Confirming HD 23478 as a new magnetic B star hosting an Hα-bright centrifugal magnetosphere

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ABSTRACT

In this paper we report 23 magnetic field measurements of the B3IV star HD 23478: 12 obtained from high resolution Stokes V spectra using the ESPaDOnS (CFHT) and Narval (TBL) spectropolarimeters, and 11 from medium resolution Stokes V spectra obtained with the DimaPol spectropolarimeter (DAO). HD 23478 was one of two rapidly rotating stars identified as potential “centrifugal magnetosphere” hosts based on IR observations from the Apache Point Observatory Galactic Evolution Experiment survey. We derive basic physical properties of this star including its mass ($M = 6.1^{+0.8}_{-0.7} M_\odot$), effective temperature ($T_{\text{eff}} = 20 \pm 2$ kK), radius ($R = 2.7^{+1.6}_{-0.9} R_\odot$), and age ($\tau_{\text{age}} = 3^{+37}_{-1}$ Myr). We repeatedly detect weakly-variable Zeeman signatures in metal, He and H lines in all our observations corresponding to a longitudinal magnetic field of $\langle B_z \rangle \approx -2.0$ kG. The rotational period is inferred from Hipparcos photometry ($P_{\text{rot}} = 1.0498(4)$ d). Under the assumption of the Oblique Rotator Model, our observations yield a surface dipole magnetic field of strength $B_d \geq 9.5$ kG that is approximately aligned with the stellar rotation axis. We confirm the presence of strong and broad Hα emission and gauge the volume of this star’s centrifugal magnetosphere to be consistent with those of other Hα emitting centrifugal magnetosphere stars based on the large inferred Alfvén to Kepler radius ratio.

Key words: Stars: early-type, Stars: magnetic fields, Stars: individual: HD 23478

1 INTRODUCTION

Upon the first detection of its magnetic field, the strong, broad, and variable Hα emission line of the main sequence
Table 1. Observations of HD 23478 obtained with ESPaDOnS and Narval. The phases are calculated using Eqn. [1]. SNRs per 1.8 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).

| HJD       | Phase | Total Exp. Time [s] | SNR [px$^{-1}$] | Instrument   | $\langle B_z \rangle_{H_{\beta}}$ [kG] | $\langle B_z \rangle_{He^{+}-metal}$ [kG] | Detection Status |
|-----------|-------|---------------------|-----------------|--------------|-------------------------------------|----------------------------------------|-----------------|
| 2456884.116 | 0.304 | 560                 | 473             | ESPaDOnS     | $-1.52 \pm 0.27$                    | $-1.98 \pm 0.25$                      | DD              |
| 2456908.146 | 0.194 | 560                 | 500             | ESPaDOnS     | $-1.68 \pm 0.24$                    | $-2.15 \pm 0.22$                      | DD              |
| 2456909.139 | 0.135 | 560                 | 381             | ESPaDOnS     | $-1.42 \pm 0.32$                    | $-2.33 \pm 0.29$                      | DD              |
| 2456909.144 | 0.145 | 560                 | 346             | ESPaDOnS     | $-1.89 \pm 0.29$                    | $-2.26 \pm 0.26$                      | DD              |
| 2456925.512 | 0.736 | 1200                | 402             | Narval       | $-2.19 \pm 0.37$                    | $-1.98 \pm 0.36$                      | DD              |
| 2456926.691 | 0.907 | 1200                | 291             | Narval       | $-2.62 \pm 0.28$                    | $-2.49 \pm 0.30$                      | DD              |
| 2456962.025 | 0.517 | 560                 | 409             | ESPaDOnS     | $-0.95 \pm 0.34$                    | $-1.93 \pm 0.26$                      | DD              |
| 2456968.937 | 0.101 | 560                 | 409             | ESPaDOnS     | $-2.13 \pm 0.31$                    | $-2.44 \pm 0.27$                      | DD              |
| 2456972.833 | 0.813 | 560                 | 353             | ESPaDOnS     | $-1.94 \pm 0.39$                    | $-2.52 \pm 0.37$                      | DD              |
| 2456972.842 | 0.822 | 560                 | 352             | ESPaDOnS     | $-2.98 \pm 0.41$                    | $-2.84 \pm 0.37$                      | DD              |
| 2456973.099 | 0.066 | 560                 | 497             | ESPaDOnS     | $-2.05 \pm 0.27$                    | $-2.11 \pm 0.22$                      | DD              |
| 2457034.695 | 0.740 | 560                 | 461             | ESPaDOnS     | $-1.63 \pm 0.29$                    | $-1.99 \pm 0.27$                      | DD              |

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 of a plasma co-rotating with the star well beyond its surface σ Ori E was 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 these correlations between rotation and the presence of magnetic fields, Eikenberry et al. (2014) concluded that the presence of a magnetic field in the brightest of these two α 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 Ho emitting CM stars. In Section 2 we describe the spectropolarimetric observations used in this study. In Section 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 4 the variability in Hipparcos epoch photometry in an attempt to infer the star’s rotational period. In Section 5 we compute the longitudinal magnetic field and search for its variability. Section 6 discusses the spectral line emission and variability. In Section 7 we derive the stellar magnetospheric parameters. Finally, in Section 8 we evaluate our hypothesis for a CM origin of HD 23478’s emission.

2 OBSERVATIONS

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 ≃ 65 000 acquiring spectra in circularly polarized light spanning the visible range of 3600 – 10 000 Å. The Heliocentric Julian Dates (HJDs), exposure times, and signal-to-noise ratios (SNRs) of these observations are listed in Table 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

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Table 2. Observations of HD 23478 obtained with dimaPol. The phases are calculated using Eqn. 6 and the magnetic field measurements correspond to the longitudinal field derived from Hβ Stokes V observations.

| HJD       | Phase | Total Exp. Time [s] | SNR [pix$^{-1}$] | (B$_{\|}$)$_{H\beta}$ [kG] |
|-----------|-------|---------------------|------------------|-----------------------------|
| 2456680.700 | 0.357 | 5400                | 300              | $-1.78 \pm 0.56$           |
| 2456681.630 | 0.422 | 3000                | 250              | $-0.92 \pm 0.72$           |
| 2456683.731 | 0.146 | 4400                | 440              | $-1.62 \pm 0.27$           |
| 2456971.888 | 0.911 | 4800                | 400              | $-2.88 \pm 0.36$           |
| 2456972.802 | 0.782 | 4800                | 520              | $-1.82 \pm 0.26$           |
| 2456973.758 | 0.693 | 4800                | 430              | $-1.29 \pm 0.41$           |
| 2456974.846 | 0.731 | 4800                | 410              | $-1.37 \pm 0.38$           |
| 2456976.032 | 0.859 | 4800                | 400              | $-2.08 \pm 0.29$           |
| 2456991.962 | 0.033 | 4800                | 480              | $-1.95 \pm 0.30$           |
| 2456992.711 | 0.748 | 4800                | 310              | $-1.86 \pm 0.49$           |
| 2457085.723 | 0.347 | 4800                | 550              | $-1.11 \pm 0.33$           |

with Narval during a single night using a total exposure time of 1200 s.

2.2 Medium resolution Hβ 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 Å [Monin et al. 2012]. The HJDs, exposure times, SNRs, and longitudinal magnetic field measurements derived from Hβ Stokes V profiles are listed in Table 2.

3 PHYSICAL PARAMETERS

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 monochromatic 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 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 $\gtrsim 0.002$ 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 3.
Table 3. Stellar parameters of HD 23478.

| Parameter | Value |
|-----------|-------|
| Sp. Type  | B3IV  |
| π [mas]   | 4.99 ± 0.62 |
| d [pc]    | 200±29−22 |
| Photometric |       |
| V [mag]   | 6.67±0.07 |
| E(B − V) [mag] | 0.30±0.04 |
| BC [mag]  | −1.97±0.24 |
| Mv [mag]  | −0.77±0.26 |
| Mbol [mag] | −2.74±0.58 |
| Physical  |       |
| Teff [kK] | 20 ± 2 |
| log(g) [cgs] | 4.2 ± 0.2 |
| vsini [km s−1] | 140 ± 10 |
| log(L/L⊙) | 3.0 ± 0.2 |
| M/M⊙    | 6.1±0.7 |
| R/R⊙    | 2.7±1.6 |
| τage [Myr] | 3±3.7 |
| Prot [d] | 1.0498 ± 0.0004 |
| v sin i [km s−1] | 17 ± 5 |

Table references: (1) Blaauw & van Albada (1963), (2) van Leeuwen (2007), (3) Syglet, Hardie & Grenchik (1969), (4) Harris (1996).

R = (1150 Å)/(3 Å) ≃ 380 to match the 3 Å UVE bin-width at λ = 1150 Å. Theoretical monochromatic fluxes were calculated by convolving Johnson UBV and 2MASS JHKs transmission functions (Landolt & Uomoto 2007; Cohen, van Leeuwen & Wheaton & Megeath 2003) with the unbroaded model spectra.

The best fitting NLTE model, shown in Fig. 1, was found to have an effective temperature, surface gravity, and colour excess of T eff = 22.00 kK, log g = 4.60 (cgs), and E(B − V) = 0.35 yielding a reduced χ^2 value of 1.70. The monochromatic fluxes were found to be adequately reproduced by a wide range of Teff, 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 Teff ≲ 20 kK and Teff ≥ 24 kK at 2,000 ≤ λ ≤ 2,500 Å. This is clearly a consequence of the respectively lower and higher values of the required extinction associated with these models. In Fig. 2, we show the LWP spectrum dereddened in order to fit models of 18, 20, 22, and 24 kK. The 2,000 − 2,500 Å region shows growing discrepancies for the lower and higher temperatures. This leads us to prefer Teff = 22 kK based on the SED fitting.

3.2 Spectral line fitting

Spectral line fitting can provide a further constraint on T eff and log g through comparisons between the obtained ESPaDOnS and Narval spectra and synthetic model 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 ≈ 4.5.

We also noticed that many line profiles were distorted. Sharp asymmetric features having depths ≲ 10% of the continuum are prevalent in many spectral orders (Fig. 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 DIB features (e.g. Walker, Bohlender & Krelowski 2000).

In addition to the DIB features, many metal lines show peculiar strengths and 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 constraint on Teff and log g because they are more weakly influenced by abundance nonuniformities. Specifically, Hγ and Hδ were chosen because 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 SYNSPEC, the IDL wrapper for SYNTHETIC (Hubeny & Lanz 2011), along with NLTE TLUSTY model atmospheres (Lanz & Hubeny 2007). The grid was linearly interpolated such that a finer resolution of δTeff = 250 K and δ 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 δv ≈ 4.6 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 [He/Hi] = −0.58 required to fit a sample of averaged He lines (where [He/Hi]⊙ = −1.01; Grevesse, Noels & Sauval 1996).

As shown in Fig. 4, the best effective temperature according to the SED fitting (22 kK) reproduces the Balmer
Figure 4. Comparisons between TLUSTY models (blue) and the averaged observed spectrum (black) for Hδ (left) and Hγ (right). The bottom frames show the residuals between the observations and the synthetic spectra (F_{obs} − F_{syn}).

Figure 5. T_{eff} = 22 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 ii λ5056 and Fe ii λ5169 lines are visible at 5055 Å and 5170.5 Å.

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.

3.2.1 Rotational broadening

To estimate the rotational broadening, we compared observed phase-averaged He and metal profiles with synthetic profiles computed assuming T_{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. 5. The inclusion of either macroturbulent or microturbulent broadening did

line wings reasonably well with log g = 4.4. However, the core depths are seriously underestimated by the model. By reducing T_{eff}, good agreement between the observed and computed wings and core is achieved for T_{eff} = 18 kK and log g = 4.0.

We therefore find that the Balmer lines and SED yield higher E(B − V) = 0.35 is required. As was expected, T_{eff} was indeed found to be closely coupled with the colour excess.

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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 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 $V = 5.62_{-0.07}^{+0.05}$ mag where the color excess of $E(B - V) = 0.30$ discussed in Section 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 $15 < Z < 30$ discussed in Section 3.2. 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 $v_{\text{rot}}/v_{\chi}$ = 0.4 (Georgy et al. 2013) 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. 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 $T_{\text{eff}}$ imply a range in the estimated age and radius for the star of $\tau = 3_{-1}^{+3}$ Myr and $R = 2.8_{-0.2}^{+1.3}$, $R_\odot$, respectively. Likewise, the main sequence mass of HD 23478 is estimated to be $M = 6.1_{-0.7}^{+0.8}$ $M_\odot$. A similar radius of $R = 2.7_{-0.6}^{+1.9}$, $R_\odot$ 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 $\log g = 4.3_{-0.4}^{+0.5}$ which is consistent with the value derived from the spectral line fitting procedure described in Section 5.2.

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 measurements between the FAST and NDAC Data Reduction Consortia. Furthermore, one observation reports a magnitude that is $2(\sigma_{\chi_{\nu}})$ larger than $(H_{\nu})$ 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 $\Delta P < 5$ days.

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 $P_{\text{rot}} = 1.0498$ d. The Hipparcos measurements phased at this best-fitting period are shown in Fig. 7 along with a subsample of the full periodogram centered on $P_{\text{rot}} = 1.0498$ d.

Assuming a $3\sigma$ confidence limit corresponding to an uncertainty of $\delta P = 0.0004$ d, we find that only one other period has a $\chi^2$ value below this threshold at $P = 1.02454$ d where the $\chi^2$ peak is shown in Fig. 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

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

where the reference JD (2448700.606) corresponds to the epoch of $H_{\nu}$ maximum.
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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 ± 0.05 and 0.50 ± 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 ~ 0.5 – 5.0 d and can be conclusively identified by the presence of multiperiodicity [Waelkens 1991]. Jerzykiewicz (1993) noted that g-mode pulsations could potentially explain 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 \( \gtrsim 5 \text{ km s}^{-1} \).

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 \( i = 69^{\pm 21}_{\circ} \) where the uncertainty is propagated from the 3\( \sigma \) value of \( \delta P_{\text{rot}} = 0.0004 \) 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 (McNally 1965). Therefore, in agreement with Jerzykiewicz (1993), we conclude that the observed Hipparcos photometric variations are mostly likely generated by the star’s rotation.

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 [Donati et al. 1997; 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 (\( \nu_{\text{mic}} \)) obtained from the Vienna Atomic Line Database.
(VALD2) (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. Pyper 1969; Bohlender et al. 1987; Yakunin et al. 2015). 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 uncertainty. 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. 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. 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 \( v \in (-140, 170) \) km s\(^{-1}\) was used. The values of \( \langle B_z \rangle \) derived from the He+metal mask are reported in Table 1. We phased these measurements according to the photometric period of Eqn. (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. 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 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 1 and the DAO measurements are listed in Table 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. 9).

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 \( \beta \) (Stiles 1950). Assuming that HD 23478’s magnetic field is characterized by an important dipole component, as typically observed in hot stars, the faint variability observed in the \( \langle B_z \rangle \) measurements shown in Fig. 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 \( i = 69_{-31}^{+21} \) calculated in Section 3. Weak variability would also be observed if the star’s rotational period is on the order of the observing timescale of \( \tau_{\text{obs}} \approx 30 \) 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 $\langle B_z \rangle$He+metal shown in Fig. 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 $\beta = 3^\circ \pm 4^\circ$. A similar value of $8^\circ \pm 8^\circ$ was found for $\langle B_z \rangle$Hβ.

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 $\langle B_z \rangle_{\text{He+metal}} = 2.4 \pm 0.2$ kG as given by the sinusoidal fit to $\langle B_z \rangle$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 $\beta \rightarrow 0^\circ$ and $i \rightarrow 90^\circ$. 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 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.

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 Hα line. Fig. 10 shows the minimum and maximum emission observed at phases of 0.740 and 0.516 and variable at all phases forming a double peak with a separation of approximately ±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. 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 $R \geq 3R_\odot$.

Although Hα 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 photometric period. This is demonstrated by the equivalent width (EW) measurements shown in Fig. 11 and the overplotted line profiles shown in Fig. 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 λ4713 and He I λ5876 shown in Fig. 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, Hα and the He lines do not vary coherently when phased by the other candidate 1.02454 d rotational period discussed in Section 4. This provides further evidence in support of a 1.0498 d rotational period.

The maximum and minimum Hα EWs occur at phases 0.39 ± 0.05 and 0.89 ± 0.05, respectively. These values are approximately in phase with both the Hipparcos photometry and the $\langle B_z \rangle$ measurements. The He I λ5876 and He I λ4713 EW measurements are in mutual agreement and have maximum and minimum values at 0.76 ± 0.06 and 0.26 ± 0.06. They are shifted in phase relative to $H_\beta$ and $\langle B_z \rangle$ by 0.24 ± 0.08, i.e. one-quarter of one cycle.

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 ($\eta_4$) which depends on the equatorial magnetic field magnitude ($B_{\text{eq}}$), 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 un-
ties on the H\textsc{$\beta$} and find the results to be consistent. The larger uncertainty derived by Petit et al. (2013), we calculate \( \eta \) using the calibration for \( \dot{M}_{\text{B}-0} \) derived by Vink, de Koter & Lamers (2000) with \( V_{\infty} = 1.3V_{\text{esc}} \) for a \( T_{\text{eff}} = 20 \text{ kK} \) star.

Assuming the \( Bz \) values calculated in Section 4, we derived \( \eta \) and \( R_A \) based on the He+metal and H\textsc{$\beta$} analyses and find the results to be consistent. The larger uncertainties on the H\textsc{$\beta$} measurements yielded the lowest minimum \( \eta \) and \( R_A \) at \( 1.3 \times 10^5 \) and \( 19.0 \text{ R}_\odot \), respectively. With a Kepler radius of \( R_K = 2.9^{+1.7}_{-1.2} \text{ R}_\odot \), 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 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 Petit et al. (2013) – populated by approximately 12 mid to early B-type stars. Six of these are reported to exhibit H\textalpha emission and only one from this subset – HD 142990 – has a rotational period shorter than that of HD 23478 (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\textalpha emission (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 \( 23 \pm 1 \text{ kK} \) (Groote & Hunger 1982) and its rotational period and projected rotational velocity differ from HD 23478 by as little as 13% and 6%, respectively (Townsend et al. 2010). Ho EW measurements of \( \sigma \) Ori E show stronger variability \( \sim 3 \text{ \AA} \) (Oksala et al. 2012) compared with the \( \Delta \text{EW}_{\text{Ho}} \sim 1 \text{ \AA} \) 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 H\textalpha emission in CM-hosting stars, these differences in emission properties are consistent with \( \sigma \) Ori E’s likely higher \( R_K/R_A \) of approximately 15 (Petit et al. 2013).

Comparisons with the rigidly rotating magnetosphere (RRM) model (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 H\textalpha emission and unsigned longitudinal field \( \langle |B_i| \rangle \) 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 \( \langle |B_i| \rangle \), 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 Krticka et al. 2013, 2015). The variable He line profiles introduced in Section 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, 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.

8 CONCLUSIONS

Based on our analysis, we draw the following conclusions:

(i) HD 23478 is a main sequence magnetic He-strong star \( T_{\text{eff}} = 20 \pm 2 \text{ kK} \) exhibiting peculiar line strengths and

\[ \sigma_{\text{H}\alpha} \approx 13\% \text{ and } 6\%, \text{ respectively (Townsend et al. 2010).} \]

\[ \text{H}\alpha \text{ variability was found in all identified He \textsc{i} lines.} \]

\[ \text{Equation: } \langle \text{EW} \rangle_{\text{He}} \text{ and } \langle \text{EW} \rangle_{\text{H}\alpha} \]

\[ \text{Figure 11. Equivalent widths of variable absorption lines phased with the star's rotational period of } P_{\text{rot}} = 1.0498 \text{ d.} \]

\[ \text{Figure 12. Overlayed line profiles associated with the EWs from each of the 12 measurements. Significant variability was found in all identified He \textsc{i} lines.} \]

\[ \text{Doula, Owocki & Townsend (2008). Following the treatment carried out by Petit et al. (2013), we calculate } \eta \text{ using the calibration for } M_{\text{B}-0} \text{ derived by Vink, de Koter & Lamers (2000) with } V_{\infty} = 1.3V_{\text{esc}} \text{ for a } T_{\text{eff}} = 20 \text{ kK star.} \]

\[ \text{Assuming the } Bz \text{ values calculated in Section 4, we derived } \eta \text{ and } R_A \text{ based on the He+metal and H}\beta \text{ analyses and find the results to be consistent. The larger uncertainties on the H}\beta \text{ measurements yielded the lowest minimum } \eta \text{ and } R_A \text{ at } 1.3 \times 10^5 \text{ and } 19.0 \text{ R}_\odot \text{, respectively. With a Kepler radius of } R_K = 2.9^{+1.7}_{-1.2} \text{ R}_\odot \text{, we obtain a ratio of } R_A/R_K = 13.3 \text{ (with a lower limit of 4.6) thereby placing HD 23478 well within the CM star regime (i.e. those with } R_A/R_K > 1 \text{). The full range of magnetospheric parameters calculated from } \langle B_{\text{He+metal}} \rangle \text{ and } \langle B_{\text{H}\alpha} \rangle \text{ are listed in Table 4.} \]

\[ \text{In the context of all known CM stars, the estimated Kepler and Alfvén radii place HD 23478 within a region of the magnetic confinement diagram – Fig. 3 of Petit et al. (2013).} \]

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

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

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

\[ \text{Photometric variability may be observed if chemical spots are present on the star’s surface, which serve to redistribute the star’s flux into the UV (e.g. Peterson 1970 Krticka et al. 2013, 2015). The variable He line profiles introduced in Section 6 provide evidence for He spots on the surface of the star. However, the He EWs do not vary in phase with } H_p \text{ but are instead shifted by one quarter of a cycle. Thus, He spots are also not able to fully account for the observed } H_p \text{ variations. On the other hand, spots of other elements (in particular Si and Fe) may well also contribute. Such an investigation would be a useful element of a future, more detailed study of HD 23478.} \]
distorted line profiles of He, Si, and Fe, indicating likely nonuniform surface distributions of these elements;
(ii) the 1.0498(4) d period found in Hipparcos epoch photometry is most likely the star’s rotational period which confirms the earlier findings of Jerzykiewicz (1993);
(iii) the presence of strong Hα emission is consistent with the discovery by Eikenberry et al. (2014) of emission in Hα and nIR H lines. This emission forms a double peaked profile separated by $v = 960$ km s$^{-1}$ which likely originates from plasma located at a distance of $R > 3R_\star$. We observe significant variability in Hα and in various He lines. Measured EWs of these lines are coherently phased by $P_{rot} = 1.0498$ d;
(iv) 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 relatively significant discrepancy in the determination of the star’s effective temperature. IUE spectra used in the SED modelling imply $T_{eff} = 22$ 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 $\beta < 16^\circ$ paired with the high $69^\circ - 10^\circ$ 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.

Future work is necessary to more precisely constrain the magnetic field topology, magnetospheric properties, and chemical peculiarities of this star. Although the class of strongly Hα emitting stars hosting centrifugal magnetospheres is growing, the total number is still relatively low. Therefore, a detailed characterization of all known cases is important in order to better understand the interaction between magnetic fields and the winds of hot stars.

ACKNOWLEDGMENTS

GAW acknowledges support in the form of a Discovery Grant from the Natural Science and Engineering Research Council (NSERC) of Canada. AuD acknowledges support by NASA through Chandra Award number TM4-15001A and DHC acknowledges support from TM4-15001B issued by the Chandra X-ray Observatory Center which is operated by the Smithsonian Astrophysical Observatory for and behalf of NASA under contract NAS8-03060. RHDT acknowledges support from NASA award NNX12AC72G.

Some of the data presented in this paper were obtained from the Multimission Archive at the Space Telescope Science Institute (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. Support for MAST for non-HST data is provided by the NASA Office of Space Science via grant NAG5-7584 and by other grants and contracts.

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