Modeling Ap stars with the help of linear polarimetry

J.L. LEROY

Observatoire Midi-Pyrenees, 14 Avenue Edouard Belin, 31400, Toulouse, France

Abstract. Classical investigations on the Ap-star magnetism relied upon measurements of the longitudinal field and of the field modulus. Our aim has been to determine the transverse component of the field, which requires a linear polarization analysis. Our approach is that of broadband polarimetry, which gives a good insight of the transverse Zeeman effect, owing to the magnetic intensification mechanism. About 50 stars have been observed at the Pic du Midi Observatory ; for a dozen objects of this sample, we have gathered a sufficient number of good measurements, so that the time-variation of the Stokes parameters displays clearly the modulation associated with the star rotation. The theoretical interpretation has been developed in close cooperation with the group of E. Landi Degl'Innocenti, at Firenze. A simple canonical model, based on the geometry of the oblique rotator, forecasts specific features (single or double-looped diagrams, in the Q,U plane), which agree very well with the observed data. We have established that the knowledge of both the longitudinal field and the linear polarization variations enables to derive accurately the two angles i and betta which specify the dipolar model. However, in a significant number of cases, the observed variations of the polarization do not fit closely the modulation expected for a uniform dipole. We have found that such peculiarities cannot result simply from abundance inhomogeneities at the surface of the star, which implies that the magnetic topology must depart from the pure dipolar configuration. We have designed an inversion procedure which allows us to determine a set of departures, with respect to the dipole, resulting in an improved fit with the observations : the main feature required is an expansion outwards of the lines of force, over a part of the magnetic equator, not far from the rotation axis. One can guess that the existence of such extended, or even open, magnetic structures would have significant consequences for the star evolution.

Key words: polarization - stars : magnetic field - stars : peculiar

1. Introduction

The first detection of a strong magnetic field at the surface of an Ap star (78 Vir) was performed 50 years ago by Babcock (1947). Since that time, numerous measurements obtained, first in U.S. observatories, then in other sites, and particularly in Zelenchuk, have provided a good knowledge of this important manifestation of stellar magnetism (actually, the most conspicuous after the magnetism of the Sun).

We will not review this topics in detail, here, since good synthesis are available. In particular, Landstreet (1992) has well described the two main types of measurements which have been obtained for several dozens Ap stars. The longitudinal field is the component which is most easily obtained through an analysis of the circular polarization in the wings of spectral lines. This measurement requires a good spectral dispersion and, even though Ap stars are relatively bright, large telescopes are obviously welcome (whence the value of the observations obtained with the 6-meter telescope). The second type of measurement is that of the field modulus. It can be made simply by measuring the line splitting, at least in those stars which show narrow spectral lines. The availability of modern photoelectric detectors has provided this type of research with a new impetus, resulting in interesting results such as those derived recently by Mathys (1990, and subsequent papers).

Now, in spite of an interesting attempt by Borra and Vaughan (1976), there has been no investigation on the transverse component of the field vector. This shortage can be understood if one remembers that the transverse magnetic field must be derived from a linear polarization analysis, which is hard to achieve with coude spectrographs (coude mirrors introduce a severe instrumental signal). However, it is clear that the complete knowledge of the magnetic field does require the measurement of the transverse component, and that the angular quantities (the customary angles i and betta) which define the oblique rotator, will be recovered safely only once the linear polarization is known. Thus, there is definitely a great need for good measurements of the linear polarization of Ap stars.

Actually, a special type of linear polarization analysis, namely broadband polarimetry, had been successfully applied to 53 Cam (Kemp and Wolstencroft, 1974) and to HD 71866 (Piirola and Tuominen, 1981). It revealed sizeable time-variations of the linear polarization (at the level of 0.05 %), with the star rotation frequency. Thus, it looked promising to tackle again this type of program, as well for the observations, which were managed at the Pic du Midi Observatory, as for the theoretical interpretation, which was developed at Firenze by the group of E. Landi Degl'Innocenti. The results of this investigation have been published in several articles (I to VI) quoted in the bibliography and the present paper is essentially a synthesis of these publications.

2. Broadband linear polarization as a consequence of the Zeeman effect

2.1. Integrated polarization over a spectral line

Everybody knows the shapes of the Stokes parameters profiles across a spectral line submitted to the Zeeman effect. The integral properties, which have been sometimes considered (see e.g. Ronan et al., 1987), entail one important feature concerning the transverse Zeeman effect: as the saturations of the sigma and pi components are not equal, there is a net residue of linear polarization, within a spectral line, as soon as the line is not optically thin (Figure 1). This phenomenon is often refered to as the magnetic intensification effect (Leroy, 1962 ; Calamai et al., 1975), because it implies also a change of the equivalent width of the line.

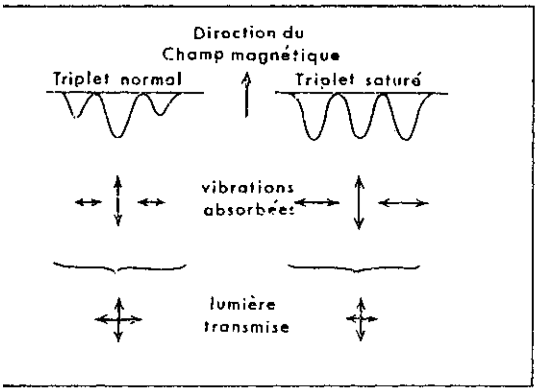

Fig. 1. The magnetic intensification mechanism. (Leroy, 1962).

The computation of the net polarization which is observed over the whole profile of a spectral line is a very simple matter if one uses a model of line formation like that of Unno (Fig 2). Calamai et al. (1975) have shown that one has to take into account the anomalous dispersion effect, with the important consequence that the polarization of the transmitted light can discard slightly (say by 10° — 20°) from the direction of the projected field vector (the discrepancy disappears in a purely transverse field).

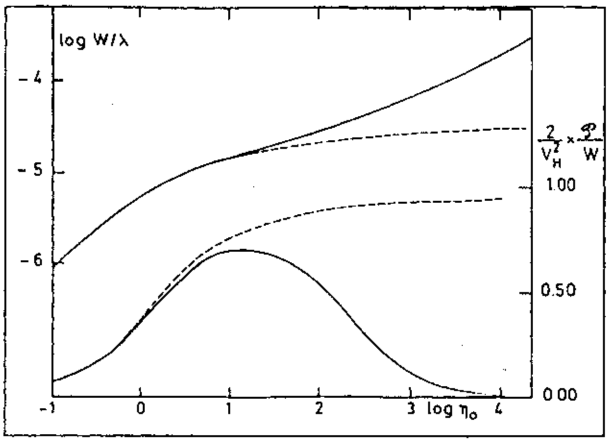

Fig. 2. Top : reduced equivalent width of a spectral line as a function of the central absorption coefficient. Bottom : net linear polarization for the same line. Both quantities have been computed under the hypothesis of pure Doppler broadening (dotted curves) and Doppler + damping broadening (full lines) (Leroy, 1989).

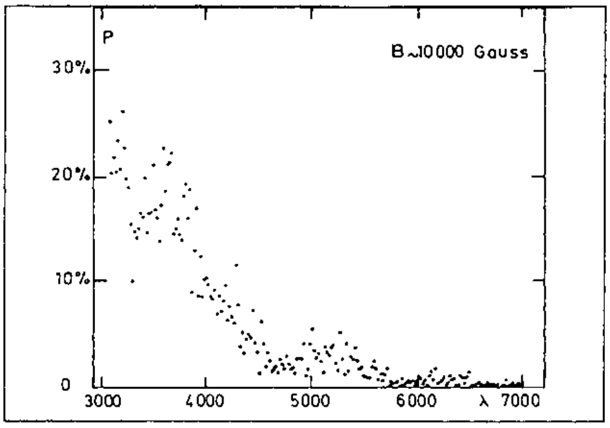

Fig. 3. The degree of linear polarization P due to magnetic intensification computed for a transverse magnetic field of 10000 G. P has been determined for every 20 Å interval in the solar spectrum, starting from 3060-3080 Å, up to 6980-7000 Å (Leroy, 1989).

2.2. Polarization within a spectral interval including many lines.

The result is reached very easily, in principle, since one has only to add the individual contributions of every line. Of course, one must know the absorption characteristics of the lines (central absorption coefficient and Doppler width) and their Zeeman splitting pattern ; these quantities are easily available in the case of the solar spectrum only. Figure 3 shows the wavelength variation derived for the Sun (Leroy, 1989). Later on, it has become apparent that the increase of the polarization towards the ultra-violet is reduced by the effect of blends (Leroy, 1990). Similar results were derived by Saar and Huovelin (1993) for various spectral types. The case of Ap star spectra has not been treated explicitly but, here too, the polarization is due mainly to the iron and chromium spectrum and the general trend of the wavelength variation should be similar. Actual measurements of Ap stars polarization in different bands confirm this view (Paper V).

2.3. Advantages and drawbacks of broadband polarimetry

The possibility to perform a diagnosis of the transverse magnetic field using simply a polarimeter results in a great gain of light : not only is the polarimeter more transparent than any spectrographic system, but one can choose really broad spectral bands (from 100 A to 1000 A) allowing to perform accurate polarimetry : at the focus of the 2-meter telescope of Pic du Midi, a 10 minutes integration reduced the photon noise down to a polarization level of 0.01 % , for stars of magnitude 6 to 7. Of course, one could fear that a broad spectral region include a major contribution of unpolarized continuum, which dilutes the magnetic signal we are interested in. Such is not the case, at least for cool Ap stars (colour index B-V of the order of 0.10-0.30) : a glance at the beautiful spectrum of β CrB, published a long time ago by Hiltner (1945), reveals that line crowding is so severe in the blue part of the spectrum that the role of the continuum is almost negligible. But it is true that for the hotter Ap stars, which have a less rich absorption spectrum, the broadband method becomes ineffective.

However, we believe that the main drawbacks of broadband measurements are different : the first one is that one cannot distinguish the magnetic signal from another broadband contribution, and in particular from the polarization due to the interstellar medium. For the brighter Ap stars, which are not far from the Sun (less than 50 pc), the interstellar polarization is of the order of some units of 0.01 % (Leroy, 1993a, 1993 b) ; the polarized signal contains a minor, constant, contribution, in addition to that due to the Zeeman effect, which is not very troublesome. But farther stars of low galactic latitude are much more contaminated and their study via broadband polarimetry is questionable. The second difficulty results from the fact that the relation between the field strength and the polarization magnitude cannot be established accurately for a combination of several tens or hundreds of lines. It means that the absolute value of the polarization variations should not be taken into account at the stage of the interpretation. Finally, it is the *shape* of the *Q(t)* and *U(t)* variations, or that of the *Q, U* diagram, which contains the information useful for magnetic modeling.

In conclusion, polarimetry with a *good* spectral resolution, measuring the Stokes parameters profiles across well known spectral lines is certainly more advisable, as well known by solar observers. In the stellar case, it is still necessary to be sure that one can reach a sufficiently low noise level but it is highly probable that the new instruments coming now into operation will provide more accurate data than broadband polarimetry (which, in turn, is probably the best way to get a fast overview of the phenomenon).

3. Measuring the time-dependent polarization of *Ap* stars

We have given already some indications on the measurements made at the Pic du Midi Observatory, during the last five years. The polarimeter "Sterenn", which was set at the Cassegrain focus of the 2-meter telescope, is a double-beam polarimeter, with a rotating half-wave plate designed for the UBV range. Most measurements were made through a standard B filter. However, the brighter stars (e.g. β CrB) were observed through a narrower filter (passband 100 Å) centered at 4200 Å. A suitable integration time reduced the photon noise down to the level of polarization of 0.01 %, and in many cases down to 0.005%. The instrumental polarization, of the order of 0.01-0.05 % , was subtracted with an uncertainty of about 0.005 %. Altogether, the standard deviation of our individual measurements was mostly in the range 0.005-0.015 % . This accuracy is absolutely needed since the amplitude of the linear polarization variations to be measured is always smaller than 0.1%.

We observed 55 different stars but the number of measurements is not the same for each object because it was soon obvious that some stars showed interesting polarization signals and that other did not. All our data (about 400 measurements) have been published in paper V, together with another

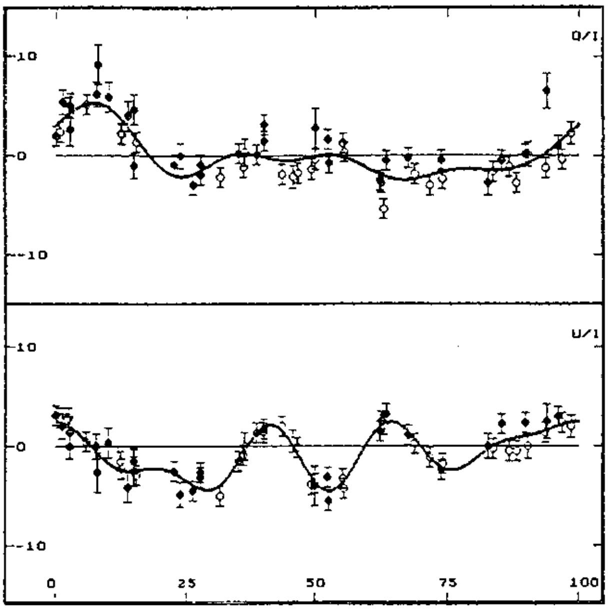

Fig. 4. Time variations of the reduced Stokes parameters of 53 Cam. The open circles refer to our measurements while the filled circles refer to the Kemp and Wolstencroft (1974) data. The continuous curve is a fit by a fifth order Fourier expansion, assuming a rotation period of 8.0269 days. The ordinates are expressed in units of 0.01 % (Paper V).

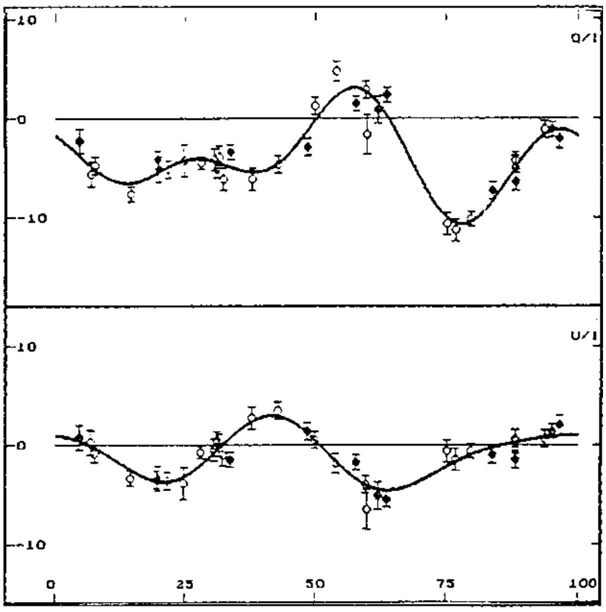

Fig. 5. Time variation of the reduced Stokes parameters of HD 71866. The open circles refer to our measurements while the filled circles refer to the Piirola and Tuominen (1981) data. The continuous curve is a fit by a third order Fourier expansion, assuming a rotation period of 6.80054 days (Paper V).

100 measurements obtained previously by various authors, and scattered in the literature. All the observations have been plotted according to the rotational phase, which implies that the star period is well known. That was generally the case since we observed many famous stars ; however, in some instances, our polarimetry has yielded the period, or at least an improved value of the period (remember that for a star observed pole on, with a magnetic axis at 90° from the rotation axis, the surface field and the longitudinal field remain constant ; but the linear polarization rotates at twice the star rotation frequency, which allows to determine the period).

Table 1 gathers all those stars for which linear polarimetry was available at the time when Paper V was written. The four classes indicate : (1) those stars which have a well determined polarization variation ; (2) those for which it will be possible to reach the same stage, after some additional observations ; (3) those which show little polarized signal, either because the magnetic field is too 'small, or because the spectrum has few saturated metallic lines ; (4) those which show a strong constant polarization, added by the interstellar medium, which seriously hampers the analysis of the signal due to the Zeeman effect.

Table 1. A catalogue of Ap stars, labeled with their HD number, for which some broadband linear polarimetry is available

(1)	(2)	(3)	(4)
24712	4778	11502	9996
62140	108662	12447	12288
65339	152107	15089	14392
71866	165474	15144	18296
80316	188041	34452	32633
98088	201601	89822	37776
115708		96707	90569
118022		108945	110066
137909		112413	111133
192678		124224	125248
		125162	126515
		140160	130158
		148112	133029
		148898	134214
		176232	137949
		196502	153882
		206088	215441
		220825	219749
		223640	224801
			335238

We have noted that, presently, the measurements accuracy is just sufficient, and it looks careful to be sure of the reliability of our data. This check may be done by comparing the observations of the same star, obtained with two different instruments. Figure 4 compares our measurements of 53 Cam with those of Kemp and Wolstencroft (1974) and Figure 5 does the same for HD 71866 (Piirola and Tuominen (1981) data compared with ours). In our opinion, these comparisons prove that the published error bars are quite realistic and that one can make serious interpretation work based upon this observational material.

4. Theoretical polarization of the oblique dipolar rotator

4.1. The canonical model

The first attempt to compute the linear polarization expected for a rotating dipolar star was done by Landi Degl'Innocenti et al. (1981), under very general conditions (the case of the decentered dipole was considered at once). The results did show clearly the main characteristic features of the solutions, which are particularly visible with the help of diagrams drawn in the Q, U plane. However, for the more simple case of the centered dipole (or quadrupole), the computations are much easier and can be performed analytically, at least in the case of the weak-field approximation (when the polarization due to magnetic intensification is proportional to the square of the field modulus). We have published in paper I a set of polarization diagrams, for different values of i and β, which are reproduced in Figures 7 and 8 (in Figure 7, magneto-optical effects are neglected while they are taken into account in Figure 8). Let us mention that general analytical results dealing with more complex multipolar configurations have been published recently by Bagnulo et al. (1996).

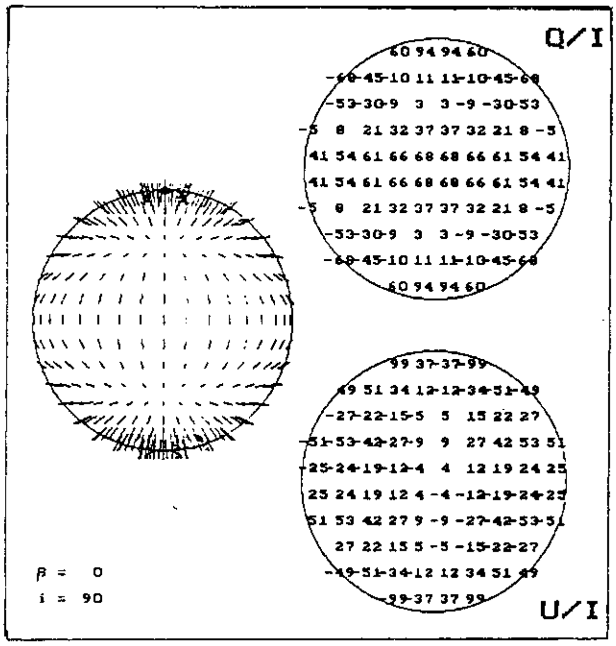

Fig. 6. The spatial distribution of Q/I and U/I (in arbitrary units) over the stellar disc, for a dipolar field with the magnetic axis in the plane of the sky (Paper IV).

The main feature visible on Fig 7 is the existence of two types of diagrams : the single-loops which are found in the lower left corner of the figure evolve as double-loops in the upper right corner. This characteristic topology is directly linked to the i and β values and one can hope that the comparison of the observed diagrams with the computed ones will give an unambiguous determination of these angles. However, one notices that the shape of the diagrams changes but slowly along the diagonal i = β ; in other words, the linear polarization is

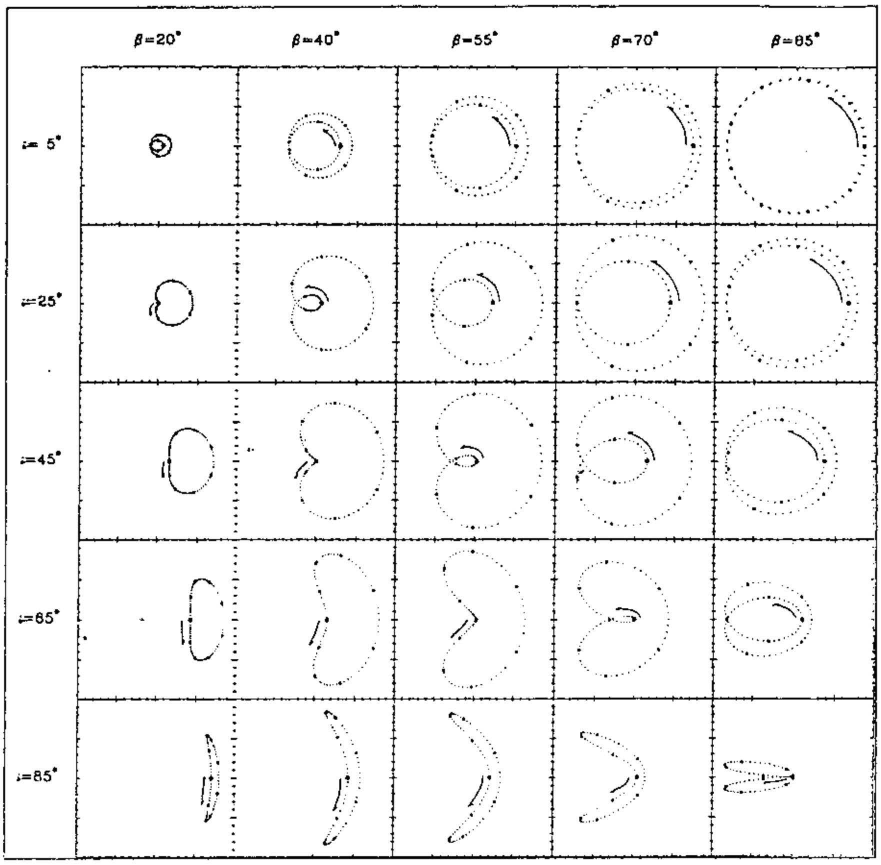

Fig. 7. Polarization diagram (U vs.Q) for a dipolar magnetic configuration, neglecting magneto-optical effects. Each diagram corresponds to one rotation sampled every 4° (small dots) ; the large dot denotes the zero-phase point and the direction is indicated by the arrow (Paper I).

moderately sensitive to the quantity $i - \beta$, while it is very sensitive to $i - \beta$. This property is quite interesting because it is well known that, on the opposite, the circular polarization is mainly sensitive to $i + \beta$ (Hensberge et al., 1979), so that one foresees the possibility to get really good values of i and β by using simultaneously the linear and circular polarization observations ; this question will be examined later.

The comparison between Fig 7 and 8 shows the consequences of the magneto-optical effects. When both i and β are small, which means that the observer always sees the same magnetic pole, the effect is essentially a global rotation of the polarization diagram (similar to that due to a different position angle of the rotation axis in the plane of the sky). For larger values of i and β, the observer sees alternatively the two magnetic poles and the magneto-optical rotation is alternatively direct and retrograde, which produces, eventually, distorsions of the diagram. In this case, the analysis is more involved because the value of the magneto-optical effect, and thus the extent of the distorsion, depend weakly on the field modulus.

4.2. *The medium field case*

In the visible spectrum, the weak field approximation remains valid as long as the field modulus is below 500 - 1000 G. On the other hand, it is well known that the field strength is often 10 times larger at the surface of Ap stars so that one can question the adequacy of the canonical model for this particular class of stars. This problem has been investigated by Bagnulo et al. (Paper III) : as the exact value of the polarization due to magnetic intensification has been previously tabulated by Landi Degl'Innocenti and Calamai (1982) (see also Calamai and Landi Degl'Innocenti, 1983), one can compute exact polarization diagrams and compare them with those derived from the canonical model.

Unexpectedly, the differences are weak, which can be explained by different factors, the main reason being the homogeneity of the field strength at the surface of a dipolar star. The extreme values of the field modulus are only within a factor of 2, and the net polarization of the integrated stellar disc is determined essentially by the mutual cancellation of the elementary signals issued from regions with different field azimuth. This cancellation process is very effective : in the canonical model, the net polarization is 15 times smaller than that which would arise from a star covered with lines of force parallel to the polar field. This behaviour is illustrated in Figure 6, which displays the repartition of Q/I and U/I over the surface of a dipolar star with its magnetic axis in the plane of the sky. We conclude that the net linear polarization of a magnetic star is more sensitive to the orientation of the field lines than to the field modulus, which has some consequences for the following of this investigation.

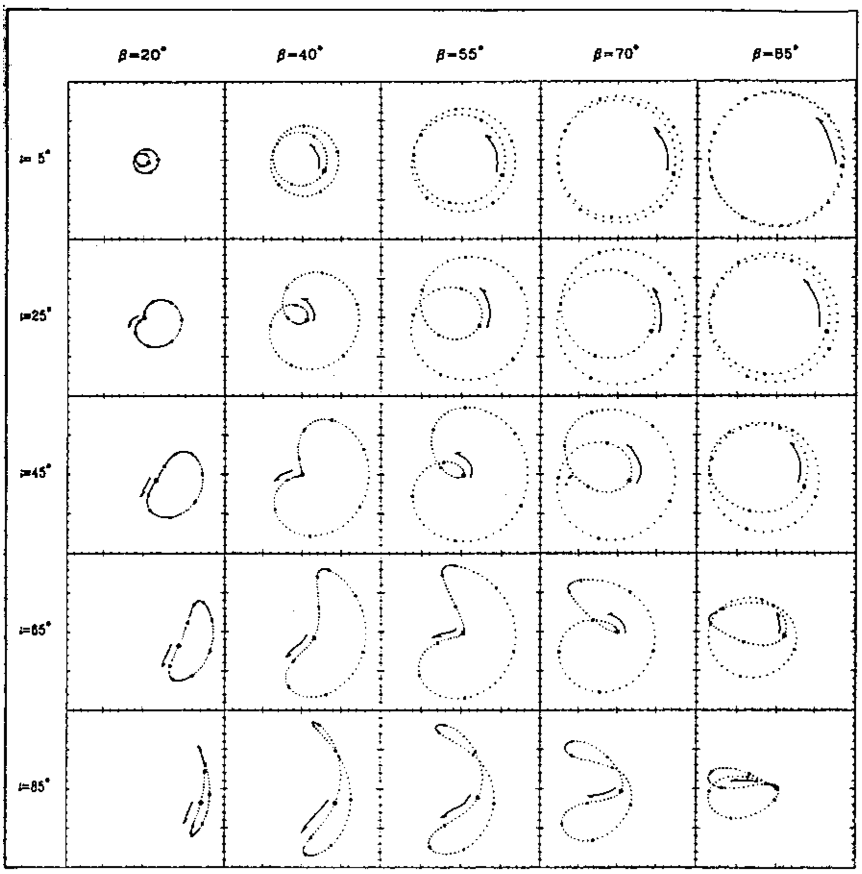

Fig. 8. Same as Fig. 4 with magneto optical effects included (Paper I).

5. Determining the characteristic angles *i* and β

We have seen that comparing an observed polarization diagram, with the theoretical diagrams of Fig 8, provides a determination of *i* and β, which is a significant progress since neither the longitudinal field, nor the surface field, allowed to disentangle these two angles. But it has been noted also that it is the joint use of linear and circular polarization data which really yields accurate values for i and β. Some examples have been given in Paper III : since one can compute both the circular and the linear polarization signals which emerge from a dipolar star, a program of residues minimization will provide the wanted quantities.

We have also proposed (Paper IV) a simplified method which requires only the knowledge of a few synthetic quantities. Let r be the ratio of the smaller extremum of the longitudinal field to the larger extremum. r, which is always between -1 and 1, has been provided, for many stars, by the standard observational methods, beginning with the Babcock work. For the linear polarization, we define P_1 and P_2 as the powers of the polarized signal for the harmonics 1 and 2 of the star rotation period. It is interesting to note that these quantities depend neither on the absolute scale of the polarization, nor on the average value of the Stokes parameters (which can be spoiled by interstellar polarization) and that, moreover, they are independent of the absolute phase of the observations (only relative phases, resulting from the knowledge of the star period, are needed). We define the quantity $s = (1 - P_1/P_2)/(1 + P_1/P_2)$ and we compute *r* and *s* for different values of i and β. The diagram which is obtained (Fig 9) provides a fast determination of *i* and β as soon as r and *s* have been deduced from the circular and linear polarization measurements.

Table 2, first presented in Paper VI, provides a list of *i* and β values for 15 stars, according to our linear polarimetry and to the longitudinal field data available in the literature (an estimate of the uncertainties δi, $\delta\beta$ is also given).

6. Observed discrepancies with respect to the dipolar model

Although the dipolar model is a very good first approximation, it is well known that some stars have a longitudinal field whose time variation is more complex than the sinusoid forecasted by this simple model. Noticeable discrepancies have also appeared when additional parameters, for instance the surface field, have become available : well-known cases are that of β CrB , well documented by Wolff and Wolff (1970), or that of 53 Cam, thoroughly investigated by Landstreet (1988). Much attention has been paid to the research of a model, more involved than the simple dipole, allowing to fit correctly the observational data ; it is not the place, here, to review these attempts, of which the more famous examples are the decentered dipole

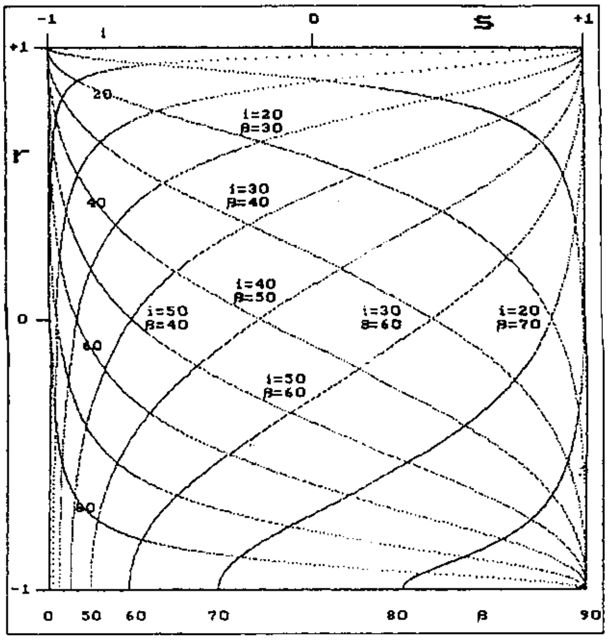

Fig. 9. The loci of constant i and β in a plane where the abscissa is fixed by the linear polarization measurements and the ordinate by the circular polarization measurement (Paper IV).

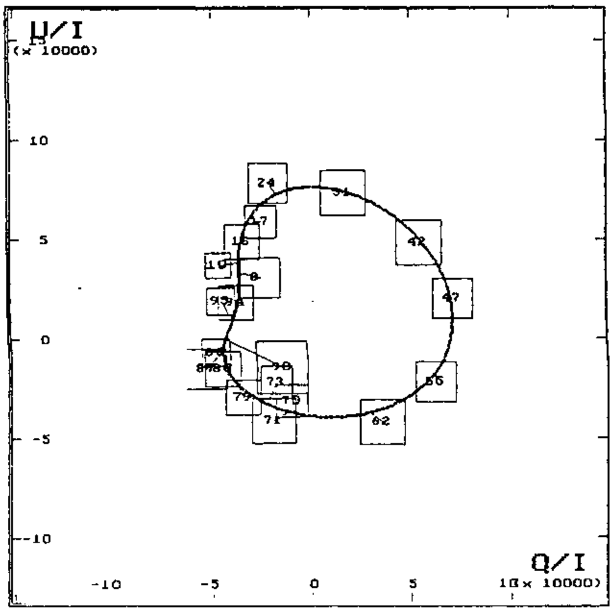

Fig. 10. The observed polarization diagram of HD 24712 (Paper V).

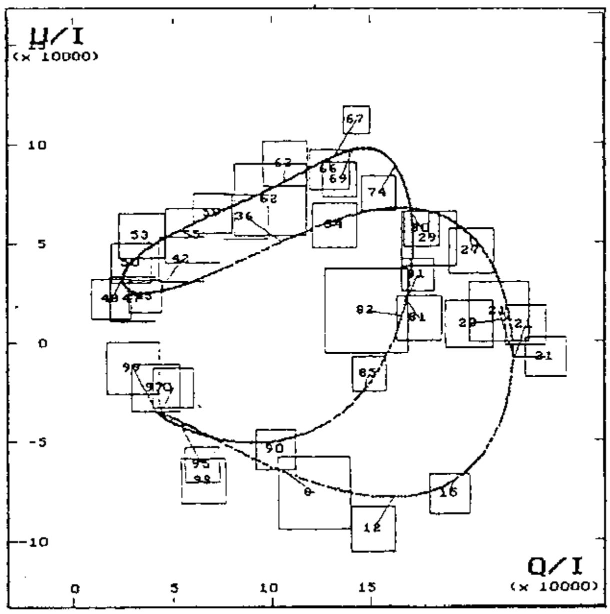

Fig. 11. The observed polarization diagram of 49 Cam (Paper V).

Table 2. Angular parameters (in degrees) for 15 stars

HD number	i	β	δi , $\delta\beta$
24712	140	147	5
62140	90	93	
65339	110	75	
71866	110	95	
98088	85	80	
118022	25	120	
137909	160	100	
115708	130	75	10
192678	170	120	
4778	70	65	15
80316	60	35	
108662	55	120	
152107	15	40	
165474	80	10	20
188041	160	120	

(Landstreet, 1970 ; Stift, 1975), or a combination of dipoles and quadrupoles (Oetken, 1977).

Thus, we did not expect that the adjustment of our measurements to a dipolar model would be always satisfactory. Actually, some stars do show a polarization diagram well consistent with the pure dipole (a good example is that of HD 24712, studied in paper III ; see also Fig 10) ; but, in many cases, interesting discrepancies have become apparent, when a sufficient number of measurements resulted in an accurate polarization diagram. A representative example is that of 49 Cam (= HD 62140) that we have investigated in detail (Leroy et al., 1994) : it is rather obvious that the polarization diagram of this star (Fig 11) is different from the theoretical diagrams of Fig 8.

In a first step, we have asked whether such peculiarities could arise as a consequence of abundance patches : the fact

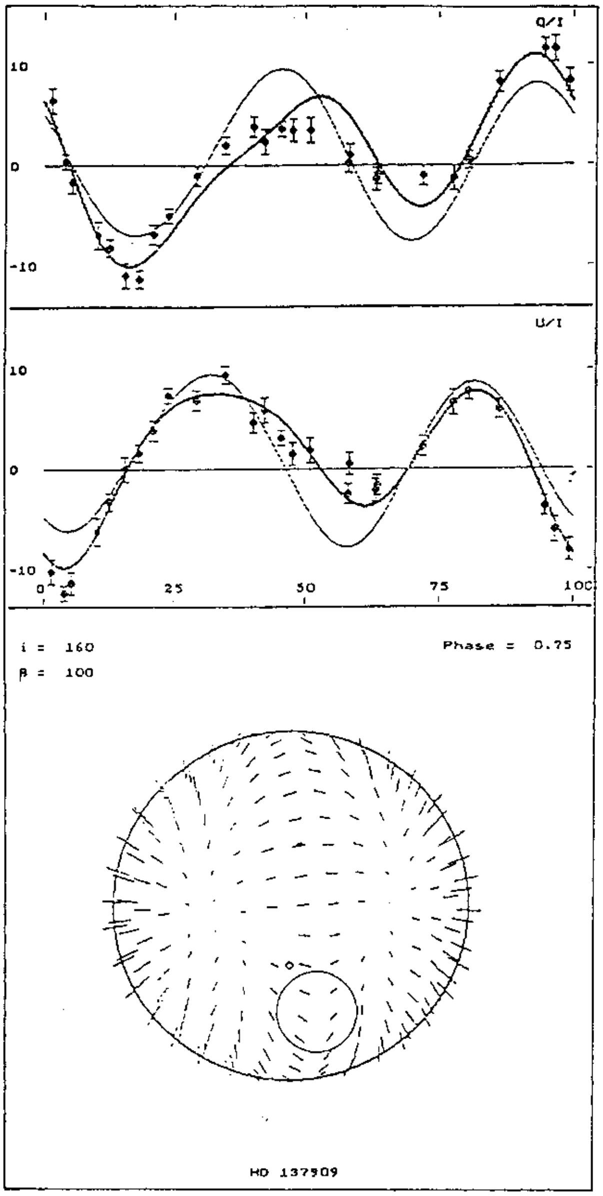

Fig. 12. Top : time variation of the reduced Stokes parameters (in units of 0.01 %) for β CrB = HD 137909. The thin and thick lines are the best fits obtained with a pure dipole and with the modified dipole pictured at the bottom of the figure, respectively. The open dot marks the position of the visible rotation pole and the small circle outlines those regions where the lines of ofrce are expanded outwards (Paper VI).

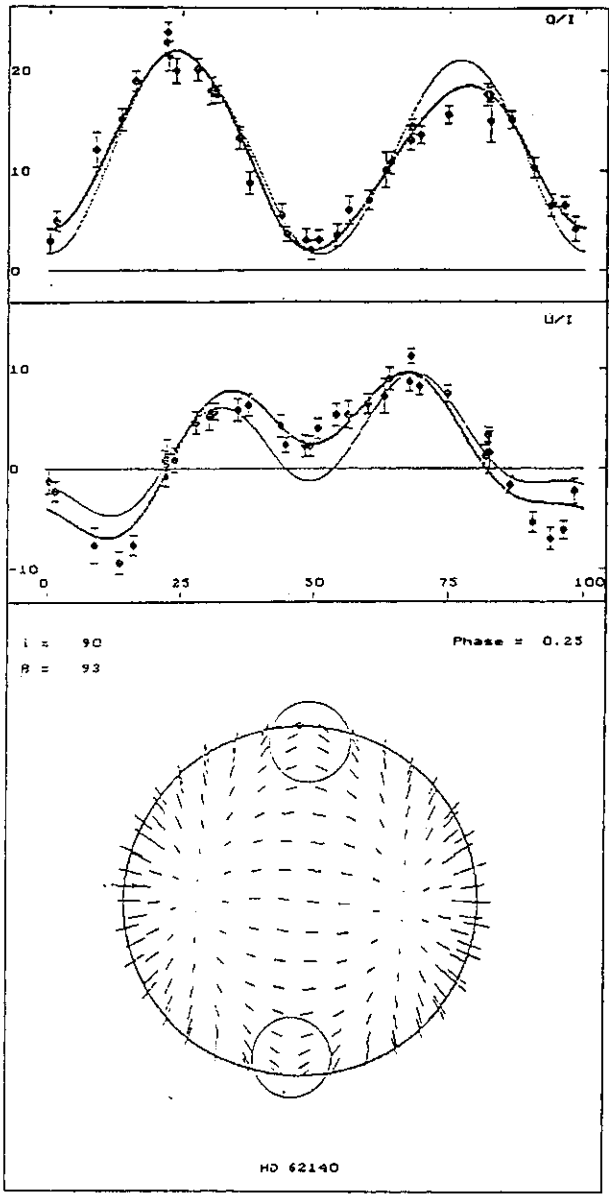

Fig. 13. Same as Fig 12 for 49 Cam = HD 62140 (Paper VI).

that the abundances of several elements can be highly different in various regions of the atmosphere of Ap stars is well established ; as the polarization that we measure results from a saturation mechanism, one could fear a cross of abundance and magnetic signatures in the observed data. This question has been adressed in Paper IV, with the conclusion that abundance variations have generally a minor effect on the polarization curves. In some cases, we may be sure that the polarization peculiarities have to be interpreted in terms of magnetic anomalies : it is the case for β CrB, which presents a non-canonical polarization diagram (Paper II), while its spectrum is rather stable along the star rotation. We will come back soon to this interesting example.

7. A modified dipolar model consistent with the observations

A polarization diagram, which departs from the diagrams computed for a magnetic dipole, can probably be explained by several non-dipolar magnetic topologies. To compensate this non-uniqueness of the solution, it looks reasonable to rely on a maximum entropy principle which, in the present case, can be expressed as the condition to find a model, fitting the observed data, as close as possible to the pure dipole.

The next stages of the model choice are as follows : as the linear polarization is but weakly sensitive to changes of the field modulus (section 4.2.), we will try to explain the observations through a change of the field line orientations. Among the possible rotations of the lines of force we reject those which result in non-meridional paths, since it is a characteristic of the dipole to have meridian lines of force. Finally, we note that the major contribution to the net polarization comes from the regions around the magnetic equator (Fig 6), since one finds here only a significant set of parallel lines of force. In conclusion, the smallest departures relative to the dipole, which will produce the largest variations in the polarization diagram, are expected to be found for equatorial lines of force rotating within their meridian plane. But, as we want that the condition *divB* = 0 remains true, we will also impose that the inclination changes must be symmetrical around the magnetic equator.

Within these limits, we see that equatorial lines of force are allowed either to rise outwards, or to plunge downwards, the sign and size of the inclination being a function of the magnetic longitude. The best solution is found through a process of residues minimization, after the perturbation has been developed into a set of spherical harmonics (up to the 3rd order). Needless to say that the solution which is retained must also agree with the observed data on the longitudinal field ; however, this additional constraint is not very severe because the field lines inclination changes have only a weak effect on the integrated longitudinal field (the surface field data are not concerned by our modified model since the field modulus is kept unchanged).

Figures 12 and 13 display the solutions obtained for two stars which presented strong departures relative to the dipole. In both cases the modification of the magnetic topology is an expansion of the lines of force outwards and it is interesting to remark that this phenomenon occurs in the vicinity of the rotation pole. The same trend was still found in four other stars (HD 65339, 71866, 98088, 118022) not pictured in this paper, and also in HD 192678 which has been studied recently, thanks to a four Institutes collaboration (Wade et al., 1996).

Figure 14 yields a schematic view of the trend emerging from this investigation. Our sketch is valid only for those stars having a β angle close to 90°, which represent the bulk of our observed data (small β angles give rise to a nearly constant polarization which is hard to study by our method). Nevertheless, the fact that several stars of our sample have expanded, or even open, lines of force, in the vicinity of their rotation axis may be very significant. Such regions could be the site of stellar winds, or may be connected with the neighbouring interstellar medium (in contrast with a dipolar field pattern which is essentially a closed structure).

While the present investigation is concerned only with the line of force orientations, recent progress in the surface field measurement (see .e.g. Mathys, 1990) also makes possible the design of models with non-bipolar field modulus. It is certainly worthwile to combine both approaches and, in a preliminary work of this type on β CrB, we have found that the region of expanded lines of force seemed to be also a region of enhanced field strength. Under these particular conditions, it has also

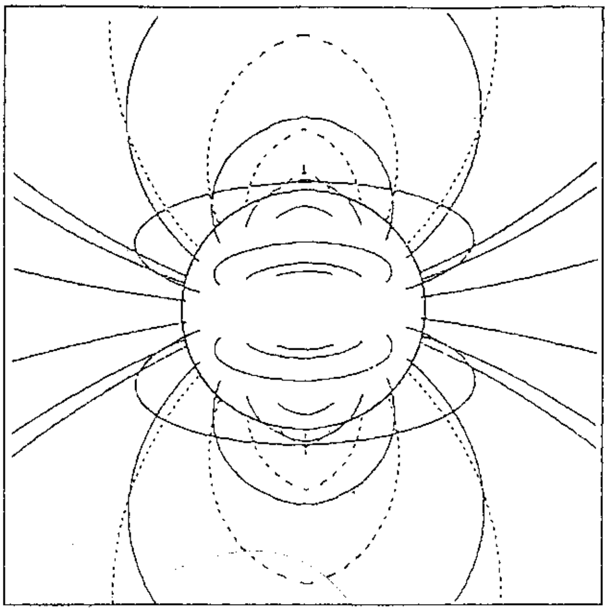

Fig. 14. A schematic model of a magnetic star ($i = 90°$, $\beta = 90°$, phase= 0.25) able to fit a large number of our polariation measurements. The lines of force are purely dipolar (full lines) except in the vicinity of the rotation poles where they expand outwards ; to keep the figure understandable we have drawn, as dotted lines, only these non-dipolar lines of force which are in the plane of the sky (Paper VI).

revealed that if the lines of force expansion is larger and larger at higher altitudes, one can forecast some shift in the phase of the longitudinal field maximum. This last finding, if confirmed, would be exciting because it corresponds to a curious observation by Wolff (1970), confirmed by Romanyuk (1986, 1987), namely that the longitudinal field maximum occurs later when the measurements are made below the Balmer jump, i.e. refer to a greater altitude in the atmosphere...

8. Conclusion

Although the study of transverse magnetic fields has been neglected in the past, it is obvious that future investigations on stellar magnetism will be really satisfactory only if they include such measurements, in addition to the customary analysis of the surface and longitudinal fields. Thus, magnetic diagnosis must include some linear polarimetry, which is becoming easier with the recent development of Cassegrain spectrographs (or of fiber-fed spectrographs), well suited to on-axis measurements. One can forecast that complete Stokes profiles will be soon available, at least for the brighter Ap stars, which will open a new era for the determination of stellar magnetic fields (Piskunov and Khoklova, 1984).

Our approach, based on broadband linear polarimetry, was less-ambitious and suffered some shortcomings. However, its simpleness has enabled to get quickly a first overview of the phenomena, owing to a survey bearing on more than 50 stars. It turns out that the characteristic features coming out from these observations are in excellent agreement with the expectations based on the simplest model, namely the oblique rotating dipole. However, some unexpected trends have emerged : the time variation of the linear polarization is weakly sensitive to the field modulus, but it depends more critically on the angular pattern of the lines of force over the star surface. It results quite naturally that linear polarimetry is an excellent tool to determine the characteristic angles i and β which define the oblique rotator (the accuracy is truly good when both linear and circular polarimetric data are available).

In some well-observed stars, our measurements have put in light serious discrepancies with respect to the diagrams computed for the standard dipole. We have investigated slightly different magnetic topologies, having only modifications of the lines of force orientation, with the aim to fit correctly the observations, with a minimal departure from the pure dipolar case. The new feature which is needed is, in all the cases, an expansion of the lines of force, above a part of the magnetic equator, not far from the rotation pole (this geometry applies best to stars having a β angle around 90°). This modified dipolar model, which still has to be checked by further work, could be significant as far as the star evolution is concerned, since it predicts a stellar magnetism open towards the interstellar medium, well different from the closed structure inherent to a dipolar configuration.

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