An observational evaluation of magnetic confinement in the winds of BA supergiants

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ABSTRACT
Magnetic wind confinement has been proposed as one explanation for the complex wind structures of supergiant stars of spectral types B and A. Observational investigation of this hypothesis was undertaken using high-resolution ($\lambda/\Delta\lambda \sim 65000$) circular polarization (Stokes V) spectra of six late B- and early A-type supergiants ($\beta$ Ori, B8Iae; 4 Lac, B9Iab; $\eta$ Leo, A0Ib; HR1040, A0Ib; $\alpha$ Cyg, A2Iae; $\nu$ Cep, A2Iab), obtained with the instruments ESPaDOnS and Narval at the Canada–France–Hawaii Telescope and the Bernard Lyot Telescope. Least-squares deconvolution (LSD) analysis of the Stokes V spectra of all stars yields no evidence of a magnetic field, with best longitudinal field 1σ error bars ranging from $\sim 0.5$ to $\sim 4.5$ G for most stars. Spectrum synthesis analysis of the LSD profiles using Bayesian inference yields an upper limit with 95.4 per cent credibility on the polar strength of the (undetected) surface dipole fields of individual stars ranging from 3 to 30 G. These results strongly suggest that magnetic wind confinement due to organized dipolar magnetic fields is not the origin of the wind variability of BA supergiant stars. Upper limits for magnetic spots may also be inconsistent with magnetic wind confinement in the limit of large spot size and filling factor, depending on the adopted wind parameters. Therefore, if magnetic spots are responsible for the wind variability of BA supergiant stars, they likely occupy a small fraction of the photosphere.

Key words: circumstellar matter – stars: early type – stars: magnetic field – stars: mass-loss – supergiants – stars: winds, outflows.

1 INTRODUCTION

Early-type stars are amongst the brightest stars in spiral galaxies. These stars are massive ($M_\star \geq 10 M_\odot$), large ($R_\star \sim 50–200 R_\odot$), and short lived, with main-sequence lifetimes of 10–25 Myr. Despite their ephemeral existence and rarity, massive stars exert a disproportionate influence within the galactic ecology: in life their light creates ionized H II regions while their powerful winds play a decisive role in sculpting molecular clouds, acting to both trigger and quench star formation; in death, their supernovae synthesize (and distribute) all elements heavier than Fe (along with numerous lighter elements).

Amongst the most luminous massive stars (up to several hundred thousand $L_\odot$) are supergiants of spectral type late B through early A. The evolution of these BA supergiant (BA SG) stars is extremely rapid, making them particularly rare; the details of their evolution, influenced largely by their winds, have significant consequences for their mass and composition at the pre-supernova stage. BA SG stars are also of potential value to extragalactic astronomy, as they are luminous enough to be relatively easily observed in nearby galaxies, thus offering both a probe of metallicity and, via the wind-momentum–luminosity relationship, the promise of a distance indicator (Kudritzki et al. 1999); the latter, obviously, must be calibrated by a proper understanding of the stellar wind.

The closest BA SGs, such as Rigel ($\beta$ Ori, B8Iae) or Deneb ($\alpha$ Cyg, A2Iae), are amongst the brightest objects in the sky and have

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been extensively monitored, revealing a unique pattern of spectral variability dubbed ‘α Cyg variability’ (Lucy 1976). This is characterized by variability in both the radial velocities of metallic lines and the detailed shapes of spectral line profiles, particularly the hydrogen Balmer α line (Hα), which evolves between P Cygni, inverse P Cygni, full absorption and full emission (Kaufer et al. 1996a,b). α Cyg variability is also characterized by an absence of clear periodicities, evolving instead ‘semiperiodically’: periodograms find no single dominant period, but rather a range of significant peaks with periods ranging from less than a day to months (Lucy 1976). Periodogram peaks may also change from season to season, and typically differ between equivalent width and radial velocity measurements (Kaufer et al. 1996a,b, 1997; Markova et al. 2008; Richardson et al. 2011; Moravveji et al. 2012a).

The Hα variability of α Cyg variables is impossible to reproduce using a simple spherically symmetric model of the stellar wind (Markova et al. 2008), implying that the circumstellar environment of these stars is highly structured. Striking evidence for complex wind structures was found by Kaufer et al. (1996b), who discovered β Ori (B8Iae), HD 91619 (B7Ia) and HD 96919 (B9Ia) to exhibit a phenomenon known as high-velocity absorption (HVA), in which the blueshifted half of the Hα line profile exhibits a sudden, large increase in absorption at high radial velocity. HVAs have since been noted in HD 199478 (B8Iae) and α Cyg (A2Ia) by Markova et al. (2008) and Richardson et al. (2011), respectively, and have been observed repeatedly in the case of β Ori (Morrison, Rother & Kurschat 2008).

Israelian, Chentsov & Musaev (1997) suggested this puzzling behaviour to be due to magnetic fields: magnetic spots at the stellar surface might lead to a large loop of magnetically supported material within the wind environment. This is in rough analogy to the loops observed within the solar corona, although of much greater radial extent (a few stellar radii) and duration (HVAs can persist and evolve over months). With density and velocity fields substantially different from either the surrounding wind or the stellar surface, such loops might give rise to HVAs as they move in and out of view in corotation with the photosphere.

When first posited, this hypothesis was considered plausible given existing polarimetric observations by Severny (1970), from which a longitudinal field measurement of \( B_z \sim 130 \, G \) suggested that β Ori possessed a magnetic field of sufficient strength to make wind confinement feasible. A longitudinal magnetic field of \( \sim 2500 \pm 250 \, G \) was also reported for ν Cep by Scholz & Gerth (1981), who found \( B_z \) to vary between null and maximum over a time-scale of years, based upon Zeeman spectrograms measured using an Abbe comparator (Gerth et al. 1977). However, a more recent study of seven A-type supergiants (including α Cyg, ν Cep and 4 Lac) was performed by Verdugo et al. (2003), who used the MuSiCoS spectropolarimeter, and found no evidence of Zeeman signatures in the line profiles, and no \( \sigma \) detections in the longitudinal field, with error bars ranging from 3 to 160 G.

The most recent results concerning the magnetic properties of BA SGs have been presented by Hubrig et al. (2012), who observed HD 92207 (A0Iae) with the FORS2 instrument on the VLT, with two of the three observations yielding detections at greater than \( 3 \sigma \) in the longitudinal field, and \( B_z \) measured at hundreds of G. However, some previous magnetic detections with FORS2 data, for β Cep stars and slowly pulsating B stars especially (e.g. Hubrig et al. 2007, 2011b,a), have not been confirmed using instrumentation with a higher spectral resolution (Silvester et al. 2009; Shultz et al. 2012), while reanalysis of published FORS measurements revealed that many reported magnetic detections may have been consequences of unaccounted for instrumental effects or the specific algorithm used to reduce the data, rather than real photospheric magnetic fields (Bagnulo et al. 2012). Bagnulo et al. (2013) have reanalysed the FORS data for HD 92207, and have convincingly demonstrated that no detectable magnetic field is present in those data. Observation at high spectral resolution is thus necessary to consider the detection of magnetic fields definitive.

This paper presents the results of observations of 6 BA SG stars obtained using high-dispersion spectropolarimeters, the most sensitive observations yet obtained for this class of stars. In Section 2, we describe the acquisition and reduction of the spectropolarimetric data set. In Section 3, the wind behaviour during the period of observation is characterized. In Section 4, we present the magnetic analysis of the data, and the resulting detection probabilities and longitudinal field measurements, together with constraints on the field strength obtained by means of spectral modelling interpreted using Bayesian statistical concepts. In Section 5, the implications of these results are interpreted in the context of magnetic wind confinement models, for both the case of a dipolar magnetic field and small-scale magnetic spots.

2 OBSERVATIONS

In the context of the Magnetism in Massive Stars (MiMeS) Large programmes, circular polarization (Stokes V) observations were collected with the cross-dispersed échelle spectropolarimeters ESPaDOnS [at the 3.6 m CFHT on Mauna Kea] and its twin Narval [installed at the 2 m Telescope Bernard Lyot at the Pic du Midi in the French Pyrénées]. Each instrument covers the spectral range from 369 to 1048 nm over 40 mostly overlapping spectral orders, with a spectral resolution of \( \lambda / \Delta \lambda \sim 65 000 \) at 500 nm. The quality of the observations is in general excellent, with the peak signal-to-noise ratio (SNR) per 1.8 km s\(^{-1}\) pixel ranging from 450 to about 1300, and mean SNRs of 883 in ESPaDOnS spectra and 698 in Narval spectra. This data set represents the highest quality spectropolarimetry yet collected for these stars.

Each spectropolarimetric sequence consisted of four individual subexposures taken in different orientations of the half-wave Fresnel rhombs. From each set of four subexposures, we derived Stokes \( I \) and Stokes \( V \) spectra following the double-ratio procedure described by Donati et al. (1997), ensuring in particular that all spurious signatures of stellar or instrumental origin are removed at first order. Diagnostic null polarization spectra (labelled \( N \)) were calculated by combining the four subexposures in such a way that stellar polarization cancels out, allowing verification that no spurious signals are present in the data [see Donati et al. (1997) for more details on the definition of \( N \)]. Frames were processed using the automated reduction package LIBRE-ESPRIT (Donati et al. 1997). The spectra were normalized by applying a manually monitored order-by-order normalization employing \( \sigma \)-clipping and polynomial fits.

In the cases of β Ori and α Cyg, their brightnesses resulted in subexposure times (a few seconds) that were much shorter than the 25–40 s CCD read-out time (see Table 2). This makes spectropolarimetric monitoring (in the case of β Ori, for which 65 observations were collected) or single-night deep observations (in the case of α Cyg, for which 100 observations were collected, 80 on two subsequent nights) a feasible investment. The remaining stars are much dimmer (see Table 1), meaning longer subexposure times were required, precluding the possibility of collecting more than a few observations in each case: 15 observations of η Leo, 17 of ν Cep, 11 of 4 Lac and 3 of HR 1040. Observation dates are given in
Table 1. Summary of the sample stars’ stellar, atmospheric and wind parameters, with theoretical wind parameters calculated from the models described in Section 5. Hz denotes the type of Hz profiles historically observed for each star; HVAs notes whether high-velocity absorption events have been witnessed in Hz; \( R(q_{\alpha}) = 1 \) gives the dipolar magnetic field necessary for minimal magnetic wind confinement (see equation 2).

| Parameter       | HD 34085 (β Ori, Rigel) | HD 212593 (ζ Ori) | HD 87737 (η Leo) | HD 21389 (HR 1040) | HD 197345 (α Cyg, Deneb) | HD 207260 (ν Cep) |
|-----------------|-------------------------|-------------------|------------------|---------------------|--------------------------|------------------|
| \( V \) (mag)   | 0.138 ± 0.032           | 4.569 ± 0.018     | 3.486 ± 0.053    | 4.54±               | 1.246 ± 0.015            | 4.289 ± 0.007    |
| Spectral type   | B8 Ia                   | B9 Ib             | A0 Ib            | A0 Ia               | A2 Ia                    | A2 Iab           |
| log\((L/L_{\odot})\) | 5.08 ± 0.084e, f     | 4.79 ± 0.21f      | 4.23 ± 0.12d     | 4.74f               | 5.30 ± 0.07h            | 4.71f            |
| Distance (kpc)  | 0.24 ± 0.054e, f         | 1.68f             | 0.6 ± 0.099e     | 0.98 ± 0.09m        | 0.80 ± 0.07l            | 0.63f            |
| \( R(\odot) \)  | 71.1 ± 14.6e, f          | 59 ± 16e          | 47 ± 8e          | 97\( d \)           | 203 ± 17\( d \)         | 92\( f \)        |
| \( T_{\text{eff}} \) (K) | 12100 ± 150f         | 11200 ± 200f      | 9600 ± 150f      | 9730f               | 8525 ± 75f              | 9080f            |
| log\( e \) (cgs) | 1.75 ± 0.10f            | 2.1 ± 0.1f        | 2.00 ± 0.15f     | 1.75f               | 1.10 ± 0.05f            | 1.67f            |
| \( M_{\text{evol}}(\odot) \) | 21 ± 3.6e             | 21 ± 6f           | 10 ± 1d          | 19.1f               | 18 ± 2f                 | 14.7f            |
| \( v\sin i \) (km s\(^{-1}\)) | 25 ± 3f               | 6 ± 3f            | 0 ± 3f           | 25 ± 5f             | 20 ± 2f                 | 15 ± 5f          |
| \( P_{\text{max}} \) (d) | 143±52               | 497±767          | 792±135         | 196±33              | 513±85                 | 310±155         |
| \( P_{\text{min}} \) (d) | 29±12\( e \)          | 20±9             | 22\( f \)        | 46                  | 146±22                 | 26               |
| \( v\sin c \) (km s\(^{-1}\)) | 207                   | 235               | 195              | 202                 | 109                    | 166              |
| \( M(\odot) \) yr\(^{-1} \) | 7.77 × 10\(^{-6} \)  | 1.64 × 10\(^{-6} \) | 2.17 × 10\(^{-7} \) | 1.22 × 10\(^{-6} \) | 2.01 × 10\(^{-6} \) | 1.40 × 10\(^{-6} \) |
| \( M(\odot) \) yr\(^{-1} \) (measured) | 129f             | 350f             | 240              | 25f                 | –                      | –                |
| \( M(\odot) \) yr\(^{-1} \) (measured) | 1.1 × 10\(^{-7} \)h, i    | 9.1 × 10\(^{-8} \)f | 4.7 × 10\(^{-8} \)h, i | 4.2 × 10\(^{-7} \)i, n | 3.1 × 10\(^{-7} \)i, n | –                |
| H\( z \)        | Variable f             | Full absorption   | Full absorption  | Double-peaked f    | P Cygni f              | P Cygni f        |
| HVAs?           | Many times f            | –                | –               | Yes f               | Yes f                  | Yes f            |

References: \(^a\)Firnstein & Przybilla (2012); \(^b\)Vink, de Koter & Lamers (1999, 2000, 2001); \(^c\)this work; \(^d\)Przybilla et al. (2006); \(^e\)Moravveji et al. (2012a); \(^f\)Markova & Puls (2008); \(^g\)Markova et al. (2008); \(^h\)Barlow & Cohen (1977); \(^i\)Chesneau et al. (2010); \(^j\)Kaufer et al. (1996a,b); \(^k\)Richardson et al. (2011); \(^l\)Verdugo, Talavera & Gómez de Castro (1999); \(^m\)Lyder (2001); \(^n\)Schiller & Przybilla (2008).

Table 2, and span ranges from a few years (α Cyg and ν Cep) to one week (4 Lac).

Spectropolarimetric monitoring of a BA SG star presents special challenges as the rotational periods of these stars remain generally undetermined. However, minimum and maximum rotational periods (see Table 1) can be calculated based upon their projected rotational velocities \( v \sin i \), stellar radii \( R \), and masses \( M \). The stellar radius and \( v \sin i \) give the maximum period \( P_{\text{rot}} \), while the minimum period is established via the rotational breakup velocity \( v_{\text{break}} = \sqrt{GM_{\odot}}/R_{\odot} \) (assuming solid-body rotation). For β Ori, η Leo and α Cyg, literature values were used for \( v \sin i \); for 4 Lac, HR 1040 and ν Cep, published rotational velocities were not compatible with observed line broadening, and \( v \sin i \) was estimated by fitting synthetic mean line profiles to the mean line profiles used in the magnetic analysis described in Section 4. In calculating \( P_{\text{min}} \), the equatorial radius \( R_{\text{eq}} \) was used in place of \( R_{\odot} \), since near critical-velocity oblateness will mean that \( R_{\text{eq}} \approx 1.5R_{\text{pol}} \), where \( R_{\text{pol}} \) is the polar radius. For η Leo, only an upper limit is available for \( v \sin i \); the range of rotational periods is calculated using this upper limit. The effect is to increase \( P_{\text{min}} \) slightly, due to the increased radius, decreased surface gravity and hence decreased \( v_{\text{break}} \).

In the cases of β Ori and α Cyg, \( R \) is derived from the Hipparcos parallax distances and interferometric angular radii (Perryman et al. 1997; Aufdenberg et al. 2002, 2008); for other stars \( R \) is determined from stellar evolution models (Przybilla et al. 2006, 2010; Markova & Puls 2008; Firnstein & Przybilla 2012). Observations of β Ori were timed so as to span at least one rotational period but also to achieve good sampling at time-scales closer to \( P_{\text{rot}} \), with the most densely time-sampled period coinciding with a 28 d photometric observing campaign conducted with the Microvariability and Oscillations in STars (MOST) space telescope, intensive ground-based spectroscopic monitoring and interferometry (Kaufer et al. 2012; Moravveji et al. 2012a; Moravveji, Moya & Guinan 2012b).

3 WIND VARIABILITY

With the exception of β Ori a detailed time series analysis of the targets is precluded by the paucity of data; however, an attempt can still be made to characterize the wind activity during the observations. This is explored through the Hz profiles shown in Fig. 1. Given the greater temporal sampling of β Ori, only a representative selection of β Ori’s Hz line profiles are shown; for the remaining stars all observations are overplotted.

The Hz profile of β Ori is almost entirely filled with highly variable emission, demonstrating both P Cygni and inverse P Cygni profiles over the course of monitoring, as reported in previous investigations (e.g. Kaufer et al. 1996b). The star appears to have been relatively quiescent in comparison to some previous observing campaigns, showing spectral variability consistent with that
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Table 2. Mean longitudinal field measurements from co-added spectra. The date corresponds to the average HJD of the individual spectra. The number of spectra used to create the profile is indicated by NS. $P_{\text{det}}$ is the detection probability. Those observations corresponding to HV A events are indicated; the parentheses in the case of $\beta$ Ori indicate the weak HV A-like behaviour discussed in the text. Sub-exposure times within the parentheses indicate those for Narval as supposed to ESPaDOnS observations. Magnetic measurements are described in more detail in Section 4.

| HJD Calendar date | HVA Subexposure time (s) | NS | LSD | $P_{\text{det}}$ | $\langle B_z \rangle / \sigma_B$ | $\langle N_z \rangle / \sigma_N$ |
|-------------------|--------------------------|----|-----|-----------------|----------------|-----------------|
| 5100–5110 25 Sept.–05 Oct. 09 N | 2 (5) | 3 | 8456 | 0.1549 | −10.3 ± 7.2 | 1.45 | 7.8 ± 7.2 | 1.08 |
| 5115–5125 10–20 Oct. 09 N | 2 (5) | 4 | 10 136 | 0.2544 | 8.9 ± 6.1 | 1.45 | 3.9 ± 6.1 | 0.63 |
| 5125–5135 20–30 Oct. 09 N | 2 (5) | 6 | 10 925 | 0.9829 | −4.8 ± 5.6 | −0.85 | −0.7 ± 5.6 | −1.72 |
| 5167–5177 01–11 Dec. 09 (Y) | 2 (5) | 32 | 31 451 | 0.8734 | 2.8 ± 2.0 | 1.39 | 1.7 ± 2.0 | 0.85 |
| 5180–5190 14–24 Dec. 09 N | 2 (5) | 5 | 10 023 | 0.0687 | 1.7 ± 6.1 | 0.27 | 7.5 ± 6.1 | 1.22 |
| 5200–5210 03–13 Jan. 10 N | 2 (5) | 6 | 13 214 | 0.3150 | 2.8 ± 4.6 | 0.61 | 4.5 ± 4.6 | 0.97 |
| 5212–5222 15–25 Jan. 10 N | 2 (5) | 5 | 11 704 | 0.9139 | 8.1 ± 5.2 | 1.55 | 4.3 ± 5.2 | 0.83 |
| 5224–5234 27 Jan.–06 Feb. 10 N | 2 (5) | 5 | 7383 | 0.2762 | 10.3 ± 8.1 | 1.27 | 9.0 ± 8.1 | 1.12 |
| 5240–5250 12–22 Feb. 10 (Y) | 2 (5) | 2 | 5535 | 0.2394 | −4.1 ± 11.1 | −0.37 | 7.4 ± 11.1 | 0.67 |
| β Ori (87 lines) | | | | | | | |
| 6197.814 27 Sept. 12 N | 130 | 5 | 12 915 | 0.0065 | 2.0 ± 3.7 | 0.53 | 0.6 ± 3.7 | 0.16 |
| 6201.887 01 Oct. 12 N | 130 | 6 | 11 339 | 0.0375 | 0.5 ± 4.3 | 0.11 | −7.0 ± 4.3 | −1.64 |
| 4956–4959 04–07 May 09 N | 35 | 12 | 24 036 | 0.9180 | −0.6 ± 1.8 | −0.35 | −0.4 ± 1.8 | −0.21 |
| 5173.006 07 Dec. 09 N | 93 | 3 | 24 783 | 0.1893 | −0.9 ± 1.8 | 0.50 | −1.5 ± 1.8 | −0.81 |
| 4 Lacertae (76 lines) | | | | | | | |
| 5405.010 27 July 10 N | 182 | 3 | 7427 | 0.5967 | 0.2 ± 4.5 | 0.04 | −1.5 ± 4.5 | −0.34 |
| 4956–4959 04–07 May 09 N | 35 | 12 | 24 036 | 0.9180 | −0.6 ± 1.8 | −0.35 | −0.4 ± 1.8 | −0.21 |
| 5173.006 07 Dec. 09 N | 93 | 3 | 24 783 | 0.1893 | −0.9 ± 1.8 | 0.50 | −1.5 ± 1.8 | −0.81 |
| 5405.010 27 July 10 N | 182 | 3 | 7427 | 0.5967 | 0.2 ± 4.5 | 0.04 | −1.5 ± 4.5 | −0.34 |
| 5544–5549 17 May 09 N | 52 | 8 | 20 077 | 0.5452 | −2.8 ± 2.8 | −0.85 | −3.7 ± 2.8 | −1.74 |
| 5173.006 07 Dec. 09 N | 93 | 3 | 24 783 | 0.1893 | −0.9 ± 1.8 | 0.50 | −1.5 ± 1.8 | −0.81 |
| 5405.010 27 July 10 N | 182 | 3 | 7427 | 0.5967 | 0.2 ± 4.5 | 0.04 | −1.5 ± 4.5 | −0.34 |

Figure 1. Hα profiles of the six programme stars. Different nights are plotted in different line styles, with the observation dates given in the legends. In the case of $\beta$ Ori, due to the large number of observations, only a representative sample of line profiles is shown. α Cyg and ν Cep both show strong absorption features extending out to $-200 \text{ km s}^{-1}$. The narrow absorption features evident in some spectra are due to telluric lines.
Figure 2. Top: Hα (left) and Si II 634.7 nm (right) dynamic spectra of β Ori during the most densely time-sampled period, computed via the difference between individual spectra and the mean line profile. Middle: one-dimensional intensity spectra. The red profile shows the mean line profile. Bottom: residual intensity relative to the mean line profile. Note that the weak HVA, which appears on day 166 with a central velocity around $-100 \text{ km s}^{-1}$, is preceded by an inverse P Cygni profile. 

seen in AST and BESO spectra (Kaufer et al. 2012; Moravveji et al. 2012a; Shultz 2012). In particular, it does not show any spectacular HVAs. However, on 2009 December 1 a weak absorption feature appeared around $-150 \text{ km s}^{-1}$. The dynamic spectrum in Fig. 2, which shows residual intensity compared to a mean line profile as a function of the heliocentric Julian date (HJD) over the most densely time-sampled period, demonstrates that the feature appears quite suddenly following an inverse P Cygni profile, before migrating redwards on a time-scale consistent with the evolution of the HVAs previously observed for this star (around a month; Kaufer et al. 1996b). The dynamic spectrum of the Si II 634.7 nm line is shown in the second panel of Fig. 2. Similarities between the two lines suggest that Hα is also affected by non-radial pulsations.

While β Ori does not show strong HVA activity in these observations, an overlapping ESO campaign captured the onset and subsequent evolution of a full HVA event approximately 20 d following the cessation of spectropolarimetric monitoring (Kaufer et al. 2012). Concurrent spectro-interferometry of the Brγ line shows a differential phase signal that is at its strongest approximately 25 d before the onset of the 2012 HVA, corresponding to the final spectropolarimetric observations. Kaufer et al. suggest that this may be due to an extended circumstellar structure rotating from next to the star (the differential phase signal) to in front of the star (the HVA). This would be consistent with a rotational period of $\sim 100 \text{ d}$.

The Hα profile of 4 Lac is in full absorption, although there is some apparent variability around the line core.

The Hα profile of η Leo is in full absorption and shows virtually no variability, aside from a small amount in the blueshifted half of the line. This is consistent with the pattern noted by previous investigations (Richardson et al. 2011).

HR 1040 shows a double-peaked profile, consistent with previous observations (Verdugo et al. 1999; Richardson et al. 2011).

In the case of α Cyg, the first of the four observations shows a strong HVA event, while during other nights the star exhibits P Cygni profiles. HVAs are particularly rare for α Cyg (Richardson et al. 2011), indicating that this observation represents a fortunate opportunity to investigate the magnetic hypothesis for the origin of these events.

In the case of ν Cep, we see an unremarkable P Cygni profile in the first observation, but a strong blueshifted absorption feature is apparent in subsequent observations, with the most recent showing the strongest redistribution of flux absorption towards high velocities. Over multiple years of monitoring, ν Cep has never been known to exhibit HVAs with an absorption depth comparable to those of β Ori; however, it does exhibit a highly variable blueshifted absorption component (Richardson et al. 2011). While a detailed analysis of this star’s wind variability based upon multiyear spectral monitoring has yet to be published, preliminary comparison of these observations to unpublished spectral monitoring suggests that the absorption feature is substantially stronger than average (Morison, private communication). We therefore tentatively identify this feature as an HVA.
4 MAGNETIC ANALYSIS

Magnetic fields are measured via the longitudinal Zeeman effect, as diagnosed through circular polarization induced in magnetically sensitive spectral lines. As a first step in the magnetic analysis, least-squares deconvolution (LSD; Donati et al. 1997; Kochukhov, Makaganiuk & Piskunov 2010) was performed on the individual spectra. LSD combines information from multiple lines to produce a mean line profile with a much higher SNR than any individual spectral line. To create this LSD profile, LSD deconvolves a ‘line mask’ from the spectra: the line mask is a list of δ functions with locations and amplitudes corresponding to the wavelengths and continuum-normalized depths of spectral lines. Whenever possible a measured value for the Landé factor $g$ (a measure of the magnetic sensitivity of the line) is used; otherwise, this is calculated quantum mechanically assuming spin–orbit coupling. While the LSD Stokes I profile is often an imperfect match to individual lines, the increase in the SNR of the Stokes V profile has been repeatedly shown to enable the detection of magnetic fields that would otherwise have been far too weak to rise above the photon noise (e.g. Wade et al. 2000). Kochukhov et al. (2010) provide a detailed discussion of the numerical implementation of LSD, together with an exploration of the inherent limitations arising due to the approximations necessary to the technique.

The line masks were adjusted for each star in order to ensure that the LSD model was as faithful to the underlying spectra as possible. Emission lines, lines blended with Balmer or Paschen lines, interstellar lines and telluric lines were not included in the mask as they introduce unacceptable distortion into the line profile, i.e. leaving only photospheric lines, which are not significantly affected by wind emission. In order to reduce noise arising from weak lines, lines with an observed central depth of less than 10 per cent of the continuum were also removed, since their contribution to the Stokes I profile is primarily to make it noisier, while contributing insignificantly to the potential signal in Stokes V. The number of lines remaining in each mask is given in Table 2. The depths of the remaining spectral lines were empirically adjusted from their theoretical values so as to match the observed line depths, ensuring a better fit to Stokes I, and proper weighting of the contribution of each line to Stokes V.

In order to increase the SNR beyond that obtainable in a single observation, the LSD profiles of individual spectra were binned in time. Due to expected rotational modulation of any Stokes V profile, binning cannot be performed over more than about 10 per cent of the rotational period without substantial distortion of any underlying Zeeman signature. While the rotational periods of these stars remain undetermined, upper and lower limits (see Table 1) indicate that they are likely to be of the order of 100 d for all stars (in the case of α Cyg, which may in fact be a ‘rapid’ rotator seen close to pole-on (Chesneau et al. 2010), the minimum period is ~140 d). In no case but that of β Ori are binned observations separated by more than 3 d. In the case of β Ori, a 10 d bin is adopted, which should correspond to approximately 10 per cent of the maximum rotational period. While it may be objected that this also corresponds to ~1/3 of the minimum rotational period, the preponderance of evidence suggests that β Ori is seen at high inclination (Chesneau et al. 2010), with a rotational period of the order of 100 d (Kaufer et al. 2012).

It must be noted that β Ori displays radial velocity variability on time-scales of the order of 10 d, with an amplitude of ~8 km s$^{-1}$. This is likely to be due to non-radial pulsations, as discussed by Moravveji et al. (2012b). Fig. 2 shows what may be an excited pulsational mode in the dynamic spectra for the Si ii 634.7 nm line, but no sign of the higher velocity absorption components in the Hα profile, lending confidence to the assumption that the photospheric metallic lines are essentially unaffected by the stellar wind (see also Kaufer et al. 1996a, 1997). This low-amplitude variability of the photospheric lines is small compared to that in other classes of stars in which magnetic fields are routinely detected, e.g. Ap/Bp stars, β Cep stars or Of?p stars (in which the variability arises due to photospheric abundance spots, pulsations and magnetically confined winds, respectively), and so is not considered an impediment to detection of magnetic fields in this sample. Line profile distortion due to pulsation is approximately corrected for the purposes of the magnetic diagnosis by shifting each LSD profile to a common central velocity before adding them. Analysis of the pulsating magnetic star HD 96446 shows radial velocity correction improves the smoothness and increases the amplitude of Stokes V profiles, thereby improving detectability, although some remaining line profile distortions are not accounted for by this method (Neiner et al. 2012). Since the profiles are being combined across at least a full pulsation period; however, distortions in Stokes V should cancel out. Radial velocity correction also reduces signatures in the null profile, although in this case there are no such signatures to begin with.

The co-added LSD profiles with the highest SNRs are shown in Fig. 3. The number of spectra combined to compute each LSD profile, the dates of observation and the resulting SNRs are tabulated in Table 2.

Two magnetic diagnostics were applied to each LSD profile: a statistical test of the significance of the polarized signal within the line profile and measurement of the mean longitudinal magnetic field. The former searches for significant departure of the Stokes V profile within the spectral line from the noise spectrum determined from both the V profile outside the spectral line and the N profile (Donati, Semel & Rees 1992). A magnetic signature is considered ‘definite’ if the formal detection probability $P_{\text{det}}$ is greater than 99.999 per cent inside the V line profile and negligible elsewhere, ‘marginal’ if the detection probability is between 99.9 and 99.999 per cent, and a non-detection otherwise. This test results in a null detection for all LSD profiles computed in this investigation (see Table 2). Hence, we conclude that no magnetic fields are detected in any of our sample stars.

The brightness-weighted, disc-averaged longitudinal magnetic field is computed from the first-order moment of the Stokes V profile within the line (see e.g. Mathys 1989):

$$
B_{\lambda g} = -2.14 \times 10^{14} \int \frac{I_v V(v) \, dv}{\lambda g_{\text{eff}}} \int \frac{[I_v - I_{\text{mod}}(v)] \, dv}{N_z},
$$

where $v$ is the velocity (in km s$^{-1}$) within the profile measured relative to the centre of gravity, and λ and $g_{\text{eff}}$ are the reference values of the wavelength (in nm) and the effective Landé factor used in computing the LSD profiles. The longitudinal field ($N_z$) of the null profile was also computed. The 1σ uncertainties associated with ($B_z$) and ($N_z$) were determined by propagating the uncertainties of each LSD pixel through equation (1). The integration ranges used for these measurements, and for the statistical test described above, are shown in Fig. 3. Error bars are a function of both the SNR and the integration range, where the latter depends on line broadening: thus, more rapidly rotating stars will have larger error bars at a given SNR.

The quantities ($B_z$) and ($N_z$) for the ESPaDOnS and Narval observations are tabulated in Table 2, together with the ratio of ($B_z$) and ($N_z$) to their error bars. All magnetic field measurements in all observations are beneath the 3σ significance threshold, with error
bars ranging from 0.5 to 11.5 G and a mean error bar of 4.3 G. In agreement with the statistical tests, no significant longitudinal magnetic field is detected in any of the stars.

The co-added LSD profiles for all stars were used as input for the Bayesian search algorithm developed by Petit & Wade (2012), in order to constrain the strength of dipole component of the stellar magnetic field. Modelling the magnetic field as a dipole and generating synthetic LSD profiles for varying dipolar field strength $B_d$, obliquity of the magnetic axis $\beta$ and inclination of the rotational axis $\iota$, the approach yields probable upper limits on undetected underlying stellar dipolar magnetic fields. This method is able to establish robust constraints with a small number of observations (Petit & Wade 2012). While the upper limits are obviously affected by the star’s intrinsic line broadening and the SNR of individual measurements, the number of observations also plays an important role: with only a small number of observations, a significant probability tail persists at high $B_d$, which diminishes as further observations are added.

The cumulative probability of the resulting probability density functions, marginalized over $i$, $\beta$ and $B_d$, are shown in Fig. 4, with the 95.4 per cent credibility region filled in red. Comparison of synthetic $N$ and Stokes $V$ profiles has shown this to represent the threshold above which definite detection of the field becomes likely (Petit & Wade 2012). The value of $B_d$ corresponding to 95.4 per cent credibility is given in Table 3, along with the logarithmic odds ratios of $M_\circ$, the null hypothesis, to $M_1$, the dipolar magnetic field hypothesis. If $\log(M_0/M_1) \approx 1$, as is the case for all stars, there is no evidence favouring a dipolar field over no magnetic field.

5 DISCUSSION

5.1 Magnetic wind confinement

As demonstrated by ud-Doula & Owocki (2002), the interaction between an outflowing line-driven stellar wind and a large-scale magnetic field can be characterized by the magnetic wind confinement parameter $\eta$, which is the ratio of magnetic to kinetic energy density at the stellar surface, given by

$$\eta = \frac{B_{eq}^2 R_\star^2}{M \upsilon_\infty} \tag{2}$$

where $R_\star$ is the stellar radius, $M$ is the mass-loss rate, $\upsilon_\infty$ is the terminal wind velocity and $B_{eq} = B_0/2$ is the equatorial magnetic field strength (all in cgs units), where the radial wind flow most directly opposes the horizontal orientation of the magnetic field.

If $\eta > 1$, the wind will be magnetically confined: the outflowing wind plasma flows along closed field lines above the stellar surface to collect at the magnetic equator, where it is channelled into a wind shock of dense plasma radiatively cooled via X-ray emission (as has been proposed and observed amongst some magnetic early-type stars, e.g. $\theta^1$ Ori C; Babel & Montmerle 1997; Donati et al. 2002).

Measurements of $M$ are available for most of the sample stars. Alternatively, theoretical mass-loss rates could be used. Both approaches suffer from a similar weakness, namely the application of a spherically symmetric model to systems that are clearly not spherically symmetric (Markova et al. 2008). In addition, there are large discrepancies between theoretical and empirical mass-loss rates for BA SG stars, and between determinations of $M$ from different spectral regions. Whether these discrepancies are a consequence of wind geometry, of systematic errors in the theoretical calculations, or of systematic errors in the translation of spectrum to $M$, is unclear.

In their study of magnetic wind confinement amongst magnetic early-type stars, Petit et al. (2013) adopted theoretical mass-loss rates calculated with the empirically calibrated recipe of Vink et al. (1999, 2000, 2001). As the recipe of Vink et al. is computed only for stars with $T_{\text{eff}} \geq 12500$ K, application to BA SG stars requires extrapolation. Although this formulation should be valid down to $\sim 7000$ K, where molecular and dust effects become important (Vink, private communication), the predicted mass-loss rates for BA SG stars are one to two orders of magnitude higher.
than measured values (e.g. Barlow & Cohen 1977; Markova & Puls 2008; Chesneau et al. 2010).

In recognition of the large discrepancy between the observed and predicted mass-loss rates, we provide constraints using empirically inferred values of $M$. However, it should be kept in mind that the empirical mass-loss rates are inferred using spherically symmetric models applied to a variety of observational diagnostics: near-infrared photometry (Barlow & Cohen 1977), Hα profile modelling (Markova et al. 2008; Schiller & Przybilla 2008), and optical and near-infrared interferometry (Chesneau et al. 2010). Therefore, to enable a consistent comparison across the sample, we also compute the theoretical mass-loss rates of Vink et al. (1999), calculated using the parameters in Table 1 and solar metallicities (a reasonable approximation for these stars; see e.g. Przybilla et al. 2006 and Schiller & Przybilla 2008).

As all stars are below the second bistability jump (Vink et al. 1999), wind terminal velocities were computed according to the relationship $v_\infty = 0.7v_{\text{esc}}$, an empirical formula derived from the UV P Cygni troughs of a sample of OBA stars by Lamers, Snow & Lindholm (1995) and employed by Vink et al. If instead the measured values of $v_\infty$ are used, wind momentum changes by $\sim 1/3$: however, as $\eta_s$ is sensitive to $B^2$, the resulting decrease in the magnetic field strength required to confine the wind is modest (a few G), and does not strongly affect the conclusions.

The dipolar field strengths required for a confinement $\eta_s = 1$, using theoretical mass-loss rates, are indicated by the solid lines in Fig. 4; dashed lines indicate the field strengths required according to empirical $M$. For $\beta$ Ori, $\alpha$ Cyg, $\nu$ Cep and 4 Lac, a magnetic dipole of sufficient polar strength to confine the wind in closed loops above the stellar surface is ruled out with a credibility greater than 95.4 per cent if the theoretical mass-loss rates are used. The relatively weak winds of $\eta$ Leo and HR 1040 mean that constraints are not as good for these stars. With the measured mass-loss rates, $\eta_s = 1$ cannot be ruled out for any of the stars.

The condition $\eta_s = 1$ is simply the threshold for magnetic confinement: in order to reproduce the variability seen in these stars, a larger value might be required. Based upon Hα visibilities, Chesneau et al. (2010) suggest that the emission line formation regions of $\alpha$ Cyg and $\beta$ Ori are extended to $\sim 1.5–1.75R_*$ from the stellar centre; differential phase signal variability additionally suggested significant perturbations in $\alpha$ Cyg’s wind at $2–3R_*$. While such precise measurements are unavailable for other programme stars, their similarity suggests that the same scales might reasonably be inferred to apply.

The Alfvén radius $R_A$ is the point at which the magnetic and kinetic energy densities in the wind are equal, and is typically taken as the outer boundary of the magnetic confinement region. At the magnetic equator, $R_A$ is related to $\eta_s$ via

$$\frac{R_A}{R_*} = \left(\frac{R_A}{R_*}\right)^{2-3} = \eta_s,$$

(3)

Table 3. 95.4 per cent credible upper limits for $B_\delta$, the probabilities that $\eta_s \leq X$, and the odds ratios $\log (M_0/M_1)$ for Stokes $V$ and diagnostic null.

| $\beta$ Ori | 4 Lac | $\eta$ Leo | HR 1040 | $\alpha$ Cyg | $\nu$ Cep |
|-------------|-------|-------------|---------|-------------|---------|
| $B_\delta (P_{\text{cred}} = 0.954) (G)$ | 22 | 14 | 15 | 30 | 3 | 13 |
| Theoretical $M$ | | | | | | |
| $P(\eta_s \leq 1)$ | 0.981 | 0.982 | 0.921 | 0.797 | 0.995 | 0.942 |
| $P(\eta_s \leq 25)$ | 0.999 | 0.999 | 0.993 | 0.985 | 0.999 | 0.999 |
| Observed $M$ | | | | | | |
| $P(\eta_s \leq 1)$ | 0.216 | 0.818 | 0.798 | 0.609 | 0.895 | – |
| $P(\eta_s \leq 25)$ | 0.929 | 0.992 | 0.976 | 0.961 | 0.995 | – |
| $\log (M_0/M_1) (V)$ | 0.988 | 0.552 | 1.192 | 0.588 | 1.267 | 0.285 |
| $\log (M_0/M_1) (N)$ | 0.909 | 0.600 | 1.094 | 0.543 | –0.299 | 0.868 |
where for a dipole $g = 3$ (ud-Doula & Owocki 2002). To achieve Alfvén radii of 2.5$R_{\odot}$, as implied by the radii of perturbations in $\alpha$ Cyg’s wind, $\eta_{s} \sim 25$ is required. The magnetic field strengths necessary for $\eta_{s} \leq 25$ assuming theoretical mass-loss rates are indicated in Fig. 4 with the dotted lines for theoretical $M$, while dot–dashed lines correspond to observed $M$. The probabilities $P(\eta_{s} \leq 25)$ for both theoretical and observed $M$ are given in Table 3. With theoretical mass-loss rates, $\eta_{s} \leq 25$ with greater than 95.4 per cent credibility for all stars; with observed $M$, $\eta_{s} \leq 25$ with greater than 95.4 per cent credibility for all stars but $\beta$ Ori.

The spectral variability attributable to the confined winds of known magnetic massive stars is notable for its precise periodicity, regardless of whether the stellar magnetospheres are purely dynamic (slow rotation) or contain a centrifugal component (rapidly rotating) (Petit et al. 2013). In many cases, such as the OF?p stars, rotational periods were determined from frequency analysis of spectral and photometric measurements before spectropolarimetry was available for magnetic analysis (Howarth et al. 2007; Wade et al. 2011). Conversely, as discussed in Section 1, unique periods have never been inferred for $\alpha$ Cyg variables. While there is evidence for rotational modulation of wind features (e.g. Kaufer et al. 1996a), this fundamental dissimilarity, in combination with the firm upper limits for $B_{\beta}$ and $\eta_{s}$, strongly indicates that magnetic wind confinement due to organized magnetic fields is not the cause of the wind variability of BA SG stars.

5.2 Local magnetic confinement

Magnetically confined winds as described above are found in the presence of large-scale, organized magnetic fields. However, in the case of the Sun by far the strongest magnetic fields are localized in sunspots, which have a substantial impact on the structure of the solar wind.

Analogous magnetic features have not been detected in early-type stars. However, bright, hot magnetic spots have been conjectured as a consequence of dynamo action within a thin Fe convection zone (FeCZ), arising from an increase in Fe opacity just below the photosphere (Cantiello et al. 2009, Cantiello & Braithwaite 2011). These spots would be transient features, forming when plasmoids rise from the FeCZ, with two footpoints remaining in the photosphere. The magnetic field within the spots is expected to be approximately normal to the stellar surface, with opposite polarities across each pair of spots (assuming magnetic flux conservation). Magnetic flux above the stellar surface could be expected to perturb the wind in its vicinity, potentially leading to a magnetically suspended loop of the sort suggested by Israeliain et al. (1997) in their examination of $\beta$ Ori’s HVAs.

Theoretical predictions of the lifetimes, sizes and number distributions of spots are quite open: spots might last anywhere from hours to decades, and have radii of the order of (or larger than) the pressure scaleheight $H_{p} = kT/\mu g$ within the FeCZ. With the temperature boundaries of the FeCZ ($10^{3}$–$10^{6}$ K), and the mean molecular weights and surface gravities of our sample stars as established through quantitative spectroscopy (Przybilla et al. 2006), we find that $H_{p}$ should be from $\sim 2–8 R_{\odot}$ at the top and bottom of the FeCZ for most stars, although in $\alpha$ Cyg (with its much lower surface gravity) $H_{p}$ may range up to 30 $R_{\odot}$.

A generous upper limit to the spot magnetic field can be determined via equipartition of energy within the FeCZ: since the features are likely to expand as they rise due to magnetic buoyancy, the magnetic field should not be stronger than that within the FeCZ. A lower limit can then be calculated via simple scaling relations. For BA SGs, magnetic features at the stellar surface could have field strengths between 5 and 1000 G (Cantiello & Braithwaite 2011).

The effect of bright spots, such as those suggested to be associated with magnetic structures such as those described above, on the stellar wind has been investigated by Cramner & Owocki (1996), who found that such spots would induce high-density, low-speed streams due to the enhanced driving force at the base of the wind. The bright spot modifies the wind density $\rho$ and wind velocity $v(r)$ from their unperturbed values $\rho_{0}$ and $v_{0}(r)$ (Cramner & Owocki 1996):

$$\rho = \rho_{0}(1 + A)^{s/\alpha},$$

$$v(r) = v_{0}(r)(1 + A)^{(1-s)/\alpha},$$

where $A = (T_{*} - T_{0})/T_{0} > 0$ is a dimensionless constant relating the relative effective temperatures of the spot, $T_{s}$, to the disc, $T_{\odot}$; $\alpha = 0.60$ is the line-driving constant; and $s = 1.77$ is an exponential constant found through a simultaneous constraint of the two fitting functions in equation (4) via conservation of mass for a spot with a Gaussian brightness distribution. From the definition of the wind magnetic confinement parameter (ud-Doula & Owocki 2002), $\eta(r, \theta)$ is modified above the bright spot from its unperturbed value $\eta_{0}(r, \theta)$ such that

$$\eta_{s}(r, \theta) = \eta_{0}(r, \theta) / (1 + A)^{2s/\alpha}.$$

The effect is to reduce $\eta(r, \theta)$, due to the overall enhancement of the wind momentum, with the magnitude of reduction increasing with $A$. Assuming $A = 0.5$ (implying temperature differences of $\sim 1000$ K), as used by Cramner & Owocki (1996), $\eta(r, \theta)$ should be depressed by around 10–15 per cent. In the context of the Cantiello & Braithwaite model, the spot’s brightness is a result of the magnetic field (which results in a lower density that makes deeper, hotter parts of the atmosphere visible; see David-Uraz et al., in preparation). The detailed atmospheric modelling required to explore the precise relationship between the magnetic field strength and spot brightness is outside the scope of this paper; in any case, spot brightness may play a limiting role in the magnetic field’s ability to confine the wind.

Since the extent of magnetic field lines is partly a function of the separation of the magnetic poles, the separation of the spots on the stellar disc also has an effect on $R_{\alpha}$. If we approximate the spots as the two poles of a magnetic dipole, $R_{\alpha}$ for a given $R_{s}$ should satisfy equation (3), with the modification that the stellar radius $R_{s}$ is replaced by the spot separation $D_{\text{spot}} = R_{s} \sin \theta / 2$, where $\theta$ is the angular separation of the spots. Equation (3) then becomes

$$\left[ \frac{R_{\alpha}}{R_{s} \sin \theta / 2} \right]^{2s/\alpha - 2} = \left[ \frac{R_{\alpha}}{R_{s} \sin \theta / 2} \right]^{2s/\alpha - 3} = \eta_{s}.$$

This increases the value of $\eta_{s}$ in equation (3) required to achieve a given $R_{\alpha}$, as shown in Fig. 5. To investigate the plausibility of equation (6), we examine a typical solar coronal giant arch (Reale 2010). The solar wind has $M \sim 2–3 \times 10^{-14} M_{\odot} \text{ yr}^{-1}$ and $v_{\infty} \sim 400 \text{ km s}^{-1}$. The footpoints of an arch possess $B_{\alpha} \sim 100 \text{ G}$, yielding $\eta_{s} \sim 5 \times 10^{3}$ from equation (2). With $D_{\text{spot}} \sim 3 \times 10^{4} \text{ km} \sim 0.04 R_{\odot} \sim 2.5$, equation (6) then gives $R_{\alpha} \sim 0.5 R_{\odot}$. The actual lengths of coronal arches vary from $\sim 0.1$ to $1.5 R_{\odot}$, in approximate agreement with equation (6).

Israeliain et al. (1997) estimated that spots were separated by $\sim 75^{\circ}$, based upon the time between blue- and redshifted HVA
Figure 5. Top: $R_A$ as a function of $\eta_\ast$ (black curves) for different spot separations (annotated, in degrees across the stellar surface). The scaling for a pure dipole is shown in red. The inner and outer regions of interest are shown with solid and dotted lines, respectively. Bottom: $R_A$ as a function of $\eta_\ast$ for different exponents $q$ (from top to bottom: 3, 4, 5, 6, 8, 11). Lines are labelled with the number of magnetic poles corresponding to each value of $q$.

absorption maxima. $R_A$ as a function of $\eta_\ast$ is shown for various separations in the top panel of Fig. 5, where $\eta_\ast$ is depressed by 15 per cent as per equation (5). Individual curves are labelled with the spot separation in degrees. Assuming a separation of $\sim 75^\circ$, $\eta_\ast \sim 25$ should be sufficient to confine the plasma to $\sim 1.5 R_\ast$; plasma can be confined out to $\sim 2.5 R_\ast$ if $\eta_\ast \sim 200$. The surface magnetic field strengths necessary to achieve these values are given in Table 1.

To investigate the detectability of magnetic spots in high-resolution Stokes $V$ spectra, Kochukhov & Sudnik (2013) performed detailed spectrum synthesis calculations for a grid of models with $v \sin i$ varying between 10 and 200 km s$^{-1}$, spot angular radii $r_\text{sp}$ between 2$^\circ$ and 40$^\circ$, and fixed parameters spot magnetic field strength $B_\ast = 500$ G, filling factor $f_{\text{sp}} = 0.5$, $T_\text{eff} = 20$ kK and $i = 60^\circ$. Each model consisted of a non-magnetic photosphere speckled with a random realization of spots, with equal numbers of positive and negative spots such that the net magnetic flux was zero. Kochukhov & Sudnik then calculated LSD Stokes $V$ profiles and $(B_\ast)$, which they used to provide upper limits based on the general characteristics of the MiMeS survey data.

Unsurprisingly, given the complexity of the magnetic topology, $(B_\ast)$ is an insensitive diagnostic of small-scale magnetism. Stokes $V$ is more sensitive: numerical experiments by Kochukhov & Sudnik showed that small-scale magnetic fields should register a marginal detection in the Stokes $V$ profile, provided the maximum Stokes $V$ amplitude is at least five times the error bar.

The stars considered in our sample differ considerably from the template used by Kochukhov & Sudnik, in particular being much cooler. Kochukhov & Sudnik note that decreasing $T_\text{eff}$ to 10 kK will increase the Stokes $V$ amplitude by $\sim 30$ per cent for slow rotators. Furthermore, the median error bars in the current sample are substantially better than those in the MiMeS survey data (25 G, as compared to 4.3 G for these stars).

After scaling for $T_\text{eff}$, we find approximate upper limits for spot magnetic fields by computing the difference between the expected maximum Stokes $V$ amplitude for a 500 G spot field (Fig. 5 of Kochukhov & Sudnik 2013) and five times the Stokes $V$ error bar in the LSD measurements (the minimum amplitude to register a marginal detection). The targets 4 Lac, $\eta$ Leo and $\upsilon$ Cep, which are slow rotators, were compared to the 10 km s$^{-1}$ $v \sin i$ curve; the other stars were compared to the 20 km s$^{-1}$ curve. The resulting upper limits are indicated as red curves in Fig. 6 (compare with Fig. 7 of Kochukhov & Sudnik 2013). For large spots, the upper limits in Fig. 6 approach those obtained for the dipolar magnetic field in Fig. 4.

These calculations assume a heavily spotted surface ($f_{\text{sp}} = 0.5$). Decreasing $f_{\text{sp}}$ will of course decrease both Stokes $V$ and $(B_\ast)$; however, the effect is not linear as with fewer spots the cancellation of magnetic flux becomes less efficient, e.g. a factor of 2.5 reduction in $f_{\text{sp}}$ will decrease the Stokes $V$ amplitude by only 50 per cent. Predictions for $f_{\text{sp}} = 0.2$ are indicated as green curves in Fig. 6. The best constraints are obtained for $\alpha$ Cyg, for which even small spots with $B_\ast > 150$ G can be ruled out; in general, $B_\ast < 10^2 \cdots 10^3$ G, depending on the spot size.

Large filling factors are unlikely to be compatible with extended magnetically confined wind structures, since the distance between any two given spots of opposite polarity (the footpoints of magnetic loops) will in general be small if the spots are randomly distributed on the photosphere. Values of $\eta_\ast$ calculated assuming a dipolar magnetic field must be modified by replacing the exponents $q = 3$ in equation (6) with a larger value, e.g. $q = 4$ for a quadrupole, $q = 5$ for an octopole, etc. In the limit of many spots, the photospheric magnetic field can be approximated with an extremely high-order multipole and a correspondingly large value of $q$, e.g. a photosphere with $f_{\text{sp}} = 0.5$ and $r_\text{sp} = 2^\circ$ will have $\sim 1640$ magnetic poles, in which case, $\eta_\ast$ of several thousand would be required to confine the wind even to $1.5 R_\ast$. The effect of varying $q$ is shown in the bottom panel of Fig. 5.

It is much easier to confine the wind if the magnetic flux is dominated by a single spot pair. A simple model was constructed to investigate the Zeeman signatures that would be produced by such a configuration (see Fig. 7). The field within the spots is normal to the stellar surface, with no magnetic field elsewhere; the surface field strength $B_\ast$ falls off azimuthally from the centre of the spot as $e^{-r/(r_{\text{pol}}^2)}$, roughly reflecting the field structure observed in sunspots. Spots are of identical $|B_\ast|$, opposite polarity, and identical angular radii (between $2^\circ$ and $40^\circ$ of the stellar surface, following Kochukhov & Sudnik). Limits were found by calculating the surface field strength necessary for the peak-to-peak amplitude of the Stokes $V$ signature to equal five times the noise level.

Given the relatively large inferred separation between spots ($\sim 75^\circ$, as discussed above), at any given time it is possible that...
only a single spot will be visible. The resulting limits are shown in Fig. 6 for the case of a single visible spot (blue lines) and two visible spots (brown lines). Note that, due to flux cancellation, a single spot is typically easier to detect than a pair of spots.

The magnetic field strengths necessary to obtain $\eta_*=25$ and 200, calculated from equations (5) and (6) with theoretical $\dot{M}$, are indicated with solid and dotted lines, respectively; dashed and dot-dashed lines indicate field strengths for the same values of $\eta_*$ calculated using observed values of $\dot{M}$. Assuming theoretical mass-loss rates, for all stars, a single spot pair with a magnetic field strong enough to confine the wind out to $2.5R_*$ could have remained undetected, so long as $r_{sp}<10^\circ$. With measured $\dot{M}$, in only a few cases can even the largest spots be ruled out.

As discussed in Section 3, some observations were fortuitously obtained during HVA events (see Fig. 1 and Table 2). In the case of $\alpha$ Cyg, the SNR is too low to obtain meaningful constraints. The same is true for the final observation of $\beta$ Ori, during which a magnetic spot may have been visible on the limb. In the case of $\nu$ Cep, however, the strongest HVAs also correspond to the highest SNR LSD profiles. Hence, the constraints provided in Fig. 6 bear directly on the magnetic hypothesis for HVA events, and it can be concluded that if magnetic spots play an important role, both $r_{sp}$

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**Figure 6.** Upper limits on spot surface fields $B_{sp}$ as a function of the spot radius $r_{sp}$ for the highest SNR observations for each star, for $f_{sp}=0.5$ (red), $f_{sp}=0.2$ (green), $N_{sp}=1$ (blue) and $N_{sp}=2$ (brown). Solid lines indicate $B_{sp}(\eta_*=25)$, dotted lines $B_{sp}(\eta_*=200)$, assuming two spots separated by 75° and theoretical $\dot{M}$. Dashed and dot-dashed lines indicate the same limits for measured $\dot{M}$.

**Figure 7.** Expected variation in Stokes $V$ for two magnetic spots separated by 75°, in rotational phase increments of 0.1. The amplitude of the signal is strongest when only a single spot is visible; furthermore, for the majority of rotational cycle, Stokes $V$ is dominated by a single spot.
and \( f_{\text{sp}} \) must be relatively small. However, it should be remembered that as this conclusion is based upon a theoretical mass-loss rate, measurement of \( M \) for this star would likely revise the magnetic field strengths necessary for wind confinement downwards by a factor of 5–10, as for the other stars in this sample, in which case these upper limits would no longer be able to rule out spots of even the largest size.

### 6 CONCLUSIONS

We have observed six BA SG stars using the high-dispersion spectropolarimeters ESPaDOnS and Narval. Spectral analysis of their H\( \alpha \) lines reveals wind behaviour consistent with previous observing campaigns. HVAs are detected in the H\( \alpha \) lines of \( \alpha \) Cyg and \( \nu \) Cep, while weak HVA-like behaviour is observed in \( \beta \) Ori \( \nu \) lines. No magnetic field is detected in any observation, with no Zeeman signatures visible in the LSD Stokes V profiles, and a mean precision of \( \sigma_{B_2} = 4 \) G in the longitudinal field, with the highest SNR LSD profile yielding \( \sigma_{B_2} = 0.5 \) G.

Spectral modelling of the LSD profiles, in conjunction with the Bayesian approach of Petit & Wade (2012), yields upper limits on the dipolar field strength that effectively rule out magnetic wind confinement due to a dipolar magnetic field with at least 95.4 per cent confidence for all stars but \( \beta \) Ori, which can only be constrained to 92.9 per cent confidence if empirical mass-loss rates are used. These measurements, and their resulting upper limits, represent the strongest constraints yet established for the magnetic fields of BA SG stars. However, these upper limits are sensitive to the mass-loss rates adopted, and should be revised if more accurate models of non-spherically symmetric wind structures, enabling more accurate measurement of \( M \), are developed.

If magnetic confinement of the stellar wind is a significant factor in the circumstellar dynamics of BA SG stars, the underlying field structure must be more complex than a global dipole. The existence of bright magnetic spots cannot be ruled out entirely based on the spot separation, requires that the spot surface magnetic fields be one to two orders of magnitude stronger than the lower limits established by Cantiello & Braithwaite (2011) if they are to confine the wind out to the radii inferred via spectro-interferometry (Chesneau et al. 2010; Kaufers et al. 2012). Whether it is realistic to produce such strong fields in the subsurface convection zones of these stars remains to be investigated. Furthermore, if theoretical mass-loss rates are assumed, the highest SNR observations of \( \alpha \) Cyg, \( \beta \) Ori and \( \nu \) Cep are able to effectively rule out magnetic wind confinement out to the observationally inferred radii of wind perturbations, even for very small spots, unless the spots cover substantially less than 20 per cent of the surface.

Due to the unknown sizes and lifetimes of spots, and the current inability to predict the circumstellar dynamics of \( \alpha \) Cyg variables, magnetic detection would require a significant investment in telescope time: first, spectral monitoring to identify moments of maximum spot detectability (e.g. the onset of an HVA event); secondly, deep spectropolarimetric observations in order to obtain LSD profiles with an SNR sufficient to detect spot magnetic fields. Such a programme would benefit from 3D magnetohydrodynamic modelling, which would help to investigate the feasibility of the bright magnetic spot model as the origin of HVA events, as well as from the development of non-spherically symmetric mass-loss models.

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