Magnetic stars, 2004, 114-120

A survey of Ap stars for weak longitudinal magnetic fields

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Abstract.

We are conducting a magnetic survey of a sample of about 30 spectroscopically-identified Ap stars (selected from the HD catalogue), but with faint or previously undetected magnetic fields. We use the MuSiCoS spectropolarimeter at Telescope Bernard Lyot (Pic du Midi Observatory, France) and the cross-correlation technique Least Squares Deconvolution (LSD; Donati et al. 1997). For 24 studied stars, we have obtained 21 detections of Stokes V Zeeman signatures (data quality and phase coverage may explain our lack of detection of any field in some objects). Our results suggest that all Ap stars are magnetic and, furthermore, that there may exist a minimum field strength for which Ap-type characteristics are produced.

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

1 Introduction

Though thousands of chemically peculiar and Ap stars are catalogued (Renson et al. 1991), only about 210 Ap stars have magnetic field measurements (Romanyuk 2000). The catalogue of magnetic chemically peculiar stars by Romanyuk (2000), contains 117 of 211 stars (55%) with maximum unsigned longitudinal fields larger than 1 kG. On the other hand, according to Bohlender & Landstreet (1990), the median root-mean-square (rms) longitudinal magnetic field of Ap stars (based on a magnitude-limited sample observed by Borra & Landstreet 1980) is approximately 300 G (the largest one they report is only 710 G). In the catalogue of Bychkov et al. (2003) the distribution of the averaged magnetic field strength is described by a decreasing exponential function above 100 gauss, which again means that weak field Ap stars represent the majority of their class. Thus the faint part of the magnetic distribution in Ap stars is not known and one may even ask if there is a minimum magnetic field needed for making an Ap star (Glagolevskij et al. 2002). In order to improve our knowledge of these stars and to be able to make an unbiased investigation of Ap star magnetic fields, we have undertaken a study of a sample of about 30 spectroscopically-identified Ap stars (selected from the HD catalogue), but with weak or previously undetected magnetic fields. We used the MuSiCoS spectropolarimeter at Telescope Bernard Lyot and took advantage of the high efficiency of Least Squares Deconvolution (Donati et al. 1997) to interpret the results.

2 The weak magnetic field Ap stars survey

2.1 Observations and reduction

Stokes V and Stokes I spectra of 24 bright Ap stars were obtained during 4 runs, from June 2001 to August 2003. We used the MuSiCoS spectropolarimeter attached to the Bernard Lyot telescope (TBL) at Pic du Midi Observatory. MuSiCoS spectropolarimeter is composed of a cross-dispersed echelle spectrograph (Baudrand & Böhm 1992) and a dedicated polarimeter module (Donati et al. 1999). The spectrograph is a table-top instrument, fed by a double optical fibre directly from the Cassegrain-mounted polarisation analyser. In one single exposure, this apparatus allows the acquisition of a stellar spectrum in a given polarisation (Stokes V in this case) throughout the spectral range 450 to 660 nm with a resolving power of about 35000. Spectra in both orthogonal polarisations are recorded simultaneously by the CCD detector. A complete Stokes V exposure consists of a sequence of four subexposures, between which the quarter-wave plate is rotated by 90°. This has the effect of exchanging the beams in the whole instrument, and in particular switching the positions of the two orthogonally polarised spectra on the CCD, thereby reducing spurious polarisation signatures. The echelle polarisation spectra are reduced using the ESPRIT package (Donati et al. 1997). Observation and reduction procedures are the same as more thoroughly described in Shorlin et al. (2002). The observed stars are listed in Table 1. Their HD number, α and δ coordinates and visual magnitude are given.

Table 1: Observed Ap stars. Columns give HD number, RA and declination (J2000), visual magnitude, number of observations and detection level (DD=definite detection; MD=marginal detection; ND=no detection).

Name	HD	α (h)	δ (^{o})	m_V	#	Detect
HN And	8441	01 24 19	+43 08 32	6.7	1	1DD
43 Cas	10221	01 42 20	+68 02 34	5.5	4	3DD
	15144	02 26 00	-15 20 28	5.8	2	2DD
56 Tau	27309	04 19 36	+21 46 24	5.3	5	5DD
	27650	04 23 35	+42 25 40	6.2	2	2ND
11 Ori	32549	05 04 34	+15 24 14	4.7	3	3ND
	32650	05 12 22	+73 56 48	5.4	2	2ND
	43819	06 19 01	+17 19 30	6.2	6	6DD
15 Cnc	68351	08 13 09	+29 39 24	5.6	4	1DD
3 Hyd	72968	08 35 28	−07 58 56	5.7	8	8DD
45 Leo	90569	10 27 39	+09 45 44	6.0	8	8DD
	94427	10 53 57	−12 26 04	7.3	1	1DD
	96707	11 09 39	+67 12 36	6.0	6	2MD 1DD
65 UMa	103498	11 55 11	+46 28 11	6.9	8	7DD
21 Com	108945	12 31 00	+24 34 01	5.4	7	7DD
	138633	15 33 34	−11 03 55	8.6	2	1DD
ω Her	148112	16 25 25	+14 01 59	4.6	5	4DD
45 Her	151525	16 47 46	+05 14 48	5.2	7	1MD
	165475	18 05 43	+12 00 14	7.0	4	1DD
	176232	18 58 46	+13 54 23	5.9	3	DD
19 Lyr	179527	19 11 46	+31 17 00	5.9	5	DD
4 Cyg	183056	19 26 09	+36 19 04	5.1	2	2DD
	204411	21 26 51	+48 50 06	5.3	2	DD
κ Psc	220825	23 26 51	+01 15 20	4.9	2	2DD

2.2 LSD method and magnetic field detection

The aim of our study is to detect circular polarisation which is characteristic of the longitudinal Zeeman effect, produced by the presence of a nonzero integrated line-of-sight magnetic field in the stellar photosphere. For this we used the Least Squares Deconvolution (LSD) procedure first used by Donati et al. (1997) to study active late type stars. This method enables the "averaging" of several hundreds (and possibly several thousand in some stars) of lines and thus to obtain Stokes I and Stokes V profiles with greatly improved S/N ratios. First, Wade et al. (2000) found that LSD was able to improve the standard errors of field measurements of Ap stars by a factor of five to ten over the previous work (for stars with $v \sin i \leq 50$ km/s). Now, and even more important in the present study, LSD gives us a single quantitative criterion for detection of Stokes V polarisation: we perform a statistical test in which the reduced χ^2 statistic is computed for the Stokes V profile, both inside and outside the spectral line (Donati et al. 1997). The statistics are then converted to detection probabilities and the probabilities are assessed to determine if we have definite detection (false alarm probability smaller than 10^{-5}), marginal detection (false alarm probability greater than 10^{-5} and smaller than 10^{-3}), or no detection at all.

We have additionally computed mean longitudinal magnetic fields for the stars in our survey in order to make comparisons with previous measurements (where such exist), to provide a simple quantitative magnetic field and in some cases to determine the parameters of an oblique rotator model (e.g. Preston 1974).

However, we want to stress that the non-detection of longitudinal fields does not preclude the existence of highly complex fields, or even simple fields observed at unfavorable phases, and *thus that it is the detection or non-detection of significant circular polarisation in LSD profiles which is the basis for our determination of a star having a magnetic field.*

3 Results and interpretation

3.1 Results and comparison with other recent work

For the 24 stars included in Table 1, 21 were found to exhibit a significant circular polarisation in their spectral lines (although only marginally significant in two cases). For the majority of the sample, the detection was obtained during the first observation. For some objects, obtaining one positive detection required to observe several times, sometimes spanning two observing seasons. This can be due to phase effects and of course to meteorological conditions. However, for all objects which were observed more than 4 times in good conditions (apart from 45 Her), we obtained a detection of the Zeeman Stokes V signal. The number of observations and of detections is given in the last column of Table 1.

Generally no significant detection of the magnetic field has been reported in the past for the stars of our sample. Shorlin et al. (1997), using MUSICOS and the same procedure as in this paper, did not detect the field for 3 Ap stars of their sample. For two of them they suggested a misclassification. We re-observed the third one, HD 148112 (ω Her), and easily detected its field. Still more recently, Glagolevskij and Chountonov (2002) observed 11 weakly magnetic CP stars and detected no magnetic fields in any of them. We re-observed 3 of them during this work and detected the magnetic field for all of them.

Our better detection rate with respect to other techniques is certainly due to the improvement associated with the LSD method. However, the fact that we insist on performing multiple observations is also an important factor. Figs. 1 – 4 show examples of clear detections for previously undetected fields in 43 Cas (HD10221) and HD 43819. Figs. 1, 2 and 3 show crossover phases, when the Stokes V profile is symmetric and thus the longitudinal field is very small (consistent with zero) but the Stokes V signal significant (definite detection). Techniques sensitive only to the longitudinal magnetic field would not have detected the fields of these stars at crossover phases.

Figs. 1–3 illustrate our ability to detect these weak magnetic fields (even in the case of nearly null longitudinal component) for the Ap star 43 Cas (HD 10221) when Glagolevskij & Chountonov report a (null) rms longitudinal field of 25 ± 41 G. We therefore suggest that the lack of detection of magnetic fields in a sample of low-field Ap stars by Glagolevski & Chountonov (2002) is associated with measurement precision, possibly coupled with a phase effect.

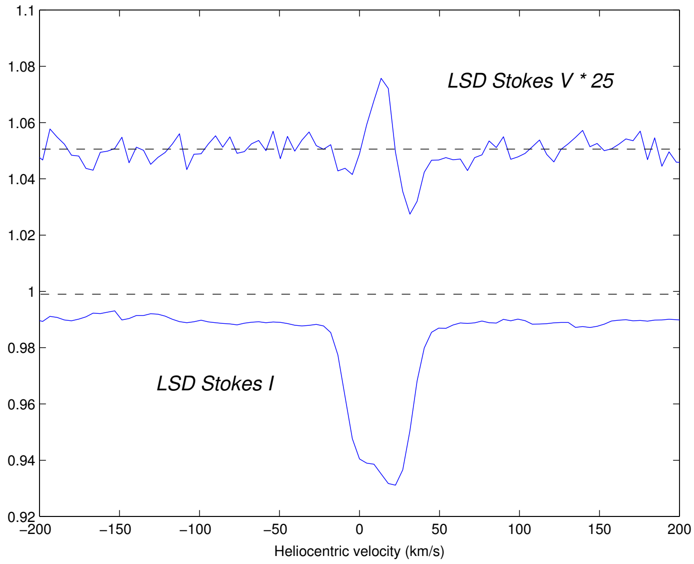

Figure 1: *Stokes I and Stokes V LSD Zeeman signatures for the weak-field magnetic Ap star 43 Cas (HD 10221). Notice the easily-detected Stokes V Zeeman signature, though at a phase when the longitudinal magnetic field is only* 93 ± 32 *G.*

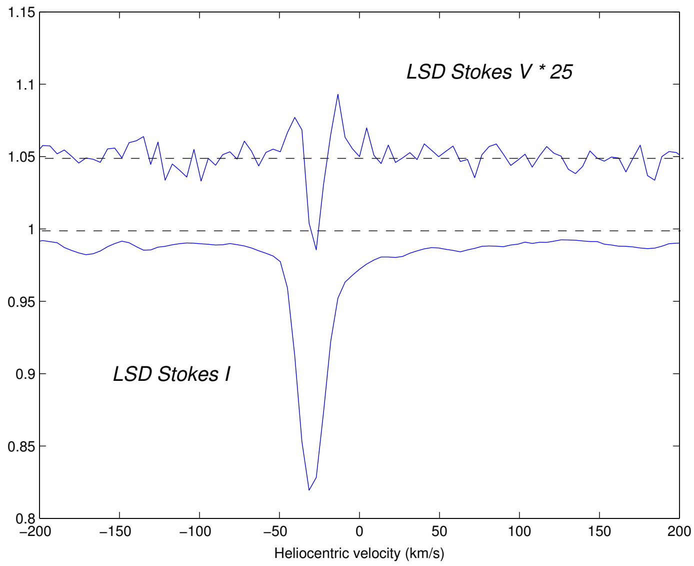

Figure 2: *Stokes I and Stokes V LSD Zeeman signatures for the weak-field magnetic Ap star 65 UMa, at a phase when the longitudinal magnetic field is only* -43 ± 26 *G.*

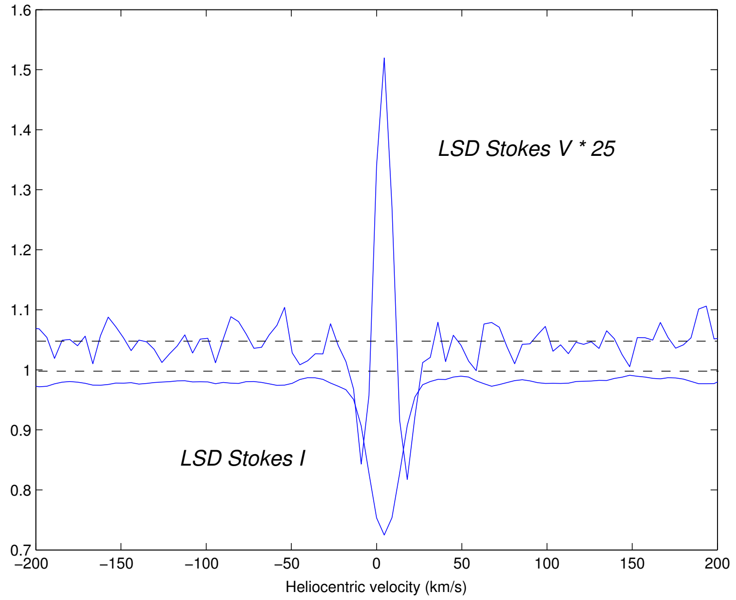

Figure 3: *Stokes I and Stokes V LSD Zeeman signatures for the magnetic Ap star HD 43819. Notice the very strong Zeeman signature, though at a phase when the longitudinal magnetic field is only* -72 ± 39 *G.*

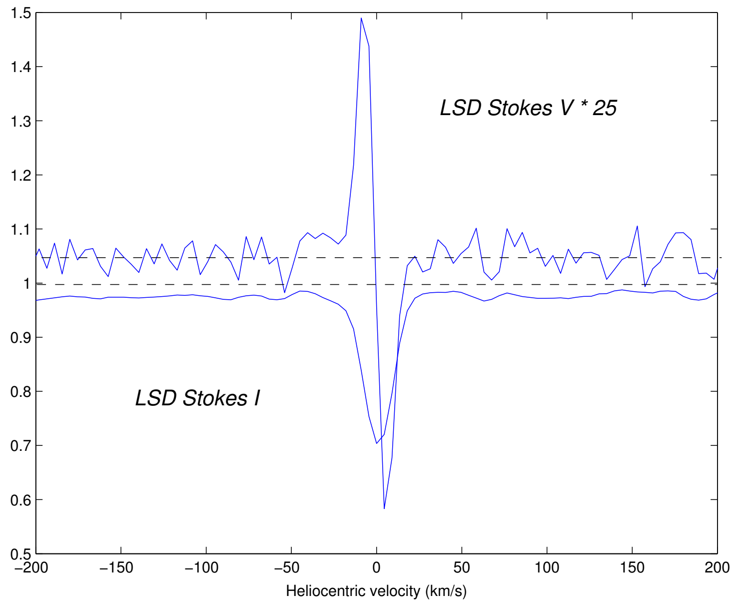

Figure 4: *Stokes I and Stokes V LSD Zeeman signatures for the magnetic Ap star HD 43819, at a phase when the longitudinal magnetic field is* $+609 \pm 43$ *G.*

3.2 Modeling with Oblique Rotator Model

For 3 of our stars with a sufficiently large number of measurements and suitable phase sampling, and having well-determined periods (3 Hya, 21 Com, 45 Leo), dipolar oblique rotator models have been determined. First the inclination i was derived from the period and a radius estimate. Then, longitudinal magnetic field values were measured, and the magnetic obliquity β and the polar strength of the dipolar field derived (e.g. Preston 1974). 3 Hya and 45 Leo are found to exhibit a single sign of the longitudinal magnetic field. 3 Hya has a rather large inclination and small β. On the contrary, 45 Leo is almost observed pole on and has a large β value. In both cases we find that the dipolar field is rather large (about 2.0 and 6.0 kG, respectively) and it is because of geometry alone that longitudinal magnetic fields are relatively small. 21 Com has an inclination similar to that of 3 Hya, but a larger β, so that its longitudinal field changes sign. Its dipolar field is about 1.0 kG.

Thus, though work is still in progress, and the analysis is rather crude (we will fit the complete Stokes I and V profiles as performed by Donati et al. 2001 and Wade et al. 2004) we find that geometry can explain the apparent faintness of the measured fields at least in some cases. Actually, the simple Oblique Rotator Model (Preston 1974) tells us that the polar field strength of a dipolar field is 3 times greater than the largest unsigned longitudinal field. Thus the dipole strength for our small sample is at least several hundreds of Gauss and we find no evidence for dipolar fields weaker than a few hundred Gauss in any Ap star. As suggested by Glagolevskij & Chountonov (2002), this result may indicate that there is a minimum field strength for which Ap-type characteristics are produced. This minimum strength is of order the photospheric equipartition field (around 230 Gauss for a main sequence A0 star), and one has also to remark that the interpretation of chemical peculiarities in Ap stars with diffusion theory has been done involving magnetic fields of more than several hundred gauss (Michaud et al. 1981, Alecian and Vauclair 1981).

4 Conclusion

The remarkable detection rate obtained in our survey strongly suggests that all Ap stars having “magnetic” behaviour (Preston 1974; i.e. essentially all stars classified spectroscopically as Ap/Bp) actually harbour magnetic fields of at least a few hundreds of Gauss. In other words, all Ap stars are magnetic stars and there is a threshold for obtaining this behaviour. Furthermore, no A star with a magnetic field smaller than 100 gauss has been detected up to now, though the LSD detection threshold is significantly smaller than this value in many cases (Shorlin et al. 2002).

If the results of this study are confirmed, one could say that A stars could be divided in two categories: A stars with surface magnetic field greater than some hundreds of gauss which are Ap, and those with fields smaller than some tens of gauss (not yet detected) which are normal, Am or HgMn. This behaviour may be related to that proposed by Abt (2000) and Abt and Morel (1995) concerning a critical equatorial rotational velocity of about 120 km/s: A stars having faster rotation are normal and those with slower rotation are chemical peculiar. In this scheme, equatorial rotation velocity and surface magnetic field would be together sufficient parameters to decide if an A star is one of the 3 categories: normal, Ap or Am/HgMn.

Acknowledgements. This research has made use of databases operated by CDS, Strasbourg, France.

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