

Magnetic fields in Herbig Ae stars[★]

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Abstract. Herbig Ae stars are young A-type stars in the pre-main sequence evolutionary phase with masses of $\sim 1.5\text{--}3 M_{\odot}$. They show rather intense surface activity (Dunkin et al. 1997, MNRAS, 290, 165) and infrared excess related to the presence of circumstellar disks. Because of their youth, primordial magnetic fields inherited from the parent molecular cloud may be expected, but no direct evidence for the presence of magnetic fields on their surface, except in one case (Donati et al. 1997, MNRAS, 291, 658), has been found until now. Here we report observations of optical circular polarization with FORS 1 at the VLT in the three Herbig Ae stars HD 139614, HD 144432 and HD 144668. A definite longitudinal magnetic field at 4.8σ level, $\langle B_z \rangle = -450 \pm 93$ G, has been detected in the Herbig Ae star HD 139614. This is the largest magnetic field ever diagnosed for a Herbig Ae star. A hint of a weak magnetic field is found in the other two Herbig Ae stars, HD 144432 and HD 144668, for which magnetic fields are measured at the $\sim 1.6\sigma$ and $\sim 2.5\sigma$ level respectively. Further, we report the presence of circular polarization signatures in the Ca II K line in the V Stokes spectra of HD 139614 and HD 144432, which appear unresolved at the low spectral resolution achievable with FORS 1. We suggest that models involving accretion of matter from the disk to the star along a global stellar magnetic field of a specific geometry can account for the observed Zeeman signatures.

Key words. stars: pre-main-sequence – stars: polarization – stars: magnetic fields – stars: individual: HD 139614 – stars: individual: HD 144432 – stars: individual: HD 144668

1. Introduction

It is generally accepted that star formation occurs via accretion. A number of Herbig Ae stars and classical T Tauri stars are surrounded by active accretion disks and, probably, most of the excess emission seen at various wavelength regions can be attributed to the interaction of the disk with a magnetically active star (e.g. Muzerolle et al. 2004). This interaction is generally referred to as magnetospheric accretion. T Tauri stars are solar type pre-main sequence stars, and from detailed magneto-hydrodynamic models it is expected that their strong magnetic fields funnel material from the disk onto the star and launch a collimated bipolar outflow (e.g. Shu et al. 2000).

Recent observations of the disk properties of intermediate mass Herbig Ae stars suggest a close parallel to T Tauri stars, revealing the same size range of the disks, similar optical surface brightness and similar structure consisting of inner dark disk and a bright ring. A large number of T Tauri stars are known to drive micro-jets as well as parsec-scale Herbig-Haro outflows (McGroarty & Ray 2004). Similar outflows have been newly discovered also from intermediate mass Herbig Ae stars

(McGroarty et al. 2004). Spectacular observations in the last years have been carried out by the Space Telescope Imaging Spectrograph on board of the Hubble Space Telescope, providing the first detections in Ly α of micro-jets associated with two of the nearest Herbig Ae stars, HD 163296 and HD 104237 (Devine et al. 2000; Grady et al. 2004).

Although magnetic fields are believed to play a crucial role in controlling accretion onto, and winds from, Herbig Ae stars, contrary to the advance achieved in magnetic studies of T Tauri stars, there is still no observational evidence demonstrating the strength, extent, and geometry of their magnetic fields. There were several attempts in the past to measure magnetic fields in these stars (e.g., Glagolevskij & Chountonov 2001a; Catala et al. 1993), but the only detection has been reported for the optically brightest Herbig Ae star HD 104237 viewed with the disk close to face-on (Donati et al. 1997). Using the Anglo-Australian Telescope with the UCL Echelle Spectrograph and a visitor polarimeter a marginal circular polarization signature has been observed in metallic lines indicating a longitudinal magnetic field of ~ 50 G.

There are certain reasons why the detection of magnetic fields in Herbig Ae stars is so difficult. The young intermediate mass stars as well as more massive stars tend to be

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surrounded by large amounts of circumstellar gas and dust, making it hard to measure magnetic fields at visual wavelengths. A number of spectral lines show circumstellar absorptions with complex profiles, and some lines appear in emission or exhibit P Cyg-type profiles. The optical spectra of Herbig Ae stars contain fewer absorption lines compared to cooler stars, and the rotational velocities of A stars as a class tend to be higher. In addition, Herbig Ae stars are less common than T Tauri stars, since the IMF favors the production of low mass stars, and, therefore, the sample of Herbig Ae stars includes rather faint objects. Yet, the lack of magnetic field detections demonstrates that magnetic fields in Herbig Ae stars should be rather weak, of the order of a few hundred Gauss and less, and a definite detection of such weak magnetic fields in faint objects certainly requires the collecting areas of large aperture telescopes of 8–10 m class coupled with highly efficient spectrographs to achieve a signal-to-noise ratio of at least 1000.

2. Observations

We have used FORS 1 (FOcal Reducer low dispersion Spectrograph) at the VLT on September 18 and 21, 2003 in spectropolarimetric mode to measure magnetic fields in three Herbig Ae stars, HD 139614, HD 144432 and HD 144668. The multi-mode instrument FORS 1 is equipped with polarization analyzing optics comprising super-achromatic half-wave and quarter-wave phase retarder plates and a Wollaston prism with a beam divergence of $22''$ in standard resolution mode. We used the GRISM 600B to cover all H Balmer lines from H_β to the Balmer jump, and the narrowest available slit width of 0.4 to obtain a spectral resolving power of $R \sim 2000$. The assessment of the longitudinal magnetic field using the FORS 1 spectra is achieved by measuring the circular polarization of opposite sign induced in the wings of broad lines, such as Balmer lines, by the Zeeman effect. The measurement of circular polarization in magnetically sensitive lines is the most direct mean of detecting magnetic fields on stellar surfaces. The errors of the measurement of the polarization in all Balmer lines from H_β to H_{16} have been determined from photon counting statistics and have been converted to errors of field measurements. For each Herbig Ae star we took eight sub-exposures with an integration time of about one minute each (half a minute for the brightest star HD 144668) with the retarder waveplate oriented at different angles. The spectropolarimetric capability of the FORS 1 instrument in combination with the large light collecting power of the VLT allowed us to achieve a S/N ratio of up to 1400 per pixel around 4600 \AA in the one-dimensional spectrum. Usually, once in a few months an additional star with a well-defined strong longitudinal field is observed to check that the instrument is functioning properly.

Details of the observing technique and of the measurement of magnetic fields in the FORS 1 spectra can be found elsewhere (e.g., Bagnulo et al. 2002; Hubrig et al. 2004a). The major advantage of using low-resolution spectropolarimetry with FORS 1 is that polarization can be detected also in relatively fast rotators as we measure the field in the hydrogen Balmer lines and not in metallic lines.

3. Results and discussion

The basic data of the studied Herbig Ae stars are presented in Table 1. The first eight columns indicate, in order, the HD number of the star, another identifier, the visual magnitude, the spectral type, the stellar parameters and their sources. The other columns list the infrared colour excess $(V-L)_{\text{obs}}$, the linear polarization P (Yudin 2000) and our determination of the mean longitudinal magnetic field $\langle \mathcal{B}_z \rangle$. The mean longitudinal magnetic field is the average over the stellar hemisphere visible at the time of observation of the component of the magnetic field parallel to the line of sight, weighted by the local emergent spectral line intensity. It is diagnosed from the slope of a linear regression of V/I versus the quantity $-g_{\text{eff}} \Delta \lambda_z \lambda^2 \frac{1}{T} \frac{dI}{d\lambda} \langle \mathcal{B}_z \rangle + V_0/I_0$ (Fig. 1). This procedure is described in detail by Bagnulo et al. (2002) and Hubrig et al. (2004a). Our experience with a study of a large sample of magnetic and non-magnetic Ap and Bp stars revealed that this regression technique is very robust and that detections with $B_z > 3 \sigma_z$ result only for stars possessing magnetic fields (Hubrig et al. 2004b).

The differences in the measured infrared colour excess and linear polarization between these stars may be interpreted in terms of different inclination of their rotation axis to the line of sight, and thus of their circumstellar (CS) disks with respect to the observer. HD 139614 and HD 144432 are very likely observed close to the rotational pole (face-on for the CS disk; Meeus et al. 1998) whereas HD 144668 is possibly observed at an intermediate angle of $68^\circ > i > 45^\circ$ (Natta & Whitney 2000). The pre-main sequence nature of HD 139614 and HD 144432 has been studied several years ago (Dunkin et al. 1997). Both stars show emission-line characteristics of $H\alpha$, Na I D and He I 5876 \AA indicating accretion activity and winds. No age determination has been found in the literature for HD 139614. Although this star has been mentioned in several studies as a Vega-type star (Sylvester et al. 1996), it is certainly a member of the Herbig Ae group, considering its spectral energy distribution in the infrared and its emission line characteristics. For HD 144432, the age between 1 and 3 million years has been determined quite recently (Perez et al. 2004). The star HD 144668 is much younger with an age of about 0.5 million years (van den Ancker et al. 1998). A search for a magnetic field was previously only performed for HD 144432. Using 26 metallic lines Glagolevskij & Chountonov (2001b) measured $\langle \mathcal{B}_z \rangle = -800 \pm 600 \text{ G}$. This measurement was severely hampered by the rather large width of the measured spectral lines as this star is rotating relatively fast.

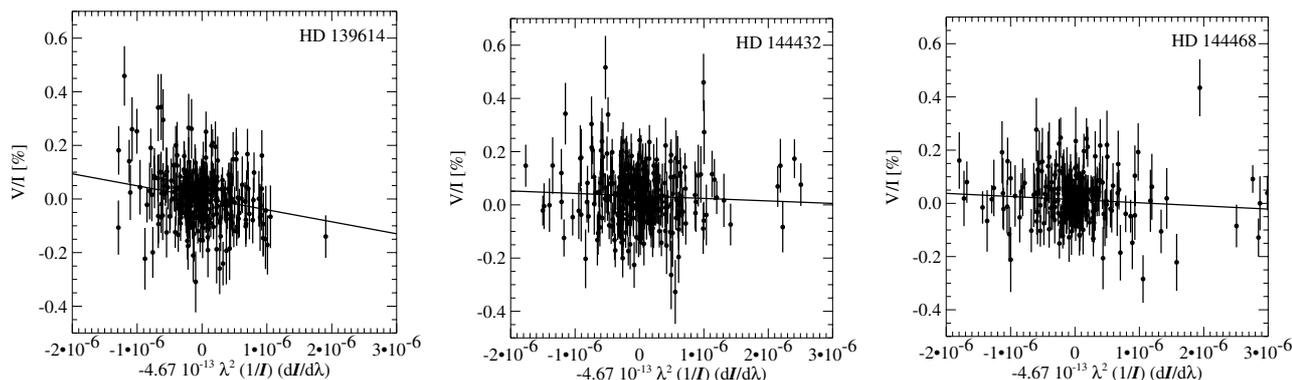
Spectra of the studied Herbig Ae stars in integral light in the spectral region around the Ca II K line and close-by H Balmer lines are presented in Fig. 2. From our data, we derive for the star HD 139614, viewed with the disk close to face-on, the mean longitudinal field $\langle \mathcal{B}_z \rangle = -450 \pm 93 \text{ G}$. This is the largest mean longitudinal magnetic field ever diagnosed for a Herbig Ae star. For the stars HD 144432 and HD 144668 we measure respectively $\langle \mathcal{B}_z \rangle = -94 \pm 60 \text{ G}$ and $\langle \mathcal{B}_z \rangle = -118 \pm 48 \text{ G}$.

In the Stokes V spectra of HD 139614 and HD 144432 the interesting but rather unexpected fact is the presence of circular polarization signatures in the Ca II K line at $\lambda 3933.7 \text{ \AA}$, which appear unresolved at the low spectral resolution

Table 1. Basic data of the studied Herbig Ae stars.

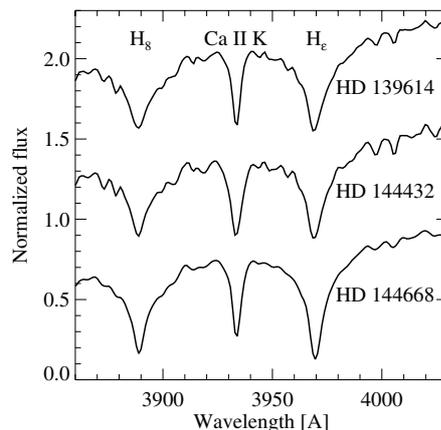
HD	Other	V	Sp. type	T_{eff}	$\log G$	$v \sin i$	Ref.	$(V - L)_{\text{obs}}$	P	$\langle B_z \rangle$
139614	CD-27 10778	8.2	A7Ve	8250	4.5	13	(1)	$\sim 2^m 0$	$\sim 0.1\text{--}0.5\%$	-450 ± 93 G
144432	CD-42 10650	8.2	A9Ve	7750	4.5	54	(1)	$\sim 2^m 0$	$\sim 0.1\text{--}0.5\%$	-94 ± 60 G
144668	HR 5999	7.0	A7IVe	7800	3.5-4.0	180	(2)	$3^m 0\text{--}3^m 5$	$\sim 0.5\text{--}1.3\%$	-118 ± 48 G

(1) Meeus et al. (1998); (2) Grady et al. (1994).

**Fig. 1.** Regression detection of a -450 ± 93 G magnetic field in HD 139614 and non-detections in HD 144432 and HD 144668.

achievable with FORS 1 (Fig. 3). The line Ca II H at $\lambda 3968.5 \text{ \AA}$ is blended with the Balmer line $H\epsilon$. As already noted, Herbig Ae stars are surrounded by circumstellar disks. Recent magnetospheric accretion models for these stars assume a dipolar magnetic field geometry and accreting gas from a circumstellar disk falling ballistically along the field lines to the stellar surface (Muzerolle et al. 2004). According to a previous study of the Ca II emissivity from dense envelopes near Herbig stars which used photoionization calculations (Hamann & Persson 1992), it is very likely that the Ca II lines form very near the photosphere. Probably, models involving accretion of circumstellar matter from the disk to the star along a global stellar magnetic field of a specific geometry can account for the Zeeman signatures observed in the Ca II lines. We note, however, that the actual geometry of magnetic fields in Herbig Ae stars is completely unknown. Obviously, further spectropolarimetric observations at higher resolution in the spectral region around the Ca II H and K lines as well as hydrogen Balmer lines would provide an essential clue for the understanding of the accretion mechanism and the geometry of magnetic fields in these stars.

The observations of the Herbig Ae stars were carried out within a framework of the study of evolution of magnetic fields in stars across the upper main sequence. It has been frequently mentioned in the literature that they are potential progenitors of the magnetic Ap stars (e.g., Stepien & Landstreet 2002; Catala 2003). A detection of magnetic fields in Herbig Ae stars is especially important in view of our recent results that Ap magnetic stars of mass below $3 M_{\odot}$ are significantly evolved and concentrated towards the centre of the main-sequence band, and practically no magnetic star of mass below $3 M_{\odot}$ can be found close to the zero-age main sequence (Hubrig et al. 2000, 2004b). The search for magnetic fields and the study of their

**Fig. 2.** Normalized Stokes I spectra of the three Herbig Ae stars. The individual spectra are displaced by 0.65 with respect to each other.

structure in the pre-main sequence counterparts to the magnetic Ap stars is a crucial step towards understanding the origin of the magnetic fields in stars of intermediate mass.

To properly assess the role of magnetic fields in the star formation process it is important to carry out magnetic field studies of a large sample of Herbig Ae stars and to try to establish the magnetic field strength and the magnetic field geometry by monitoring over several rotation cycles. In T Tauri stars, time series of circular polarization measurements of spectral lines formed throughout the photosphere and those in accretion regions show that the photosphere as a whole lacks globally organized magnetic fields, but accretion regions have highly ordered fields of the order of a few kG (Johns-Krull et al. 2003). Such contrary behaviour is usually reconciled by a notion that accreting material is loaded onto magnetic field lines at several stellar radii, where the dipolar component dominates

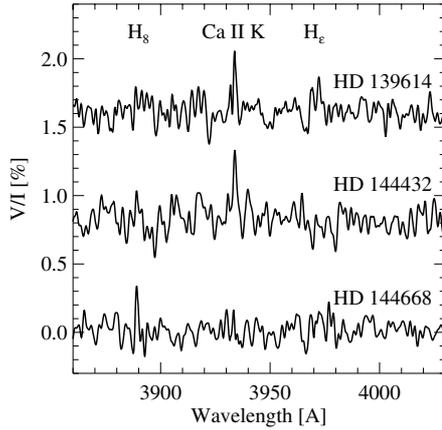


Fig. 3. Stokes V/I spectra of the studied stars around the Ca II doublet. The individual spectra are shifted by 0.8 with respect to each other.

higher order components of a more complicated surface geometry. The net longitudinal magnetic field in T Tauri stars with an upper limit of 200 G is modulated on rotational time scales, implying significant obliquity between the magnetic and rotational axes (Johns-Krull et al. 2003). The current magnetohydrodynamic models of Herbig Ae stars should be modified by inclusion of magnetic fields of proper strength and geometry and we should look forward towards future magnetohydrodynamic calculations of processes taking place in the accretion regions and the photosphere of these pre-main sequence stars.

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