Contrib. Astron. Obs. Skalnaté Pleso **38**, 211 – 216, (2008)

Weak magnetic fields in CP stars

M. Aurière[1], G.A. Wade[2], F. Lignières[1], J.D. Landstreet[3], J.-F. Donati[1], A. Hui Bon Hoa[1], I. Iliev[4], P. Petit[1], T. Roudier[1], J. Silvester[2] and S. Theado[1]

[1] *Laboratoire d'Astrophysique de Toulouse Tarbes, Université Paul Sabatier, CNRS, Observatoire Midi-Pyrénées, 57 Avenue d'Azereix, 65008 Tarbes, France*

[2] *Department of Physics, Royal Military College of Canada, PO Box 17000, Station 'Forces', Kingston, Ontario, Canada K7K 4B4*

[3] *Department of Physics & Astronomy, The University of Western Ontario, London, Ontario, Canada, N6A 3K7*

[4] *Institute of Astronomy, Bulgarian Academy of Sciences, 72 Tsarigradsko shose, 1784 Sofia, Bulgaria*

Received: December 3, 2007; Accepted: December 13, 2007

Abstract. We present the first results of a magnetic survey of main sequence A and late B stars with NARVAL, the new generation spectropolarimeter available at Telescope Bernard Lyot at Pic du Midi Observatory. We observed 3 HgMn stars, 12 Am stars and the only Ap star for which no Zeeman detection was obtained with MuSiCoS.

If we combine our results with those of our previous survey of weak magnetic fields in spectroscopically selected Ap/Bp stars we get the following situation:

- Ap/Bp stars: all these stars appear to host a detectable magnetic field. A threshold dipolar magnetic field of 300 G appears to exist, below which fields are very rare and perhaps altogether absent.

- Am and HgMn stars: no magnetic field is detected up to now for the 15 observed stars. An accuracy down to 0.3 G (respectively 1 G) is reached on longitudinal magnetic field measurements for Am (respectively HgMn) stars.

We propose a possible interpretation of the observed threshold field which naturally explains the magnetic dichotomy: there exists a critical field strength above which stable magnetic configurations exist and below which any large scale field configuration is destroyed by some instability.

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

1. Introduction

Whereas some intermediate-mass main sequence (MS) stars are known to host relatively strong, ordered magnetic fields (the Ap/Bp stars, corresponding to about 5% of MS A and B stars), the remaining 95% of MS stars at these spectral types appear to have no magnetic field whatsoever. This is the so called magnetic dichotomy. In order to confirm (or not) this dichotomy and to refine our understanding of its nature, we undertook a very sensitive magnetic study of a sample of apparently non-magnetic A and B stars. For our first run in march 2007, we choose to observed bright and slow rotators among HgMn and Am stars, mainly already observed by Shorlin *et al.* (2002). We also observed HD 32650, the only Ap star which could not be magnetically detected with MuSiCoS (Aurière *et al.*, 2007). In the next sections we will describe our observations, our results, and discuss a possible interpretation for the magnetic dichotomy.

2. Observations

The observations took place in march 2007, at the 2-m Telescope Bernard Lyot (TBL) of Pic du Midi Observatory with NARVAL (Aurière, 2003). In operation since december 2006, NARVAL is a copy of ESPaDOnS installed at CFHT at the end of 2004 (Donati *et al.*, 2007). NARVAL is a fiber–fed echelle spectrometer allowing the whole spectrum from 370 nm to 1000 nm to be recorded in each exposure, the resulting 40 orders are aligned on the CCD frame thanks to 2 cross-disperser prisms. NARVAL was used in polarimetric mode with a spectral resolution of about 65 000. Stokes I (unpolarised) and Stokes V (circular polarisation) parameters were obtained by means of 4 sub-exposures between which the retarders, Fresnel rhombs, were rotated in order to exchange the beams in the whole instrument and to reduce spurious polarization signatures. We aimed to get long exposures, up to 6400 s, on our bright targets in order to be able to detect ultra-weak or complex magnetic fields. In order to avoid saturation of the CCD we made short sub exposures (8 s in the case of Sirius!). During the technical tests and science demonstration time, magnetic and non magnetic stars were observed which showed that NARVAL worked properly and was 30 times more efficient than the previous instrument MuSiCoS (Baudrand, Boehm 1992; Donati *et al.*, 1999). The extraction of the spectra was done using Libre-ESpRIT (Donati *et al.*, 1997, 2007), a fully automatic reduction package installed at TBL. In order to make the Zeeman analysis, least-square deconvolution analysis (LSD, Donati *et al.*, 1997) was applied to all observations. We used masks with solar abundances, and temperatures and logg compatible with values given by Shorlin *et al.* (2002). For our sample this method enabled to average about 1000 lines and to get Stokes I and Stokes V profiles with greatly improved S/N. LSD provides a single quantitative criterion for the detection of Stokes V Zeeman signatures: 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 into detection probabilities, which are assessed to determine if we have a definite detection (DD, false alarm probability smaller than 10^{-5}), a marginal detection (MD, false alarm probability greater than 10^{-5} and smaller than 10^{-3}), or no detection at all (nd). We then computed the longitudinal magnetic field B_l in

Table 1. Summary of observations

Name	HD	V (mag)	Spec.	Date	Exposure (s)	Detection level
HgMn						
κ Cnc	78316	5.2	B8	13 Mar 07	3200	nd
ι CrB	143807	4.9	A0	11 Mar 07	6400	nd
ϕ Her	145389	4.2	B9	12 Mar 07	4800	nd
Am						nd
Sirius	48915	-1.47	A1m	12 Mar 07	1024	nd
α Gem B	60178	2.9	A2m	13 Mar 07	2800	nd
15 Uma	78209	4.5	F3m	14 Mar 07	3200	nd
τ Uma	78362	4.6	F3m	11 Mar 07	3200	nd
λ Uma	89021	3.4	A2m	11 Mar 07	3600	nd
β Uma	95418	2.3	A1V	14 Mar 07	2880	nd
θ Leo	97633	3.3	A2V	12 Mar 07	3600	nd
32 Vir	110951	5.2	F0IVm	12 Mar 07	3600	MD
				13 Mar 07	3600	MD
λ Vir	125337	4.5	A2m	13 Mar 07	3200	nd
22 Boo	126661	5.4	F0m	13 Mar 07	3200	nd
	141675	5.8	A3m	14 Mar 07	3600	nd
ϵ Ser	141795	3.7	A2m	12 Mar 07	3200	nd
Ap						
	32650	5.4	B9sp	12 Mar 07	3200	DD

gauss, using the first-order moment method (Donati *et al.*, 1997; Rees, Semel 1979). Table 1 gives the summary of our observations.

3. Results

3.1. Results of the present survey

Our first result was to detect and measure the magnetic field in HD 32650. Fig. 1 (left) shows the LSD profiles on 12 march 2007 for which we obtain $B_\mathrm{l} = 91 \pm 18$ G.

The second result was to obtain extremely small noise on the Stokes V profiles for the HgMn and Am stars. Fig. 2 shows the composite LSD profiles of Sirius, an Am star besides being the brightest star in the sky after the sun. The left part shows the rather sharp Stokes I profile. On the right side the huge enlargement in Stokes V shows that the noise is currently smaller than 10^{-5} the intensity on this 1024 s total exposure LSD spectrum, which is near the expected sensitivity of NARVAL. No magnetic field is detected and the corresponding B_l

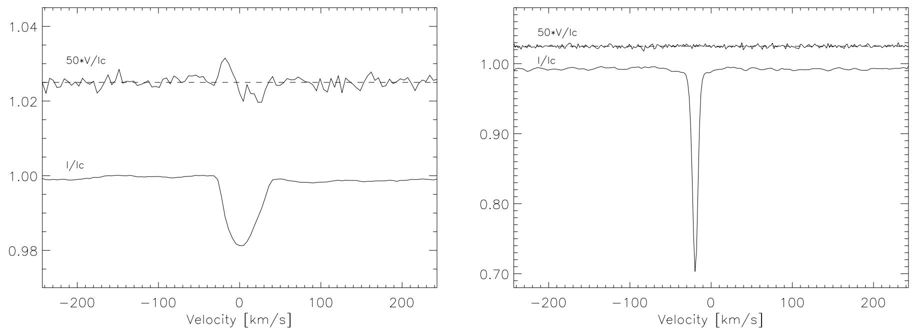

Figure 1. LSD profiles of the magnetic Ap star HD 32650 on 12 Mar 07 (**left**) and of the HgMn star ι CrB on 11 Mar 07 (**right**) as observed with NARVAL From bottom to top, Stokes I and Stokes V are presented. For display purposes, the profiles are shifted vertically, and Stokes V profiles are expanded by a factor of 50. The dashed line illustrates the zero level for the Stokes V profiles. Definite Zeeman detection for HD 32650, no Zeeman detection for ι CrB.

value is 0.1 ± 0.3 G (1σ). The best precision obtained for HgMn stars of our sample corresponds to 1G (for ι CrB). Fig.1 (right) shows the LSD profiles for ι CrB.

No definitive detection was obtained for any of the stars of our sample. Only two marginal detections have been observed for 32 Vir (the corresponding measured longitudinal magnetic field is in the range 1-2 G with errors of 1.6 G). Even if we got only one observation for the majority of the stars of our sample, this result is of significance since the amplitude of the variations of Stokes V with phase is much smaller than the variations of $B_{\rm l}$. The overall conclusion of our work up to now is that we have not detected a longitudinal magnetic field in any of the HgMn and Am stars of our sample at the 0.3 - 3 G sensitivity.

3.2. Conclusions of Ap/Bp and present surveys

At the present state of our work the magnetic dichotomy in the A-type range is confirmed and can be refined:

- From the survey of 28 Ap/Bp stars with weak, poorly-determined or previously undetected magnetic fields (Aurière *et al.*, 2007): all Ap/Bp stars appear to host a large scale magnetic field, with a threshold value of about 300 G.

- From our NARVAL's survey, which confirms Shorlin *et al.* (2002) results but with an order of magnitude of improvement on the accuracy: no magnetic fields are detected (at the DD level, up to now) within the historical class of "non magnetic" CP stars. The corresponding $B_{\rm l}$ is of a very few G which correspond to a few tens of G for the dipole intensity of possible large scale fields.

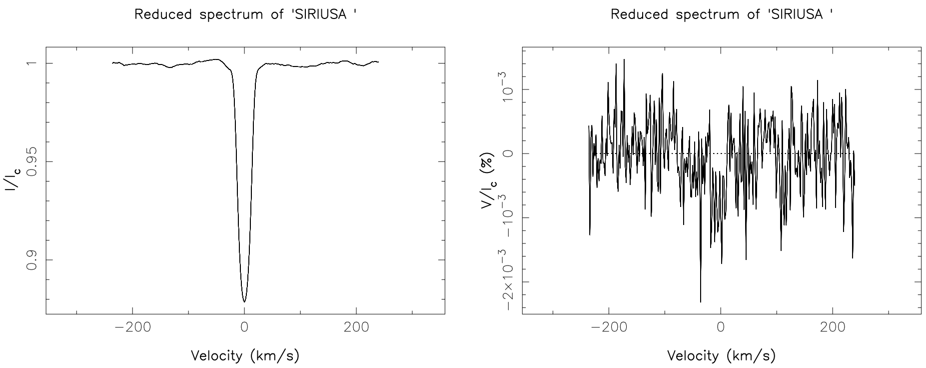

Figure 2. LSD profiles of the Am star Sirius. On the left is the Stokes I profile. The Stokes V profile on the right is greatly expanded to show the noise near the limit of sensitivity of NARVAL. No Zeeman detection.

4. Discussion

From the existence of a magnetic threshold of about 300 G for Ap/Bp magnetic field intensity, Aurière *et al.* (2007) gave a scenario to explain the magnetic dichotomy. The present results support this scenario since they suggest that the Ap/Bp stars are the only CP stars to host a large scale (fossil) magnetic field. We thus propose as a possible interpretation of this result that there exists a critical field strength above which stable magnetic configurations exist and below which any large scale field configuration is destroyed by some instability. The instability is expected to result in the presence of opposite polarities at small length scales, thus strongly reducing the magnitude of the integrated longitudinal field through cancellation effects.

The existence of stable large scale magnetic fields in stars is primarily supported by the observations of the magnetic fields of Ap stars and white dwarfs. Theoretically, although no stable field configuration is known in an analytical form, it has been proposed that the combination of azimuthal and poloidal field might be stable as a recent numerical simulation tends to confirm (Braithwaite, Spruit 2004). However, when the magnetic field is sufficiently weak to be wound up by differential rotation, the resulting field, predominantly azimuthal with respect to the rotation axis, can be subject to various instabilities. As reviewed by Spruit (1999; 2004), the most vigorous of these instabilities is a pinch-type instability first considered in a stellar context,by Tayler (1973). Aurière *et al.* (2007) estimated the critical magnetic field $B_{\rm c}$ below which the winding-up process induces an instability and above which the action of magnetic torques on the differential rotation limits the winding-up before the instability sets in. Its value can be expressed in terms of the equipartition field $B_{\rm eq}$ of a typical Ap star as follows:

$$\frac{B_{\rm c}}{B_{\rm eq}} \simeq 2 \left(\frac{P_{\rm rot}}{5_{\rm day}}\right)^{-1} \left(\frac{r}{3R_{\odot}}\right) \left(\frac{T}{10^4{\rm K}}\right)^{-1/2}, \tag{1}$$

where $B_{\rm eq}^2 = 8\pi P$, P is the pressure, $P_{\rm rot}$ the rotational period, r the radius and T the effective temperature of the star.

As $B_{\rm eq} = 170$ G at the surface ($\tau_{5000} = 2/3$) of a typical Ap star ($\log g = 4, T_{\rm eff} = 10^4$ K) the derived critical field is close to the 300 G observational threshold.

This scenario can easily produce a population of stars in which a majority display no evidence of magnetic fields, and in which a minority display relatively strong, organised fields. Those stars in which magnetic fields are retained are the Ap/Bp stars.

Acknowledgements. This research made use of Simbad, maintained by CDS at Strasbourg Observatory, France.

References

Aurière, M., Wade, G.A, Silvester, J., Lignières, F., Bagnulo, S., et al.: 2007, *Astron. Astrophys.* **475**, 1053

Aurière, M.: 2003, in *Magnetism and activity of the Sun and stars*, eds.: J. Arnaud and N. Meunier, *EAS Publ. Series* 9, 105

Baudrand, J., Boehm, T.: 1992, *Astron. Astrophys.* **259**, 711

Braithwaite, J., Spruit, H.C.: 2004, *Nature* **431**, 14

Donati, J.-F., Semel, M., Carter, B.D., Rees, D.E., Collier Cameron, A.: 1997, *Mon. Not. R. Astron. Soc.* **291**, 658

Donati, J.-F., Catala, C., Wade, G.A., Gallou, E., Delaigue, G. Rabou, P.: 1999, *Astron. Astrophys., Suppl. Ser.* **134**, 149

Donati, J.-F. et al.: 2007, in preparation

Shorlin, S.L.S., Wade, G.A., Donati, J.-F., Landstreet, J.D., Petit, P., Sigut, T.A.A., Strasser, S.: 2002, *Astron. Astrophys.* **392**, 637

Spruit, H.C.: 1999, *Astron. Astrophys.* **349**, 189

Spruit, H.C.: 2004, in *IAU Symp.* 215, eds.: A. Maeder and P. Eenens, Astron. Soc. Pacific, San Francisco, 356

Tayler, R.J.: 1973, *Mon. Not. R. Astron. Soc.* **161**, 365