The two magnetic components in the Herbig Ae SB2 system HD 104237

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ABSTRACT

We present longitudinal magnetic field measurements ($B_z$) for the Herbig Ae primary and the T Tauri secondary in the SB2 system HD 104237. These measurements were carried out using high spectral resolution observations obtained with the High Accuracy Radial velocity Planet Searcher in polarimetric mode, installed at the ESO La Silla 3.6 m telescope. In agreement with previous studies of Herbig Ae stars, the longitudinal magnetic field in the primary is rather weak, ranging from 47 G to 72 G. The secondary component possesses a variable, much stronger magnetic field, up to 600 G, as expected for a magnetically active T Tauri star. We estimated the rotation period of the primary, $P_{\text{rot}} = 4.33717 \pm 0.00316 \text{d} (= 104 \pm 0.08 \text{h})$, from metal line equivalent width variations.

Key words: stars: individual: HD104237 – stars: magnetic field – stars: pre-main sequence – stars: variables: T tauri, Herbig Ae/Be

1 INTRODUCTION

It is generally accepted that magnetic fields are important ingredients in the star formation process (e.g., McKee & Ostriker 2007) and are already present in stars during the pre-main sequence (PMS) phase. However, it is still not clear whether these fields persist until the main sequence stage in the intermediate mass Herbig Ae stars with radiative envelopes. Studies of magnetic fields in such stars are of special interest to get an insight into the origin of strong kiloGauss-order magnetic fields observed in Ap and Bp stars on the main sequence.

While T Tauri stars with strong magnetic fields stand out by their strong emission in chromospheric and transition region lines, the presence of weak magnetic fields in the higher mass Herbig Ae/Be stars has long been suspected. The model of magnetically driven accretion and outflows successfully reproduce many observational properties of the classical T Tauri stars, but this picture is completely unclear for the Herbig Ae/Be stars due to the poor knowledge of their magnetic field topology. So far, only about 20 Herbig stars have been reported to host magnetic fields (Hubrig et al. 2015, and references therein), and the magnetic field geometry has been constrained only for two Herbig Ae/Be stars, V380 Ori (Alecian et al. 2009) and HD101412 (Hubrig et al. 2011). Magnetic fields in Herbig Ae stars are generally very weak: only a few stars have magnetic fields stronger than 200 G and half of the known cases possesses magnetic fields of about 100 G or less (Hubrig et al. 2015).

HD 104237 (DX Cha) is a spectroscopic and visual binary system with a companion at a distance of $2.2 \pm 0.7 \text{mas}$ (Garcia et al. 2013). The primary component is known to show δ Scuti-like pulsations (Böhm et al. 2004). Garcia et al. (2013) give mass estimates for both companions, $M_1 = 2.2 \pm 0.2 M_\odot$ and $M_2 = 1.4 \pm 0.3 M_\odot$, and the system inclination angle $i = 175^{\circ}12$. Böhm et al. (2004) estimated the orbital elements of the system $P_{\text{orb}} = 19.859 \text{d}$ and $e = 0.665$. The rotation period $P_{\text{rot}} = 100 \pm 5 \text{h}$ of the primary has been reported by Böhm, Dupret & Aynedjian (2006).

The basic stellar parameters of HD 104237 were determined in a number of studies (Grady et al. 2004; Böhm et al. 2004; Fumel & Böhm 2012; Cowley, Castelli & Hubrig 2013). The most recent analysis by Cowley, Castelli & Hubrig (2013) yielded $T_{\text{eff}} = 8250 \text{K}$, $\log g = 4.2$, and $v \sin i = 8 \text{km s}^{-1}$ for the primary and...
The orbital phases of the observations, following the orbital parameters of Böhm et al. (2004). The filled symbols correspond to the primary component and the open symbols to the secondary. The square symbol at phase 0.914 shows the observation published by Järvinen et al. (2015). The horizontal dashed line indicates the $\gamma$ velocity and the vertical dashed line indicates $\varphi = 0$ (periastron).

$T_{\text{eff}} = 4800$ K, $\log g = 3.7$, and $v \sin i = 12$ km s$^{-1}$ for the secondary. The spectrointerferometric study by Garcia et al. (2013) with AMBER on the Very Large Telescope Interferometer in the K-band continuum and the Br$\gamma$ line suggested the presence of a circumbinary disc with a radius of about 0.5 AU. However, about 50 per cent of the flux remained unresolved and not fully accounted for by the stellar photospheres. The authors suggested that this unresolved flux likely arises in compact structures inside the tidally disrupted circumbinary disk.

The possible presence of a magnetic field in HD 104237 of the order of 50 G was announced over 20 years ago by Donati et al. (1997). However, the first low-resolution polarimetric spectra with FORS 1 on the Very Large Telescope yielded a non-detection (Wade et al. 2007). The observations obtained with the University College London Échelle Spectrograph (UCLES)/Semelpol at the Anglo-Australian Telescope (AAT) showed a field of negative polarity, but no field strength was reported (Wade et al. 2011). Hubrig et al. (2013) estimated $B_2 = 63 \pm 15$ G for the primary from a HARPSpol spectrum obtained on May 3, 2010. More recently, Järvinen et al. (2015) reanalyzed the 2010 data using a different technique and reported a definite detection for the T Tauri secondary ($B_2 = 129 \pm 12$ G) and a marginal detection of 13 G for the primary.

In the following, we report on our most recent longitudinal magnetic field measurements in both components of this SB2 system using ESO archival observations obtained with the High Accuracy Radial velocity Planet Searcher polarimeter (HARPSpol; Snik et al. 2008) in March 2015.

## 2 OBSERVATIONS AND MAGNETIC FIELD MEASUREMENTS

All HARPS spectropolarimetric observations used in our study have a spectral resolution of about 115 000 and cover the spectral range 3780–6910 Å, with a small gap between 5259 A and 5337 A. Each observation obtained in 2010 consisted of eight subexposures with exposure times of about two minutes whereas in 2015 each observation consisted of four subexposures with exposure times of about four minutes. The quarter-wave retarder plate was rotated by 90° after each subexposure. The final polarimetric spectrum is the combination of the subexposures recorded at four different positions of the quarter-wave retarder plate. The reduction and calibration of these spectra was performed using the HARPS data reduction software available at the ESO headquarter in Germany. The continuum normalization of the spectra is described in detail by Hubrig et al. (2013). The distribution of the observations over the orbital phase is illustrated in Fig. 1. The orbital solution of this system was presented by Böhm et al. (2004): HJD = 2451647.505, $P_{\text{orb}} = 19.859$ d, $e = 0.665$, $\gamma = 13.943$ km s$^{-1}$, $K_1 = 17.8$ km s$^{-1}$.

As all HARPS spectra have a rather low signal-to-noise ratio (S/N), in the range of 60–100, to increase the S/N, we applied the Least Squares Deconvolution (LSD; Donati et al. 1997) technique. LSD is a cross-correlation technique for computing average Stokes profiles from tens or hundreds of spectral lines simultaneously. It is based on the assumption that all spectral lines have the same profile and that they can be added linearly. Our line mask containing 715 spectral lines made use of the Vienna Atomic Line Database (VALD; e.g. Kupka et al. 2011; Ryabchikova et al. 2015) and was based on the stellar parameters of the primary component of HD 104237 ($T_{\text{eff}} = 8250$ K, $\log g = 4.2$; Cowley, Castelli & Hubrig 2013). The results of the application of the LSD technique to all available 88 spectra are presented in Fig. 2.

As illustrated in this figure, the LSD spectra still appear very noisy. Therefore, to more accurately characterize the magnetic field variability in both components, we applied the dedicated Singular Value Decomposition technique (SVD; Carroll et al. 2012) to a number of spectra recorded around three orbital phases, which represent the distribution of the observations over the orbital cycle. Around phase 0.94 we see the largest separation of the components and around orbital phases 0.45 and 0.54 the components come closer and appear blended. The SVD approach is very similar to that of the Principle Component Analysis (PCA). In this technique, the similarity of the individual Stokes $V$ profiles allows one to describe the most coherent and systematic features present in all spectral line profiles as a projection onto a small number of eigenprofiles. The excellent potential of the SVD method, especially in the analysis of weak magnetic fields in Herbig Ae stars, was already presented by Hubrig et al. (2015) and Järvinen et al. (2015, 2018).

The mean longitudinal magnetic field is deduced by computing the first-order moment of the Stokes $V$ profile according to Mathys (1989):

$$
\langle B_s \rangle = -2.14 \times 10^{11} \frac{\int uV(u)du}{\log \left | I_e - I(0) \right | du},
$$

(1)

where $u$ is the Doppler velocity in km s$^{-1}$, and $\lambda_0$ and $g_0$ are the mean values for the wavelength (in nm) and the Landé factor obtained from all lines used to compute the SVD profile, respectively. The results of the magnetic field measurements are presented in Table 1 and the corresponding SVD profiles are shown in Fig. 3.

The three SVD profiles shown on the bottom panel of Fig. 3 ($\varphi_{\text{orb}} = 0.934 - 0.950$) represent the situation where both components are well separated. These observations
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were obtained within 7.6 h. We detect a definite magnetic field of positive polarity in both components. The magnetic field of the primary is weak varying from 47 G to 72 G, in agreement with previously reported values. Within the same time interval, the magnetic field of the T Tauri component shows strong variability, decreasing from $\langle B_z \rangle = 609 \pm 27$ G to $\langle B_z \rangle = 124 \pm 13$ G.

To measure longitudinal magnetic fields in other phases, where the components are blended, we assumed that the contribution of the primary to the magnetic field is weak and the strong Stokes V Zeeman features are related to the T Tauri star. To be able to estimate its magnetic field strength, we have calculated the average Stokes I profile of the secondary using the individual profiles in spectra obtained in the phases where the components are well separated. As we show in the left of Fig. 4, the line profile variability for the secondary component on short and long-time scales is not very strong.

The three SVD profiles shown in the middle panel of Fig. 3 ($\phi_{\text{orb}} = 0.453 - 0.455$) correspond to observations taken within 57 minutes. Within this time interval, the $\langle B_z \rangle$ increases from 144 G to 410 G and then decreases back to 189 G. As we show in the right of Fig. 4, also the Stokes I profiles show strong variability at this orbital phase range. The Stokes I and V profiles shown in the top panel of Fig. 3 ($\phi_{\text{orb}} = 0.544 - 0.547$) also show significant variability, but the field strength remains almost constant with $\langle B_z \rangle \approx 350$ G over a 1.4 h time interval.
The resulting $F$-statistics (2019) can be thought of as the total sum, in-

Table 1. Mean longitudinal magnetic field strengths of HD 104237 on different orbital phases obtained using the Single-

| HJD     | $\varphi_{\text{orb}}$ | $\langle B_{2,\text{prim}} \rangle$ (G) | $\varphi_{\text{rot}}$ | $\langle B_{2,\text{sec}} \rangle$ (G) |
|---------|-----------------|-----------------|-----------------|-----------------|
| 57097.8646 | 0.453 | — | 0.666 | 144±15 |
| 57097.8773 | 0.454 | — | 0.669 | 410±22 |
| 57097.9026 | 0.455 | — | 0.675 | 189±19 |
| 57099.6739 | 0.544 | — | 0.083 | 366±21 |
| 57099.6865 | 0.545 | — | 0.086 | 349±22 |
| 57099.7245 | 0.547 | — | 0.095 | 338±20 |
| 55319.2131 | 0.914 | 13±8 | 0.687 | 129±12 |
| 57087.5575 | 0.934 | 72±6 | 0.290 | 609±27 |
| 57087.7215 | 0.943 | 47±6 | 0.328 | 440±23 |
| 57087.8880 | 0.950 | 63±6 | 0.366 | 124±13 |

Note: $^1$ From Järvinen et al. (2015).

3 SEARCHING FOR THE ROTATION PERIOD OF THE PRIMARY

The EWs of the Stokes $I$ LSD profiles of the primary component can be used to search for a periodicity corresponding to the rotation period. The search for the period was carried out using a non-linear least-squares fit to multiple harmonics using the Levenberg–Marquardt method (Press et al. 1992).

We calculate the frequency spectrum with a specific number of trial frequencies within the region of interest. A weighted linear least-squares fit is used for each frequency to fit a sine curve and bias offset. Based on the result of the fit, we make a statistical test to check the null hypothesis on the absence of periodicity, i.e. to check the statistical significance of the amplitude of the fit (Seber 1977). The resulting $F$-statistics presented in Fig. 5 can be thought of as the total sum, including covariances of the ratio of harmonic amplitudes to their standard deviations. The measured EWs phased with the best period of $4.33717\pm0.00316$ d ($T_p = 2457886.3$) are presented in Fig. 5. The contribution of the secondary to the EWs ($0.36$ km s$^{-1}$) at phases where the components are blended was removed from the measured values. The dispersion seen in the EW measurements is probably caused by 8 Scuti-like pulsations in the primary component and a possible presence of temperature spots in the secondary. Due to the weakness of the Stokes $I$ LSD profiles calculated for the secondary component, no analysis of the its periodicity can be carried out.

4 DISCUSSION

Our analysis of HARPSpol observations of the SB2 system HD 104237 shows that both components, the Herbig Ae star and the lower mass T Tauri star possess a magnetic field. The magnetic field of the Herbig Ae primary was measured at phases where both components are well separated. In other phases, where the components are blended, the Stokes $V$ profiles were assumed to be dominated by the magnetic field of the T Tauri secondary. The longitudinal magnetic field of the Herbig Ae star is weak and is only slightly changing from $47$ G to $72$ G. According to Alecian (2014), the magnetic properties of A- and B-type stars must have been shaped.

Figure 3. Single-Value-Decomposition Stokes $I$ (bottom), $V$ (middle), and diagnostic null ($N$) profiles (top) obtained for HD 104237 at different orbital phases. The Stokes $V$ and $N$ profiles have been amplified by a factor of 50. The profiles are sorted according to the observing date. The components in the system are marked with ticks below the Stokes $I$ profiles. The horizontal dashed lines indicate the ±1σ-ranges.

Figure 4. Line profile variability observed in the LSD Stokes $I$ profiles. The profiles were shifted according to the orbital motion. Left: Profiles of the secondary component of HD 104237 obtained during the nights when the components are well separated. There are 17 spectra taken within a nine hour interval during the night of MJD 57087 (bottom panel) and 20 for the following night (MJD 57088; middle panel). The total exposure time of each spectrum obtained from the combination of the four subexposures is about 18 minutes. The average profiles for each night are shown on the top panel. Right: Profiles of the primary component during the night where we detect strong variability in the magnetic field strength.
before the Herbig Ae/Be phase of stellar evolution. Using pre-main sequence evolutionary tracks calculated with the CESAM code (Morel 1997), she concluded that even stars above three solar masses will undergo a purely convective phase before reaching the birthline. Therefore, it is plausible that the weak magnetic fields detected in a number of Herbig Ae/Be stars are just leftovers of the fields generated by a dynamo mechanism during the convective phase. If this scenario is valid, we should expect a significantly larger number of Herbig stars possessing weak magnetic fields.

The rather strong longitudinal magnetic field of the T Tauri star was estimated on multiple epochs and shows strong variability. In orbital phases where the T Tauri component indicates a rotation period of 4.33717 d. The peak at 0.23057 d−1 corresponds to a period of 4.33717 d. The window function is denoted with a blue dotted line. Bottom: EWs measured in the primary phased with the period of 4.33717 d.

A search for magnetic fields and the determination of their geometries in close binary systems is very important as the knowledge of the presence of a magnetic field and of the alignment of the magnetic axis with respect to the orbital radius vector in Herbig binaries may hint at the mechanism of the magnetic field generation. Järvinen et al. (2018) reported a magnetic field detection on the secondary component of the Herbig Ae double-lined spectroscopic binary AK Sco in the region of the stellar surface facing permanently the primary component. This indicates that the magnetic field geometry in the secondary component is likely related to the position of the primary component. A similar magnetic field behaviour, where the field orientation is linked to the companion, has previously been detected in two other binaries, the so far only known close main-sequence binaries with Ap components, HD 98088 and HD 161701 (Babcock 1958; Hubrig et al. 2014).

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