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BINARITY VERSUS MAGNETIC FIELDS IN UPPER MAIN-SEQUENCE STARS

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Abstract. We review the status of the work on the detection, possible origin, and modelling of magnetic fields in binary systems with intermediate- and higher-mass primaries at different evolutionary stages. This review also includes interesting findings on a few exotic systems.

Key words: magnetic fields - binary stars - PMS stars - stellar evolution

1. Introduction

The presence of a convective envelope is a necessary condition for significant magnetic activity. Magnetic activity is found all the way from the late A-type stars (e.g. in Altair: Robrade and Schmitt, 2009) with very shallow convective envelopes down to the coolest fully convective M-type stars. Quite recently, the presence of a convective zone in the outer envelopes of hot massive stars was studied by Cantiello *et al.* (2009) using a stellar evolution code to compute a grid of massive star models at different metallicities. They mapped the strength of the iron convective zone (FeCZ) in the H-R diagram, showing its prominence as a function of stellar parameters. Since in their models the FeCZ has a spatial extent similar to the solar convection zone, the authors suggest that a dynamo may also work in rapidly rotating OB stars.

No systematic study of the presence of magnetic fields in binary systems in upper main-sequence stars was carried out yet, and the role of binarity on the magnetic field generation in binary components is unclear. Only for classical Ap stars several studies indicate that the incidence of global, large-scale organised magnetic fields is rather rare among Ap stars with close companions. On the other hand, although the number of massive stars with detected magnetic fields is still small compared to the group of magnetic Ap and Bp stars, several magnetic O-type stars are already known to belong to binary systems. In the following we discuss a few O and B-type magnetic stars detected in binary systems. Some of them, such as β Lyr and υ Sgr appear rather complex with intricate environments.

Furthermore, since recent spectropolarimetric observations of a few progenitors of A and B-type stars, the Herbig Ae/Be stars, have shown that magnetic fields are also important ingredients of the intermediate-mass star formation process, we discuss spectropolarimetric observations of the complex binary system Z CMa composed of a Herbig Be and an FU Ori star. Recent polarimetric observations of this system reveal the presence of a dust cocoon of variable geometry, and an infalling envelope.

2. The Most Massive Magnetic Stars in Binary Systems

Six years ago, magnetic measurements for only two O stars were published, namely for θ^1 Ori C and HD 191612 with $\langle B_{\rm z}\rangle$ of a few hundred G (Donati *et al.*, 2002, 2006). At present, FORS 1/2, ESPaDOnS, NARVAL, and HARPS spectropolarimetric observations are used to search for magnetic fields in several hundreds of O- and B-type stars. Detections are achieved in more than a dozen O-type stars, among them all five presently known Of?p stars, in Ofc stars, in rapidly rotating runaway stars, in young cluster members, and in the long-period SB2 binary 9 Sgr with colliding winds (e.g., Martins *et al.*, 2012; Hubrig *et al.*, 2008a; Hubrig *et al.*, 2011a; Hubrig *et al.* 2012, submitted, and the references therein). Walborn (1973) introduced the Of?p category for massive O stars displaying recurrent spectral variations in certain spectral lines, sharp emission or P Cygni profiles in He I and the Balmer lines, and strong C III emission lines around 4650 Å. The stars of the Ofc category exhibit typical normal O-type spectra with C III $\lambda\lambda$ 4647-4650-4652 emission lines of comparable intensity to those of the Of defining lines N III $\lambda\lambda$ 4634-4640-4642 (Walborn *et al.*, 2010).

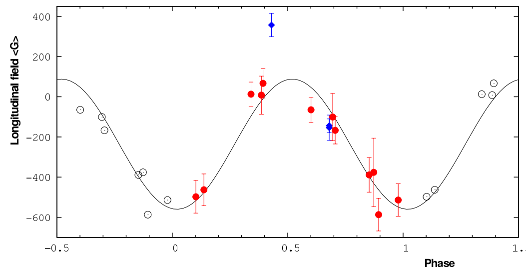

Figure 1: Longitudinal magnetic field variation of the Of?p star HD 191612 according to the 537.6 d period determined by Howarth *et al.* (2007). Red symbols correspond to ESPaDOnS observations, while blue symbols are SOFIN measurements (Hubrig *et al.* 2010 and Hubrig *et al.* 2013).

2.1. The Of?p system HD 191612

Among magnetic O-type stars belonging to binary systems, the following systems are currently studied in more detail: HD 191612, 9 Sgr, and Cyg X-1. The Of?p system HD 191612 consists of an O8 giant and a B1 main-sequence secondary. The orbital period is 1542 d and the mass ratio is 0.483. The variations of the Balmer and He I lines are consistent with the rotation/magnetic period of 538 d. Wade *et al.* (2011) presented 13 new magnetic field measurements of this star demonstrating that the magnetic data can be modelled as a periodic, sinusoidal signal with a period of 538 d inferred from spectroscopy. However, one out of three magnetic field measurements based on high-resolution polarimetric observations with the echelle spectrograph SOFIN (Tuominen *et al.*, 1999) mounted at the Cassegrain focus of the Nordic Optical Telescope (NOT) indicates a stronger positive magnetic field in the phase 0.43 than presented by Wade *et al.* (Hubrig *et al.*, 2010; Hubrig *et al.* 2012, submitted). In Figure 1 we present SOFIN observations together with those published by Wade *et al.* (2011). Clearly, additional magnetic field observations of this star are needed to properly characterise the variation of the longitudinal magnetic field and the magnetic field geometry.

2.2. The SB2 system 9 Sgr with colliding winds

The search for the presence of a magnetic field in 9 Sgr was carried out using FORS 1, SOFIN. and HARPS spectropolarimetric observations. The magnetic field appears to be variable with negative and positive extreme values of -265 G and $+242$ G. Since the change of polarity takes place within a few nights, we expect that the rotation period of the primary is just a couple of days. These are the only magnetic field measurements of 9 Sgr available to date. This system belongs to the young cluster NGC 6530 and has a classification O4 V ((f)) (Maíz-Apellániz *et al.*, 2004), exhibiting weak N III emission and strong He II λ 4686 absorption. It is a well-known non-thermal radio emitter and, according to van Loo *et al.* (2006), the most likely mechanism is synchrotron emission from colliding winds, implying that all O stars with non-thermal radio emission should be members of binary or multiple systems. Hints of a wind-wind interaction were indeed detected in the X-ray domain (Rauw *et al.*, 2002). A long-term study of its binary nature and spectrum variability has recently been presented by Rauw *et al.* (2012) who derived an orbital solution and an orbital period of 8.6 yr.

2.3. The black-hole binary Cyg X-1

The X-ray binary Cyg X-1 is a micro-quasar containing the historically first black-hole (BH) candidate. The system shows periodic and aperiodic variations and flares. Theoretical models to describe physical processes in such systems are dominated by the magnetic-disk-accretion paradigm. The orbital period is 5.6 d and the optical component (O9.7 Iab supergiant) is responsible for about 96% of the system optical luminosity. The rest is due to the accretion structure (disk and surrounding gas) near the BH. The first reliable magnetic field measurements were achieved using polarimetric FORS 1 spectra (Karitskaya *et al.*, 2010). The measurements showed that the behaviour of the mean longitudinal magnetic field has probably changed from 2007 to 2008. Note that the rotation period of the supergiant is unknown.

2.4. The runaway star ζ Ophiuchi

One more massive O-type star, the runaway star ζ Ophiuchi, displaying a wonderful bow-shock nebula (Hubrig *et al.*, 2011b), is probably associated with the pulsar PSR B1929+10. Tetzlaff *et al.* (2010) suggested that both objects were ejected from Upper Scorpius during the same supernova event. It is possible that ζ Oph rotates with almost break-up velocity with $v \sin i = 400\,\mathrm{km\,s^{-1}}$ (Kambe *et al.*, 1993). The first detection of a mean longitudinal magnetic field in this star was announced by Hubrig *et al.* (2011b).

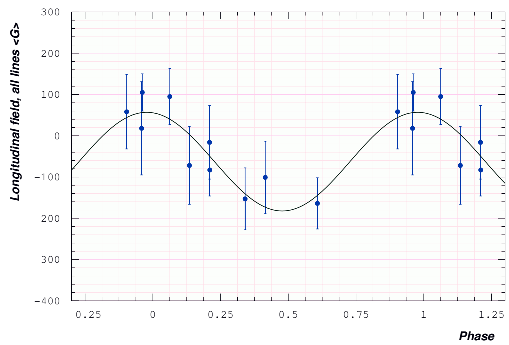

Figure 2: Phase diagram for the best sinusoidal fit corresponding to a period of 1.3 days for the longitudinal magnetic field measurements for ζ Oph using the whole spectrum.

Nine additional FORS 2 spectropolarimetric observations showing a change of polarity have been obtained over four consecutive nights in May 2011 (Hubrig et al. 2012, submitted). The resulting periodogram for magnetic field measurements using all lines visible in FORS 2 spectra indicates a rotation/magnetic period of 1.3 days. In Figure 2 we present these magnetic field measurements phased with this period. Interestingly, just a few months ago Pollmann (2012) presented equivalent width changes of He I λ 6678 with a period of 0.643 d, which is roughly half of the magnetic period of 1.3 d determined using the whole spectral region. For the rotation period of $\sim$1.3 d the equivalent width of the He I line would display a double wave. Such a behaviour of He I lines is frequently found in He variable early-type Bp stars (e.g. Briquet *et al.*, 2004). More measurements are needed to determine the true periodicity of the magnetic field in this star.

3. Binary Systems Among B-type Stars with Detected Magnetic Fields

Current magnetic field studies indicate that magnetic fields are more widespread in B-type stars than in the more massive O-type stars. Up to 20% of B-type stars belong to the group of chemically peculiar strongly variable Bp stars exhibiting chemical spots of He and Si and possessing large-scale organised magnetic fields of the order of kG. Besides, the presence of weak magnetic fields in pulsating B-type stars, Be stars, and a few exotic systems was reported by researchers in recent years.

3.1. β Cephei and slowly pulsating B stars

Several β Cephei stars possess magnetic fields, among them β Cephei itself (Henrichs *et al.*, 2000). In the group of magnetic β Cephei stars only ξ^1 CMa shows a longitudinal magnetic field as large as 350 G (Hubrig *et al.*, 2006, 2011c) and is the hottest β Cephei star (BO.7IV). The presence of weak magnetic fields was also reported for a dozen slowly pulsating B (SPB) stars by Hubrig *et al.* (2006) and Hubrig *et al.* (2009a). Although a number of pulsating B-type stars belong to SB systems, no hint of a relation between the magnetic field strength and the membership of the pulsating star in a binary system was found in previous studies (Hubrig *et al.*, 2009a). All magnetic β Cephei and SPB stars for which several magnetic field measurements were gathered, showed that the field varies in time, but the effect of the fields on the oscillation properties is not well understood yet.

3.2. Be stars

The group of Be stars consists of rapidly rotating B-type stars losing mass and initially accumulating it in a rotating circumstellar disk. Much of the mass loss is in the form of outbursts and thus additional mechanisms such as the beating of nonradial pulsation modes or magnetic flares must be at work. Indirect evidence for the presence of a magnetic field is based on variations of the X-ray emission and the presence of transient features in absorption line profiles. Furthermore, angular momentum transfer to a circumstellar disk, channeling stellar wind matter and accumulation of material in an equatorial disk are more easily explained if magnetic fields can be invoked.

A sample of Be stars in the field and in the cluster NGC 3766 (14.5–25 Myr old) has been observed in 2006-2008 with FORS 1 (Hubrig *et al.*, 2009b). A few Be stars show weak magnetic fields with the strongest field detected in the Be star HD 62367 ($\langle B_z \rangle = 117 \pm 38$ G). The detected magnetic fields in Be stars are usually weak, below 100 G. We note that the few recent unsuccessful searches for magnetic fields in Be stars have been based on low signal-to-noise ESPaDOnS and NARVAL observations. The large inaccuracies of those measurements did not allow the authors to discover magnetic fields below 100 G (e.g. Neiner *et al.*, 2012).

The cluster NGC 3766 appears to be extremely interesting, where we find evidence for the presence of a magnetic field in seven early-B type stars (among them three Be stars) out of the observed 14 cluster members.

However, no Be star with a detected weak field is known to belong to a binary system with certainty. probably due to a lack of binary systems among this group of stars. According to Oudmaijer and Parr (2010), the binary fraction among Be stars is only about 10%.

3.3. The B0.2V SB1 binary θ Carinae

One of the exotic systems studied in recent years is the B0.2V SB1 binary θ Carinae, which belongs to a group of peculiar early-type stars (OBN) with enhanced nitrogen and carbon deficiency. Walborn (2006) listed this star among a few other massive stars with unexplained spectral peculiarities or variations for which a magnetic field could be expected. It has a peculiar, variable spectrum in both optical and UV, and a high $L_{\rm X}/L_{\rm bol}$ ratio. θ Car is an SB1 system with one of the shortest orbital periods known among massive stars ($P = 2.2$ d; Lloyd *et al.*, 1995). A discussion of the possibility of mass transfer in the binary system, which would be a natural explanation for the remarkable spectral peculiarities and for the singular location of this object in the H-R diagram of the 30 Myr old open cluster IC 2602, was presented by Walborn (1976).

The first spectropolarimetric observations of θ Car with FORS 1 were obtained in 2004 January (Hubrig *et al.*, 2008b) at a signal-to-noise ratio of about 1000. The observations consisted of four series of two exposures with the retarder waveplate oriented at two different angles ($\alpha = +45°$ and $-45°$) at a spectral resolving power of $R \approx 2000$. Surprisingly, the magnetic field measurements on the Stokes V spectra obtained with an exposure time of 0.2 s showed a change of the field polarity after the first series (which took 2.5 min) from a positive magnetic field to a negative magnetic field.

To solve the puzzle, θ Car was re-observed in 2007 March at a higher signal-to-noise ratio (S/N $\sim$ 1200) in the spectral region from 3805 Å to 4960 Å at a spectral resolving power of $R \approx 4000$. To monitor the behaviour of the magnetic field over at least a part of the stellar surface, time series of exposures with a short integration time over the time span of $\sim$1.2 h were carried out. The observations obtained in 2007 March confirmed the previous finding of the magnetic field variations on a short time scale. The observed magnetic field changed several times from positive to negative values over the observing time span, and the frequency 0.0019 Hz (=8.8 min) was found to be present in all data sets. The Fourier spectrum is shown on the left of Figure 3 with an amplitude of the magnetic field

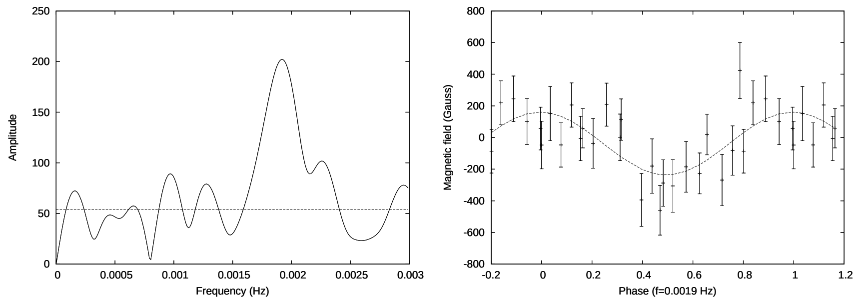

Figure 3: *Left:* Fourier spectrum for the magnetic field data derived from hydrogen lines without Hβ for θ Car. The horizontal line gives the noise level. *Right:* Phase diagram for the same dataset for the best candidate frequency of 0.0019 Hz, i.e. a period of about 8.8 minutes.

variation of 202±43 G. The corresponding phase diagram is shown on the right of Figure 3. Additional time-resolved magnetic field observation would be worthwhile to confirm these interesting results.

3.4. The complex systems β Lyr and υ Sgr

Two very complex systems with B-type components have been intensively studied in the past by several research groups: β Lyr and υ Sgr. υ Sgr is one of the few known hydrogen-deficient binaries. It was frequently classified as a Be star due to the presence of strong emission lines in the visible spectrum. A spectroscopic study of υ Sgr by Koubský *et al.* (2006) pointed out that the object could be similar to β Lyr observed under non-eclipsing inclination. The system of υ Sgr has long been known as a single-lined spectroscopic binary (P = 137.9 d). The secondary orbit was determined by the cross-correlation technique applied to IUE spectra (Dudley and Jeffery, 1990). The secondary ('invisible') component appears to be more massive (q = 1.59), while the luminosity ratio of visible to 'invisible' seems to be about 100. The optically visible star is extremely line rich (see left panel in Figure 4).

The first magnetic field measurement in 2005 May by Hubrig *et al.* (2009b) resulted in $\langle B_z \rangle = 38 \pm 10$ G. A few additional observations in 2007 showed a longitudinal magnetic field of the order of -70 G. The visible component seems to be a magnetic variable star, probably on a few months timescale with a maximum longitudinal magnetic field $\langle B_z \rangle = -102 \pm 10$ G measured in hydrogen lines. In the right panel of Figure 4 we present the

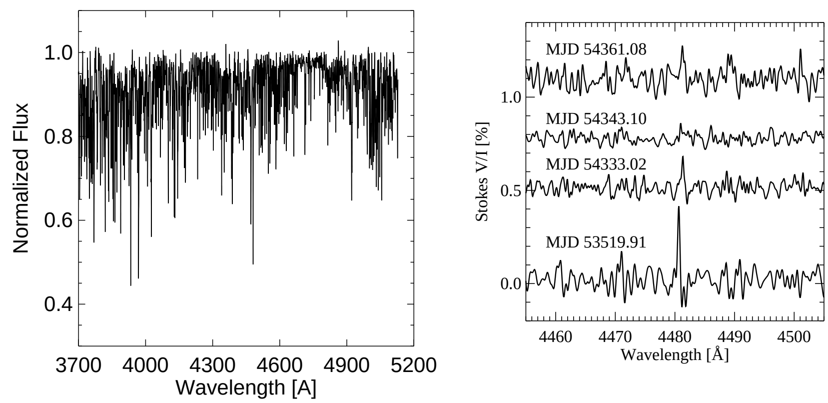

Figure 4: *Left:* Normalised FORS 1 Stokes I spectrum of υ Sgr. *Right:* Observed Stokes V spectra of the emission line star υ Sgr over two years (from 2005 May to 2007 September) in the vicinity of Mg II 4481.

Stokes V spectra in the vicinity of Mg II 4481 taken on four different dates over two years. Distinct Zeeman features are clearly visible at the position of the Mg II 4481 line. The star dominating the optical and UV line spectra is less massive and probably has a spectral type B8p I, while the second, almost invisible component, probably has a spectral type O9 V. Hubrig *et al.* (2007) reported the detection of distinct Zeeman signatures in the Ca II H&K lines, which are probably formed in the circumstellar disk around this star. Future monitoring of the magnetic field of υ Sgr over a few months with a high resolution spectropolarimeter would be of extreme interest to understand the role of the magnetic field in the evolutionary process of mass exchange in a binary system.

β Lyrae is a bright eclipsing binary star system (see e.g. Harmanec, 2002) with the B 6-B8 II primary ("loser") transferring matter to its main-sequence B0.5 V companion via Roche lobe overflow (Hubeny and Plavec, 1991; Harmanec and Scholz, 1993). A bipolar flow or jet was also detected through interferometric and spectropolarimetric methods (e.g. Harmanec *et al.*, 1996). The inclination of the system is $83 - 85°$ and the orbital period is 12.9 d. Broad-band spectropolarimetric data acquired in the last years indicate the possible presence of an accretion hot spot on the disk edge (Lomax *et al.*, 2012). No sign of a hot spot was reported for υ Sgr. Recent VEGA/CHARA observations showed the huge extent of the Hα environment, larger than the scale of the orbits for both υ Sgr and β Lyr, giving evidence for a non-conservative evolution (Bonneau *et al.*, 2011).

The most extensive studies of the magnetic field of β Lyr were carried out by Skulskij and collaborators from 1980 to 2004 (e.g. Skulskij, 1993). According to their measurements, the magnetic field of β Lyr shows an intricate time-dependent behaviour, the exact character of which is not understood yet. According to Leone *et al.* (2003), the magnetic field variation in strength and sign on a long time scale could indicate a dynamo origin of the field.

4. Recent Magnetic Studies of Herbig Ae/Be Stars, Including the Complex System Z CMa

Magnetic fields are important ingredients of the star formation process (McKee and Ostriker, 2007). For young stars, the magnetic field and its geometry affect how and where the accretion disk couples to the star and are thought to be important in launching bipolar outflows. Magnetic processes are responsible for the high-energy radiation of young stars, which in turn may be critical for the annealing and melting of some refractory grain species (Shu *et al.*, 2001), for heating intermediate-depth portions of disks around young stars (Najita, 2004), and for mass loss from planets forming in those disks (Penz *et al.*, 2008).

4.1. Herbig Ae/Be stars

Herbig Ae/Be stars are pre-main-sequence objects with pronounced emission line features and an infrared excess indicative of dust in the circumstellar disks. Despite the general notion that they have convectively stable envelopes that do not support cTTS-like dynamo action, in the last years it was demonstrated that a number of Herbig Ae/Be stars have globally organised rather strong magnetic fields (e.g., Hubrig *et al.*, 2004; Wade *et al.*. 2005; Hubrig *et al.*, 2009c; Hubrig *et al.*, 2011d; Hubrig *et al.*, 2011e). The evidence of the large-scale organised magnetic fields detected in Herbig Ae/Be stars is reminiscent of the classical Ap/Bp stars, of which the Herbig stars may be precursors. Magnetic fields in these stars might be fossils of the early star formation epoch in which the magnetic field of the parental magnetised core was compressed into the innermost regions of the accretion disks (e.g. Banerjee *et al.*, 2006). Alternatively, Tout and Pringle (1995) proposed a non-solar dynamo that could operate in rapidly rotating A-type stars based on rotational shear energy.

A majority of the Herbig Ae/Be stars are binary or multiple systems. The existence of a magnetic field, however, does not seem to be related to binarity. We note however, that the presence of a close companion contributing to the observed polarimetric spectra can cause a non-detection of the magnetic field due to blending of spectral lines of the primary. The contribution of the secondary component can be disentangled only by means of high resolution spectropolarimetric observations, but not with low resolution FORS 1/2 spectropolarimetry. In previous spectropolarimetric studies, some targets, e.g. HD 97048 or HD 100546, show a magnetic field (Hubrig *et al.*, 2011d), but have no known companions, while other binary Herbig Ae stars possess no magnetic field.

4.2. The FU Ori type system Z CMa

The outbursting FU Ori type system Z CMa was intensively studied during its optical outburst in 2008–2009. It is a binary system that consists of two young stars: a Herbig AeBe 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. Associated to the binary system is a giant parsec-size jet. Past spectropolarimetric observations showed that the position angle of the linear optical polarization is perpendicular to the jet axis, indicating that the visual light escapes the cocoon via cavities aligned with the jet axis and is then scattered back into the line of sight of the observer. In 2008-2009 the system showed the largest outburst reported during the almost 90 years of available observations. The nature of this outburst is still under debate: it is not clear whether it originated as a consequence of a real outburst, or because of changes (such as the formation of a new hole) in the dust. Currently Z CMa is experiencing a new, even stronger outburst, which started in April 2010 and lasts until today.

Z CMa has been studied during the optical outburst in 2008–2009 using linear and circular spectropolarimetric observations with FORS 1 (Szeifert *et al.*, 2010). The spectropolarimetric data sets provide very important insights into the nature of the optically unresolved binary star. Szeifert *et al.* (2010) found significant changes of the line shapes in linear polarized light with respect to the data published by Whitney *et al.* (1993). In data obtained during the extreme outburst, a flat polarization spectrum with an average polarization $P = 3\%$ with a polarization angle perpendicular to the parsec scale jet associated with Z CMa is observed, similar to observa-

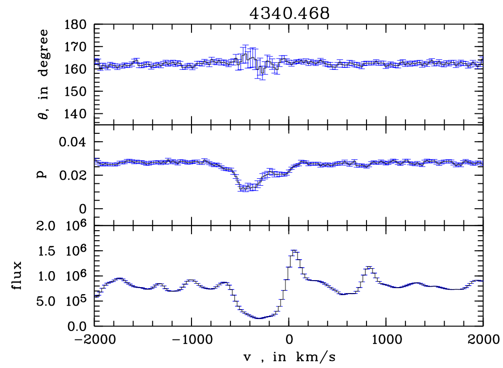

Figure 5: Spectropolarimetry of Z CMa in H_γ.

tions presented by Whitney *et al.* (1993) who measured $P = 1.4 - 2\%$ and $P.A = 154°$. However, in the deep absorption troughs of the Balmer lines and other strong wind absorption lines, Szeifert *et al.* (2010) detect depolarization signatures (see Figure 5). These line components caused by the accelerated wind show a composite spectrum. The authors observe a broad blue trough typically associated with an accelerated wind, visible to about $-600\,\mathrm{km\,s^{-1}}$, with less deep absorption up to about $-800\,\mathrm{km\,s^{-1}}$.

As is shown in Figure 6, this is not mirrored by emission on the red side of the lines as would be expected for spherical symmetric winds. The trough is rather deep, indicating that a large fraction of the stellar disk is obscured by the wind acceleration zone. Superimposed to the wind feature is a very narrow emission component of 50 to $60\,\mathrm{km\,s^{-1}}$ half width, which can be seen as well for faint low excitation lines like Fe II and similar species.

In contrast to the observations of Whitney *et al.* (1993), Szeifert *et al.* (2010) find that the narrow emission lines show the same degree (3%) and position angle of polarization as the continuum. These observations can be understood within the above mentioned model that the light can only escape via cavities from the dust cocoon, most likely aligned with the bipolar jet. In these recent observations the continuum radiation as well as the emission components are dominated by the NW component, while in the deep absorption troughs the unpolarized SE component is still contributing. Whitney *et al.* (1993) observed the binary in a different state, when the SE component dominated the flux in the near-UV and visual. The strongest emission lines reached up to a polarization of about 6%. This was higher

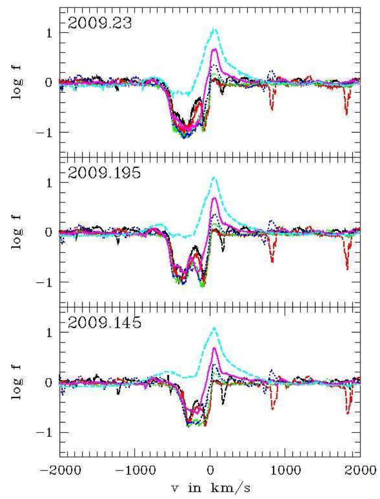

Figure 6: Logarithmic spectral shape of the Balmer lines H_α to H_9 in Z CMa. The variability is most pronounced in the absorption troughs and for H_α in the symmetric electron scattered broad wings (Szeifert *et al.*, 2010).

than what is currently seen in the visual and near-UV continuum. The change of the degree of polarization, together with the brightening of the target indicates 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 toward the observer, became more efficient, causing an increase in the visual brightness by about 2.5^m.

The analysis of circular polarization measurements obtained during the outburst reveals no significant detection. In the data obtained in 2008 May, Szeifert *et al.* (2010) detect a weak signal of circular polarization in the trough of all Balmer lines, which however does not match in wavelength the unpolarized line profile. However, while reviewing the archive data already published by Wade *et al.* (2007), Szeifert *et al.* (2010) do detect a clear circular polarization signal in particular at the blue shifted side of the high-number Balmer lines. For the low excitation lines from Hβ to Hϵ they measure -160 ± 84 G, while from the higher excitation Balmer lines a very significant field of -1231 ± 164 G (see Figure 7) was obtained.

To properly interpret the circular polarization signal, it is necessary to consider the composite nature of the binary system spectrum, the superimposed effects of the stellar wind, and the variability of the target. It is unclear

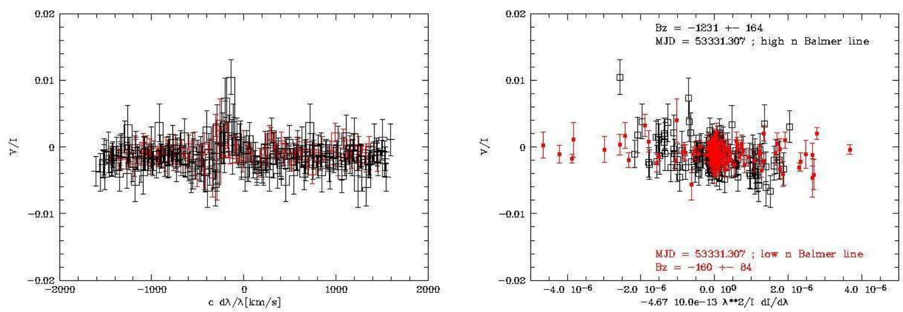

Figure 7: *Left panel:* Circular polarization in the Balmer line spectra observed in November 2004. The spectra are plotted in the velocity frame to display Balmer lines from 4861 Å to 3734 Å. *Right panel:* Magnetic field measurements using the data obtained in 2004 November. The longitudinal magnetic field is derived following the equation $V/I = -\mathrm{g_{eff}} \mathrm{C}_z \lambda^2 \frac{1}{I} \frac{\mathrm{d}I}{\mathrm{d}\lambda} \langle B_z \rangle$ 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.

if these fields were detected in the dust embedded Herbig Ae star or in the SE companion. In the first case the strong field is only seen in the fainter Balmer lines, because the high opacity of the expanding wind at the blue shifted part of the strong lines would not allow light from the photosphere to escape from the NW component. Alternatively, without any indication of the contribution of the respective two stars to the UV and visible spectra, one can as well explain the data if the magnetic field was detected in the SE component, which may have dominated the spectra of 2004 in the wavelength range of the Balmer lines in which Szeifert *et al.* (2010) measure the Stokes V features. Clearly, high-resolution spectropolarimetric observations are urgently needed to understand the magnetic nature of this system.

Using imaging polarimetry, Canovas *et al.* (2012) detected three polarized features over Z CMa. Two of these features are related to the two jets previously reported in this system: the large jet associated to the Herbig star, and the micro-jet associated to the FU Ori star. The third feature suggests the presence of a hole in the dust cocoon that surrounds the Herbig star of this system.

5. Concluding Remarks

Theory offers essentially two explanations for the origin of the observed surface fields: fossil fields, particularly for strong and ordered fields, or different dynamo mechanisms, preferentially for less ordered fields. Numerical simulations yield the first concrete stable (fossil) field configurations, but give contradictory results as to whether dynamo action in the radiative envelope is possible.

In close binary stars the tidal torque varying with depth and latitude in a star induces differential rotation. In a radiative envelope that has driven differential rotation, it is possible to construct a dynamo that feeds only off the differential rotation (e.g. Braithwaite and Spruit, 2004).

Due to the lack of close binaries among the best studied magnetic Ap/Bp stars, a merger scenario was suggested by Ferrario *et al.* (2009). Towards the end of the formation process, after the stars have developed a substantial radiative envelope, a fraction of stars merge. Such late mergers would produce a brief period of strong differential rotation and give rise to large-scale magnetic fields in the radiative envelopes. This scenario would actually explain why no Ap stars are found close to the ZAMS, in contrast to the location of Bp stars in the H-R diagram (Hubrig *et al.*, 2000).

Clearly, the decision between the fossil and the dynamo explanations for the magnetic field origin can be made only through careful consolidation of magneto-hydrodynamic theory and observations.

References

Banerjee, R., Pudritz, R. E., and Anderson, D. W.: 2006, *Mon. Not. R. Astron. Soc.* **373**, 1091.

Bonneau, D., Chesneau, O., Mourard, D., Bério, P., Clausse, J. M., Delaa, O., Marcotto, A., Perraut, K., Roussel, A., Spang, A., Stee, P., Tallon-Bosc, I., McAlister, H., Ten Brummelaar, T., Sturmann, J., Sturmann, L., Turner, N., Farrington, C., and Goldfinger, P. J.: 2011, *Astron. Astrophys.* **532**, A148.

Braithwaite, J. and Spruit, H. C.: 2004, *Nature* **431**, 819.

Briquet, M., Aerts, C., Lüftinger, T., De Cat, P., Piskunov, N. E., and Scuflaire, R.: 2004, *Astron. Astrophys.* **413**, 273.

Canovas, H., Min, M., Jeffers, S. V., Rodenhuis, M., and Keller, C. U.: 2012, *Astron. Astrophys.* **543**, A70.

Cantiello, M., Langer, N., Brott, I., de Koter, A., Shore, S. N., Vink, J. S., Voegler, A., Lennon, D. J., and Yoon, S.-C.: 2009, *Astron. Astrophys.* **499**, 279.

Donati, J.-F., Babel, J., Harries, T. J., Howarth, I. D., Petit, P., and Semel, M.: 2002, *Mon. Not. R. Astron. Soc.* **333**, 55.

Donati, J.-F., Howarth, I. D., Bouret, J.-C., Petit, P., Catala, C., and Landstreet, J.: 2006, *Mon. Not. R. Astron. Soc.* **365**, L6.

Dudley, R. E. and Jeffery, C. S.: 1990, *Mon. Not. R. Astron. Soc.* **247**, 400.

Ferrario, L., Pringle, J. E., Tout, C. A., and Wickramasinghe, D. T.: 2009, *Mon. Not. R. Astron. Soc.* **400**, L71.

Harmanec, P.: 2002, *Astronomische Nachrichten* **323**, 87.

Harmanec, P. and Scholz, G.: 1993, *Astron. Astrophys.* **279**, 131.

Harmanec, P., Morand, F., Bonneau, D., Jiang, Y., Yang, S., Guinan, E. F., Hall, D. S., Mourard, D., Hadrava, P., Bozic, H., Sterken, C., Tallon-Bosc, I., Walker, G. A. H., McCook, G. P., Vakili, F., Stee, P., and Le Contel, J. M.: 1996, *Astron. Astrophys.* **312**, 879.

Henrichs, H. F., Neiner, C., Hubert, A. M., Floquet, M., and MuSiCoS Team: 2000, *in* M. A. Smith, H. F. Henrichs, and J. Fabregat (eds.), *IAU Colloq. 175: The Be Phenomenon in Early-Type Stars*, Vol. 214 of *Astronomical Society of the Pacific Conference Series*, p. 372.

Howarth, I. D., Walborn, N. R., Lennon, D. J., Puls, J., Nazé, Y., Annuk, K., Antokhin, I., Bohlender, D., Bond, H., Donati, J.-F., Georgiev, L., Gies, D., Harmer, D., Herrero, A., Kolka, I., McDavid, D., Morel, T., Negueruela, I., Rauw, G., and Reig, P.: 2007, *Mon. Not. R. Astron. Soc.* **381**, 433.

Hubeny, I. and Plavec, M. J.: 1991, *Astron. J.* **102**, 1156.

Hubrig, S., Briquet, M., De Cat, P., Schöller, M., Morel, T., and Ilyin, I.: 2009a, *Astronomische Nachrichten* **330**, 317.

Hubrig, S., Briquet, M., Morel, T., Schöller, M., González, J. F., and De Cat, P.: 2008b, *Astron. Astrophys.* **488**, 287.

Hubrig, S., Briquet, M., Schöller, M., De Cat, P., Mathys, G., and Aerts, C.: 2006, *Mon. Not. R. Astron. Soc.* **369**, L61.

Hubrig, S., Ilyin, I., and Schöller, M.: 2010, *Astronomische Nachrichten* **331**, 781.

Hubrig, S., Ilyin, I., Schöller, M., Briquet, M., Morel, T., and De Cat, P.: 2011c, *Astrophys. J., Lett.* **726**, L5.

Hubrig, S., Mikulášek, Z., González, J. F., Schöller, M., Ilyin, I., Curé, M., Zejda, M., Cowley, C. R., Elkin, V. G., Pogodin, M. A., and Yudin, R. V.: 2011e, *Astron. Astrophys.* **525**, L4.

Hubrig, S., North, P., and Mathys, G.: 2000, *Astrophys. J.* **539**, 352.

Hubrig, S., Oskinova, L. M., and Schöller, M.: 2011b, *Astronomische Nachrichten* **332**, 147.

Hubrig, S., Schöller, M., Ilyin, I., Cowley, C. R., Mikulášek, Z., Stelzer, B., Pogodin, M. A., Yudin, R. V., and Curé, M.: 2011d, *Astron. Astrophys.* **536**, A45.

Hubrig, S., Schöller, M., Ilyin, I., Kharchenko, N. V., Oskinova, L. M., Langer, N., González, J. F., Kholtygin, A. F., Briquet, M., and Magori Collaboration: 2013, *Astron. Astrophys.* **551**, A33.

Hubrig, S., Schöller, M., Kharchenko, N. V., Langer, N., de Wit, W. J., Ilyin, I., Kholtygin, A. F., Piskunov, A. E., Przybilla, N., and Magori Collaboration: 2011a, *Astron. Astrophys.* **528**, A151.

Hubrig, S., Schöller, M., Savanov, I., Yudin, R. V., Pogodin, M. A., Štefl, S., Rivinius, T., and Curé, M.: 2009b, *Astronomische Nachrichten* **330**, 708.

Hubrig, S., Schöller, M., Schnerr, R. S., González, J. F., Ignace, R., and Henrichs, H. F.: 2008a, *Astron. Astrophys.* **490**, 793.

Hubrig, S., Schöller, M., and Yudin, R. V.: 2004, *Astron. Astrophys.* **428**, L1.

Hubrig, S., Stelzer, B., Schöller, M., Grady, C., Schütz, O., Pogodin, M. A., Curé, M., Hamaguchi, K., and Yudin, R. V.: 2009c, *Astron. Astrophys.* **502**, 283.

Hubrig, S., Yudin, R. V., Pogodin, M., Schöller, M., and Peters, G. J.: 2007, *Astronomische Nachrichten* **328**, 1133.

Kambe, E., Ando, H., and Hirata, R.: 1993, *Astron. Astrophys.* **273**, 435.

Karitskaya, E. A., Bochkarev, N. G., Hubrig, S., Gnedin, Y. N., Pogodin, M. A., Yudin, R. V., Agafonov, M. I., and Sharova, O. I.: 2010, *Information Bulletin on Variable Stars* **5950**, 1.

Koubský, P., Harmanec, P., Yang, S., Netolický, M., Škoda, P., Šlechta, M., and Korčáková, D.: 2006, *Astron. Astrophys.* **459**, 849.

Leone, F., Plachinda, S. I., Umana, G., Trigilio, C., and Skulsky, M.: 2003, *Astron. Astrophys.* **405**, 223.

Lloyd, C., Stickland, D., and Walborn, N. R.: 1995, *Publ. Astron. Soc. Pac.* **107**, 1030.

Lomax, J. R., Hoffman, J. L., Elias, II, N. M., Bastien, F. A., and Holenstein, B. D.: 2012, *Astrophys. J.* **750**, 59.

Maíz-Apellániz, J., Walborn, N. R., Galué, H. Á., and Wei, L. H.: 2004, *Astrophys. J., Suppl. Ser.* **151**, 103.

Martins, F., Escolano, C., Wade, G. A., Donati, J. F., Bouret, J. C., and Mimes Collaboration: 2012, *Astron. Astrophys.* **538**, A29.

McKee, C. F. and Ostriker, E. C.: 2007, *Ann. Rev. Astron. Astrophys.* **45**, 565.

Najita, J.: 2004, *in* D. Johnstone, F. C. Adams, D. N. C. Lin, D. A. Neufeeld, and E. C. Ostriker (eds.), *Star Formation in the Interstellar Medium: In Honor of David Hollenbach*, Vol. 323 of *Astronomical Society of the Pacific Conference Series*, p. 271.

Neiner, C., Grunhut, J. H., Petit, V., ud-Doula, A., Wade, G. A., Landstreet, J., de Batz, B., Cochard, F., Gutiérrez-Soto, J., and Huat, A.-L.: 2012, *Mon. Not. R. Astron. Soc.* **426**, 2738.

Oudmaijer, R. D. and Parr, A. M.: 2010, *Mon. Not. R. Astron. Soc.* **405**, 2439.

Penz, T., Erkaev, N. V., Kulikov, Y. N., Langmayr, D., Lammer, H., Micela, G., Cecchi-Pestellini, C., Biernat, H. K., Selsis, F., Barge, P., Deleuil, M., and Léger, A.: 2008, *Planet. Space Sci.* **56**, 1260.

Pollmann, E.: 2012, *Information Bulletin on Variable Stars* **6034**, 1.

Rauw, G., Blomme, R., Waldron, W. L., Corcoran, M. F., Pittard, J. M., Pollock, A. M. T., Runacres, M. C., Sana, H., Stevens, I. R., and Van Loo, S.: 2002, *Astron. Astrophys.* **394**, 993.

Rauw, G., Sana, H., Spano, M., Gosset, E., Mahy, L., De Becker, M., and Eenens, P.: 2012, *Astron. Astrophys.* **542**, A95.

Robrade, J. and Schmitt, J. H. M. M.: 2009, *Astron. Astrophys.* **497**, 511.

Shu, F. H., Shang, H., Gounelle, M., Glassgold, A. E., and Lee, T.: 2001, *Astrophys. J.* **548**, 1029.

Skulskij, M. Y.: 1993, *Astronomy Letters* **19**, 45.

Szeifert, T., Hubrig, S., Schöller, M., Schütz, O., Stelzer, B., and Mikulášek, Z.: 2010, *Astron. Astrophys.* **509**, L7.

Tetzlaff, N., Neuhäuser, R., Hohle, M. M., and Maciejewski, G.: 2010, *Mon. Not. R. Astron. Soc.* **402**, 2369.

Tout, C. A. and Pringle, J. E.: 1995, *Mon. Not. R. Astron. Soc.* **272**, 528.

Tuominen, I., Ilyin, I., and Petrov, P.: 1999, *in* H. Karttunen and V. Piirola (eds.), *Astrophysics with the NOT*, p. 47.

van Loo, S., Runacres, M. C., and Blomme, R.: 2006, *Astron. Astrophys.* **452**, 1011.

Wade, G. A., Bagnulo, S., Drouin, D., Landstreet, J. D., and Monin, D.: 2007, *Mon. Not. R. Astron. Soc.* **376**, 1145.

Wade, G. A., Drouin, D., Bagnulo, S., Landstreet, J. D., Mason, E., Silvester, J., Alecian, E., Böhm, T., Bouret, J.-C., Catala, C., and Donati, J.-F.: 2005, *Astron. Astrophys.* **442**, L31.

Wade, G. A., Howarth, I. D., Townsend, R. H. D., Grunhut, J. H., Shultz, M., Bouret, J.-C., Fullerton, A., Marcolino, W., Martins, F., Nazé, Y., Ud Doula, A., Walborn, N. R., and Donati, J.-F.: 2011, *Mon. Not. R. Astron. Soc.* **416**, 3160.

Walborn, N. R.: 1973, *Astron. J.* **78**, 1067.

Walborn, N. R.: 1976, *Astrophys. J.* **205**, 419.

Walborn, N. R.: 2006, *IAU Joint Discussion*, Vol. 4 of *IAU Joint Discussion.*

Walborn, N. R., Sota, A., Maíz Apellániz, J., Alfaro, E. J., Morrell, N. I., Barbá, R. H., Arias, J. I., and Gamen, R. C.: 2010, *Astrophys. J., Lett.* **711**, L143.

Whitney, B. A., Clayton, G. C., Schulte-Ladbeck, R. E., Calvet, N., Hartmann, L., and Kenyon, S. J.: 1993, *Astrophys. J.* **417**, 687.