Magnetic fields of B and Herbig Ae stars measured with FORS1 at the VLT

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Abstract. We present the results of a magnetic survey with FORS1 in polarimetric mode of a sample of B and Herbig Ae stars with previously undetected magnetic fields. For the first time a mean longitudinal magnetic field at a level higher than $3\sigma$ has been detected in one normal B star, two HgMn stars, one PGa star and four SPB stars. The observations of the three Herbig Ae stars (also known as Vega-like stars) reveal a definite longitudinal magnetic field in the star HD 139614 at $4.8\sigma$ level: $\langle B_z \rangle = -450 \pm 93$ G. This is the largest magnetic field ever diagnosed for a Herbig Ae star. A hint of a magnetic field is found in the other two stars, HD 144432 and HD 144668, for which magnetic fields are measured at the $\sim1.6\sigma$ and $\sim2.5\sigma$ level respectively.

1. Observations

The multi-mode instrument FORS1 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 have recorded circular polarization spectra using GRISM 600B and an 0.4'' slit. The observed spectral range ($\approx 345$-590 nm) includes all Balmer lines from H$_\beta$ to the Balmer jump. The major advantage of using low-resolution spectropolarimetry with FORS1 is that polarization can be detected in relatively fast rotators as we measure the field in the hydrogen Balmer lines.

Our sample of B stars consisted of various groups including normal B stars, HgMn stars, He weak Si stars, PGa stars and Slowly Pulsating B (SPB) stars. Their position in the H-R diagram obtained from accurate Hipparcos parallaxes ($\sigma(\pi)/\pi < 0.2$) and using photometric data in the Geneva and Strömgren systems for the determination of the effective temperatures is shown in Fig. 1.
Hubrig et al. (left). The basic data together with the measured magnetic fields are presented in Table 1.

Our sample included also three Herbig Ae stars which sometimes in the literature are called as Vega-like stars. As potential progenitors of the magnetic Ap stars, Herbig Ae stars provide an excellent opportunity to study the early evolution of magnetic fields in stars of same masses. A detection of magnetic fields in these 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 (ZAMS) (Hubrig, North & Mathys (2000), Hubrig et al. (2004)). The search for magnetic fields and the study of their structure in the pre-main-sequence counterparts is a crucial step towards understanding of the origin of the magnetic fields in stars of intermediate mass. The observations of three Herbig Ae stars, HD 139614, HD 144432 and HD 144668, have been carried out with FORS 1 in September 2003. Spectra of these stars in integral light in the spectral region around the Ca II K line and close-by H Balmer lines are presented in Fig. 1 (right). The corresponding Stokes V spectra are shown in Fig. 2 (left). The last two bottom panels in these figures show the spectra of the non-magnetic HgMn star HD 175640 observed during the same night as the Herbig Ae stars and of the classical Ap star HD 94660 with a well-defined longitudinal field of $-2\,kG$, occasionally observed by us to check a proper instrument functionality. The assessment of the longitudinal magnetic field using 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. Using Balmer lines from $H_\beta$ to $H_{16}$ and Ca II K for the measurements, we derived for the star HD 139614 the mean longitudinal field $\langle B_z \rangle = -475 \pm 94$ G. For the stars HD 144432 and HD 144668 we measured respectively $\langle B_z \rangle = -94 \pm 60$ G and $\langle B_z \rangle = -118 \pm 48$ G.

| HD     | mass | $\log T_{\text{eff}}$ | $\log L$ | $\log g$ | $R/R_\odot$ | $d$ [pc] | $B_{\text{eff}}$ | $\sigma(B_{\text{eff}})$ | $\text{Sp. Type}$       |
|--------|------|-----------------------|---------|---------|-------------|---------|-------------------|--------------------------|--------------------------|
| 358    | 3.60 | 4.140                 | 2.220   | 4.29    | 2.25        | 30      | $-369$           | 82                      | B8IV HgMn                |
| 19400  | 3.997| 4.148                 | 2.489   | 4.10    | 2.96        | 165     | $+332$           | 64                      | B3V PGa                  |
| 26326  | 4.970| 4.182                 | 2.947   | 3.87    | 4.30        | 244     | $+119$           | 75                      | B5IV SPB                 |
| 34798  | 4.674| 4.193                 | 2.746   | 4.09    | 3.24        | 285     | $+117$           | 52                      | B5IV/V SPB               |
| 53921  | 3.819| 4.137                 | 2.406   | 4.11    | 2.84        | 152     | $-295$           | 59                      | B9IV SPB                 |
| 53929  | 4.201| 4.143                 | 2.641   | 3.95    | 3.61        | 256     | $-248$           | 102                     | B9.5II HgMn              |
| 55522  | 4.958| 4.208                 | 2.848   | 4.07    | 3.40        | 241     | $+873$           | 66                      | B2IV/V Bp                |
| 71066  | 3.184| 4.083                 | 2.094   | 4.13    | 2.54        | 123     | $+21$            | 48                      | A0IV HgMn                |
| 74196  | 3.504| 4.108                 | 2.275   | 4.09    | 2.79        | 148     | $+381$           | 107                     | B7Vp                     |
| 85953  | 9.182| 4.266                 | 4.130   | 3.29    | 11.41       | 870     | $-204$           | 66                      | B2III SPB                |
| 92287  | 6.841| 4.215                 | 3.574   | 3.51    | 7.59        | 524     | $-88$            | 42                      | B3IV SPB                 |
| 93030  | 13.223| 4.477               | 4.448   | 3.97    | 6.21        | 137     | $-189$           | 78                      | B0Vp                     |
| 105382 | 4.965| 4.211                 | 2.836   | 4.10    | 3.30        | 119     | $-430$           | 102                     | B6III He Bp              |
| 120709 | 4.712| 4.214                 | 2.607   | 4.25    | 2.70        | 94      | $-79$            | 72                      | B5III He wP Ga           |
| 123515 | 3.465| 4.079                 | 2.329   | 3.92    | 3.39        | 179     | $-173$           | 52                      | B9IV SPB                 |
| 131120 | 4.931| 4.231                 | 2.720   | 4.29    | 2.65        | 122     | $-280$           | 88                      | B7III He w                  |
| 138764 | 3.582| 4.115                 | 2.308   | 4.10    | 2.80        | 111     | $+132$           | 75                      | B6IV SPB                 |
| 138769 | 5.069| 4.209                 | 2.907   | 4.02    | 3.62        | 139     | $-348$           | 98                      | B3IVp                    |
| 179761 | 4.767| 4.114                 | 2.973   | 3.55    | 6.06        | 232     | $-267$           | 63                      | B8III                   |
| 186122 | 3.986| 4.112                 | 2.590   | 3.85    | 3.93        | 264     | $+269$           | 76                      | B9III HgMn               |
| 209459 | 3.216| 4.025                 | 2.246   | 3.75    | 3.96        | 179     | $+144$           | 60                      | B9.5V                    |
| 215573 | 3.862| 4.144                 | 2.407   | 4.15    | 2.75        | 138     | $+165$           | 53                      | B6IV SPB                 |
| 221507 | 3.072| 4.096                 | 1.945   | 4.32    | 2.01        | 55      | $-28$            | 55                      | B9.5IV HgMn            |
Figure 1. **Left:** The positions of the studied stars in the HR-diagram. **Right:** Normalized Stokes I spectra of three Herbig Ae stars (HD 139614, HD 144432, HD 144668), the HgMn star HD 175640 and the classical Ap star HD 94660. The individual spectra are displaced by 0.65 with respect to each other.

Figure 2. **Left:** Stokes V spectra of the studied Herbig Ae stars around the Ca II doublet. The individual spectra are shifted by 0.01 with respect to each other. **Right:** Stokes V spectra of the Herbig Ae star HD 144668 and the classical Ap star HD 94660. The thickness of the plotted lines corresponds to the uncertainty of the measurement of polarization determined from photon noise.
2. Discussion

Normal B, HgMn, PGa and SPB stars are usually regarded as non-magnetic stars. The only detection of a magnetic field in an SPB star (ζ Cas) has been presented by Neiner et al. (2003). However, the role that magnetic fields play in the understanding of pulsational properties of SPB stars is still unclear and further observations are needed to look for possible relations between magnetic field and pulsation patterns. It may be an essential clue for the understanding of the origin of the chemical anomalies of HgMn stars that many stars of this peculiarity type are very young and are located on the ZAMS or close to it. Previous searches for magnetic fields in HgMn stars had shown that these stars, unlike classical Ap stars, do not have large-scale organized fields detectable through polarimetry. However, we were able to detect longitudinal fields of the order of a few hundred Gauss in two HgMn stars. We also detected a magnetic field at 4.2σ level in the normal B-type star HD 179761. Three years ago we already showed for this star evidence for a relative magnetic intensification of Fe II lines produced by different magnetic desaturations induced by different Zeeman-split components (Hubrig & Castelli (2003)). As the relative intensification is roughly correlated with the strength of the magnetic field, it is a powerful tool for detecting magnetic fields which have a complex structure and are difficult to detect by polarization measurements. The intriguing discovery of mean longitudinal magnetic fields of the order of a few hundred Gauss in a sample of so-called "non-magnetic" stars rises a fundamental question about the possible ubiquitous presence of a magnetic field in upper main sequence stars. The structure of the field in these stars must be, however, sufficiently tangled so that it does not produce a strong net observable circular polarization signature.

In the Stokes V spectra of HD 139614 and HD 144432 the interesting fact is the presence of circular polarization signatures in the CaII K line, which appear unresolved at the low spectral resolution achievable with FORS 1 (Fig. 2, left). The line CaII H is blended with the Balmer line H\(\epsilon\). As the Herbig Ae stars of our sample are surrounded by circumstellar disks, 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 Zeeman signatures observed in the CaII K line. A longitudinal field at 4.8σ level has been diagnosed for HD 139614 and the fields of the other two stars, HD 144432 and HD 144668, have been measured at \(~1.6\sigma\) and \(~2.5\)σ levels respectively. Given the very low \(v\sin i\) value for HD 139614 with the largest magnetic field measured, we are very likely observing this star pole-on. For HD 144668, viewed at edge-on, no obvious polarization signature is visible in the CaII K line. However, a magnetic field is certainly present since weak polarization signatures are clearly seen in the H Balmer lines (Fig. 2, right). More magnetic studies of Herbig Ae stars are needed to properly assess the role of magnetic fields in the formation process of stars of intermediate mass.

References

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