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Recent advances in magnetic field diagnosis techniques

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Abstract. This review examines current efforts to find find and exploit more powerful methods of measurement of the magnetic fields of the Ap stars. The methods now being explored include (1) the measurement of various moments of spectral lines in intensity and polarization spectra, and their interpretation in terms of moments of the observed fields, and (2) field mapping by direct comparison of synthesized lines with observed $IQUV$ spectra.

1. Introduction

Magnetic fields have been detected and studied in Ap stars for a longer time than the fields of any other type of star, excepting only the fields of sunspots first observed by Hale in 1908. The fields of Ap stars are strong enough (typically of order 10^3 G = 0.1 T), and sufficiently simple in geometrical structure, that they can be detected relatively easily, generally through the observation of a non-zero (but usually variable) net longitudinal (line-of-sight) field component $\langle B_z \rangle$. The observed field variations invariably appear to be periodic, with the same period as (sometimes spectacular) spectrum and brightness variations. The variation period P always satisfies

$$P \leq (2\pi R)/(v \sin i) = P_{\rm rot}/\sin i,$$

where i is the inclination of the rotation axis and $P_{\rm rot}$ is the rotation period of a star of radius R and equatorial velocity v. P thus appears to be the rotation period (typically of the order of a few days, but sometimes dramatically longer) of the underlying star. We are led to a simple phenomenological model of a magnetic Ap star as a star in which a roughly dipolar field is fixed in the star, with its axis inclined to the stellar rotation axis by an angle β. The field in turn somehow induces or controls substantial abundance variations over the surface, which are thus also not axi-symmetric about the rotation axis. As the star rotates, the observed magnetic field varies because we see it from different aspects, and the spectral lines and monochromatic brightness vary because of the changing abundances on the visible stellar hemisphere.

The study of Ap star fields opens a window for us into a whole range of interesting physical questions, such as (1) why are some A and B stars strongly magnetic while other very similar stars are apparently practically non-magnetic; (2) what physics determines the structure of the observed fields; (3) how (and when) do magnetic fields reduce the rotational angular moment of the host star, sometimes by several orders of magnitude compared to "normal" A and B stars; and (4) how do the observed fields interact with gravitational settling and radiative levitation of trace elements, and with convection, turbulence, circulation, and (perhaps) winds or accretion to produce remarkably varied – and horizontally inhomogeneous – surface chemical abundance patterns?

This review will focus on recent advances in the methods of measuring the magnetic fields of Ap/Bp stars, and of using such measurements to obtain information about the underlying stellar fields. For conceptual simplicity, we may consider that there are two main categories of measurement: (1) measurements of *moments* of spectral lines (often as observed in one or more polarizations), which turn out to be related to moments (disk averages) of the global field, thus facilitating modelling (up to a point); and (2) *direct comparison* of hypothetical field models or maps with observed line profiles, without the intermediary of field moments.

2. Modelling by field moments

All field detection in Ap/Bp stars are based on the Zeeman (or Paschen-Back) splitting of spectral lines. The key aspects of this splitting for stellar field measurements are the following: (1) in a magnetic field field $\mathbf{B}$, the line splits into π and σ components, with separation of components proportional to B; (2) a transverse field leads to orthogonal linear polarizations in π and σ components, parallel and perpendicular to field; and (3) a longitudinal field suppresses the π components, while the long- and short-λ σ components have opposite circular polarizations

The behaviour of stellar spectral lines results from the combination of Zeeman splitting with polarized radiative transfer. To get an idea of how spectral lines are changed by a magnetic field, it is useful to consider solutions of the four polarized transfer equations for the Stokes components I (intensity), Q and U (linear polarization) and V (circular polarization) in the Milne-Eddington case (linear source function, constant line-to-continuum opacity; *cf.* for example Mathys 1989, Sec 2.5). In the case of weak lines, or of weak field, the solutions are particularly simple. The fundamental results which are used in most stellar magnetic field measurement methods are the following: (1) the mean separation of circularly polarized $(I+V)$ and $(I-V)$ line centroids is proportional to $z\langle B_{\rm z}\rangle$ (weak-line limit), where z is the mean Landé splitting factor and $\langle B_{\rm z}\rangle$ is the mean of the line-of-sight component of the magnetic field; (2) in the weak-field limit, $V \sim zB_{\rm z}\, dI/d\lambda$ in the *local* line (and for small $v \sin i$ broadening, $\langle V\rangle \sim z\langle B_{\rm z}\rangle d\langle I\rangle/d\lambda$); and (3) the separation of resolved σ components is proportional to $z\langle B\rangle$ (weak-line limit). These relations are the basis of field measurements by moments.

Moment techniques have a long history. Babcock's (1947) original detection of field in 78 Vir was a detection of mean separation of left circularly polarized (LCP) and right circularly polarized (RCP) line profiles, and Babcock showed that his observations yield a measure of $\langle B_{\rm z}\rangle$, in the weak line approximation. His method of measuring the mean longitudinal field strength using metal lines (sometimes called the "photographic technique") has been exploited to study the magnetic field of dozens of stars by Babcock (1958), Preston, Wolff, Glagolevskij, Romanyuk, Mathys (e.g. 1991) and others. Field measurements obtained from the detection of circular polarization in Balmer line wings (somewhat like the method used in Babcock's original solar magnetograph) are an alternative method for measuring $\langle B_{\rm z}\rangle$, this time based on the weak field limit rather than the weak line approximation. This method has been exploited by Bohlender, Borra, Hill, Landstreet, Thompson, and Wade (e.g. Bohlender et al. 1993). A recent catalogue of magnetic observations of Ap and Bp stars is described by Romanyuk elsewhere in these Proceedings.

Similarly, the detection of direct line splitting by Babcock (1960) and Preston (1969) provided a measure of $\langle B\rangle$, and thus of a moment of the magnetic field which is complementary to $\langle B_{\rm z}\rangle$. This techniques has been particularly developed by Mathys and his collaborators (e.g. Mathys et al. 1997). Until about a decade ago, measurements of these two field moments, $\langle B_{\rm z}\rangle$ and $\langle B\rangle$, provided almost all the information about fields in most Ap stars.

Field modelling using such measurements has traditionally been carried out by computing the expected values of $\langle B_{\rm z}\rangle$ and $\langle B\rangle$ for a multipole expansion (or sometimes a decentred dipole equivalent) of the field, evaluating the expansion parameters by comparison with the observed field moments. Different authors differ in which (few) terms (or parameters) to retain. However, the data obtained with older techniques contain limited information. Since most $\langle B_{\rm z}\rangle$ and $\langle B\rangle$ variations are roughly sinusoidal, a $\langle B_{\rm z}\rangle$ curve provides only two constraints. Even the simplest dipole model has three parameters (inclination of the rotation axis i, obliquity of the magnetic to the rotation axis β, polar dipole field strength $B_{\rm d}$), so a unique model cannot be established without independent data on i. For stars with both $\langle B_{\rm z}\rangle$ and $\langle B\rangle$ data, the situation is markedly more favorable. Four constraints determine a dipole plus quadrupole model (i, β, $B_{\rm d}$, $B_{\rm q}$), but without any redundancy. However, until a decade ago, $\langle B\rangle$ data were available for only a few stars. It is clear that such data, while informative, provide only rudimentary information about the stellar magnetic field geometry.

Clearly "more" data are needed to progress. Mathys has made a major contribution in two important directions. First, he has carried out with collaborators (e.g. Mathys et al. 1997) a huge survey of $\langle B\rangle$in stars of low /vsi/ (mostly stars of long period). This has increased the number of stars that may be modelled by low order multipoles by an order of magnitude. Secondly, he has explored wavelength moments of spectral lines, showing that in spectra with *unsplit* lines, the second wavelength moment $\int(I(\lambda)-I_{\rm c})(\lambda-\lambda_0)^2d\lambda$ yields field moment $(\langle B^2\rangle+\langle B_z^2\rangle)^{1/2}$, similar to $\langle B\rangle$ data. He has also showed that second wavelength moment of lines in V spectra (essentially Babcock's "crossover effect") gives a measure of $v\sin i\langle xB_{\rm z}\rangle$, another useful field moment. Finally, he has carried out a major survey of these moments using CASPEC (e.g. Mathys & Hubrig 1997). These data have made possible much more strongly constrained multipole field models (Landstreet & Mathys 2000), and have revealed that the really slowly rotating Ap stars, *unlike* their shorter period cousins, have nearly aligned magnetic and rotation axes (small β angles).

None of methods above provide information about *transverse* field component. This requires measurement of linear polarization, a *second-order* effect in field strength, and tiny in stars of small fields. However, it is now detectable. The first useful detection of this field component was by means of measurement of the net broadband linear polarization introduced by saturated lines in strong field. Such data are extremely difficult to interpret completely, since they depend on broad-band aspects such as total line blocking, degree of saturation of typical lines, etc, but they have nevertheless tremendous value. Leroy, with E and M Landi Degl'Innocenti, Landolfi, and Bagnulo (e.g. Leroy et al 1995) have shown that broad-band linear polarization variations provide direct information about the movement of the magnetic axis on the plane of the sky, and thus about the angles i and β. Using both broad-band linear polarization and $\langle B_z \rangle$ data, one can determine both angles. Leroy (1995) has carried out a major survey of broad-band linear polarization in Ap stars at Pic-du-Midi, detected variable intrinsic linear polarization in ~ 15 stars, and derived i and β angles. Such data have greatly narrowed region of parameter space in which acceptable models are found, thus allowing better constrained models, and even providing some redundancy as compared with the two-term expansion (which turns out to demand a more complex model...).

Field measurements by line moments provide a practical way to obtain basic data for many stars. However, modelling via field moments has important limitations. First, the field moments are derived through various approximations (weak line, weak field, etc) which have effects on the derived moments that are difficult to evaluate. Furthermore, it is awkward to take too many atmospheric complications into account at once – but in reality one does have important abundance variations over the stellar surfaces, and probably in many cases variations of abundances with depth as well. Finally, some important approximations are made in the physics, for example in a rather schematic treatment of Zeeman splitting in Balmer line measurements. Thus, although these methods provide a straight-forward means for fitting field models, the models cannot be taken as being very well-determined. The fact that simple multipole models do not yield very good fits of the most complete and constraining data sets is a hint that we do not obtain completely adequate models from moment modelling. It is essential to complement such data and modelling with more detailed studies of at least a few stars to assess how reliable the field models are, and to determine their main weaknesses.

3. Modelling/mapping by Doppler Zeeman imaging

A major recent advance in observational capability has been achieved with the development of Musicos spectropolarimeter (Donati et al. 1999) at Pic-du-Midi. This instrument allows one to routinely obtain spectra in *all* of $IQUV$ over almost 2000 Å at $R = 35{,}000$. Since the QU data constrain the transverse component of the field rather than the longitudinal, they provide in principle an extremely important new kind of information about field structure, closely related to the information content of broad-band linear polarization. This instrument has been used by a consortium (Wade et al. 2000a) to carry out an $IQUV$ spectropolarimetric observing campaign to obtain good rotational phase coverage of several bright Ap stars, to provide a data base suitable for modelling.

This major new data set has made possible an important test of models derived from field moments. Bagnulo et al. (2001) took as a starting point models derived from field moments, and used them in polarized spectrum synthesis codes (Stift's COSSAM and my ZEEMAN) to *predict* the individual observed line profiles in $IQUV$ for β CrB and 53 Cam. In both cases the agreement is really not satisfactory. The conclusion is that field models from moments are at best a rather rough first approximation to true field structure. (A second important conclusion of this project has been to confirm that *vertical* stratification of several elements has quite significant effects on the total spectrum.) Thus modelling from field moments really does need to be tested and complemented by more powerful methods, at least in enough stars to allow one to interpret field moment models with confidence.

As an alternative to finding models by parameter determination through comparison with derived field moments, one may compare spectrum synthesis predictions from an assumed field distribution directly with observed line profiles in $IQUV$, and attempt to iterate the field model to good agreement with the observed $IQUV$ line profiles. (This method has been widely used for mapping distribution of elements and of temperature over stellar surfaces, a scalar – and hence somewhat simpler – problem.) This method makes use of all the information in a chosen set of line profiles, which of course contain more information than is retained by line moment techniques. Furthermore, the synthesis method does not filter the data through as many – possibly inaccurate – model assumptions. In the case where there is significant Doppler broadening of the lines, we have real longitude information in the wavelength coordinate, and latitude information in the Doppler excursions and durations of individual features, making possible real two-dimensional field reconstruction, although with low space resolution over the stellar surface.

This method was used with I spectra (and $\langle B_z \rangle$ curves) for 53 Cam (Landstreet 1988) and Babcock's star (Landstreet et al. 1989), where it clearly revealed the need for a more complex field geometry than a dipole-quadrupole model. The method was generalized to polarized spectra by Khokhlova, and has been applied to several stars including HD 37776 (Khokhlova et al. 2000). However, the cost in complexity and cpu cycles increases rapidly with the number of lines considered, and the demands on atomic data are large, so one tends to work with only a few lines, thus diluting an important advantage of large spectral coverage.

Recently, stimulated by the possibility of $IQUV$ spectra, and by the online availability of the VALD atomic line database (Piskunov et al. 1995, Ryabchikova et al. 1999, Kupka et al. 2000), a number of investigators (Wade, Bagnulo, Stift, Piskunov, Kochukov, etc.) are using this method to try to map fields more completely. Several major problems arise, starting with non-uniqueness of all but lowest-resolution maps because of limited information content (particularly resolving power, phase coverage, and S/N) in the line profiles. Furthermore, one is trying to reconstruct a vector field over the star, so that in principle three times as much information is needed as for a single scalar (e.g. abundance) field; it is basically for this reason that full $IQUV$ coverage is so important. Codes are large and quite specialized, and computation is very laborious and cpu-intensive. A further problem is that in general only a part of the stellar surface is seen, so one can at best only determine field over some fraction of star surface. This method is however in an exciting stage of development.

A major problem of reconstruction from $IQUV$ spectropolarimetry is the difficulty of obtaining adequate spectral coverage, resolution, and signal to noise ratio, with good phase coverage. This problem is just as severe for cool stars as for Ap's, since for cool stars one has weaker, less coherent fields: one cannot usually even recover the V signal with good S/N in single lines in such objects. The S/N problem has led Donati to consider the possibility of co-adding all the sufficiently deep spectral lines available in the data in order to obtain an effectively higher S/N ratio. One basis on which this could be done, particularly for V spectra for weak fields, results from examining the analytical solution to the Unno equations for the Milne-Eddington case, where

$$V(v) = CzB_{\rm z}(dI/d\lambda) \approx C'zB_{\rm z}(d/v\sin i),$$

where d is the line depth. This result means that to the extent that the I profiles are self-similar, all the V profiles are expected to have about the same form, with signal amplitude scaling as (zd), and it appears that it should be possible to co-add the V signals of many lines by rescaling each by the appropriate factor and combining them in velocity space.

This idea has been developed by Donati et al. (1997) into a co-addition tool, "least-squares deconvolution" or LSD, that has by now been extensively used for cool stars. The correctness of the basic idea is supported by numerical line synthesis experiments which indeed show that the form of the V profile for a number of field orientations and strengths is fairly independent of the line except for scaling (see Figure 1). Donati and collaborators have been able to use LSD profiles for modelling of cool star fields, particularly in the case of the active K star AB Dor (Donati & Collier Cameron 1997).

LSD has also been applied to Ap stars, where the weak field approximation is not really appropriate (Wade et al 2000b). For V profiles, it appears that LSD can be used for magnetic Ap stars in spite of the failure of the weak-field approximation for most of the stars studied; the field moment $\langle B_{\rm z}\rangle$ derived from LSD is internally coherent (small scatter), smoothly varying, and in excellent agreement with other previous measures of this field moment. (However, interpretation is as uncertain as for other moment-based methods.)

More importantly, LSD has been used for detection of weak QU polarization in Musicos spectra (using a different re-scaling, as z^2d). LSD allows confident detection of non-zero QU polarization in a number of magnetic Ap's in which the effect is not detectable in individual lines, and thus is an extremely valuable guide to which stars to observe more closely. The Musicos survey has clearly detected non-zero LSD QU profiles in about ten stars, including some in which variable broad-band linear polarization is not detectable because of large interstellar polarization and low line density or saturation. Q and U are detected in single lines in five of these stars (Wade et al. 2000a). In cases where both broad-band and Musicos data exist, the phase variation of integrals created from the LSD data agree extremely closely with the broad-band data, showing clearly that the observed broad-band polarization variations observed are indeed due to linear polarization in saturated spectral lines, the usual interpretation of this effect (Wade et al. 2000b).

However, the predicted QU profiles of individual spectral lines even with simple field configurations differ a lot from one another in form and amplitude;

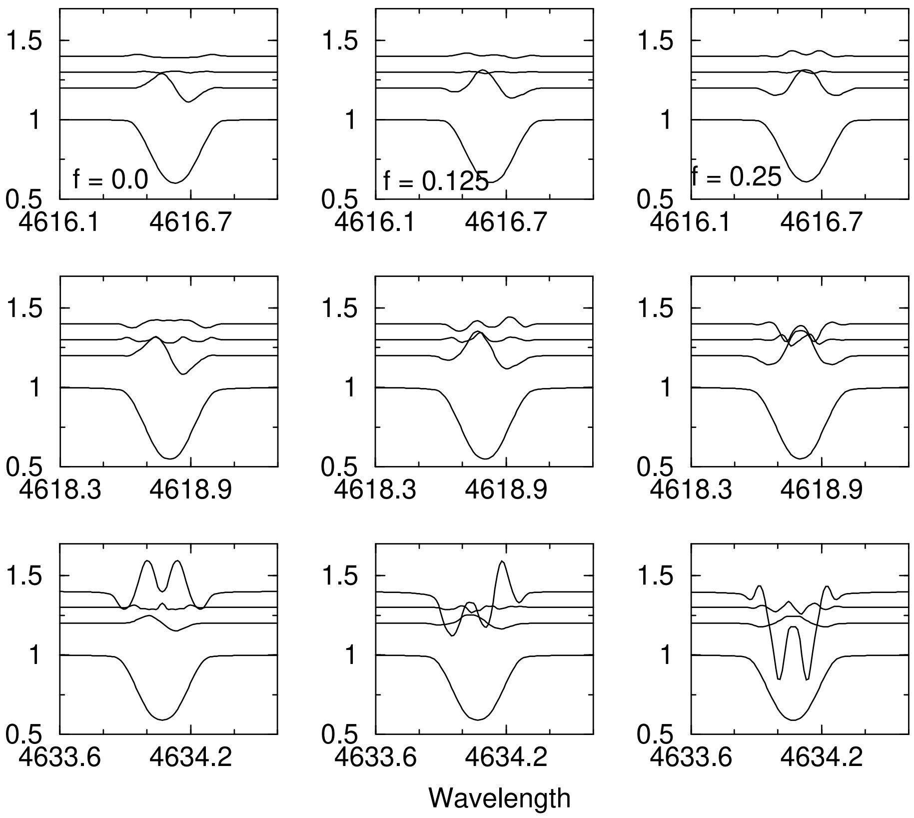

Figure 1. This figure shows a series of test calculations (made with ZEEMAN) of integrated stellar $IQUV$ line profiles for three lines of Cr II formed in a dipolar field with a polar strength of 1000 G. Each row of graphs shows one line at three phases, with the dipole axis oriented along the line of sight, at 45° to the line of sight, and at 90° to the line of sight. The z value of the three lines are, from top to bottom, 0.89, 0.91, and 0.51. The star is assumed to have a $v \sin i$ of 10 km s^{-1}. The four curves in each panel, from bottom to top, are I, $(4V + 1.2)$, $(40U + 1.3)$, and $(40Q + 1.4)$. It is clear that the V signatures of the three lines are very similar, and roughly scale with z, as assumed in LSD. However, the three linear polarization signatures are very different from one another and are *not* closely related to the value of z.

although LSD makes it possible to *detect* linear polarization, the relationship of LSD QU profiles to profiles of single lines is currently far from clear. This is clearly illustrated by numerical experiments for even quite simple fields (Figure 1). The profiles are very sensitive to $v \sin i$ as well as the field structure, with different lines responding differently as the $v \sin i$ shifts cause different parts of complex profiles to beat with one another. This makes comparison of model line profiles (necessarily computed for only a small number of spectral lines) with

LSD profiles very uncertain. The result is that LSD may well not provide an easy way of beating the S/N barrier in Ap's for precisely the polarization for which it is needed most. This important problem is currently being studied by Shorlin.

4. Conclusions

To summarize, a number of very interesting new directions in field diagnosis are presently being explored for the study of the magnetic fields of Ap stars. These include (1) the exploitation of extensive series of line moment measurements by Mathys and collaborators which provide estimates of several field moments with dense phase coverage for a number of stars; (2) extensive broad-band linear polarization data obtained by Leroy and collaborators for a number of cool Ap stars that enable us to fix model angle parameters with greatly improved confidence; (3) the obtaining of full phase coverage of $IQUV$ spectra of several well-known Ap stars, which have for the first time revealed clear QU signatures in some lines; (4) the development by Donati of line co-addition methods which enable detection of really tiny (e.g. QU) polarization signals in lines; and (5) important efforts by several groups to exploit the new $IQUV$ spectroscopy for detailed modelling of single stars, using numerical spectrum synthesis.

We may confidently look forward to a number of important results within the next few years in this field.

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Discussion

MATHYS: For linear polarization studies, one should also try to apply the moment technique. The multiplex gain will be lower than for LSD, but the technique can deal in a natural manner with the differences between individual Zeeman patterns.
LANDSTREET: This is an excellent idea.
PISKUNOV: How accurate is the weak-field approximation for active late-type stars where the local fields can be of the order of a kilogauss?
LANDSTREET: In the very cool stars in which Zeeman broadening and splitting are observed, the weak-field approximation is certainly no longer a good approximation. However, for AB Dor, one star for which field mapping has been done using Zeeman-Doppler imaging with LSD line profiles, the deduced fields are no more than about 500 gauss (Donati & Collier Cameron 1997). This should be safely within the weak-field limit.
VAN BALLEGOOIJEN: Is the variation in Q, U profiles from one spectral line to another due to the different Zeeman patterns? If so, could one use a modified LSD technique with different classes of spectral lines?
LANDSTREET: The variation in Q and U profiles from one line to another seems to be essentially due to the different Zeeman patterns. Shorlin is studying this idea as one aspect of his PhD thesis, and in fact this looks like a hopeful direction to pursue.