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Measurements and modelling of magnetic fields of chemically peculiar stars

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Abstract. Chemically peculiar stars of the upper main sequence are the most popular targets for the detection and modelling of stellar magnetic fields. In this paper we review the relevant observational and modelling techniques. We also discuss which physical questions the observations that are nowadays routinely carried out may help to address.

Key words: stars: chemically peculiar – magnetic fields – polarization

1. Introduction

Before this CP 2007 conference, the previous meeting that was explicitly dedicated to the chemically peculiar (CP) stars was the "26th Meeting and Workshop of the European Working Group on CP stars", which was held in 1997 in Vienna. At that workshop, 38 talks were presented, but only five of them were related to the magnetic field. Later, in 2004, the IAU Symposium No. 224 was dedicated to A-type stars in general, with one full session dedicated to the magnetic A- and B-type stars. At this conference, the titles of more than half of the 44 oral presentations refer explicitly to the magnetic field. A glance to the histogram of the number of individual measurements of magnetic fields published per year (Fig. 1) offers further evidence of the growth of interest in magnetic A- and B-type stars in the last few years. In fact, this growth of interest in magnetic fields is evident not only for CP stars, but it is a general characteristic of the stellar astrophysics.

The interplay between magnetic fields and the other physical phenomena in the photosphere of CP stars is discussed in various contributions to this conference. This review is dedicated to the techniques for detection and modelling of the magnetic field. In this context, CP stars play a very special role, since they are the stars where the magnetic field can be more easily detected and modelled (except for the Sun). CP stars thus represent a kind of astrophysical laboratory to test our techniques for detection and modelling of magnetic fields.

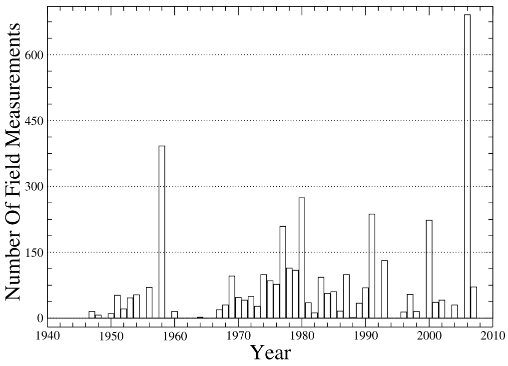

Figure 1. The number of magnetic field measurements presented in refereed publications (mainly based on information collected by Bychkov *et al.*, 2003).

2. Techniques for magnetic field detection

The magnetic field is detected through the analysis of the Zeeman effect on Stokes profiles of the spectral lines. Stokes V, which describes the circular polarization, is sensitive to the component of the magnetic field along the line of sight. In fact, the most common techniques adopted to detect the magnetic field are based on measurements of circular polarization, and the observable quantity that is most easily and frequently extracted is the so-called *mean longitudinal magnetic field* $\langle B_z \rangle$ (see Sect. 2.1), i.e., the component of the magnetic field along the line of sight, averaged over the stellar disk. It can be obtained either by measuring the shift of the spectral line observed in left and right circular polarization or from the first order moment of Stokes V about the line centre. Additional information about the magnetic morphology can be obtained from the second order moment of Stokes V about the line centre (Sect. 2.4).

Spectral lines observed in unpolarized light (Stokes I) of slow rotating stars with strong magnetic fields appear split by typically a few tenths of Å (see Fig. 2). From the measurement of the Zeeman splitting it is possible to measure the *mean magnetic field modulus*, i.e., the average of the field modulus over the stellar disk (Sect. 2.2). In most cases, the Zeeman effect in Stokes I is washed out by rotational Doppler broadening, thus the effect of the magnetic field turns to be just a broadening of the spectral lines, from which it is still possible to get information about field strength (Sect. 2.4).

Stokes Q and U describe the linear polarization, and are sensitive to the components of the magnetic field that are perpendicular to the line of sight. The linear polarization signal is much smaller (up to $\sim 1/10$) than the circular polarization signal because of two reasons: *i)* the amplitudes of Stokes Q and U are proportional to the field modulus $|\boldsymbol{B}|$, whereas Stokes V amplitude is proportional to the square of the field strength; therefore the contribution to

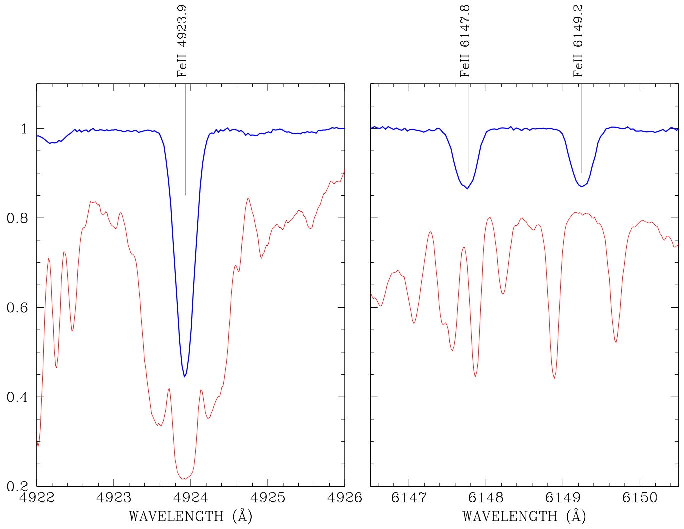

Figure 2. Spectral lines of the non-magnetic star HD 73666 (upper thicker lines) and of the star HD 47107 (lower thinner lines), split by the magnetic field. Fe II 6149.2 a doublet; the blue component is deeper and narrower than its red component: this is a signature of the partial Paschen-Back effect. Fe II 6147.8 is a quadruplet, blended to the components of a Cr II line at 6147.2 Å.

the total fraction of linear polarization of a spectral line due to each element of the stellar surface is intrinsically smaller than the contribution to the fraction of circular polarization; *ii)* linear polarization depends on the projection of the field vector on two directions (perpendicular to the line of sight), whereas circular polarization depends on the projection of the magnetic field vector on one direction (the line of sight). Therefore, the contributions to the linear polarization produced in different elements of the stellar disk tend to cancel out more efficiently than the contributions to the circular polarization.

The most complete analysis that can be performed is a detailed modelling of a time series of all Stokes profiles, sampling the full rotation cycle. This analysis may in principle lead to recover the magnetic model and the distribution of the chemical elements over the stellar photosphere (Sect. 2.5).

The magnetic field diagnostic is performed assuming that spectral lines are formed in (anomalous) Zeeman regime. For many spectral lines, and for the typical field strength that is found in CP stars ($100 - 30\,000$ G), this is a reasonable assumption, but there are exceptions. For instance, the shape of the Fe II Zeeman doublet at 6149.2 Å, which is often used to measure the field modulus, shows a clear signature of the partial Paschen-Back effect in all stars where it is resolved, namely, its blue component is deeper and narrower than its red component (Mathys, 1990). Therefore, both chemical abundance analysis and magnetic field determinations should be carried out either disregarding lines subject to Paschen-Back effect, or taking it into account. For a deeper discussion of the impact of the Paschen-Back effect on the polarized spectrum of CP stars see, e.g., Landolfi *et al.* (2001), and Stift (2008).

2.1. The mean longitudinal magnetic field

After his detection of a magnetic field in a star other than the Sun, i.e., the CP star CU Vir (Babcock, 1947), Babcock (1958) produced a large catalogue of longitudinal magnetic field measurements. Babcock's technique was based on the measurement of the split of metal lines observed with high spectral resolution in left and right circular polarization.[1] Based on similar techniques, the database of $\langle B_z \rangle$ determinations has been substantially increased, e.g., by the work of Mathys (1994) and Kudryatsev *et al.* (2006).

2.1.1. Least Square Deconvolution

Introduced by Donati *et al.* (1997), the Least-Square Deconvolution (LSD) is a cross-correlation technique which allows one to obtain average Stokes profiles by combining a large selection of spectral metallic lines. The LSD technique is based on somehow rough approximations: practically, a spectral line is simply treated as a line pattern convolved with an average line profile. Still, under many respects, the average Stokes I and V profiles obtained via LSD may be regarded as an individual spectral line measured with a huge signal to noise ratio, and from this spectral line it is possible to extract physical information with very high precision. For instance, one can determine the mean longitudinal magnetic field with very high accuracy ($\sigma_{\langle B_z \rangle} < 10\,\mathrm{G}$). LSD technique applied to Stokes I and V is routinely used for studies of magnetic fields in various kinds of star, and is implemented in the automatic data reduction pipeline of the MuSiCoS and NARVAL spectropolarimeter (Pic-du-Midi Observatory), and of the ESPaDONs spectropolarimeter (CHFT). The actual precision that can be reached in the $\langle B_z \rangle$ determination depends not only on the S/N ratio of the observations, but also on the number and sharpness of the spectral lines: $\langle B_z \rangle$ may be measured with higher precision in cool and slow rotating stars than in hotter and faster rotating stars. Extensive use was made of the LSD technique for studies of magnetic CP stars, and the major surveys based on this technique are those by Wade *et al.* (2000 b), Shorlin *et al.* (2002), and Aurière *et al.* (2007).

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[1] As noted by Stępień (1997), when Babcock considered A-type stars with sharp lines as the best targets to search for magnetic fields, he was in fact guided by wrong assumptions. Babcock thought that A-type stars with sharp lines were fast rotating stars seen pole-on. He expected the magnetic field to be stronger in faster rotating stars than slow rotating stars, and Zeeman effect was easier to be detected in sharped line stars because it tends to be washed out by Doppler broadening effect. Ironically, Babcock work led instead to the discovery that most of slow rotating A-tpye stars have a magnetic field of fossile origin.

The interpretation of the LSD Q and U profiles is less straightforward than that of LSD I ad V profiles; the individual Q and U profiles vary a lot from one line to another, both because of different Zeeman patterns, but also because rotational broadening and Zeeman splitting produce quite line-specific observed patterns; furthermore, the amplitude of Q and U profiles is remarkably smaller than the Stokes V amplitude, with the consequence that substantially less effort has been invested in linear polarization measurements than in circular polarization measurements.

2.1.2. Narrow band circular polarimetry and low resolution circular spectropolarimetry

The mean longitudinal magnetic field can be determined also by correlating the amount of circular polarization of spectral lines to the derivative of Stokes I with respect to wavelength, i.e., by using the relationship

$$\frac{V}{I} = -g_{\text{eff}} 4.67 \times 10^{-13} \lambda^2 \, \frac{1}{I} \, \frac{\mathrm{d}I}{\mathrm{d}\lambda} \, \langle B_z \rangle \, , \tag{1}$$

where g_{eff} is the effective Landé factor. Of special interest is the application of Eq. (1) to H Balmer lines through the use of a narrow band polarimeter or a spectropolarimeter.

Narrow band polarimetry on the wings of Hβ has been used e.g. by Borra and Landstreet (1979; 1980), and by Borra *et al.* (1983) to perform large magnetic surveys in CP stars.

Bagnulo *et al.* (2002 a) have introduced the use of low resolution spectropolarimetric data obtained with the FORS1 instrument of the ESO Very Large Telescope to perform $\langle B_z \rangle$ measurements of CP stars. Because of the low spectral resolution ($R \lesssim 2000$), it is convenient to apply Eq. (1) to Hydrogen Balmer lines. However, metal lines are also useful, even though they are not fully resolved by the instrument (see Bagnulo *et al.*, 2006). The results of a large FORS1 survey of magnetic fields of CP stars have been presented by Kochukhov and Bagnulo (2006). The FORS1 instrument is equipped with multi-object capabilities, and polarized spectra can be obtained for up to nine stars at once within a $6.8' \times 6.8'$ field of view. In most cases, this is not of much use, as it is a rare circumstance to have two or more interesting targets of similar magnitude within a so restricted field of view, but it may considerably boost the efficiency of the observations in clusters. Indeed, FORS1 has been used for an extensive survey of magnetic stars in open clusters by Bagnulo *et al.* (2006) (for the scientific outputs see Landstreet *et al.*, 2007; 2008).

2.2. The mean field modulus

In slow rotating stars (typically $v \sin i \lesssim 10\,\mathrm{km\,s^{-1}}$) characterized by a strong magnetic field (a few kG), it is possible to detect the Zeeman splitting of the spectral lines. The first clear detection of the Zeeman splitting was made by Babcock (1960) on HD 215441. Further detections and detailed studies of a very few additional stars were performed, e.g., by Preston (1970) and Huchra (1972), and the first systematic large survey was performed by Mathys and Lanz (1992) and Mathys *et al.* (1997), who used the Zeeman doublet at 6149.2 Å to determine the mean magnetic field modulus $\langle |B| \rangle$ for about 40 stars. It should be noted that the stars in which $\langle |B| \rangle$ has been measured belong to a specially biased sample, that was selected using small $v \sin i$ as a selection criterium.

In many cases, the spectral lines are only broadened by the Zeeman effect; the Zeeman broadening can still be studied to get information about the field strength. Magnetic field diagnosis from unresolved line profiles was carried out e.g., by Preston (1971). Mathys (1995 b) measured the second order moment of Stokes I about the line centre to estimate the mean quadratic field for a large sample of stars (see Sect. 2.4).

2.3. Broadband linear polarization measurements

A spectral line formed in a magnetic atmosphere is split into several polarized components. Because of a *differential saturation* effect, σ components absorb an amount of radiation different than that absorbed by π components, and the net result of a broadband measurement is non-zero linear polarization (in CP stars, typically a few units in 10^{-4}). This differential saturation mechanism was first invoked by Leroy (1962) to explain the broadband linear polarization (BLP) observed in solar active regions. The first BLP observation in a CP star was made by Kemp and Wolstencroft (1974), who monitored throughout the rotation cycle the star 53 Cam. These observations were interpreted seven years later by Landi Degl'Innocenti *et al.* (1981) in terms of the same differential saturation mechanism used by Leroy (1962) to explain similar observations in sunspots. In the '90s, Leroy performed a survey of magnetic CP stars (Leroy 1995 and references therein). Analytical models were developed by Landolfi *et al.* (1993), and applications to the observations were made, e.g., by Bagnulo *et al.* (1995) and Leroy *et al.* (1995). From these new observations it became clear that Ap stars are characterised by a quite complex magnetic morphology, that cannot be described by a simple dipolar field (see, e.g., Leroy *et al.,* 1995).

Since nowadays Stokes Q and U profiles of CP stars are routinely observed, one may conclude that BLP measurements deserve interest just for historical reasons. On the other hand, it should be noted that rotational Doppler broadening damps Stokes profiles, so that Stokes Q and U profiles can hardly be detected in fast rotators, whereas the amount of wavelength-integrated linear polarization does not depend on the stellar rotational velocity. Hence, in fast rotating stars, BLP observations may still help to detail the magnetic morphology of CP stars.

2.4. The moment technique

Mathys (1993 and references therein) made theoretical considerations on the diagnostic content of the low order moments of Stokes I and V about the line centre. He has shown that the mean longitudinal magnetic field could be formally obtained from first order moment of Stokes V about the line centre; that the second order moment gives information on the mean asimmetry of the longitudinal field with respect to the plane defined by the line of sight and the star's rotation axis; that the second order moment of Stokes I is related to the sum of the squares of the field modulus and of the longitudinal field. The mean longitudinal field has been discussed in Sect. 2.1. The other two applications of this *moment technique* are described below.

Babcock (1951) discovered that in HD 125248, at the instant when the mean longitudinal field is zero, spectral lines exhibit a different strength when observed in left and right circular polarization. This phenomenon is called *crossover effect*, because it is maximum at the point of the magnetic curve where the mean longitudinal field changes from positive to negative or viceversa. The crossover effect is naturally explained in terms of a combination of Doppler effect and Zeeman effect, and is produced when elements of the stellar surfaces that are characterized by different field polarity have opposite radial velocities (for a more detailed explanation see Babcock, 1951). Mathys (1995 a) gave a formal description of this phenomenon, and published a catalogue of crossover determinations for a large sample of magnetic CP stars.

In weakly magnetic stars, or in magnetic stars where rotational broadening prevails over the Zeeman splitting, the Zeeman broadening of spectral lines can still be quantitatively analysed to get information about magnetic strength. The Zeeman broadening was exploited by Preston (1971) to study the surface magnetic field of CP stars. Mathys (1995 b) published a catalogue of determinations of the so-called *mean quadratic magnetic field*, a quantity that is related to the sum of the square of the field modulus and of the longitudinal component, and that can be obtained by measuring the second order moment of Stokes I about the line centre.

2.5. Detailed observations of all Stokes profiles

All the techniques mentioned above were actually conceived in order to overcome the fact that all observations of Stokes profiles were characterized by a very low S/N ratio, thus making it necessary to think of ways of extract global features of the field, to the detriment of a detailed analysis. At the end of the '90s, the MuSiCoS spectropolarimeter attached to the 2 m telescope Bernard Lyot of the Pic-du-Midi Observatory became available to the astronomical community (Wade *et al.*, 2000 a), making it possible to routinely carry out high quality observations of Stokes $IQUV$ profiles in stars up to $V \simeq 8$. MuSiCoS observations represented a giant step from the previous situation for several reasons.

i) MuSiCoS was an echelle spectropolarimeter and, as such, capable of providing spectra of mid-high resolution ($\simeq$ 38 000) covering a large wavelength range ($\simeq 4500 - 6500$ Å). MuSiCoS data allowed one to perform a simultaneous analysis of all Stokes profiles, making it possible to recover both the stellar magnetic morphology and the abundance of the chemical elements. *ii)* For the first time, it was possible to routinely obtain and study Stokes Q and U spectra. *iii)* MuSiCoS data were made available to a large community of collaborators.

3. What magnetic field measurements tell us

Magnetic field measurements have been used to characterise the morphologies and to make considerations about field origin and evolution.

From the observations of mean longitudinal field we have learnt that the magnetic field at the surface of CP stars is organized at a large scale, is probably stable over a time scale of a few decades, and is not symmetric about the rotation axis, so that the observer sees a magnetic configuration that changes as the star rotates. Stibbs (1950) introduced the *Oblique Rotator Model* to model the $\langle B_z \rangle$ measurements of HD 125248 assuming that the magnetic field of the star was a dipole tilted with respect to the rotation axis. While the general idea of a globally organized field is still accepted, nowadays it is known that whenever an obervable quantity other than the mean longitudinal field is available, the simple dipolar field is not sufficient to satisfy the observational constraints. More sophisticated models have been introduced to explain the observations, like the dipole field decentred along the direction of the magnetic axis (Landstreet, 1970), the dipole field shifted at an arbitrary direction (Stift, 1975), the dipole plus the quadrupole arbitrarily oriented in space (Landolfi *et al.*, 1998), the dipole plus linear quadrupole and linear octupole (Landstreet, Mathys 2000). Most of the modelling efforts carried out so far are based on the observable quantities like the longitudinal field, the crossover, the quadratic field, the mean field modulus, and the broadband polarization (e.g., Bagnulo *et al.*, 2000 b). For the slow and cooler rotating Ap stars, Landstreet and Mathys (2000) have found that the magnetic axis tends to be aligned at a small angle with respect to the rotation axis, and Kochukhov (2008) has proposed that the magnetic field has a fairly homogeneous structure, departing from a low-order multipolar geometry. Bagnulo *et al.* (2002 b) claimed that the magnetic field of CP stars is generally non axi-symmetric. The ultimate modelling technique is the direct inversion of the observed Stokes profiles, e.g., Magnetic Doppler Imaging (MDI, Piskunov, Kochukhov 2002; Kochukhov, Piskunov 2002). So far, MDI results are consistent with the picture of a field more complex than what can be described with low-order multipolar expansion (Kochukhov *et al.*, 2004).

Recent works permit us to conclude that the magnetic field of CP stars is present from the pre-main sequence phase (Wade *et al.*, 2007) and that during the star's life in the main sequence, the field strength tend to decay (Landstreet *et al.*, 2007; 2008).

We have reached a situation where we have a bulk of data, and we have the possibility of easily obtaining much more (see, e.g., Silvester *et al.*, 2008). Thus, we should give a high priority to the questions: what do we really want to know, and what knowledge can we actually attain thanks to these observations? A pretty obvious goal is to perform a more systematic investigation of the magnetic morphologies of CP stars based on MDI. While the global characteristics of the magnetic fields are understood, there is a lot of work to do to study the correlations between magnetic field morphology and the 3D distribution of the chemical elements on the photosphere (and, in roAp stars, the pulsation characteristics). These correlations should be found as a function of the stellar evolution. Getting such a global overview will require huge observational and modelling efforts, including extensive surveys and monitoring, but will permit us to set very strong constraints on the diffusion theory, and help us to explain the origin of the magnetic field in CP stars.

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