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RECENT ADVANCES IN THE STUDIES OF MAGNETIC FIELDS IN AP/BP STARS AND THEIR PREDECESSORS, THE HERBIG AE/BE STARS

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Ap/Bp stars are unique astrophysical laboratories.Studies of these stars are of particular importance to improve our understanding of the physical processes taking place in the presence of strong magnetic fields. The focus of current Ap/Bp star research is on providing information on the statistics of magnetic field properties, the distribution of their rotation periods, and on the possible relations between the magnetic field strength and other stellar parameters.In contrast to the kG-order magnetic fields detected in Ap/Bp stars, the latest analyses of the magnetic fields of their predecessors, the Herbig~Ae/Be stars, support the idea that the low detection rate of magnetic fields in these stars can be explained by the weakness of these fields: only a few stars have longitudinal magnetic fields stronger than 200 G, and half of the sample possesses longitudinal magnetic fields weaker than 100 G, unlike their lower mass T Tauri counterparts, which possess kG magnetic fields.

Keywords: magnetic field –evolution –chemically peculiar –pre-main sequence –variables: T Tauri, Herbig Ae/Be

1. INTRODUCTION

Globally ordered magnetic fields are observed in roughly 10–20% of the intermediate and massive main-sequence stars with spectral types between approximately B2 and F0. These stars, generally called the chemically peculiar Ap and Bp stars, exhibit strong overabundances of certain elements,such as iron peak elements and rare earths,and underabundances of He, C, and O, relative to solar abundances, and are characterized observationally by anomalous line strengths.

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Massive Bp stars usually show overabundances of He and Si. As the star rotates, the magnetic field and the surface abundance distribution is observed from various aspects,resulting in variability of the measured magnetic field and the spectral line strengths.

Variable magnetic fields are most frequently diagnosed through measurements of the mean longitudinal magnetic field, the mean magnetic field modulus, or the net broadband linear polarization. Chemical abundance anomalies are commonly believed to be due to radiatively driven microscopic diffusion in stars rotating sufficiently slow to allow such a process to be effective (e.g. [1]). The indirect surface mapping Zeeman Doppler Imaging (ZDI) method has been used to derive magnetic field maps. However, it has been applied only for a few Ap/Bp stars so far. The global magnetic field geometry usually changes little from one star to another, with nearly all stars showing dominant dipolar magnetic fields, with a varying degree of distortion. The past two decades have seen a significant step forward in our understanding of the occurrence of magnetic fields in upper-main-sequence A- and B-type stars and their predecessors, the Herbig∼Ae/Be stars. However, the most important aspects, such as the origin of stellar magnetic fields and the evolution of magnetic field configurations, are still not understood. For massive and intermediate mass stars with radiative envelopes, it has been argued that their magnetic fields could be fossil relics of the fields that were present in the interstellar medium from which these stars have formed (e.g. [2]). A search for the presence of magnetic fields in massive stars located in active sites of star formation, in the ρ Ophiuchus star-forming cloud and in the Trifid nebula, led to the detection of magnetic fields of several kG in two early B-type stars, the B2 V star HD 147933 and the B1 V star HD 164492Cb [3, 4]. However, the fossil field hypothesis has several problems as it does not explain the low ($\sim 10-20\%$) occurrence of magnetic stars and their broad range of field strengths. Moreover, a study of the distribution of magnetic Ap stars in the H-R diagram using accurate Hipparcos parallaxes [5] main-sequence band and only rarely can be found close to the zero-age main sequence (ZAMS). Similar studies using Gaia DR2 data are on the way, but their results are not published yet. Alternatively, the magnetic fields may be generated by strong binary interaction, i.e., in stellar mergers, or during a mass transfer or common envelope evolution (e.g. [6]). The resulting strong differential rotation is considered as a key ingredient for the generation of magnetic fields [7]. Especially studies of magnetic fields in Herbig Ae/Be stars at early evolutionary stages, before they arrive on the main sequence, are of great importance to get an insight into the magnetic field origin. Moreover, such studies enable us to improve our understanding of how the magnetic fields in these stars are generated and how they interact with their environment, including their impact on the planet formation process and the planet-disk interaction.

In the following we discuss recent advances in the studies of Ap/Bp stars and their predecessors,the Herbig Ae/Be stars,along with the underlying assumptions in the interpretation of magnetic field measurements and the requirements, both observational and theoretical, for obtaining a realistic overview of the role of magnetic fields in these types of stars.

2. NEW DIRECTIONS IN THE STUDIES OF AP/BP STARS

The recent analysis of a sub-sample of 43 Ap/Bp stars with resolved, magnetically split lines [8] and the announcement of the APOGEE sample of 157 Ap/Bp stars with similar characteristics and representing a187% increase in the number of stars with magnetic field modulus measurements $\langle B\rangle$(compared with the 84 such objects known before) [9], indicate the existence of a significant population of stars exhibiting strong magnetic fields and rotating slowly. The lines most frequently resolved into their split components in the H-band primarily pertain to Ce III, Cr II, Fe I, Mn II, Si I, and Ca II for these 157 stars. They represent the extreme magnetic end of a still-growing sample of more than 1000~ Ap/Bp stars selected among the APOGEE telluric standard stars as those with Ce III absorption lines and/or literature Ap/Bp classifications.

While the study of the characteristics of the APOGEE magnetic stars is currently underway, the analysis of the sub-sample of 43 Ap/Bp stars [8] revealed that the geometrical structures of their magnetic fields in general depart only slightly from centred dipoles.In more than half of the stars with magnetically resolved lines that have a rotation period shorter than 150 days,the mean magnetic field modulus $\langle B\rangle$ is larger than 7.5 kG,while those stars with a longer period all have a $\langle B\rangle$ smaller than 7.5 kG. A possible correlation between magnetic flux and the rotation period, or, in other words, a correlation between magnetic flux and angular rotational velocity was already indicated earlier [5]. One of the questions still remaining open is the presence of very weak magnetic fields, below 100 G,in Ap stars with very sharp spectral lines, with no hint of magnetic splitting or broadening. A search for magnetic fields in a small sample of Ap stars gave rise to the suggestion of a cut-off of about 300 G as the ultimate lower limit for the dipole strength [10]. On the other hand, current much more accurate magnetic field measurements of Ap and Bp stars do not confirm this conclusion (e.g. [11, 12]). Clearly, observations of a representative sample of Ap/Bp stars– volume-limited, with low and high projected rotation velocities,high accuracy magnetic field measurements, etc. –have to be obtained to properly characterise the low end of the magnetic field strength distribution.

Of the 43~Ap stars that were studied in detail [8], 22 are in wide binary systems. The shortest orbital periods of those systems is 27~days. The lack of

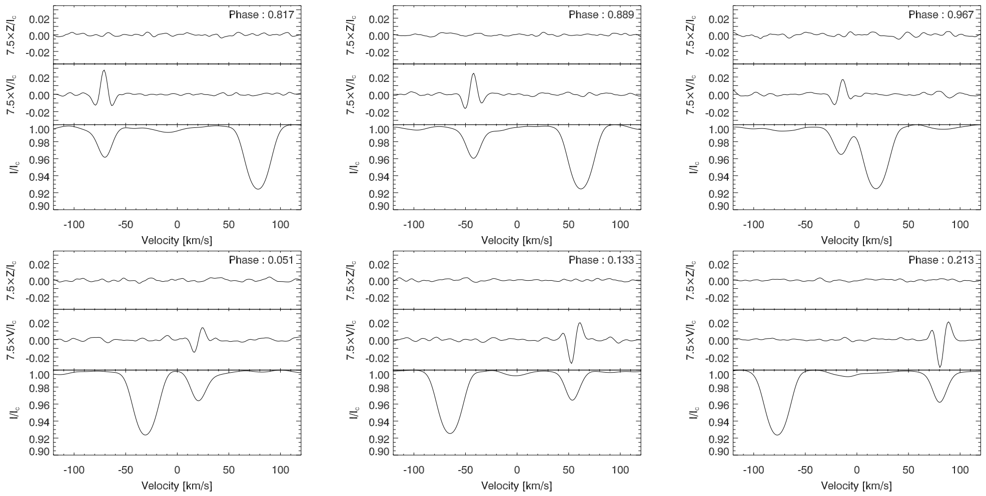

Fig. 1. SVD Stokes I, V, and diagnostic null Z profiles (from bottom to top) of HD 161701 obtained over six consecutive nights using 206 Fe II and Fe I lines. The V and Z profiles have been expanded by a factor of 7.5 and shifted upwards. No polarization is observed at the position of the average profile of the primary.

short orbital periods among binaries containing an Ap/Bp component with magnetically resolved lines is probably related to their slow rotation and remains to be fully understood. In addition to the binary system HD 161701, with a HgMn primary,only one other close binary system with a magnetic Ap component, the system HD 98088 with a lower mass Am companion, is currently known [13, 14]. The Ap component inHD 98088 exhibits a primary intensity maximum of the rare earth element europium at the surface persistently facing the companion, similar to the behaviour found in the Ap component in HD 161701 [4]. In Fig1 we present singular value deconvolution (SVD) Stokes I, V, and diagnostic null Z profiles obtained over six consecutive nights of HD 161701. The detected spectrum variations take place with the same period as the orbital motion [14]. According to [13],also the longitudinal magnetic field varies with the same period and, similar to the magnetic field behaviour in the secondary of the HD 161701 system, the surface of the Ap component in HD 98088 facing the companion carries a positive magnetic field. The alignment of the magnetic axis with the orbital radius vector may indicate that the generation of the magnetic field was a dynamic process during tidal synchronization. A magnetic instability was proposed [15, 16] to generate magnetic fields in Ap stars. Tidal forces may alter the flows during unstable phases to align the final field geometries in the observed way. A search for magnetic fields and the determination of their geometries in close binary systems is very important as the knowledge of the presence of a magnetic field and of the

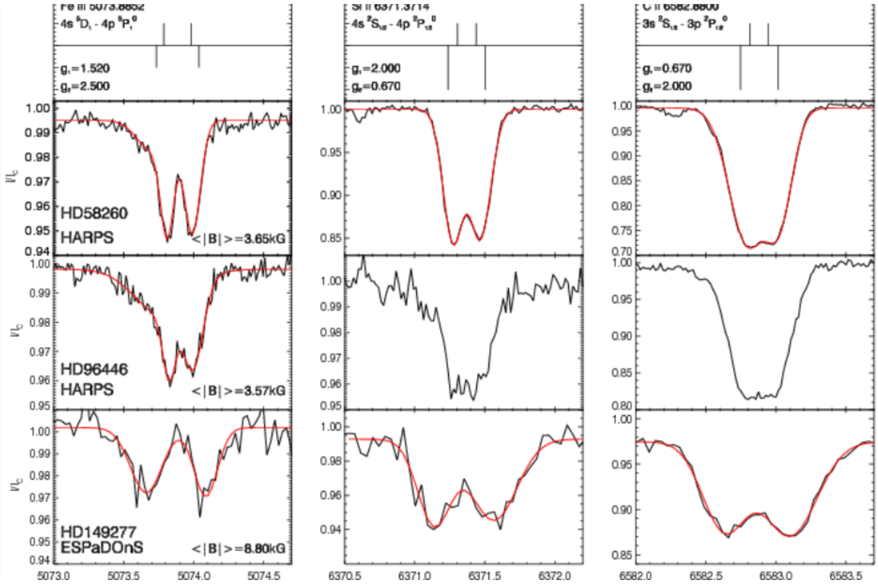

Fig. 2. The magnetically split lines Fe III λ5074, Si II λ6371, and C II λ6583 in high-resolution Stokes I spectra of the early B-type stars HD 58260, HD 96446, and HD 149277. The red lines denote the fit of a multi-Gaussian to the data. For two lines in the spectrum of HD 96446, the splitting is not sufficient to allow a proper fit.

alignment of the magnetic axis with respect to the orbital radius vector in Ap/Bp binaries may hint at the mechanism of the magnetic field generation.

More massive early B-type stars rotate generally faster than Ap and late Bp stars. Currently, only three early B-type stars, HD 58260, HD 96446, and HD 149277, with low projected rotation velocities and kG order magnetic fields are known to show resolved Zeeman split spectral lines [17]. In Fig. 2 we present several examples of magnetically split lines in these stars. Although they are expected to have radiative envelopes, chemically peculiar Ap and Bp stars [13] are the most magnetic non-degenerate stars, with surface field strengths up to 34 kG [18]. To answer the question on the origin of their magnetic fields it is important to establish their exact evolutionary status. Evidence based on Hipparcos measurements showed that magnetic Ap stars below 3 $M_\odot$ have completed at least 30% of their main sequence lifetime [5]. Knowing the distribution of strongly magnetic Ap stars in the Hertzsprung-Russell diagram also allows us to study the evolution of their magnetic fields across the main sequence. With a newly extended Ap star sample from APOGEE and available Gaia DR2 data, we can now critically

review the results of previous studies based on Hipparcos data [19].

3. THE WEAK MAGNETIC FIELDS OF HERBIG∼ AE/BE STARS

As already mentioned above,studies of magnetic fields in stars at early evolutionary stages, before they arrive on the main sequence, are of special interest to get an insight into the magnetic field origin. The presence of magnetic fields in the Herbig Ae/Be stars has long been suspected, in particular on account of Hα spectropolarimetric observations pointing out the possibility of magnetospheric accretion, similar to that of classical T Tauri stars. While models of magnetically driven accretion and outflows successfully reproduce many observational properties of the classical T Tauri stars, the picture is completely unclear for the Herbig∼Ae/Be stars, mostly due to the poor knowledge of their magnetic field topology. So far, the magnetic field geometry was constrained only for two Herbig∼Ae/Be stars, V380 Ori [20] and HD 101412 [21], and only about 20 Herbig∼ stars were reported to host magnetic fields ([22] and references therein). Notably, the evolutionary status of V380 Ori is uncertain, as it appears to be already at an advanced age [23]. The best studied Herbig Ae/Be star HD 101412 exhibits a single-wave variation in its mean longitudinal magnetic field during the stellar rotation cycle. This behaviour is usually considered as evidence for a dominant dipolar contribution to the magnetic field topology. Presently, this star possesses the strongest magnetic field ever measured in any Herbig Ae star, with a surface magnetic field $\langle B \rangle$ of up to 3.5 kG. HD 101412 is also the only Herbig Ae/Be star for which the rotational Doppler effect was found to be small in comparison to the magnetic splitting, presenting several spectral lines resolved into magnetically split components observed in unpolarised light at high spectral resolution [24]. Notably, the task of magnetic field measurements in Herbig stars is very challenging, as demonstrated in a compilation of all magnetic field measurements reported in previous spectropolarimetric studies [22].This study indicates that the low detection rate of magnetic fields in Herbig∼Ae stars, about 7% [25], can indeed be explained not only by the limited sensitivity of the published measurements, but also by the weakness of these fields. The obtained density distribution of the rms longitudinal magnetic field values reveals that only a few stars have magnetic fields stronger than 200 G, and half of the sample possesses magnetic fields of about 100 G and less. Consequently, the currently largest spectropolarimetric survey of magnetic fields in several tens of Herbig stars [25]using ESPaDOnS and NARVAL cannot be considered as representative: the measurement accuracy in this study is worse than 200 G for 35% of the measurements, and for 32% of the measurements it is between 100 and 200 G. Clearly, to improve our understanding of the origin of magnetic fields in Herbig∼ Ae/Be stars and their interaction with the protoplanetary disk,it is of utmost importanceto study magnetic fields with high accuracy measurements in a representative sample of Herbig∼Ae/Be stars.

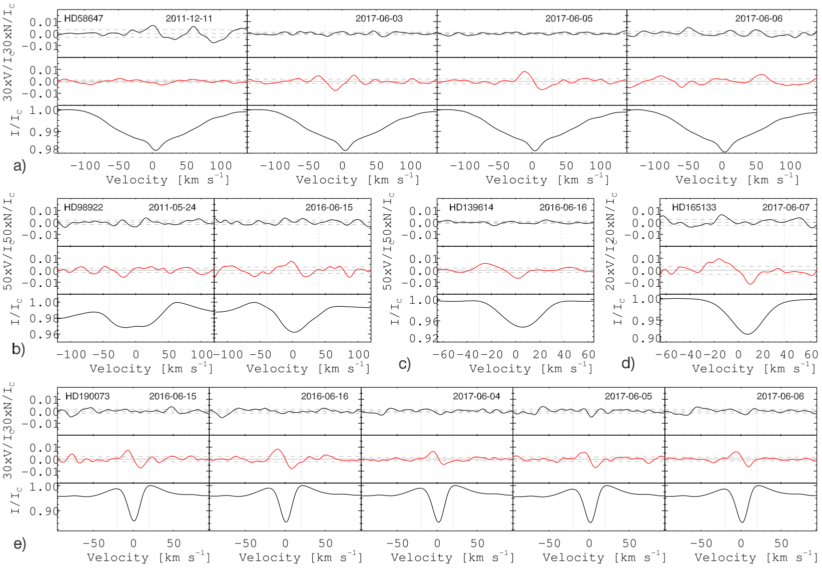

Fig. 3. SVD Stokes I (bottom), V (middle), and diagnostic null (N) profiles (top) for five Herbig∼Ae/Be stars [27].

Zeeman signatures in the spectra of Herbig Ae/Be stars are generally very small, and increasing the S/N by increasing the exposure time is frequently limited by the short rotation period of the star. Therefore, multi-line approaches such as the Least Square Deconvolution (LSD) and the Singular Value Decomposition (SVD) are commonly used to increase the S/N. The SVD approach [26] is very similar to that of thePrinciple Component Analysis(PCA). In this technique, 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.

A few examples of very weak Zeeman features of Herbig∼Ae/Be stars are displayed in Fig. 3, where we present HARPSpol observations of the two Herbig Ae stars HD 139614 and HD 190073, the two late Herbig Be stars HD 58647 and HD 98922, and the early Herbig Be star HD 165133, which were obtained on 2016 June 15 and 16, and on 2017 June 3 to 6 [27]. Each observation consisted of subexposures with exposure times varying between about 6 and 47 minutes, depending on the target visual magnitude. After each subexposure, the quarter-wave retarder plate was rotated by 90°. The resolving power of HARPSpol is about $R = 115\,000$, with spectra covering the spectral range 3780–6910 Å, with a small gap between 5259 Å and 5337 Å. The reduction and calibration of the obtained spectra was performed using the HARPS data reduction software available on La∼Silla.

The presented magnetic field measurements – with the strongest longitudinal magnetic field of 209 G detected in the Herbig∼Be star HD 58647 and the weakest field of 17 G measured for HD 190073 – provide further evidence that Herbig∼Ae/Be stars possess much weaker magnetic fields than their lower mass counterpart T Tauri stars, which have magnetic fields of kG order.

Importantly, single snapshot observations are not sufficient to judge whether a Herbig∼Ae/Be star is magnetic or not. 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.

4. DISCUSSION

In the future, the focus of Ap/Bp and Herbig Ae/Be star research should be related to providing information on the statistics of magnetic field properties, to be able to study possible relations between the magnetic field strength and other stellar parameters. Unfortunately, stellar parameters of Herbig Ae/Be stars still remain poorly known. As an example, while the distribution of rotation periods of Ap/Bp stars was intensively studied in the last two decades,rotation periods of Herbig∼Ae/Be stars are almost unknown [21, 28]. Only for two Herbig∼Ae stars, HD 101412 and HD 104237, were rotation periods determined in the past [21, 29]. For most Herbig stars photometric observations are in general not useful because the observed light variations are likely of stochastic nature and caused by fluctuating disk accretion. Multi-epoch rotation-modulated longitudinal magnetic field measurements are frequently used to determine rotation periods, but such monitoring with HARPSpol is possible only in the framework of a large programme.

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