The prevalence of weak magnetic fields in Herbig Ae stars: The case of PDS 2

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ABSTRACT
Models of magnetically driven accretion and outflows reproduce many observational properties of T Tauri stars, but the picture is much less clear for the Herbig Ae/Be stars, due to the poor knowledge of their magnetic field strength and topology. The Herbig Ae star PDS 2 was previously included in two magnetic studies based on low-resolution spectropolarimetric observations. Only in one of these studies the presence of a weak mean longitudinal magnetic field was reported. In the present study, for the first time, high-resolution HARPS spectropolarimetric observations of PDS 2 are used to investigate the presence of a magnetic field. A firm detection of a weak longitudinal magnetic field is achieved using the multi-line singular value decomposition method for Stokes profile reconstruction ($\langle B_z \rangle = 3.5 \pm 5$ G). To gain better knowledge of typical magnetic field strengths in late Herbig Be and Herbig Ae stars, we compiled previous magnetic field measurements, revealing that only very few stars have fields stronger than 200 G, and half of the sample possesses fields of about 100 G and less. These results challenge our current understanding of the magnetospheric accretion in intermediate-mass pre-main sequence stars as they indicate that the magnetic fields in Herbig Ae/Be stars are by far weaker than those measured in T Tauri stars.

Key words: stars: pre-main sequence — stars: individual (PDS 2) — stars: magnetic field — stars: oscillations — stars: variables: general

1 INTRODUCTION
Recent observations of the disk properties of intermediate mass Herbig Ae and late Herbig Be stars suggest a close parallel to T Tauri stars, revealing the same size range of disks, similar optical surface brightness and similar structure consisting of inner dark disk and a bright ring. Models of magnetically driven accretion and outflows successfully reproduce many observational properties of low-mass pre-main sequence stars, the classical T Tauri stars. However, due to the very poor knowledge of the magnetic field strength and magnetic field topology in Herbig stars, current theories are not able to present a consistent scenario of how the magnetic fields in Herbig Ae/Be stars are generated and how these fields interact with the circumstellar environment, consisting of a combination of accretion disk, magnetosphere, and disk-wind region or jets.

As of today, only about 20 late Herbig Be and Herbig Ae stars have been reported to possess large-scale organized magnetic fields (e.g., Hubrig et al. 2009; Alecian et al. 2013a), using low- and/or high-resolution spectropolarimetric observations. Moreover, only for the two Herbig Ae stars HD 101412 and V380 Ori (Hubrig et al. 2011a; Alecian et al. 2009), the magnetic field geometry has been constrained in previous studies. It is very likely that the rather low detection rate of magnetic fields in Herbig Ae stars can be explained by the weakness of these fields and/or by rather large measurement uncertainties. Indeed, in the currently largest high-resolution spectropolarimetric survey of the magnetic field in these stars by Alecian et al. (2013a) with 132 measurements for 70 Herbig stars, the measurement uncertainty is worse than 200 G for 35% of the measurements, and for 32% of the measurements it is between 100 and 200 G, i.e. only 33% of the measurements showed a measurement accuracy below 100 G. Therefore, any new detection/confirmation of the presence of a magnetic field in a Herbig Ae/Be star is important to increase the sample of magnetic Herbig stars. Clearly, only after we gain knowledge of the magnetic field strength and its topology, can we start to understand how it interacts with the circumstellar environment.

Polarimetric observations of the Herbig Ae star PDS 2 (CD −53° 251) were obtained on two different epochs using the HARPS polarimeter. This star has been identified as a Herbig Ae candidate star in the Pico dos Dias Survey by Gregorio-Hetem et al. (1992). PDS 2 displays Hα in emission, and the pre-main sequence nature is indicated by its IRAS colours. The mass accretion rate was determined by Pogodin et al. (2012) on eight epochs using different spectral accretion indicators from the near-UV to the near-IR. This work revealed short-term night-to-night variability, as well as long-term variability on a time scale of tens of days.
Using the 0.6 m R.E.M. telescope on La Silla, a preliminary analysis of PDS 2 by Bernabei et al. (2007) showed the presence of δ Scuti-like pulsations with three frequencies on a time scale of 1.0–1.7 h. The refined analysis of the same data by Marconi et al. (2010) revealed pulsations at four frequencies with pulsation periods between 0.9 and 2.0 h. The relatively low projected rotation velocity, $v \sin i = 12 \pm 2 \text{ km s}^{-1}$, and the fundamental parameters, $T_{\text{eff}} = 6500 \text{ K}$ and $\log g = 3.5$, were recently determined by Cowley et al. (2014) using high-resolution HARPS spectra. According to their results, PDS 2 belongs to the class of Herbig Ae stars resembling the chemical composition of α Boo stars.

Due to the relative faintness of PDS 2 ($V = 10.8$), the presence of a magnetic field was not previously studied using high-resolution polarimetric spectra. In the past, this star was included in two magnetic studies based on low-resolution spectropolarimetric observations obtained with FORS1 (Focal Reducer low dispersion Spectrograph) mounted at the 8-m Kueyen telescope of the VLT. While in the first study by Wade et al. (2009) no convincing evidence for the presence of a magnetic field in PDS 2 was found, Hubrig et al. (2009) reported on the detection of a mean longitudinal magnetic field ($B_z = 103 \pm 29 \text{ G}$). Bagnulo et al. (2012) disputed this detection after re-examining the FORS1 data using their semi-automatic measurement procedure.

In Sect. 2 we describe the observations and data reduction, and in Sect. 3 we discuss the methods and results of our magnetic field measurements. The density distribution of longitudinal magnetic fields in magnetic late Herbig Be and Herbig Ae stars is presented in Sect. 4. Finally, in Sect. 5 we discuss the significance of the obtained results for the improvement of our knowledge of the role of magnetic fields in intermediate-mass pre-main sequence stars.

2 OBSERVATIONS AND DATA REDUCTION

Two spectropolarimetric observations of PDS 2 were obtained with the HARPS polarmeter (HARPSpol; Snik et al. 2008) attached to ESO’s 3.6 m telescope (La Silla, Chile) on the nights of 2012 July 15 and 18. These spectra were originally recorded as part of ESO programme 187.D-0917(C) (PI: Alecian) and were downloaded from the ESO archive under request MSCHOELLER 77411. Each observation was split into eight subexposures with an exposure time of 15 min, obtained with different orientations of the quarter-wave retarder plate relative to the beam splitter of the circular polarimeter. The time to complete the cycle of eight subexposures for each observation accounted for 2 h and 4 min. The achieved signal-to-noise ratio ($S/N$) in the final Stokes $I$ spectra summed over eight subexposures is rather low, accounting for a $S/N = 74$ during the night of 2012 July 15, and a $S/N = 65$ for the second night on 2012 July 18. The spectra have a resolving power of about $R = 115 000$ and cover the spectral range 3780–6910 Å, with a small gap between 5259 and 5337 Å. The reduction and calibration of these spectra was performed using the HARPS data reduction software available at the ESO headquarters in Germany.

The normalisation of the spectra to the continuum level consisted of several steps described in detail by Hubrig et al. (2013b). The Stokes $I$ and $V$ parameters were derived following the ratio method (Timbergen & Rutten 1992; Donati et al. 1997), and null polarisation spectra were calculated by combining the subexposures in such a way that polarisation cancels out. These steps ensure that no spurious signals are present in the obtained data (e.g. Ilyin 2012).

| HJD   | S/N | S/N$_{\text{SVD}}$ | (B$_{\text{I}}$)$_{\text{SVD}}$ [G] | Moment technique (B$_{\text{I}}$)$_{\text{FF}}$ [G] | (B$_{\text{I}}$)$_{\text{FF,$\text{SVD}$}}$ [G] |
|-------|-----|-------------------|-------------------------------|---------------------------------|---------------------------------|
| 2456123.906 | 74 | 2420 | 5±5 | 23±5 | 22±26 |
| 2456126.904 | 65 | 2350 | 33±5 | 85±26 | 18±28 |

3 MAGNETIC FIELD MEASUREMENTS

The software packages used by our group to study stellar magnetic fields are the moment technique developed by Mathys (e.g. 1991) and the so-called multi-line Singular Value Decomposition (SVD) method for Stokes profile reconstruction recently introduced by Carroll et al. (2012). Usually, before we apply the SVD method, we examine the presence of wavelength shifts between right- and left-hand side circularly polarized spectra (interpreted in terms of a longitudinal magnetic field ($B_z$)) in a sample of clean unblended spectral lines using the moment technique. This technique allows us not only the estimation of the mean longitudinal magnetic field, but also to prove the presence of crossover effect and of the quadratic magnetic field. This information is highly important as, depending on the magnetic field geometry, even stars with rather weak longitudinal magnetic fields can exhibit strong crossover effects and kG quadratic fields (see e.g. Mathys 1995; Landstreet & Mathys 2000; Mathys & Hubrig 1995, 2005). In the study of PDS 2, for each line in the selected sample of 44 unblended Fe II lines, the measured shifts between the line profiles in the left- and right-hand circularly polarized HARPS spectra are used in a linear regression analysis in the $\lambda_{\text{I}}$ versus $\lambda_{\text{I,rad}}$ diagram, following the formalism discussed by Mathys (1991, 1994). Our measurements $(B_z) = 23 \pm 25 \text{ G}$ and $(B_z) = 82 \pm 26 \text{ G}$ achieved on the first and second epochs, respectively, indicated the probable presence of a weak magnetic field on the second epoch. No crossover or mean quadratic magnetic field at a significance level of 3σ has been detected on either observing night, probably due to the rather low S/N of the observed spectra. The measured values for the mean longitudinal magnetic field ($B_z$) are presented in the fifth column of Table 1. In the last column, we also present the results of the magnetic field measurements using the null polarisation spectra, labeled with $n$. Since no significant fields could be determined from the null spectra, we conclude that no noticeable spurious polarisation is present.

The basic idea of the SVD method is similar to the Principal Component Analysis (PCA) approach of Martínez González et al. (2008, Semel et al. 2009), where 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.

As we mentioned above, the star PDS 2 was reported to show δ Scuti-like pulsations on a time scale between 0.9 and 2.0 h. Since the full HARPS exposure times of about 2 h on both nights are of the same order, and pulsations are known to have an impact on the analysis of the presence of a magnetic field and its strength (e.g., Schnerr et al. 2006; Hubrig et al. 2011b), as a first step, we verified that no change in the line profile shape or radial velocity shifts are present in the obtained spectra. In Fig. 1 on the left side we present overlapped Stokes $I$ profiles computed for the individual subexposures recorded on both nights. On the right side of this figure we
show differences between the Stokes I profiles computed for the individual subexposures and the average Stokes I profile. No impact of pulsations at a level higher than the spectral noise is detected in the Stokes I profiles.

The resulting mean Stokes I, Stokes V, and Null profiles obtained by using the SVD method with 2094 metallic lines in the line mask are presented in Fig. 2. The line mask was constructed using the VALD database (e.g. Kupka et al. 2000) and the respective stellar parameters of PDS 2. Due to the very low signal-to-noise at the blue and red ends of the HARPS spectra, the spectral lines used for the computation of the SVD profiles have been selected in the wavelength region from 4200 to 6200 Å. The mean longitudinal magnetic field is estimated from the SVD reconstructed Stokes V and I using the center-of-gravity method (see e.g. Carroll & Strassmeier 2014). A velocity range ±21 km s\(^{-1}\) was adopted to determine the detection probability and the longitudinal magnetic field value. For both observations the null spectra appear flat, indicating the absence of spurious polarisation. No longitudinal magnetic field is detected on the first epoch on 2012 July 15, where we measure \(\langle B_z \rangle = 5 \pm 5\) G. A definite detection of a field, \(\langle B_z \rangle = 33 \pm 5\) G, with a false alarm probability (FAP) smaller than \(10^{-6}\), is achieved on the second epoch three nights later.

In Table 1 we list for the two observations the heliocentric Julian date, the \(S/N\) reached in the final Stokes I profiles, the \(S/N\) obtained in the SVD profile, the longitudinal magnetic field \(\langle B_z \rangle\) determined with SVD, and \(\langle B_z \rangle\) determined with the moment technique from iron lines.

### 4 MAGNETIC FIELD MEASUREMENTS REPORTED IN PREVIOUS SPECTROPOLARIMETRIC STUDIES

As the magnetic field strength and the magnetic field geometry in Herbig stars are poorly known – only about 20 late Herbig Be and Herbig Ae stars have been reported to possess large-scale organized magnetic fields – we compiled for them all magnetic field measurements reported in previous spectropolarimetric studies. In Table 2 we present the \(\langle B_z \rangle\) values selected from previous low-resolution spectropolarimetric studies with FORS 1/2, where magnetic field measurements were carried out using the entire spectra, and high-resolution spectropolarimetric studies using the HARPS, ESPaDOnS, and Narval spectrographs. The rms longitudinal magnetic field, the rms standard error, and the reduced \(\chi^2\) for these measurements have been computed following the equations of Borra et al. (1983):

\[
\langle B_z \rangle = \left( \frac{1}{n} \sum_{i=1}^{n} \langle B_z \rangle_i \right)^{1/2},
\]

\[
\sigma = \left( \frac{1}{n} \sum_{i=1}^{n} \sigma_i^2 \right)^{1/2},
\]

\[
\chi^2/n = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{\langle B_z \rangle_i}{\sigma_i} \right)^2.
\]
5 DISCUSSION

In this work, we present the first detection of a weak magnetic field in the Herbig Ae star PDS 2 using high-resolution spectropolarimetric observations with HARPS. Previous observations using low-resolution spectropolarimetry with FORS 1 indicated \( \langle B_z \rangle = 103 \pm 29 \) G (Hubrig et al. 2009). Apart from PDS 2, the authors announced the detection of a weak longitudinal magnetic fields in six other Herbig Ae stars. Confirmation of the definite presence of the magnetic field based on accurate high-resolution spectropolarimetry with low uncertainties is still pending for these other six stars. Among these Herbig Ae/Be stars, three show longitudinal magnetic fields below 100 G, while for the remaining three stars the magnetic field ranges from 100 to 200 G.

Magnetospheric accretion has been well established for T Tauri stars and depends on a strong ordered predominantly dipolar field channeling circumstellar disk material to the stellar surface via accretion streams. However, no convincing scenario on how magnetospheric accretion works in Herbig Ae stars possessing rather weak magnetic fields currently exists. Cauley & Johns-Krull (2014) recently studied He \( \lambda \) 110830 morphology in a sample of 56 Herbig Ae/Be stars. They suggest that Herbig Be stars do not accrete material from their inner disks in the same manner as T Tauri stars, while late Herbig Be and Herbig Ae stars show evidence for magnetospheric accretion. Further, due to their high rotation rates (Muzerolle 2004) and weak magnetic fields, more compact magnetospheres in Herbig stars are proposed. We note that since the rotation period of PDS 2 is currently unknown, it is not clear whether it might be a rapid rotator with a low inclination of the rotation axis.

In fact, the density distribution of the rms longitudinal magnetic field strength clearly indicates that the magnetic fields in Herbig Ae stars are by far weaker than those measured in their lower mass counterparts, the T Tauri stars, usually possessing kG magnetic fields. As is shown in Fig. 3 out of the sample of twenty magnetic late Herbig Be and Herbig Ae stars, only very few stars have rms fields stronger than 200 G, and half of the sample possesses magnetic fields of about 100 G and less. The obtained results seem to support the existence of a different accretion mechanism mediating the mass flow from the disk to the intermediate-mass star, compared to that working in T Tauri stars. Noteworthy, for the currently best studied Herbig Ae stars, HD 101412 and V380 Ori with strong magnetic fields monitored over the rotation cycles, the obtained magnetic field models assuming a simple centered dipole indicate rather large obliquity \( \beta \) of the magnetic axis to the rotation axis (Hubrig et al. 2011b; Alecian et al. 2009). The fact that the dipole axes are located close to the stellar equatorial plane is very intriguing in view of the generally assumed magnetospheric accretion scenario. As was shown in the past (Romanova et al. 2003), the topology of the channeled accretion critically depends on the tilt angle between the rotation and the magnetic axis. For large inclination angles \( \beta \), many polar field lines would thread the inner region of the disk, while the closed lines cross the path of the disk matter, causing strong magnetic braking. Clearly, the qualitative picture is expected to be different if the magnetic field topology was proven to be more complex than a simple centered dipole model.

For a better understanding of the role of magnetic fields in Herbig Ae/Be stars, it is important to carry out additional highly accurate magnetic field measurements of a representative sample of Herbig Ae stars over their rotation periods using high quality, high-resolution polarimetric spectra. Using multi-epoch observations, it will become possible to disclose the magnetic topology on the surface of Herbig Ae stars necessary to understand the interaction of the magnetic field with winds, accretion disks, convection, turbulence, and circulation.

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Catala C., et al., 2007, A&A, 462, 293
### Table 2.

| Name      | Sp. T. | N_{lowres} | N_{hires} | ⟨Bz⟩ [G] | σ [G] | χ^2/n     | References                  |
|-----------|--------|------------|-----------|----------|-------|-----------|----------------------------|
| PDS 2     | F2     | 3          | 2         | 75       | 25    | 14.69     | W07 H09 H15                 |
| HD 31648  | A3     | 2          | 5         | 416      | 125   | 9.25      | H07 W07 H11b A13a           |
| HD 35929  | F2     | 1          | 5         | 54       | 23    | 5.84      | W07 A13a                    |
| HD 36112  | A5     | 1          | 2         | 89       | 84    | 1.11      | W07 A13a                    |
| V880 Ori  | A1     | 3          | 24        | 348      | 137   | 10.09     | W05 W07 A09                 |
| BF Ori    | A2     | 1          | 2         | 87       | 36    | 16.18     | W07 A13a                    |
| HD 58647  | B9     | 0          | 1         | 218      | 9     | 6.98      | H13                         |
| Z CMa     | B9     | 1          | 0         | 1231     | 164   | 56.34     | S10                         |
| HD 97048  | A0     | 19         | 0         | 105      | 58    | 4.64      | W07 H09 H11b A13a           |
| HD 9822   | A2     | 1          | 2         | 135      | 64    | 6.33      | W07 A13a H13                |
| HD 100546 | B9     | 2          | 0         | 106      | 52    | 7.40      | W07 H09                    |
| HD 101410 | A0     | 16         | 0         | 273      | 53    | 33.11     | W05 W07 H09 H11a            |
| HD 104237 | A4     | 3          | 2         | 56       | 35    | 5.75      | D97 W07 H13                 |
| HD 135344A| A0     | 2          | 1         | 80       | 85    | 5.76      | H09 A13a                    |
| HD 139614 | A7     | 6          | 3         | 73       | 26    | 8.33      | W05 H07 H09 A13a            |
| HD 144432 | A7     | 6          | 1         | 100      | 50    | 3.52      | H07 W07 H09 A13a            |
| HD 144668 | A7     | 2          | 3         | 106      | 34    | 8.55      | H07 W07 H09 A13a            |
| HD 150193 | A1     | 15         | 1         | 159      | 136   | 6.84      | H09 H11b A13a               |
| HD 176386 | B9     | 15         | 1         | 130      | 81    | 4.28      | H09 H11b A13a               |
| HD 190073 | A1     | 6          | 68        | 62       | 21    | 16.10     | C07 W07 H09 H13             |

References: A09 – Alecian et al. (2009); A13a – Alecian et al. (2013a); A13b – Alecian et al. (2013b); C07 – Catala et al. (2007); D97 – Donati et al. (1997); H07 – Hubrig et al. (2007); H09 – Hubrig et al. (2009); H11a – Hubrig et al. (2011a); H11b – Hubrig et al. (2011b); H13 – Hubrig et al. (2013b); H15 – this paper; S10 – Szeifert et al. (2010); W05 – Wade et al. (2005); W07 – Wade et al. (2007).