modulated and thus, strongly indicative of an approximately 0.8538 d rotational period.
CHAPTER 4. HD 35502

With multiple parameters identified as being rotationally modulated, those exhibiting the greatest statistically significant variability were used to derive $P_{\text{rot}}$. This included $\langle B_z \rangle_{\text{H}_\alpha}$, $\langle B_z \rangle_{\text{He+metal}}$, and the EWs of H$\alpha$ and He i $\lambda 4713$. The best-fitting periods associated with these parameters were averaged resulting in $P_{\text{rot}} = 0.85380(4)$ d. An ephemeris given by

$$JD = 2456295.80800 \pm 0.85380(4) \cdot E$$

was adopted where the reference JD (2456295.808(93)) corresponds to the epoch of $\langle B_z \rangle_{\text{He+metal}}$ maximum magnitude.

4.7 Magnetosphere

As described by Petit et al. (2013), various properties of a B star’s magnetosphere may be approximated by essentially comparing two parameters: the Kepler radius, $R_K$, and the Alfvén radius, $R_A$. $R_K$ is the radius at which the gravitational force is balanced by the centrifugal force of a rigidly-rotating star while $R_A$ characterizes the point within which the magnetic field dominates over the wind (ud-Doula & Owocki, 2002). Their ratio, $R_A/R_K$, can therefore be used to define a magnetosphere as either dynamical ($R_A/R_K < 1$) or centrifugal ($R_A/R_K > 1$). It also serves as an indicator of the volume of the magnetosphere: those stars having comparatively larger $R_A/R_K$ will be capable of confining the emitted wind at larger radii. Furthermore, since a stronger field would be capable of confining more mass, a correlation between the Alfvén radius and the magnetosphere’s density may be expected.

The maximum emission observed in HD 35502’s spectrum occurs at velocities of
approximately ±350 km s\(^{-1}\) (e.g. see Fig. 4.12). This indicates that a region of hot plasma surrounds the central B star at a distance of \(\approx 2\) times the star’s radius. Similar examples of magnetic B-type stars producing H emission well beyond the stellar radius (at distances of \(\approx 2 R_\ast\) and as high as \(\approx 4 R_\ast\)) have been previously discovered (e.g. Bohlender & Monin 2011; Oksala et al. 2012; Grunhut et al. 2012). In each of these cases, the star’s Alfén radius exceeds its Kepler radius by approximately an order of magnitude (Petit et al. 2013; Shultz et al. 2014).

Using the mass and rotational period of HD 35502’s B star, we find a Kepler radius of \(R_K = 2.2^{+0.3}_{-0.8} R_\ast\) where \(R_\ast\) is the stellar radius at the magnetic equator which we approximate using \(R_{eq}\). The Alvén radius is estimated using equation (9) of ud-Doula, Owocki & Townsend (2008) for a dipole magnetic field \((q = 3)\). This expression requires the calculation of the wind confinement parameter, \(\eta_\ast\), which in turn depends on the dipole magnetic field strength, the equatorial radius, the terminal wind speed \((V_\infty)\), and the wind mass loss rate in the absence of a magnetic field \((\dot{M}_{B=0})\). Following the recipe outlined by Vink, de Koter & Lamers (2000), \(\dot{M}_{B=0}\) and \(V_\infty\) are derived for a B star having \(12.5 < T_{\text{eff}} \leq 22.5\) kK using \(V_\infty/V_{\text{esc}} = 1.3\) where \(V_{\text{esc}}\) is the escape velocity. We obtain \(\dot{M}_{B=0} = (1.3^{+6.8}_{-1.0}) \times 10^{-10} M_\odot/\text{yr}\) and \(V_\infty = 250^{+20}_{-50}\) km s\(^{-1}\). Finally, \(\eta_\ast\) is found to be \((1.2^{+5.0}_{-0.6}) \times 10^7\) using the value of \(B_d\) derived from \(\langle B \rangle_H\) which then yields \(R_A = 59^{+30}_{-9} R_\ast\). The magnetospheric parameters associated with both the H and He+metal longitudinal field measurements derived in Section 4.4 are listed in Table 4.5.

The magnetic confinement-rotation diagram compiled by Petit et al. (2013) allows these parameters to be understood within the broader context of all known O and B stars which host magnetospheres. Our characterization of the magnetosphere hosted
Table 4.5: Magnetospheric parameters derived from $\langle B_z \rangle_H$ and $\langle B_z \rangle_{\text{He+metal}}$ measurements.

<table>
<thead>
<tr>
<th></th>
<th>H</th>
<th>He+metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i$ (°)</td>
<td>$24^{+6}_{-10}$</td>
<td>$24^{+6}_{-10}$</td>
</tr>
<tr>
<td>$\beta$ (°)</td>
<td>$63^{+13}_{-11}$</td>
<td>$64^{+12}_{-15}$</td>
</tr>
<tr>
<td>$B_d$ (kG)</td>
<td>$14^{+10}_{-3}$</td>
<td>$23^{+20}_{-6}$</td>
</tr>
<tr>
<td>$\dot{M}<em>{B=0}$ ($M</em>\odot/\text{yr}^{-1}$)</td>
<td>$(1.3^{+6.8}_{-1.0}) \times 10^{-10}$</td>
<td>$(1.3^{+6.8}_{-1.0}) \times 10^{-10}$</td>
</tr>
<tr>
<td>$V_\infty$ (km/s)</td>
<td>$250^{+20}_{-60}$</td>
<td>$250^{+20}_{-50}$</td>
</tr>
<tr>
<td>$\eta_*$</td>
<td>$(1.2^{+5.0}_{-0.6}) \times 10^7$</td>
<td>$(3.2^{+8.6}_{-1.5}) \times 10^7$</td>
</tr>
<tr>
<td>$R_A$ ($R_\ast$)</td>
<td>$59^{+30}_{-9}$</td>
<td>$75^{+29}_{-11}$</td>
</tr>
<tr>
<td>$R_K$ ($R_\ast$)</td>
<td>$2.2^{+0.3}_{-0.8}$</td>
<td>$2.2^{+0.3}_{-0.8}$</td>
</tr>
<tr>
<td>$R_A/R_K$</td>
<td>$27^{+36}_{-7}$</td>
<td>$34^{+39}_{-8}$</td>
</tr>
</tbody>
</table>

by HD 35502’s B star suggest that it is well within the centrifugal magnetosphere regime. Indeed, only two other stars have been discovered exhibiting similar $R_A$ and $R_K$ values within the derived $R_A > 40 R_\ast$ (a conservative lower limit obtained using the $\langle B_z \rangle_{\text{Fe}}$ measurements) and $1.4 \leq R_K \leq 2.5 R_\ast$. Although approximately four other stars have lower limits of $R_A$ and $R_K$ that are consistent with HD 35502’s, only HD 182180 ([Rivinius et al.] 2013) and HD 142184 ([Grunhut et al.] 2012) have reported upper and lower uncertainties. These two examples have similar effective temperatures, surface gravities, radii, and masses to HD 35502. However, HD 182180 and HD 142184 are slightly faster rotators ($P_{\text{rot}} \approx 0.5 \text{ d}$) and host magnetic fields with weaker dipolar components ($B_p \approx 10 \text{ kG}$).
Chapter 5

Summary and Conclusions

5.1 Summary

In this thesis we have analyzed the properties of the B3IV star HD 23478 and the triple system HD 35502 containing a B5IVsnp star; both of these hot magnetic stars were recently discovered to host extreme centrifugal magnetospheres. We derived the effective temperatures, surface gravities, masses, radii, luminosities, and rotational periods of these stars. The effective temperatures and surface gravities were derived through a combination of fitting model spectral energy distributions and model spectral lines to photometric and spectroscopic data sets. The masses, radii, and approximate ages of these two stars were found by comparing their positions on the Hertzsprung-Russell Diagram with theoretical isochrones.

We derived the rotational periods by investigating the variability exhibited by a number of properties. For HD 23478, the rotational period was derived using the variability of photometric measurements. On the other hand, HD 35502 did not exhibit significant photometric variations. We found that the equivalent widths measured
from various spectral lines did, however, exhibit strong variability. In conjunction with the significant variations in the longitudinal magnetic field measurements, we were able to derive a consistent rotational period.

We analyzed high-resolution spectropolarimetric measurements of both HD 23478 and HD35502. These measurements were used to derive the polar strengths and the obliquity angles associated with the dipolar components of each stars' magnetic field. Our results allowed the magnetospheres to be characterized in terms of the derived Kepler and Alfvén radii.

5.2 Conclusions

Based on our analysis, we draw the following conclusions regarding HD 23478:

1. it is a main sequence magnetic He-strong star \( T_{\text{eff}} = 20 \pm 2 \text{kK} \) exhibiting peculiar line strengths and distorted line profiles of He, Si, and Fe, indicating likely nonuniform surface distributions of these elements;

2. the \( 1.0498(4) \text{d} \) period found in HiPParCoS epoch photometry is most likely the star’s rotational period which confirms the earlier findings of Jerzykiewicz (1993);

3. the presence of strong H\( \alpha \) emission is consistent with the discovery by Eikenberry et al. (2014) of emission in H\( \alpha \) and nIR H lines. This emission forms a double peaked profile separated by \( v \approx 960 \text{km s}^{-1} \) which likely originates from plasma located at a distance of \( R > 3 R_* \). We observe significant variability in H\( \alpha \) and in various He lines. Measured EWs of these lines are coherently phased by \( P_{\text{rot}} = 1.0498 \text{d} \);
4. the surface magnetic field is inferred to have an important dipole component, with a minimum polar strength 9.5 kG, nearly aligned with the star’s rotation axis.

Our results unambiguously imply the presence of a centrifugally supported, magnetically confined plasma around HD 23478, and therefore confirm the hypothesis of Eikenberry et al. (2014) that it is a member of the growing class of magnetic B stars hosting centrifugal magnetospheres.

Our analysis yielded a non-negligible discrepancy in the determination of the star’s effective temperature. IUE spectra used in the SED modelling imply $T_{\text{eff}} = 22$ kK while the observed Balmer lines require a lower temperature of 18 kK to provide the best fit. Chemical peculiarities, line profile distortions, and relatively weak and scarce metal lines prevent this ambiguity from being confidently resolved within the scope of the present study.

The low inferred obliquity angle of $\beta \leq 16^\circ$ paired with the high $69^{+21}_{-10}^\circ$ inclination angle introduce basic uncertainties in modelling the star’s magnetic field and magnetosphere. Consequently, only lower limits on the Alfvén to Kepler radius ratio and the magnetic field’s dipole component were obtained. We find that the derived $R_A/R_K \geq 4.1$ and $B_d \geq 9.5$ kG place HD 23478 within the more extreme subset of stars hosting centrifugal magnetospheres.

In the case of HD 35502, our analysis presents a number of new discoveries regarding the nature of this system. The high-resolution spectroscopic and spectropolarimetric observations obtained using ESPaDOnS, Narval, and FEROS indicate that it is an SB3 system containing a central magnetic B-type star and two cooler A-type stars, all of which lie on the main sequence. Based on radial velocity measurements,
we find that the two A stars form a binary system with an orbital period of 5.6686(2) d. No radial velocity variations in the B star were detected over the 5.3 year observing period suggesting that the binary orbits about the central B star over a significantly longer period. We confirm that HD 35502’s speckle companion reported by Balega et al. (2012) is indeed the A star binary system.

We draw the following results for the two A stars found within HD 35502’s triple system:

1. they are nearly physically identical with a mass ratio of 1.05, effective temperatures of 8.9 kK, and masses of 2.1 $M_\odot$;

2. no Stokes $V$ Zeeman signal was detected from either A star’s spectral lines indicating longitudinal magnetic fields strengths with upper limits of $\langle B_z \rangle \lesssim 25$ G;

3. while no chemical abundance analysis was carried out, the spectral lines were accurately fit using LTE models with solar abundances suggesting the stars are not chemically peculiar.

Our analysis of HD 35502’s central B star revealed the following:

1. it has an effective temperature of 18.4 kK, a mass of 5.7 $M_\odot$, and a polar radius of 3.0 $R_\odot$;

2. it rotates relatively rapidly with a rotational period of 0.85380(4) d;

3. we detect a strong magnetic field and derive the magnitude of its dipolar component $(B_d \approx 14$ kG);

4. it exhibits significant line variability in the form of emission and chemical spots.

The emission is predominantly observed in Hα at a distance of approximately twice
the stellar radius. Strong He abundance variations indicate a higher concentration near the negative pole of the magnetic field’s dipole component;

5. we derive Alfvén and Kepler radii of $R_A \approx 59 R_\ast$ and $R_K \approx 2.2 R_\ast$ indicating that HD 35502’s B star hosts one of the most extreme cases of a centrifugally supported magnetosphere currently known.

HD 35502’s large $R_A$ implies that this star likely hosts the largest magnetospheric volume yet reported in the known population of hot magnetic stars.

The positions of HD 23478 and HD 35502 (i.e. the primary component) on the magnetic confinement-rotation diagram are shown in Fig. 5.1. It is evident that, like HD 23478 and HD 35502, the majority of the stars in this region exhibit Hα emission in their spectrum. The strength of this emission can be compared by measuring the Hα equivalent widths at maximum and minimum emission epochs. We find that the stars in this study exhibit ratios of the minimum to maximum emission EWs of approximately 0.4 and 0.6 for HD 23478 and HD 35502, respectively, while σ Ori E yields a significantly lower value of $\approx 0.1$. This may be a result of σ Ori E’s reported higher effective temperature of 23 kK which would be expected to produce a higher density wind. This interpretation is also consistent with the properties of the two most rapidly rotating B-type stars, HR 5907 (Grunhut et al. 2012) and HR 7355 (Rivinius et al. 2013), which exhibit similar values of $T_{\text{eff}}$ and Hα emission strength to that of HD 23478 and HD 35502.

Our results also suggest that the strength of Hα emission may be anti-correlated with the magnitude of the magnetic field. HD 35502 exhibits the largest dipolar field strength amongst the extreme CM hosts and also the minimum emission strength. Conversely, σ Ori E produces the largest amount of Hα emission and exhibits a
CHAPTER 5. SUMMARY AND CONCLUSIONS

Figure 5.1: Magnetic confinement-rotation diagram reproduced by M. Shultz using values (other than HD 23478 and HD 35502) published by (Petit et al., 2013). HD 23478 corresponds to the red, filled diamond where the arrow indicates that $R_A = 21 R_\ast$ is a lower limit. HD 35502’s B star corresponds to the red, filled triangle. $\eta_\ast$ is the wind magnetic confinement parameter and $W$ is the ratio of the equatorial rotational to orbital velocities.
weaker field. This is also reflected in the derived Alfvén radii which tend to increase with decreasing $H_\alpha$ emission. Since the Alfvén radius characterizes the volume of the magnetosphere and thus, the size of the region which may potentially accumulate plasma, one might expect to observe an increase in emission with $R_A$. However, an increase in $R_A$ may not result in an increase in the confined plasma mass but instead, simply reduce the magnetospheric density thereby yielding weaker emission. This scenario suggests there may be a mechanism which limits the total mass of the confined plasma. Regardless of the most plausible explanation, it is clear that in order to draw any significant conclusions from these results, a larger more precisely characterized sample is required.

5.3 Future Work

Given the extreme nature of the stellar magnetospheres discussed in this work, HD 23478 and HD 35502 serve as useful diagnostics to test the limits of the current theoretical models. For example, a detailed analysis of $\sigma$ Ori E (which has an $R_A/R_K$ of $\approx 15$, Petit et al., 2013) was recently carried out by Oksala et al. (2012, 2015) in order to identify any failings of the Rigidly-rotating Magnetosphere (RRM) model (Townsend & Owocki, 2005). Currently, this is the only in-depth comparison between the observations of centrifugal magnetospheres and the theoretical models developed to physically describe these systems that has been carried out. Similar studies of stars which exhibit greater emission, faster rotation, or stronger magnetic fields may provide additional insight of ways in which our current theoretical framework must be modified.

Although our results qualitatively agree with the RRM model, a more detailed
analysis of HD 23478 and HD 35502 is required in order to identify more subtle discrepancies. Moreover, several important yet intensive analyses are not presented in this study. For instance, we did not carry out an analysis of the chemical abundances of these stars. This would require the accurate modelling of the spectral lines produced by various elements. In the case of HD 23478, various anomalous features in the observed spectra imposed challenges which we considered to be beyond the scope of this study. For instance, sharp absorption lines present throughout the spectra were identified as diffuse interstellar bands and therefore, were not associated with the star’s atmosphere. Care would be required in order to avoid instances in which these lines were potentially blended with the stellar absorption lines. Furthermore, very few strong metal lines could be clearly identified; higher quality data would need to be obtained in order to determine the depths (and thus, the abundances) of nearly all elements heavier than He.

We also encountered various difficulties when modelling the spectral lines of HD 35502. The lines produced by the two A stars were found to be prevalent throughout the observed spectrum. Therefore, most lines associated with the primary component were contaminated by absorption from the A stars; any errors in modelling the spectrum of the A stars would likely affect the inferred depths of the B lines as well. More importantly, the total normalized flux of the triple system depends on the luminosities of each of the three stellar components. Although the effect of rotational broadening can be accurately derived without precisely constraining this additional parameter, the line depths cannot. In order to accurately measure any chemical anomalies in the stars composing HD 35502, their luminosities would likely need to be constrained more precisely than was done in this study.
Stars hosting strongly emitting centrifugal magnetospheres can provide useful insights towards our understanding of both stellar winds and stellar magnetism. Therefore, it is important that these rare systems be studied in detail. While this particular class of magnetic stars is certainly growing, the number of confirmed examples are still insufficient to solve various outstanding issues. For instance, the inferred densities of CM-hosting stars are largely inconsistent with currently predicted values (e.g. Rivinius et al., 2013; Shultz et al., 2014). Moreover, testing the validity of theoretical models describing the physical nature of these magnetospheres (e.g. the Rigidly-rotating Magnetosphere model derived by Townsend & Owocki, 2005) requires detailed comparisons with a diversity of observations such as those recently carried out by Oksala et al. (2012, 2015).
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## Appendix A

### Abbreviations

Table A.1: Abbreviations used throughout this work.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>APOGEE</td>
<td>Apache Point Observatory Galactic Evolution Experiment</td>
</tr>
<tr>
<td>BinaMiCS</td>
<td>Binarity and Magnetic Interactions in various classes of Stars</td>
</tr>
<tr>
<td>CFHT</td>
<td>Canada-France-Hawaii Telescope</td>
</tr>
<tr>
<td>CM</td>
<td>centrifugal magnetosphere</td>
</tr>
<tr>
<td>DAO</td>
<td>Dominion Astronomical Observatory</td>
</tr>
<tr>
<td>DD</td>
<td>definite detection</td>
</tr>
<tr>
<td>DM</td>
<td>dynamical magnetosphere</td>
</tr>
<tr>
<td>DIB</td>
<td>diffuse interstellar band</td>
</tr>
<tr>
<td>EW</td>
<td>equivalent width</td>
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<tr>
<td>ESO</td>
<td>European Southern Observatory</td>
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<tr>
<td>HAeBe</td>
<td>Herbig Ae/Be</td>
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<td>HJD</td>
<td>Heliocentric Julian Date</td>
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<td>HRD</td>
<td>Hertzsprung-Russell diagram</td>
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<tr>
<td>LTE</td>
<td>local thermodynamic equilibrium</td>
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### Table A.1 – continued from previous page

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>LSD</td>
<td>least squares deconvolution</td>
</tr>
<tr>
<td>MCMC</td>
<td>Markov Chain Monte Carlo</td>
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<td>MCR</td>
<td>magnetic confinement-rotation</td>
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<td>MD</td>
<td>marginal detection</td>
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<td>MiMeS</td>
<td>Magnetism in Massive Stars</td>
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<td>MS</td>
<td>main sequence</td>
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<td>nIR</td>
<td>near-infrared</td>
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<td>NLTE</td>
<td>non-local thermodynamic equilibrium</td>
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<tr>
<td>ND</td>
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<td>ODF</td>
<td>opacity distribution function</td>
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<td>ORM</td>
<td>Oblique Rotator Model</td>
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<td>IUE</td>
<td>International Ultraviolet Explorer</td>
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<td>RMS</td>
<td>root mean square</td>
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<td>RRM</td>
<td>Rigidly-Rotating Magnetosphere</td>
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<td>SED</td>
<td>synthetic energy distribution</td>
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<td>SNR</td>
<td>signal-to-noise ratio</td>
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<td>TAMS</td>
<td>terminal age main sequence</td>
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<td>TBL</td>
<td>Télescope Bernard Lyot</td>
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<td>UV</td>
<td>ultraviolet</td>
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<td>VALD</td>
<td>Vienna Atomic Line Database</td>
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<td>zero age main sequence</td>
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