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Magnetic Fields of Herbig Ae/Be Stars

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Abstract. Only recently direct spectropolarimetric observations of several Herbig Ae/Be stars showed that magnetic fields are indeed present in the intermediate mass pre-main sequence stars, indicating that magnetic fields are the important ingredients of the star formation process. For the first time we examined the relation of the measured field strengths with various parameters that characterize the star–disk system. We could show that stronger magnetic fields tend to be found in younger Herbig stars and completely disappear when the stars arrive on the ZAMS, indicating that the magnetic fields of Ap/Bp stars are not fossil. The knowledge of the magnetic field structure combined with determination of the chemical composition and the surface element distribution are indispensable to constrain the theories on star formation and magnetospheric accretion.

Key words: stars: pre–main sequence – stars: atmospheres – stars: magnetic field – stars: variables: general – stars: winds, outflows, jets

1 Introduction

It is generally accepted that accretion from a disk is an integral phase of star formation. 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. 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 onto the stellar surface.

By the age of the β Pictoris Moving Group ($t \approx 12$ Myr), many A stars lack conspicuous signatures of activity. Yet, enhanced emission, FUV excess light, and X–ray activity are known for a number of Herbig Ae stars (e. g., Hamaguchi et al., 2005; Feigelson et al., 2003; Stelzer et al., 2008). Bipolar outflows, or associated Herbig–Haro knots are now known for six optically visible Herbig Ae stars drawn from the coronographic imaging surveys (e. g. Melnikov et al., 2008). The jet frequency appears to be comparable to that for T Tauri stars. Due to the probable role of magnetic fields in the launching and collimating jets, this implies that a significant fraction of Herbig Ae stars should have measurable magnetic fields, which could persist through much, if not all, of the star's PMS

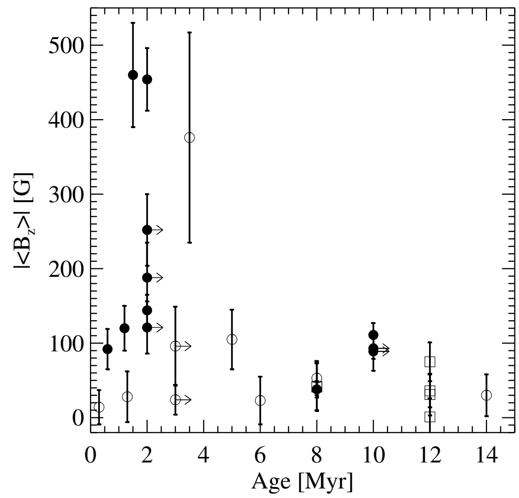

Figure 1: The strength of the longitudinal magnetic field as a function of age. Open circles denote Herbig Ae stars and open squares indicate debris disk stars.

lifetime.

Recent advances in instrumentation have resulted in the first magnetic field measurements for Herbig Ae stars, derived from spectropolarimetry. A few stars have magnetic field strengths derived from the circular polarisation measurements of a few hundred Gauss or near 100 G (e. g., Hubrig et al., 2004, 2006, 2007b; Wade et al., 2005, 2007). Other objects seem to have either smaller average field strengths, or exhibit significant variability. In our recent and previous work we were seeking to expand the sample of intermediate–mass PMS stars with circular polarisation data, which are used to derive the stellar magnetic fields.

2 Previous Work

In the course of our spectropolarimetric study of 23 Herbig Ae/Be stars and six debris disk stars two years ago, we for the first time detected magnetic fields in eight stars, PDS 2, HD 53179, HD 85567, HD 97048, HD 100546, HD 135344B, HD 150193, and HD 176386 (Hubrig et al., 2009). The presence of a magnetic field was confirmed in the stars HD 101412, HD 144668, and HD 190073.

We examined for the first time the relation of measured field strengths with various parameters that characterize the star–disk system. Among the most important connections for the interpretation of the fields is the one between the magnetic field strength and accretion rate. We did not find a clear trend between those two parameters in our sample of Herbig Ae stars but the measured field strengths are compatible in the order of magnitude with the values, expected from magnetospheric accretion scenarios for a dipole field (tens to a few hundreds of Gauss). This contrasts with the situation for the cTTS. For the typical cTTS parameters, accretion models predict fields, ranging between $\sim 200-2000$ G. However, the observed mean magnetic field strengths of the cTTS are not correlated with the predictions (Johns–Krull, 2007). For most cTTS the observed fields are larger than the expected values, possibly indicating that magnetic field pressure dominates the gas pressure in these systems. In addition, the dipole approximation is known not to be valid for the case of cTTS that have complex field geometries (e. g. Gregory et al., 2008), while our results suggest that it may be a reasonable description for Herbig Ae stars.

We find that stronger magnetic fields tend to be found in younger Herbig stars (Fig. 1). It has been frequently mentioned in the literature that magnetic Herbig Ae stars are potential progenitors of the magnetic Ap stars (e. g., Stepien & Landstreet, 2002; Wade et al., 2005). On the other hand, from Fig. 1 it is obvious that stronger magnetic fields appear in very young Herbig Ae stars, and magnetic fields become very weak at the end of their PMS life. These results clearly confirm the conclusions of Hubrig et al. (2000, 2005, 2007a) that magnetic fields in stars with masses less than $3\,M_{\odot}$ are rarely found close to the ZAMS, and that kG magnetic fields appear in A stars already evolved from the ZAMS. In contrast, magnetic Bp stars with masses $M > 3\,M_{\odot}$ seem to be concentrated closer to the ZAMS.

Magnetic fields become very weak or completely disappear in stars when they arrive on the ZAMS. Similarly, strong X–ray sources are only found at the youngest age in a qualitative agreement with the predictions of a shear dynamo that decays within a few Myrs, as the rotational energy of the star decreases (Tout & Pringle, 1995). It is premature, however, to claim a direct connection between the magnetic field and X–ray luminosity. The Herbig Ae stars seem to follow the power–law between magnetic flux and X–ray luminosity established for the Sun and main–sequence active stars. We do not find any trend between the presence of a magnetic field and disk inclination angles.

The membership in binary or multiple systems does not seem to have any impact on the presence of a magnetic field, whereas there is a hint that the appearance of magnetic fields is more frequent in Herbig stars with flared disks and hot inner gas. Since flared disks are the least evolved, this is possibly another indication for the decay of magnetic fields with increasing age. However, no trend of the strength of the magnetic field with rotation velocity and rotation period was detected in our study.

3 Recent Work

About half of stars with magnetic field detections possess longitudinal magnetic fields larger than 100 G. These stars are the best candidates for future spectropolarimetric studies to analyze the behaviour of their magnetic fields over the rotation periods, to disclose the magnetic topology on their surfaces, and to study the complex interaction between the stellar magnetic field, the disk, and the stellar wind. Therefore, we applied for the observational time with the FORS2 at Antu/UT1 at the VLT to obtain multi–epoch high–resolution spectra in service mode to study the magnetic field, and to characterize the behaviour of their magnetic fields. As we already reported in several publications, HD 101412 is the first Herbig Ae star for which the rotational Doppler effect was found to be small in comparison to the magnetic splitting and several spectral lines, observed in the unpolarised light at high dispersion are resolved into magnetically split components. The measured mean magnetic field modulus varies from 2.5 to 3.5 kG, while the mean quadratic field was found to vary in the range of 3.5 to 4.8 kG (Hubrig et al., 2009, 2010). The rotation period of 42 days was determined from the measurements of the longitudinal magnetic field and from photometry (Hubrig et al., 2011). Apart from the observation of HD 101412, we obtained 36 observations of three other Herbig Ae/Be stars, HD 97048, HD 150193, and HD 176386, and determined a provisional rotation period and magnetic field geometry. The longitudinal magnetic field measurements phased with provisional periods of these three Herbig Ae stars are presented in Figures 2 – 4.

New high–resolution polarimetric spectra were obtained for MWC 480 with the high–resolution spectrograph SOFIN installed at the Nordic Optical Telescope. This star demonstrates notable emissions in the Hβ, Hγ, and Hδ lines, which indicate the presence of a significant stellar wind. The measurements of MWC 480 revealed the presence of a significantly strong magnetic field, which remained undetected in our previous low–resolution polarimetric observations with the FORS1. Strong circular polarisation signatures associated with the circumstellar envelope imply the presence of a considerable magnetic field in the outflowing gas. More evidence for the existence of the field is

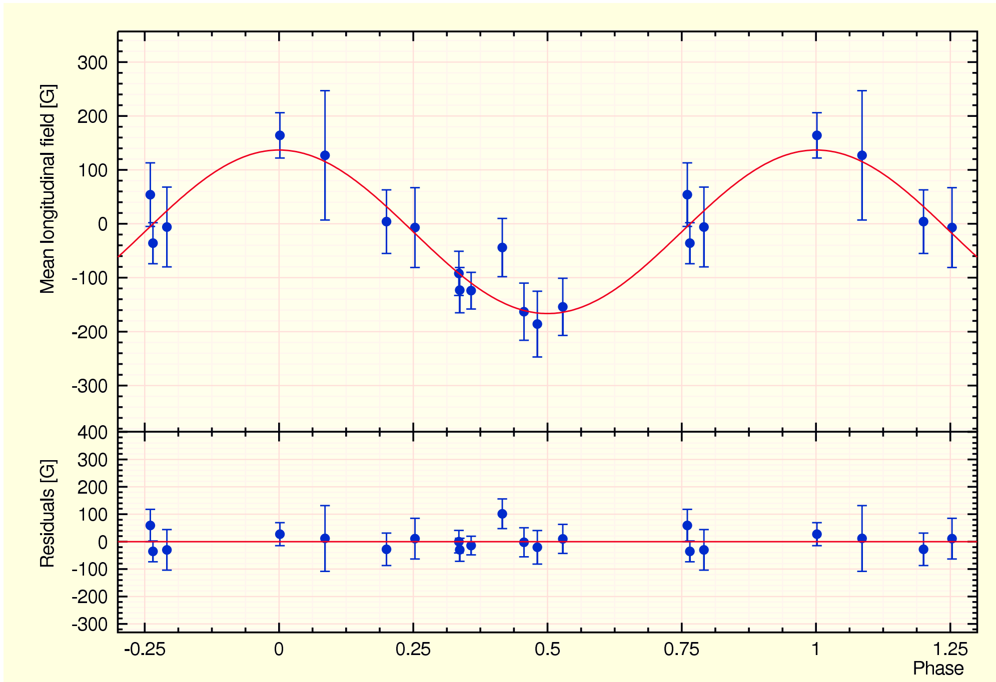

Figure 2: Phase diagram with the best sinusoidal fit for the longitudinal magnetic field measurements of HD 97048. The residuals (Observed – Calculated) are shown in the lower panel. The deviations are mostly of the same order as the error bars, and no systematic trends are obvious, which justifies a single sinusoid as a fit function.

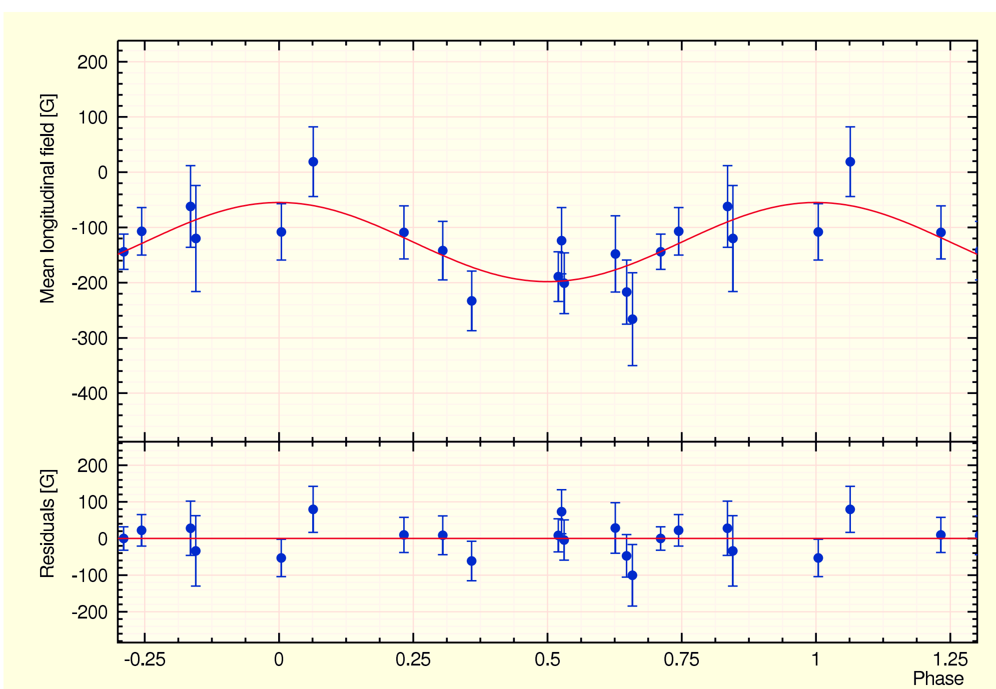

Figure 3: Phase diagram with the best sinusoidal fit for the longitudinal magnetic field measurements of HD 150193. The residuals (Observed – Calculated) are shown in the lower panel.

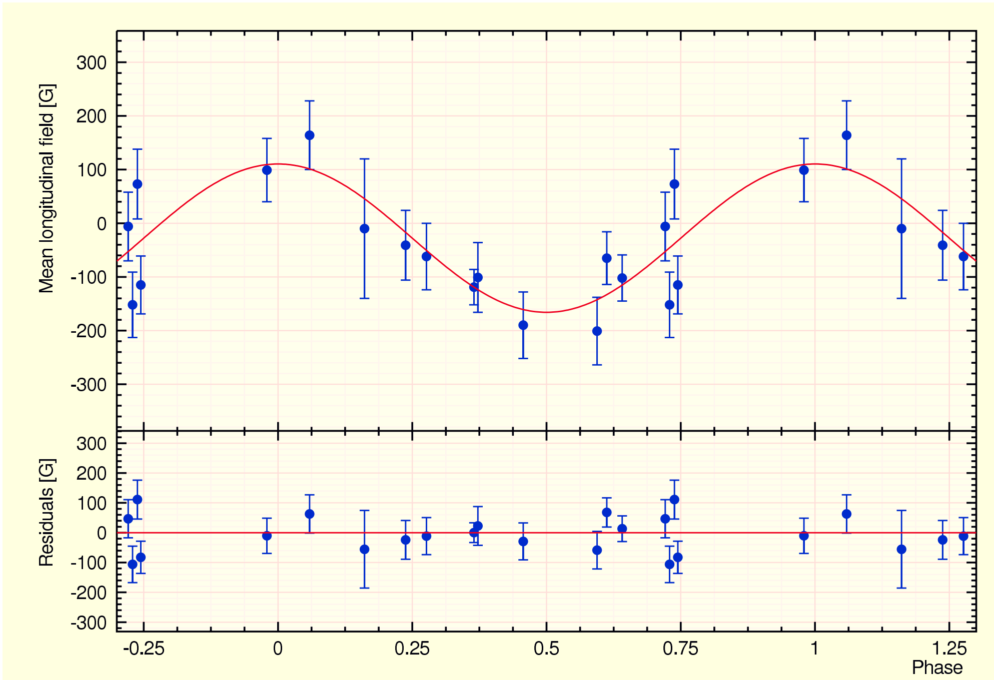

Figure 4: Phase diagram with the best sinusoidal fit for the longitudinal magnetic field measurements of HD 176386. The residuals (Observed – Calculated) are shown in the lower panel.

provided by the presence of notable polarisation signatures in the Ca II doublet lines. The K profile of the doublet is complex and consists of two components: a blueshifted deep and a redshifted narrow absorption, indicating that the Ca II doublet lines are very likely formed at the base of the stellar wind, as well as in the accretion gaseous flow. We conclude that a significant magnetic field is present in the photosphere of MWC 480, but it is also detectable in the circumstellar environment. Interestingly, other authors (e. g. Wade et al., 2007) were not able to detect such features in their observations with the FORS1 and ESPaDOnS, probably due to the low flux in their spectra. To emphasize the importance of high–resolution spectropolarimetric observations, we present in Fig. 5 (upper and lower panels) our recent spectropolarimetric observations (the Stokes I and V spectra) of this star with the high–resolution ($R = 30\,000$) SOFIN spectrograph at the NOT at the positions of the Ca II H doublet line $\lambda\,3968.5$ and the Na I doublet. The Stokes V spectrum confirms the presence of a complex interaction between the stellar magnetic field, the disk, and the stellar wind.

Last but not least, we would like to mention our recent study of the binary system Z CMa, which consists of two young stars. A Herbig Ae/Be component "Z CMa NW" embedded in a dust cocoon and a less massive component "Z CMa SE", which is classified as a FU Orionis type star (Szeifert et al., 2010). A giant parsec–size jet is associated to the binary system. Past spectropolarimetric observations showed that the position angle of the linear optical polarisation is perpendicular to the jet axis, indicating that the visual light escapes the cocoon via the cavities, aligned with the jet axis, and is then scattered back into the line of sight of the observer. Recently, the system showed the largest outburst reported during almost 90 years of available observations. During this outburst, we detect that the Z CMa system is polarised 3% in the continuum and emission line spectrum, with a position angle still perpendicular to the jet. From the high level of polarisation we conclude that the outburst is associated with the dust–embedded Herbig AeBe NW component. The deep absorption components of the Balmer lines in the velocity frame extending from zero velocity reaching a wind velocity of $\sim$700 km/s, along with the absence of a red–shifted broad emission at similar velocities

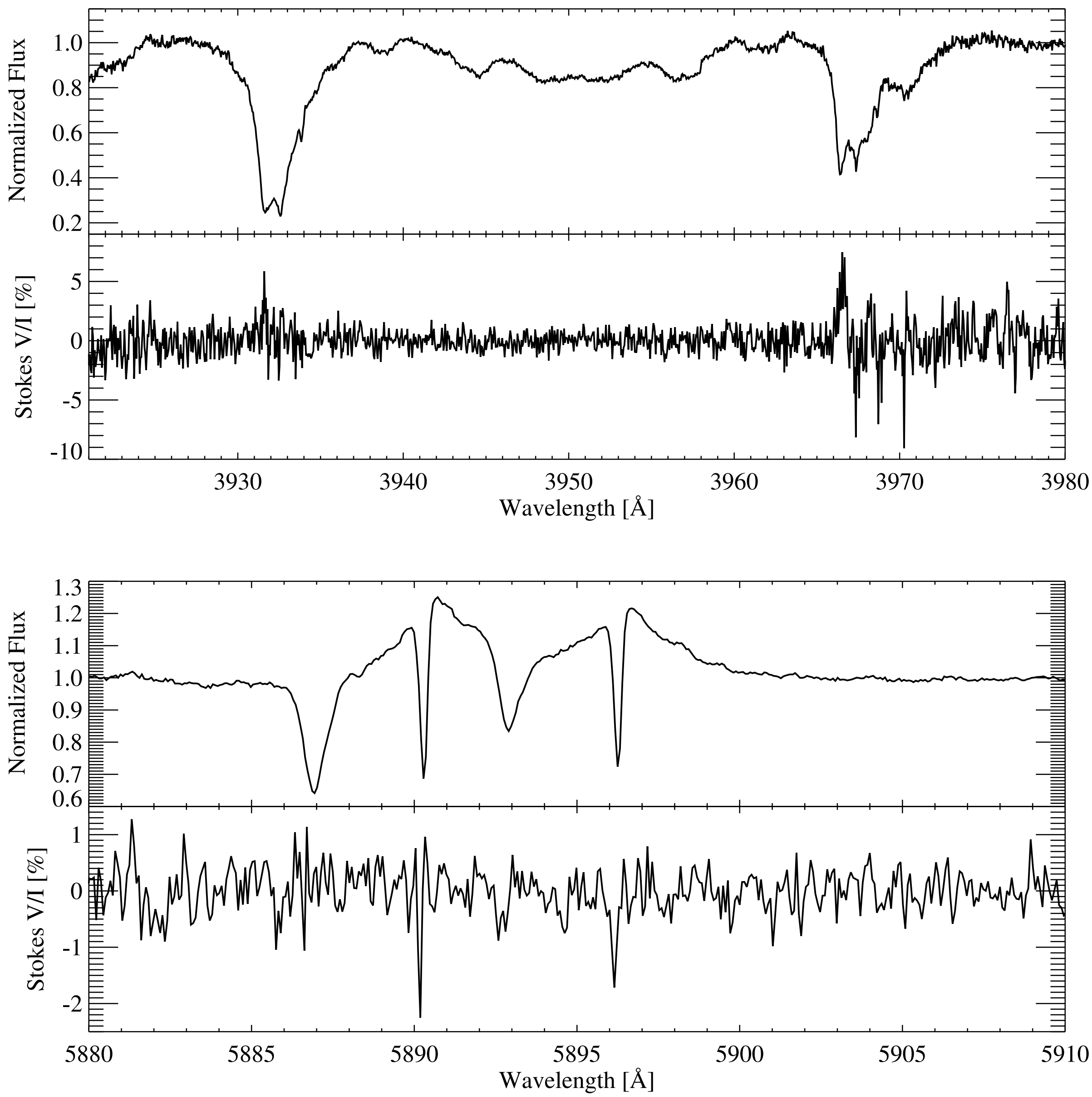

Figure 5: *Upper:* The complex multi–component structure of the circular polarisation signature in MWC 480 is clearly visible at the position of the Ca II doublet line $\lambda\,3968.5$ and the Hϵ line $\lambda\,3970.1$. *Lower:* Circular polarisation signatures in MWC 480 observed in both the photospheric and the CS Na I doublet lines.

indicate a bi–polar wind.

Our spectropolarimetric observations suggest that the geometry of the cavity through which the light escapes from the cocoon has opened a new path, or that the screen of dust, which reflects the light towards the observer became more efficient causing an increase in the visual brightness by about $2\overset{\mathrm{m}}{.}5$. We do not detect a significant mean longitudinal magnetic field in the data sets, obtained during the outburst, but an inspection of the FORS1 spectropolarimetric observations obtained in 2004 indicates a possible presence of a rather strong magnetic field of the order of ~ 1 kG. In Fig. 6

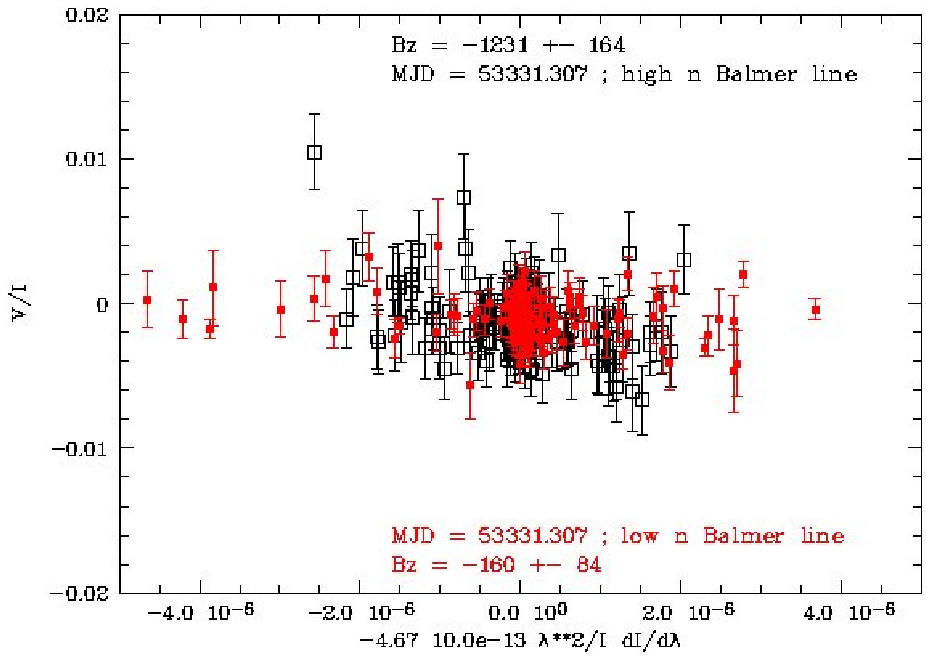

Figure 6: Magnetic field measurements for Z CMa using the data obtained in November 2004. The longitudinal magnetic field is derived following the equation $V/I = -\mathrm{g}_{\mathrm{eff}}\mathrm{C}_z\lambda^2\frac{1}{I}\frac{\mathrm{d}I}{\mathrm{d}\lambda}\langle B_z\rangle$ from the slope of the linear fit through the data points. Large open and small filled symbols are obtained from the high–number and low–number Balmer lines, respectively.

we present the archive data already published by Wade et al. (2007), where we do detect a clear circular polarisation signal in particular at the blue–shifted side of the high–number Balmer lines. For the low excitation lines from Hβ to Hϵ we measure -160 ± 84 G, while from the higher excitation Balmer lines a very significant field of -1231 ± 164 G was determined. We note that the presence of such a strong magnetic field was completely missed by Wade et al. (2007), who measured a mean longitudinal magnetic field $\langle B_z\rangle = -126 \pm 66$ G from the same data set.

4 Summary

While considerable progress has been made with respect to the presence of magnetic fields in the Herbig Ae stars, a number of questions remains open. The most important question is related to the origin of the magnetic fields in these stars. Although our results provide new clues, the observational results presented in this work are still inconclusive as to the magnetic field origin. Tout & Pringle (1995) proposed a non–solar dynamo that could operate in rapidly rotating A–type stars based on the rotational shear energy. Their model predicts that the coronal activity at the observed rates of $\log L_{\mathrm{X}}$ can be sustained for a period of the order of 10^6 yr. Other possible mechanisms causing magnetic activity involve fossil magnetic fields or magnetically–confined wind shocks (e. g. Babel & Montmerle, 1997). A more comprehensive survey of the presence of magnetic fields, and a detailed study of the magnetic field topology in a Herbig Ae/Be star sample of increased size will provide important additional information to test the predictions of different theories.

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