Weak Magnetic Fields in Two Herbig Ae Systems: The SB2 AK Sco and the Presumed Binary HD 95881

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Abstract

We report the detection of weak mean longitudinal magnetic fields in the Herbig Ae double-lined spectroscopic binary AK Sco and in the presumed spectroscopic Herbig Ae binary HD 95881 using observations with the High Accuracy Radial velocity Planet Searcher polarimeter (HARPSpol) attached to the European Southern Observatory’s (ESO’s) 3.6 m telescope. Employing a multi-line singular value decomposition method, we detect a mean longitudinal magnetic field \(B_\ell = -83 \pm 31\) G in the secondary component of AK Sco on one occasion. For HD 95881, we measure \(B_\ell = -93 \pm 25\) G and \(B_\ell = 105 \pm 29\) G at two different observing epochs. For all the detections the false alarm probability is smaller than \(10^{-5}\). For AK Sco system, we discover that accretion diagnostic Na I doublet lines and photospheric lines show intensity variations over the observing nights. The double-lined spectral appearance of HD 95881 is presented here for the first time.

Key words: binaries: spectroscopic – stars: abundances – stars: individual (AK Sco, HD 95881) – stars: magnetic field – stars: pre-main sequence

1. Introduction

Studies of the presence of magnetic fields in Herbig Ae/Be stars are extremely important because they enable us to improve our insight into how the magnetic fields of these stars are generated and how they interact with their environment, including their impact on the planet formation processes and the planet–disk interaction. Fourteen years ago, Muzerolle et al. (2004) confirmed magnetospheric accretion Balmer and sodium line profiles in the Herbig Ae star UX Ori. Since then, a number of magnetic studies have been attempted, indicating that about 20 Herbig Ae/Be stars likely have globally organized magnetic fields (Hubrig et al. 2015, and references therein). While Herbig Ae stars show evidence for magnetospheric accretion, it was suggested that Herbig Be stars might accrete directly from a boundary layer instead of the magnetosphere (e.g., Hamann & Persson 1992; Günther & Schmitt 2009). Interestingly, the compilation of existing magnetic field detections in Herbig Ae/Be stars by Hubrig et al. (2015) showed that only very few Herbig Be stars, all of them of spectral type B9, possess mean longitudinal magnetic fields.

Because only about 20 Herbig Ae/Be stars have been reported to possess magnetic fields, several arguments have recently been presented that favor a scenario in which the low detection rate of magnetic fields of Herbig Ae stars can be explained by the weakness of these fields and rather large measurement uncertainties (Hubrig et al. 2015). The obtained density distribution of the rms longitudinal magnetic field values revealed that only a few stars have fields stronger than 200 G, and half of the sample possess magnetic fields of about 100 G or less. These results call into question our current understanding of the magnetospheric accretion process in intermediate-mass pre-main-sequence stars, as they indicate that the magnetic fields of Herbig Ae/Be stars are by far weaker than those measured in their lower-mass classical T Tauri star counterparts, usually possessing kG magnetic fields. We note that the task of detecting weak magnetic fields of Herbig stars is very challenging due to the complex interaction between the stellar magnetic field, the accretion disk, and the stellar wind. Therefore, to analyze the presence of weak stellar magnetic fields, we usually employ a dedicated software package, the so-called multi-line singular value decomposition (SVD) method for Stokes profile reconstruction developed by Carroll et al. (2012).

In this Letter, we present our search for a magnetic field in the close double-lined spectroscopic binary with a Herbig Ae component AK Sco and in the presumed Herbig Ae binary system HD 96881 using high-resolution spectropolarimetric observations obtained with the High Accuracy Radial velocity Planet Searcher polarimeter (HARPSpol; Snik et al. 2008) attached to the European Southern Observatory’s (ESO’s) 3.6 m telescope (La Silla, Chile). Herbig Ae/Be binaries are of special interest as no close double-lined spectroscopic binary with a magnetic Herbig Ae component was detected among the 20 Herbig stars known to possess magnetic fields. AK Sco is a ninth-magnitude close SB2 system \((P_{\text{orb}} = 13.6\) days) with approximately equal components surrounded by a circumbinary disk (Alencar et al. 2003) and classified as a class II Herbig Ae/Be system by Menu et al. (2015). A study of this actively accreting system is of particular importance because of its prominent ultraviolet excess and the high eccentricity \((e = 0.47)\) of its orbit—the components get as close as \(11R_*\) at periastron passage. It was suggested by Gómez de Castro et al.
Table 1. Logbook of AK Sco and HD 95881 HARPSpol Observations

| AK Sco | HD 95881 |
|--------|----------|
| HJD 2,400,000+ | S/N | Phase | HJD 2,400,000+ | S/N |
| 57554.798230 | 144 | 0.946 | 57554.588158 | 193 |
| 57555.782879 | 195 | 0.018 | 57508.553735 | 184 |
| 57908.706901 | 224 | 0.950 | 57909.538751 | 260 |
| 57909.716316 | 282 | 0.025 | 57910.551552 | 219 |
| 57910.605621 | 205 | 0.090 | 57911.546578 | 203 |
| 57911.684945 | 207 | 0.169 | ... | ... |

Note. The columns give the heliocentric Julian date (HJD) for the middle of the exposures and the signal-to-noise ratio (S/N) of the spectra. The orbital period of AK Sco is based on the period \( P = 13.609453 \pm 0.000026 \) days and periastron passage time \( T = 2.446,654.3634 \pm 0.0086 \) (Alencar et al. 2003).

(2013) that the strong UV emission is caused by reprocessing of the high-energy magnetospheric radiation by the circumstellar material and that the eccentric orbit acts like a gravitational piston.

Whereas AK Sco was intensively studied in the last few years, there is little information available on the eighth-magnitude target HD 95881 in the literature. Based on spectro-astrometric observations, Baines et al. (2006) considered HD 95881 as a possible sub-arcsecond binary. The authors report a displacement of the FWHM over the H\( \alpha \) profile by 0.02 arcsec, consistent with a binary detection. Verhoeff et al. (2010) mapped the spatial distribution of the gas and dust around HD 95881 and concluded that it is in the transition phase from a gas-rich flaring dust disk to a gas-poor self-shadowed disk. The double-lined spectral appearance of HD 95881 is presented here for the first time.

2. Observations and Magnetic Field Analysis

HARPSpol spectropolarimetric observations of AK Sco and HD 95881 were obtained in the nights of 2016 June 15 and 16, and on four consecutive nights between 2017 June 4 and 7. Each observation consisted of subexposures with exposure times varying between 30 and 48 minutes for AK Sco and between 38 and 45 minutes for HD 95881. The quarter-wave retarder plate was rotated by 90° after each subexposure. All spectra have a resolving power of about 110,000 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 on La Silla. The normalization of the spectra to the continuum level is described in detail by Hubrig et al. (2013). The summary of our HARPSpol observations is given in Table 1. For AK Sco, the orbital phases were calculated using the orbital period \( P = 13.609453 \pm 0.000026 \) days and the epoch of periastron \( T = 2.446,654.3634 \pm 0.0086 \) (Alencar et al. 2003). At four orbital phases, from 0.950 to 0.090, the spectral lines of both components are fully overlapped. Only at the phase 0.169, corresponding to conjunction time, are the spectral lines of both components detected. The noisy HARPS observation obtained in 2015 June 15 at the orbital phase \( \phi = 0.946 \) shows strong contamination, where the secondary component is hardly detectable probably due to the presence of clumpy dust clouds in the circumbinary disk and/or inside the orbit of the system. We discuss the appearance of this spectrum in more detail in Section 3.

The magnetic field analysis of both systems is done based on the SVD method developed by Carroll et al. (2012). The SVD method is similar to the Principle Component Analysis approach (see also Carroll & KJos 2007; 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 (Carroll et al. 2012). This method is most useful for analyzing the presence of weak stellar magnetic fields and has been proven to achieve accuracies of just a few Gauss (e.g., Hubrig et al. 2015). The SVD Stokes \( I \) and \( V \) spectra for AK Sco and HD 95881 are calculated using the line masks based on their atmospheric parameters (Alencar et al. 2003; Fairlamb et al. 2015) and were constructed using the Vienna Atomic Line Database (VALD; Kupka et al. 2011; Ryabchikova et al. 2015). For the study of AK Sco, we have selected 50 spectral lines, and 32 for HD 95881. These lines are blend-free and belong to iron-peak elements. The SVD Stokes \( I \) and \( V \) spectra for both systems are then used for the measurement of the longitudinal magnetic field through the first-order moment of the Stokes \( V \) profile (e.g., Mathys 1989), assuming the mean Landé factor \( g_{\text{eff}} = 1.192 \) for AK Sco and \( g_{\text{eff}} = 1.186 \) for HD 95881. The Stokes \( I \), \( V \), and diagnostic \( N \) SVD profiles for the system AK Sco obtained using HARPSpol observations distributed over the orbital phases 0.950–0.090 are presented in Figure 1, and those for HD 95881 are presented in Figure 2. The diagnostic \( N \) profiles are usually used to identify spurious polarization signatures. They are calculated by combining the subexposures in such a way that the polarization cancels out.

For the system AK Sco we observe in the Stokes \( V \) spectra a number of small signatures corresponding to the position of the components, but a definite magnetic field detection, \( B_\parallel = -83 \pm 31 \text{G} \), with a false alarm probability (FAP) smaller than \( 10^{-5} \) was achieved only for the secondary component at the orbital phase \( \phi = 0.090 \). We classify the magnetic field measurements making use of the FAP (Donati et al. 1992), considering a profile with FAP < \( 10^{-3} \) as a definite detection, \( 10^{-5} < \text{FAP} < 10^{-3} \) as a marginal detection, and FAP > \( 10^{-3} \) as a non-detection. According to Alencar et al. (2003) both components are expected to be tidally synchronized, so we observe at this phase the region of the stellar
surface facing permanently the primary component, meaning that the magnetic field geometry in this component is likely closely related to the position of the primary component. We note that a similar magnetic field behavior, where the field orientation is linked to the companion, was previously detected in two other (the only known) close main-sequence binaries with Ap components, HD 98088 and HD 161701 (Babcock 1958; Hubrig et al. 2014). We do not detect a magnetic field in the primary, but as our observations cover only a fraction of the orbital cycle, we cannot exclude the possibility that the primary also possesses a magnetic field. In such a case, both stars could undergo common magnetospheric accretion. This idea is supported by Hubble Space Telescope observations indicating the presence of unresolved macroscopic motions in the dense and warm circumstellar material surrounding this system (Gómez et al. 2013).

Our HARPSpol spectra of HD 95881 clearly show the presence of two components that remain blended with each other on all five observing nights. Definite detections with FAP < 10^{-5} are achieved from the SVD profiles on two observing epochs, with the measured magnetic field strengths $\langle B_y \rangle = -93 \pm 25$ G and $\langle B_y \rangle = 105 \pm 29$ G, respectively. As mentioned in Section 1, Baines et al. (2006) used long-slit spectra for a spectro-astrometric analysis of HD 95881 and suggested it as a possible binary. Because the binary nature of this target is not convincingly ascertained, we cannot exclude that the variability of the shape of the SVD Stokes I profile is caused by a contribution of the circumstellar material around the star. Long-term spectroscopic monitoring is certainly needed to be able to separate the photospheric and non-photospheric contributions in the line profiles of HD 95881 and to come to a conclusion on the binarity status.

3. Spectral Variability

The preliminary abundance analysis of AK Sco performed by directly fitting synthetic spectra to the observations at phase $\phi = 0.090$, where the weak magnetic field was discovered for the secondary, revealed Sr and Ba overabundances of 0.5 dex in the secondary and a Sr underabundance of 0.4 dex in the primary. Strong Li absorption lines indicate an overabundance of 2.2 dex in the primary and 2.7 dex in the secondary. We used for both components the ATLAS9 model with $T_{\text{eff}} = 6500$ K (Alencar et al. 2003), log g = 4.0, and microturbulent velocity $\xi = 2$ km s$^{-1}$. Synthetic spectra of both stars were computed with the SYNTHE code (Kurucz 2005).

We discovered that all accretion diagnostic lines and photospheric lines show intensity variations over the observing nights. In view of the complexity of this system, it is impossible to distinguish between the contributions of surface chemical spots or other processes invoked in the magnetospheric accretion model to the observed profiles. As an example, we show in Figure 3 the behavior of the spectral lines Fe I 5616, Ca I 6122, Li I 6708, and the accretion diagnostic Na I doublet at different orbital phases. As already mentioned above, at the orbital phase $\phi = 0.946$ the secondary component suffers from obscuration and is only marginally detectable, probably due to the presence of clumpy dust clouds in the circumbinary disk and/or inside the orbit of the system. The fact that the secondary component becomes well visible at almost the same orbital phase $\phi = 0.950$ in the observations obtained one year later indicates that the dust obscuration in this system is varying from cycle to cycle, with clouds probably existing at small scales as was already pointed out by Alencar et al. (2003). Linear polarimetric observations of Manset et al. (2005) reported the presence of significant variations of intrinsic percent polarization and position angle indicating the presence of circumstellar matter distributed in an asymmetric geometry. According to the authors, the intrinsic polarization in AK Sco is one of the highest among the PMS binaries. Variations were found to be periodical with a period equal to the gravitational tidal period (half of the orbital period).

As already pointed out by Alencar et al. (2003), the line profiles of the Na I doublet are strongly perturbed by the interaction with the disk. In Figure 4 we show the opposite character of the variability of equivalent widths in both components. The equivalent widths of photospheric lines in the primary component are decreasing over the observed orbital phases range, while those for the secondary component are increasing.

A number of Herbig Ae stars are known to exhibit $\delta$ Scuti-like pulsations (e.g., Zwintz et al. 2008). Furthermore, Gómez et al. (2013) reported the detection of a 1.3 mHz
ultra-low-frequency oscillation in the ultraviolet light curve of AK Sco at periastron passage. The authors suggested that this oscillation is most likely fed by the gravitational energy released when the tails of the accretion stream spiraling onto each star come into contact at periastron passage, enhancing the accretion flow. Because HARPSpol observations cover the orbital phases corresponding to the periastron passage and are split into subexposures taken at different angles of the quarter-wave retarder plate, we checked for any changes in the line profile shape or radial velocity (RV) shifts on the timescales of tens of minutes. We detect clear RV shifts with a decrease from 4.8 km s\(^{-1}\) at phase 0.946 to 0.9 km s\(^{-1}\) at phase 0.169. However, this RV variability corresponds to the RV changes expected for the orbital movement during the periastron passage. No typical feature characteristic for the pulsational variability is detected at any orbital phase.

Not much can be reported on the short-term spectral variability of HD 95881 on a timescale of about 40–45 minutes, as no line profile or RV variation were detected.

4. Discussion

Our detections of weak magnetic fields in two Herbig Ae stars confirm the conclusion of Hubrig et al. (2015) that the previously accepted low incidence (5%–10%) of magnetic Herbig Ae stars can be explained by the weakness of these fields and the limited accuracy of the published measurements. The magnetic field was previously searched but not detected in AK Sco by Alecian et al. (2013) using Echelle Spectro-Polarimetric Device for the Observation of Stars (ESPaDOnS) observations. To our knowledge, the presence of a magnetic field in HD 95881 is reported in this work for the first time. Wade et al. (2007) used a single low-resolution \((R = 1560)\) spectropolarimetric observation of this star obtained with FORS 1 at the VLT to search for the presence of a longitudinal magnetic field. Using different spectral regions, the most accurate measurement, \(\langle B_e \rangle = 20 \pm 42\) G, was achieved for the whole spectrum. We should keep in mind that the longitudinal magnetic field is defined as the disk-integrated magnetic field component along the line of sight and therefore shows a strong dependence on the viewing angle of the observer, i.e., on the rotation angle of the star. The limitations set by the strong geometric dependence of the longitudinal magnetic field are usually overcome by repeating observations several times, so as to sample various rotation phases, hence various aspects of the magnetic field.

The double-lined system AK Sco appears to be of special interest for a number of reasons: Czekala et al. (2015) estimated the age of 18 ± 1 Myr, fully in line with its membership in the Upper Centaurus–Lupus association, but surprisingly old for it to still host a gas-rich disk. Recently, Donaldson et al. (2017) measured the ages of PMS stars in the Upper Scorpions OB association and showed that stars with disks have an older mean isochronal age than stars without disks. The authors concluded that evolutionary effects in young stars can affect their apparent ages. It is not clear whether the presence of a magnetic field of AK Sco can influence the derived age.

The finding of the line intensity variability over the fraction of the orbital period in AK Sco is intriguing and it is important to understand whether it is caused by the star–disk interaction or by the inhomogeneous surface element distribution.

Knowledge of the magnetic field structure combined with the determination of the chemical composition is indispensable when constraining theories on star formation and magnetospheric accretion in intermediate-mass stars. As of today, magnetic phase curves (i.e., the dependence of the magnetic field strength on the rotation phase) have been obtained only for two Herbig Ae/Be stars, V380 Ori (Alecian et al. 2009) and HD 101412 (Hubrig et al. 2011). Furthermore, only very few close spectroscopic binaries with orbital periods below 20 days are known among Herbig Ae stars (Duchêne 2015). A search for magnetic fields and the determination of their geometries in close binary systems will play an important role for understanding of the mechanisms that can be responsible for the magnetic field generation.

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![Figure 4](https://example.com/figure4.png)
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