Discovery of a Centrifugal Magnetosphere Around the He-Strong Magnetic B1 Star ALS 3694

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Abstract. We report the results of 6 nights of Canada-France-Hawaii Telescope spectropolarimetric ESPaDOnS observations of the He-strong, magnetic B1 type star ALS 3694. The longitudinal magnetic field is approximately 2 kG in all 6 observations, showing essentially no variation between nights. The Hα line displays variable emission on all nights, peaking at high velocities (\(\sim 3v\sin i\)). Given the presence of a strong (\(B_d > 6\) kG) magnetic field, and the similarity of the emission profile to that of other magnetic B-type stars, we interpret the emission as a consequence of a centrifugal magnetosphere.

1. Introduction

ALS 3694 is a poorly studied star in the young open cluster NGC 6193 (Landstreet et al. 2007). It is relatively dim (\(V = 10.4\)), near the magnitude limit for high-resolution spectropolarimeters. Two FORS1 circularly polarized (Stokes \(V\)) observations have been reported by Bagnulo et al. (2006). A magnetic field was detected in both observations, with the mean longitudinal (line-of-sight) magnetic field \(B_Z = -1.9 \pm 0.2\) kG.

2. Observations

We have acquired 6 nights of ESPaDOnS observations of ALS 3694 with the Canada-France-Hawaii Telescope (CFHT). ESPaDOnS is a high-resolution (\(\lambda/\Delta \lambda \sim 65,000\)) spectropolarimeter, with a spectral window from 369 nm to 1050 nm. Each observation consists of four polarized sub-exposures, which are combined via the double-ratio method to yield a Stokes \(I\) (unpolarized intensity) and Stokes \(V\) spectrum (Donati et al. 1997). The 4 sub-exposures can also be combined in such a way that the intrinsic source polarization cancels out, yielding a diagnostic null \(N\) spectrum (Donati et al. 1997) which can be used to check for spurious Stokes \(V\) signatures arising at the instrumental level, or from radial velocity variation of the source due to binary motion or pulsation (e.g. Neiner et al. 2012).

The large visual magnitude of this star necessitated long integration times, 20 min per spectropolarimetric sequence. Between 2 and 4 successive sequences were col-
lected each night (16 individual polarized spectra in total). These were binned nightly. The mean peak SNR of the binned spectra is 145.

Figure 1.  Left: An example LSD profile. Top (filled circles), Stokes \( V \); middle (open diamonds) diagnostic null \( N \); bottom (solid line) Stokes \( I \). Vertical dotted lines indicate the integration range used for measurement of the longitudinal magnetic field. Horizontal dashed lines indicate continuum levels. Right: \( B_z \) measurements as a function of HJD. There is no variation from between nights outside the error bars. The solid and dotted horizontal lines indicate the mean \( B_z \) and the \( 1\sigma \) uncertainties from the two FORS1 measurements.

3. Magnetic Field

In order to increase the SNR, we performed Least Squares Deconvolution (LSD; Donati et al. 1997), using the ‘improved’ iLSD package provided by Kochukhov et al. (2010). This consists of deconvolving a mean line profile (the LSD profile) from the spectrum using a ‘line mask’: a series of delta functions at the laboratory wavelengths of the spectral lines, each weighted by the depth of the line, and the Landé factor (a dimensionless measure of the magnetic sensitivity of the line).

The line mask was downloaded from the Vienna Atomic Line Database, VALD2 (Piskunov et al. 1995; Ryabchikova et al. 1997; Kupka et al. 1999, 2000), created for a star with \( T_{\text{eff}} = 22 \) kK, \( \log g = 4.0 \), and solar metallicity. The raw line mask was cleaned of strong, pressure-broadened H lines, since these lines have a substantially different shape from the majority of photospheric absorption lines. Also removed were any He and metallic lines blended with H lines, interstellar lines, or telluric lines. While the usual cleaning procedure also removes the stronger He lines (since these are subject to pressure-broadening), in this case all such lines were included, as their contribution to increasing the SNR of the LSD profile outweighs their distortion of the Stokes \( I \) profile. The depths of the remaining lines were then empirically adjusted (‘tweaked’) so as to match the observed depths of the absorption lines (see Shultz et al. 2012 for an explanation of this process).

An example LSD profile is shown in Fig. 1. Stokes \( I \) shows extended wings due to the inclusion of strong He lines. The Zeeman signature of a magnetic field is clearly seen in Stokes \( V \), while the \( N \) profile is consistent with noise.

The line-of-sight (longitudinal) magnetic field was measured from the LSD profiles using zeroth moment of Stokes \( V \) normalized by the equivalent width of Stokes \( I \),
as described by Mathys (1989). $B_z$ is shown in Fig. 1 as a function of HJD. There is no variation outside error bars from night to night. Furthermore, all measurements are consistent with the earlier FORS1 data (Bagnulo et al. 2006).

4. Hα Emission

![Image](image.png)

Figure 2. Hα profiles. Solid vertical lines indicate $\pm v \sin i$, centred on the stellar systemic velocity. *Left:* ALS 3694 arranged in order of HJD. There is substantial night-to-night variability. *Right:* δ Ori C as a function of rotational phase.

Fig. 2 shows Hα profiles for ALS 3694, and for the magnetic B3 Vp star δ Ori C (note that δ Ori C is an SB2 (Leone et al. 2010), and has not been corrected for radial velocity variations). In both cases, emission is present in essentially all observations, either double- or single-peaked, with peaks in either the red- or blue-shifted wings of the lines. Vertical lines indicate $\pm v \sin i$: in both cases, emission peaks at $\sim 2 - 3v \sin i$. Note that we have re-measured $v \sin i$ for ALS 3694 using He, N, O, Ne, Si, and S lines, finding $v \sin i = 47 \pm 4$ km s$^{-1}$, substantially lower than the 82 km s$^{-1}$ reported by Landstreet et al. (2007).

5. Discussion

While the rotational period $P_{\text{rot}}$ is unknown, $P_{\text{rot}} < 1.5$ d for every known example of a magnetic B-type star with circumstellar emission (Shultz et al., these proceedings). Proceeding on the assumption that ALS 3694 is no exception, we estimate that the inclination $i$ of the rotational axis from the line of sight must be in the range $5^\circ < i < 21^\circ$, where the lower bound comes from the requirement that the equatorial rotational velocity must be less than the breakup velocity.
Adopting the method of Preston (1967) for determining the angle $\beta$ between the magnetic and rotational axes and the strength of the magnetic dipole $B_d$, we find that $15^\circ < \beta < 63^\circ$, and $B_d > 7$ kG. A small $i$ is also supported by the lack of variation in $B_Z$ (although of course, it is also possible that $i$ is large and $\beta$ is small). This arrangement, with a small $i$, moderate $\beta$, and substantial $B_d$, is reminiscent of that of $\delta$ Ori C ($i = 12 \pm 3^\circ$, $\beta < 52^\circ$, $B_d = 9.7 \pm 2.4$ kG; Leone et al. 2010).

Using the stellar parameters ($T_{\text{eff}} = 20 \pm 3$ kK, $\log (L_*/L_\odot) = 3.7 \pm 0.3$) given by Landstreet et al. (2007), and the mass-loss recipe of Vink et al. (2001) (yielding $\log M = 9 \pm 1$ and $v_\infty = 1750 \pm 750$ km s$^{-1}$), we estimate the Alfvén radius $R_A$ (that is, the maximum extent of closed magnetic loops) to be $R_A > 20R_*$ (ud-Doula & Owocki 2002). The Kepler radius $R_K$ (the radius at which centrifugal and gravitational forces balance; see Townsend & Owocki 2005, Ud-Doula et al. 2008, also Shultz et al., these proceedings) can be estimated from $v \sin i$, $R_*$, and the likelihood that $i$ is large: we then have $R_K < 2.9R_*$.

Given that $R_A >> R_K$, and the strong resemblance of ALS 3694’s H$\alpha$ emission to that of other magnetic B-type stars with detected magnetospheres, it seems very likely that ALS 3694 is the most recent example of the growing sub-class of magnetic B-type stars with centrifugal magnetospheres.

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