

# Search for magnetic fields in HgMn stars by using relative strengths of multiplet 74 Fe II lines. \*

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**Abstract.** The anomalous strength of the Fe II  $\lambda$  6147.7 line relative to Fe II  $\lambda$  6149.2 in the stars with magnetic fields is used for detecting magnetic fields in very slowly rotating HgMn stars. The diagnosis based on this pair of magnetically sensitive Fe lines is a simple and fast tool, but its application to more rapidly rotating HgMn stars is hampered by blending with Hg II  $\lambda$  6149.5. For spectra of sharp-lined HgMn stars (with  $v \sin i < 4 \text{ km s}^{-1}$ ) taken at high resolving power ( $R \geq 100\,000$ ) both lines, Fe II  $\lambda$  6149.25 and Hg II  $\lambda$  6149.48, become fully unblended. The observed relative differences between the equivalent widths of the two Fe II lines are compared with those derived from synthetic spectra computed by neglecting magnetic field effects. This comparison has shown that three HgMn stars, HD 175640, HD 178065 and HD 186122 are very likely to possess a magnetic field that could be larger than 2 kG.

**Key words:** stars: abundances - stars: atmospheres - stars: chemically peculiar - stars: magnetic fields

## 1. Introduction

The origin of the abundance anomalies observed in HgMn stars is still rather poorly understood. HgMn stars are chemically peculiar (CP) stars of late B spectral types. Their most distinctive characteristics at optical wavelengths are extreme atmospheric overabundances of Hg (up to 5.7 dex) and of Mn (up to 3 dex) compared with the solar system abundances.

Until recently, the issue of the presence of a magnetic field in HgMn stars remained open, and the rôle that magnetic fields possibly play in the development of anomalies in these stars had never been critically tested. This is a

fundamental question whose answer is essential for the understanding of the physical processes taking place in HgMn stars and, more generally, during the formation and evolution of B stars.

Previous searches for magnetic fields in HgMn stars had shown that these stars, unlike classical Ap stars, do not have large-scale organized fields detectable through spectropolarimetry (Landstreet 1992). Babcock's (1958) original measurements of weak longitudinal magnetic fields in some such stars could not be confirmed in later studies (Conti 1969, 1970a, 1970b).

It has never been ruled out, though, that they might have tangled magnetic fields of the order of a few thousand gauss with no net longitudinal component. Earlier results of magnetic field measurements in the two SB2 stars 74 Aqr (HD 216494) and  $\chi$  Lup (HD 141556) with the Zeeman analyzer of the CASPEC spectrograph attached to the ESO 3.6 m telescope applied the moment technique to look for possible differential broadening of spectral lines having different magnetic sensitivities (Mathys & Hubrig 1995). In this approach, the second order moments of the profiles of a sample of lines of a single ion (namely, Fe II) were measured and their dependence on the atomic parameters characterizing the magnetic line broadening was studied. That study revealed that the HgMn primary of the system 74 Aqr has a quadratic field of  $3.6 \pm 0.8 \text{ kG}$ . They were also able to detect a longitudinal field of a few hundred gauss in the secondary component of  $\chi$  Lup at the  $4.6 \sigma$  level. No quadratic field was detected for  $\chi$  Lup A. However, the standard error of the determination was rather large, 1.25 kG. The fact that only weak fields are observable in circular polarization while quadratic magnetic fields of kG order are probably present most likely means that the field has a fairly complex structure, such that in disk-averaged observations, the contribution of various regions of the stellar surface to the net polarimetric signal mostly cancels out. This does not necessarily imply a very discontinuous field structure like in the sun. Some types of large-scale organization, such as high-order mul-

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tipoles or toroidal fields (which appear as predominantly transversal), may lead to the observed cancellation.

An interesting and simple way of estimating the field strength in early type stars was indicated by Mathys (1990), who noticed that for stars not later than spectral type A6 the ratio,  $\Delta W/\overline{W}$ , of the difference in the equivalent widths between the two Fe II lines of mult. 74, Fe II  $\lambda$  6147.7 and Fe II  $\lambda$  6149.2 (in that order), to their mean value, is roughly correlated with the strength of the magnetic field. The two lines have approximately the same intensity and the observations show that in non-magnetic A stars they have the same equivalent width to within 2.5 % (Mathys & Lanz 1990). In stars with resolved magnetically split lines having a field modulus larger than 3 kG, the difference in equivalent widths is typically larger than 10 % (Mathys & Lanz 1992).  $\Delta W/\overline{W}$  does not exceed 0.10 for magnetic stars where resolved magnetically split lines are not observed.

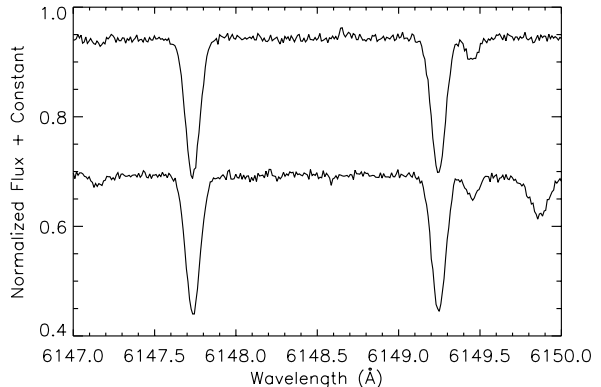
The discrepancy between the equivalent widths of Fe II  $\lambda$  6147.7 and Fe II  $\lambda$  6149.2, observed in magnetic Ap and Bp stars, is attributed to magnetic intensification due to different magnetic desaturation induced by different Zeeman-split components (Takeda 1991). This relative intensification is a credible, powerful tool for detecting magnetic fields which have a complex structure and cannot be detected by polarization measurements.

Mathys & Lanz (1990) and Lanz & Mathys (1993) applied this method to the hot metallic-line A stars and to four HgMn stars. Although Am stars have been assumed to be nonmagnetic stars, it was found that the hot Am star  $\sigma$  Peg (HD 214994) has a magnetic field of the order of 2 kG, with a complex structure. Two other hot Am stars are also likely to possess a magnetic field of about the same strength. However, the observations of the four HgMn stars did not give significant results because in all four HgMn stars the line Fe II  $\lambda$  6149.253 is severely disturbed by blending with a Hg II line at  $\lambda$  6149.5 and therefore this method could not provide a satisfactory diagnosis (see also Takada-Hidai & Jugaku 1992). However, when slowly rotating stars are observed at high resolutions these two lines become well separated and fully unblended, so that Mathys' spectroscopic method can be reasonably applied to detect magnetic fields.

In this paper, we report on a new search for magnetic fields in very slowly rotating HgMn stars based on the study of relative strength of magnetically sensitive Fe II lines. To this purpose we observed a sample of slowly rotating ( $v \sin i < 4$  km/s) HgMn stars at the European Southern Observatory, using the Coude Echelle Spectrograph (CES) and its Long and Very Long Cameras at a resolving power,  $R \geq 100\,000$ .

## 2. Observations

Our sample consists of nine slowly rotating HgMn stars and one normal late B star as a comparison star. The



**Fig. 1.** Spectra of the double-lined spectroscopic binary  $\chi$  Lup around the two Fe II lines of multiplet 74 observed on two consecutive nights. Both spectra have been wavelength shifted to place the primary star spectrum on the laboratory rest frame. The Fe II  $\lambda$  6147 feature in the secondary star is seen in the lower spectrum at the far right.

observations of eight HgMn stars have been performed at the European Southern Observatory with the 1.4 m CAT telescope and the CES Very Long Camera equipped with CCD Loral #38. The spectra were recorded during two consecutive nights in July 1998 at a resolving power of 135 000. One HgMn star, HD 71066, and normal late B star, HD 196426, were observed several years ago. At that time the CES Very Long Camera was not installed, so that the observations were performed with the 1.4 m CAT telescope and the CES Long Camera equipped with as detectors a Reticon and CCD Loral #34 at the resolving power of  $R = 100\,000$ .

The 10 selected stars are all sharp-lined stars with  $v \sin i$  below  $4.0 \text{ km s}^{-1}$ . Programme stars are listed in Table 1, where we give the HD number and another identifier in Cols. 1 and 2, the  $V$  magnitude and the spectral type (both from the catalog of Renson (1991)) in Cols. 3 and 4, and for each observation, the Heliocentric Julian Date of mid-exposure in Column. 5. Spectra were reduced using MIDAS procedures, in a standard manner. Wavelength calibrations were executed by utilizing the Th-Ar comparison spectra recorded immediately before and after recording the stellar spectrum. The rms errors of each calibration were negligible (typically  $8.5 \times 10^{-4} \text{ \AA}$ ). The achieved signal-to-noise ratios in the continuum are given in Col. 6 of Table 1. They were measured after reduction in portions of the spectrum apparently devoid of lines: accordingly, the measurements provide upper limits to the noise level and lower limits to the S/N ratio in the continuum.

**Table 1.** Journal of observations and the measured equivalent widths

HD	Other id.	$V$	Sp. type	HJD	S/N	$W_g$	$W_g$	$(\Delta W/\overline{W})_g$	$W_i$	$W_i$	$(\Delta W/\overline{W})_i$
						6147	6149		6147	6149	
35548	HR 1800	6.9	B9 HgMn	2451025.929	145	20.1	18.6	0.078	19.5	18.6	0.047
71066	HR 3302	5.7	A0 SiMn	2447286.513	220	42.2	40.8	0.034	41.8	38.7	0.077
141556	$\chi$ Lup	4.0	B9 YHg	2451024.484	230	29.1	28.0	0.039	29.2	27.8	0.049
				2451025.480	280	28.9	27.8	0.039	28.7	27.4	0.046
158704	HR 6520	6.0	B9 MnHg	2451024.504	190	20.5	20.1	0.020	19.3	18.6	0.037
165493	HR 6759	6.2	B8 HgMn	2451025.616	260	20.9	20.2	0.034	21.0	19.5	0.074
175640	HR 7143	6.2	A0 HgMnY	2451025.512	220	11.8	10.7	0.098	11.9	10.0	0.082
178065	HR 7245	6.6	B9 HgMn	2451024.674	185	21.8	20.4	0.067	21.6	20.2	0.067
186122	HR 7493	6.3	B9 MnHg	2451024.602	280	38.5	35.2	0.090	38.1	35.1	0.082
193452	HR 7775	6.1	B9 HgPtSr	2451025.662	200	35.0	33.6	0.082	33.0	33.0	0.000
196426	HR 7878	6.2	B8	2449534.796	180	16.2	16.2	0.000	15.7	16.0	-0.019

### 3. The Analysis

We searched for a possible intensification of the line Fe II 6147.7 Å relative to the line Fe II 6149.2 Å by measuring the equivalent widths of the two absorption profiles. Because, at our resolution, Fe II 6149.2 Å is almost unblended, we derived the iron abundance from its measured equivalent width and computed synthetic profiles, in the absence of magnetic fields, for the two Fe II transitions. The difference between the observed and computed  $\Delta W/\overline{W}$  ratios yields the amount of the intensification of Fe II 6147.7 Å related with the magnetic field.

#### 3.1. The measured equivalent widths and the measured $\Delta W/\overline{W}$ ratio

The equivalent widths were measured by Gaussian fitting and by direct integration of the line profiles. The equivalent widths from the fit to Gaussians are given in Cols. 7 and 8 of Table 1. Column 9 contains the ratio  $\Delta W/\overline{W}$  of the difference between the equivalent widths of the two lines to their mean for Gaussian fitting. The values measured by direct integration are given in Cols. 10 and 11. Column 12 shows the corresponding relative intensification for integration. All values for equivalent widths in Table 1 are given in mÅ.

We repeated our equivalent width measurements for the  $\lambda$  6147.7 and  $\lambda$  6149.2 features for all 10 stars and estimated the uncertainty to be about 0.2 mÅ in the worst case. Thus, the uncertainty on  $\Delta W/\overline{W}$  is of the order of  $\pm 0.02$ .

The difference between equivalent widths measured by Gaussian fitting and by integration is very small, which indicates that the Fe II  $\lambda$  6147.7 and  $\lambda$  6149.2 line wings are not significantly affected by blends with weaker lines, in particular Hg II  $\lambda$  6149.5. The accuracy of the resulting spectra may also be judged from repeated observations for the double-lined spectroscopic binary  $\chi$  Lup. The spectra

of this star were recorded on two consecutive nights (Fig 1). The ratio  $\Delta W/\overline{W}$  is the same for both nights for Gaussian fitting method and differs by only 0.003 for the direct integration method. It can also be noted that since the two lines lie in close proximity to each other, the relative uncertainties due to continuum placement are very small. Any systematic error in placement of the continuum level leads to insignificant differences when deriving the relative intensification, even for systematic errors in equivalent width as large as 1 mÅ.

For the HgMn stars of our sample the equivalent width of Fe II  $\lambda$  6147.7 is always larger than that of Fe II  $\lambda$  6149.2. This behaviour is similar, even if less conspicuous, to that observed by Mathys & Lanz (1992) for the magnetic Ap stars. The measurements by Gaussian fitting and by direct integration are consistent for eight out the nine HgMn stars of our sample. Only for one HgMn star, HD 193452, the measurements by direct integration give the same equivalent width for both Fe II lines.

For the normal B-type star HD 196426 the equivalent widths of the two Fe II lines are equal when measured by the Gaussian fit method, while  $W$  from Fe II 6147.7 Å is lower than  $W$  from Fe II 6149.2 Å when the integration is used.

#### 3.2. Atomic line data

To test that the larger measured equivalent widths of the feature at  $\lambda$  6147.7 are the effect of a magnetic field rather than of blending with known lines, we computed synthetic spectra for all 10 stars in the 6145–6151 Å region. For the atomic-line data we used the Kurucz (1995) line list as the starting point. For Fe II the wavelength  $\lambda$  6149.258 Å, as given in the listing of Kurucz, was replaced by  $\lambda$  6149.253, on the basis of our comparisons of the high-resolution observed spectra with the computed spectra.

The oscillator strength data was tested by comparison with spectra for Procyon and the chemically normal late B

star HD 196426. The comparison of the 6100–6200 Å region of the Procyon Atlas (Griffin & Griffin 1979) with synthetic spectra computed from models with parameters  $T_{\text{eff}}=6550$  K,  $\log g=4.06$  and  $T_{\text{eff}}=6650$  K,  $\log g=4.06$ , led us to prefer for Fe II 6147.741 and Fe II 6149.253,  $\log gf=-2.721$  and  $-2.724$ , respectively, from the Kurucz listing rather than  $\log gf=-2.924$  taken from the Fuhr et al. (1988) critical compilation for the latter line. The listing by Fuhr et al. is an astrophysical  $gf$  value derived from the solar spectrum by Blackwell et al. (1980) with an estimated uncertainty of 50%. The Kurucz and Blackwell et al.  $gf$  values lie within the quoted uncertainty but the former provides much better fit to our observed spectra. For the radiative, Stark, and Van der Waals damping constants we assumed the values listed by Kurucz, which, for both Fe II lines are:  $\log\gamma_{\text{rad}}=8.53$ ,  $\log\gamma_{\text{Stark}}=-6.63$ ,  $\log\gamma_{\text{VDW}}=-7.88$ .

The comparison of the computed and observed equivalent widths of the normal B-type star HD 196426 led us to lower the  $\log gf$  value of Fe II 6147.775 Å from  $-0.819$ , as given by Kurucz, to  $-2.519$ . This latter value was fixed by imposing that the computed equivalent widths of Fe II 6147.741 Å and Fe II 6149.253 Å have to be equal within 0.1 mÅ, in agreement with the measured equivalent widths. Therefore, the adopted  $\log gf=-2.519$  is an upper limit, needed to suppress the computed, but not observed, contribution of Fe II 6147.775 Å to Fe II 6147.741 Å. Table 2 lists the line data employed in this analysis for the synthetic spectrum calculations. Its Columns present the ion designation, air wavelength, transition label, excitation energy of the lower and upper levels, logarithm of the  $gf$  value, isotope designation for lines of the Hg II feature, and the literature source of the  $gf$  value.

For sake of completeness, we also analysed the observed spectra for any possible influence by Hg II 6149.5 Å, which, at our resolution, only weakly affects the extreme red wing of the Fe II 6149.2 Å profile in stars with high Hg abundance, but which at lower resolutions constitutes a severe blend (Takada-Hidai & Jugaku 1992). For this Hg II line the wavelength  $\lambda$  6149.873 Å, as listed by Kurucz, was replaced in our line list by the wavelengths of the nine isotopic and hyperfine components (hfs) given in Table 2. The absolute wavelength of this feature is set by the measurement of  $^{198}\text{Hg}$  (Reader & Sansonetti 1986). Wavelengths for the even isotope components  $^{200,202,204}\text{Hg}$  were determined from the relative measurements of Murakawa (1932). The hfs structure components for the odd isotopes are based upon center of gravity estimates from Reader & Sansonetti (private communication) and the theoretically determined hyperfine A constant of Brage, Proffitt, & Leckrone (1999). There are no estimates for the A and B hfs constants for the upper level, and therefore these were taken to both be zero. Changing the value of A for the upper level by  $\pm 100$  to 200 mK has the effect of changing the wavelengths of the hfs components by up to 0.1 Å. The  $gf$ -values for the nine components result from assuming a

terrestrial Hg isotopic composition, including the isotope  $^{196}\text{Hg}$ , and the total  $gf$  value ( $= 2.126$ ) from the relativistic calculation of Migdalek (1976). There is no estimate for the wavelength of the  $^{196}\text{Hg}$  component for this line, which is weaker by two orders of magnitude than other components. The energy level values for the Hg II line in Table 2 correspond to the natural isotopic composition case presented by Reader & Sansonetti.

In conclusion, the analysis of the line list data has shown that, at our resolution, Fe II 6147.741 Å may be contaminated by Fe II 6147.775 Å and Fe I 6147.829 Å, while Fe II 6149.253 Å is either unblended or only weakly affected on the extreme red wing by Hg II 6149.5 Å in stars with large Hg overabundance.

### 3.3. The parameters of the atmospheric models

To calculate the synthetic spectra we determined the model parameters  $T_{\text{eff}}$  and  $\log g$  by interpolating in the uvby $\beta$  grid of Strömgren indices computed for  $[\text{M}/\text{H}]=0.0$  from ATLAS9 models and fluxes (Castelli 1998). Observed indices were taken from the catalogue of Mermilliod et al. (1997) and were dereddened using the UVBYLIST code of Moon (1985). Table 3 lists the observed and dereddened Strömgren indices together with the derived stellar parameters. Column 12 specifies which indices were used to obtain  $T_{\text{eff}}$  and  $\log g$ . The definition of the indices  $a$  and  $r^*$  adopted for stars with parameters  $8500 \leq T_{\text{eff}} \leq 11000$  K and  $3.5 \leq \log g \leq 4.5$  can be found in the papers of Strömgren (1966) and Moon & Dworetzky (1985). The errors associated with the parameters were derived by assuming an uncertainty of  $\pm 0.015$  mag for all the observed indices, except  $\beta$ , for which a probable error of  $\pm 0.005$  mag was adopted. Adelman (1994) showed that most HgMn stars have little or no microturbulence. Therefore, for all the stars we assumed zero microturbulent velocity, while the rotational velocity was derived from the comparison of the observed and computed spectra, after having degraded the computed spectra for instrumental broadening. The last column of Table 3 lists the rotational velocities which were used for computing the synthetic spectra.

### 3.4. The computed equivalent widths and the computed $\Delta W/\overline{W}$ ratio

For each star, the iron abundance was derived from the equivalent width of Fe II  $\lambda$  6149.2, which is essentially unblended for our sample of stars observed at resolving powers  $\geq 100000$ . In all stars the lines Fe II  $\lambda$  6147.7 and Fe II  $\lambda$  6149.2 have very symmetrical profiles, not different from Gaussian, therefore only the equivalent width measured by Gaussian fitting was used for the analysis. The fact that both of these lines originate from within the same multiplet, both lines have the same upper energy level

**Table 2.** Lines in the 6147-6150 Å region

Ion	$\lambda(\text{Å})$	Transition	$E_{\text{low}} (\text{cm}^{-1})$	$E_{\text{up}} (\text{cm}^{-1})$	$\log gf$	isotope	$gf$ Source
Fe II	6147.741	$b^4D_{3/2-z}^o - 4P_{1/2}^o$	31364.440	47626.076	-2.721		Kurucz 1988
Fe II	6147.775	$5p^4D_{5/2}^o - 4d^2G_{7/2}$	90638.822	106900.379	-2.519		This paper
Fe I	6147.829	$c^3F_{4-v} - 3D_3^o$	32873.619	49135.022	-1.700		Fuhr et al. 1988
Fe II	6149.253	$b^4D_{1/2-z}^o - 4P_{1/2}^o$	31368.450	47626.076	-2.724		Kurucz 1988
Hg II	6149.419	$7s^2S_{1/2} - 7p^2P_{3/2}^o$	95714.408	111971.460	-1.047	199	Migdalek 1976
Hg II	6149.451				-0.757	201	
Hg II	6149.461				-0.680	204	
Hg II	6149.469				-0.042	202	
Hg II	6149.477				-0.153	200	
Hg II	6149.483				-0.518	198	
Hg II	6149.504				-0.570	199	
Hg II	6149.513				-0.978	201	

**Table 3.** Strömgren indices and stellar parameters

HD	$(b-y)$	$(b-y)_0$	$m_1$	$m_0$	$c_1$	$c_0$	$\beta$	$E(b-y)$	$T_{\text{eff}}$ (K)	$\log g$	C.I.	$v \sin i$ ( $\text{km s}^{-1}$ )
35548	-0.009	-0.028	0.119	0.125	0.894	0.890	2.792	0.019	$11088 \pm 86$	$3.79 \pm 0.05$	$c_1-\beta$	1.75
71066	-0.053	-0.053	0.122	0.122	0.731	0.731	2.769	0.000	$12010 \pm 100$	$3.95 \pm 0.04$	$c_1-\beta$	2.00
141556	-0.020	-0.022	0.129	0.130	0.948	0.948	2.841	0.002	$10664 \pm 400$	$3.98 \pm 0.04$	$a-r^*$	2.50
158704	-0.020	-0.055	0.117	0.129	0.577	0.570	2.757	0.035	$13163 \pm 124$	$4.22 \pm 0.05$	$c_1-\beta$	3.75
165493	-0.014	-0.066	0.092	0.109	0.498	0.488	2.703	0.052	$13890 \pm 125$	$3.90 \pm 0.04$	$c_1-\beta$	2.75
175640	+0.001	-0.043	0.103	0.117	0.747	0.739	2.771	0.044	$11958 \pm 100$	$3.95 \pm 0.04$	$c_1-\beta$	2.50
178065	+0.073	-0.046	0.077	0.116	0.729	0.706	2.718	0.119	$12193 \pm 100$	$3.54 \pm 0.05$	$c_1-\beta$	1.50
186122	-0.019	-0.054	0.094	0.105	0.641	0.634	2.729	0.035	$12717 \pm 120$	$3.80 \pm 0.05$	$c_1-\beta$	0.00
193452	-0.007	-0.024	0.138	0.143	0.909	0.906	2.845	0.017	$10776 \pm 400$	$4.10 \pm 0.04$	$a-r^*$	0.75
196426	-0.029	-0.054	0.099	0.107	0.626	0.621	2.735	0.025	$12815 \pm 124$	$3.89 \pm 0.05$	$c_1-\beta$	3.00

while the lower levels have only slightly different energies, ensures that the synthetic spectrum calculations are insensitive to uncertainties in the atmospheric parameters and assumptions of the synthetic spectrum program. The WIDTH code was used to fix the iron abundance. The SYNTH code and the iron abundance from WIDTH were used to compute a synthetic spectrum at 1200 000 resolution. Equivalent widths of the computed profiles were then determined by direct integration of the synthetic spectrum. The results of this procedure are listed in Table 4.

For each star, Cols. 2 and 3 list the equivalent width measured by Gaussian fitting of the observed  $\lambda$  6149.2 line and the corresponding iron abundance. Abundances are presented on a scale where  $\log \epsilon(\text{H}) = 12.00$ . The next two columns present the equivalent widths of the two Fe II lines at 6147.7 Å and 6149.2 Å derived from synthetic spectra computed with the iron abundance given in Column 3 and the atomic data listed in Table 2. Cols. 6 and 7 present the equivalent widths of the two Fe II lines derived from synthetic spectra computed with iron abundance listed in Column 3, but with the original Kurucz line list, having  $\log gf = -0.819$  for Fe II 6147.775 Å and Hg II at

$\lambda$  6149.5 Å, so that Hg II does not affect at all Fe II 6149 Å. Column 8 lists the Hg abundances used in the calculations of synthetic spectra. For the stars HD 35548, HD 158704 and HD 193452 isotopic composition and Hg abundance were found from the Hg II line at  $\lambda$  3984 (Hubrig et al. 1999). For the other stars in the sample we assumed terrestrial isotopic mixture. In Columns 9 and 10 of Table 4 we present the values  $\Delta W/\overline{W}$  corresponding to the computed equivalent widths  $W_c$  and  $W_c(\text{K})$ , respectively. These ratios, in effect, correspond to those in non-magnetic stars with similar stellar parameters since our synthetic spectrum modelling ignored any presence of a magnetic field. Finally, the last two columns of Table 4 present the ratio  $\Delta W/\overline{W}$  for the Gaussian and integration measurements, respectively, from Table 1, which facilitate the comparison between the observed and computed quantities.

We did not include results for SB2 star  $\chi$  Lup in Table 4 owing to the contamination of the Fe II 6147.741 Å of the primary by absorption lines from the secondary star. An updated version of the BINARY code of Kurucz (1995) was used to construct the computed spectrum in the region around 6150 Å resulting from the contribution of

**Table 4.** Results of spectral analysis

HD	$W_g$	$\log\epsilon(\text{Fe})$	$W_c$		$W_c(\text{K})$		$\log\epsilon(\text{Hg})$	$(\Delta W/\overline{W})_c$	$(\Delta W/\overline{W})_K$	$(\Delta W/\overline{W})_g$	$(\Delta W/\overline{W})_i$
	6149	6149	6147	6149	6147	6149					
35548	18.6	7.44	18.72	18.60	18.97	18.58	6.36	0.006	0.021	0.078	0.047
71066	40.8	8.24	41.23	40.91	41.99	40.99	5.84	0.008	0.024	0.034	0.077
158704	20.1	7.79	20.12	20.00	20.74	20.10	6.23	0.006	0.031	0.020	0.037
165493	20.2	7.85	24.24	20.11	21.05	20.12	5.84	0.006	0.045	0.034	0.074
175640	10.7	7.21	10.83	10.76	11.06	10.76	5.54	0.006	0.027	0.098	0.082
178065	20.4	7.51	20.46	20.35	20.89	20.35	5.19	0.005	0.026	0.067	0.067
186122	35.2	8.11	35.33	35.17	36.17	35.17	1.09	0.005	0.028	0.090	0.082
193452	33.6	7.97	33.95	33.69	34.30	33.64	6.73	0.008	0.019	0.082	0.000
196426	16.2	7.53	16.26	16.17	16.72	16.17	1.09	0.006	0.033	0.000	-0.019

both components. Following Wahlgren et al. (1994), we adopted  $R_A/R_B = 1.67$  for the ratio of the radii of the primary to the secondary stars, and  $T_{\text{eff}} = 9200$  K,  $\log g = 4.2$ , a microturbulent velocity  $\xi = 2.0$  km s<sup>-1</sup>, and  $v \sin i = 2$  km s<sup>-1</sup> for the secondary. The constructed synthetic spectrum shows that the Fe II line at  $\lambda 6147.7$  in the primary is very likely blended with secondary star lines of the chemical elements Si I and Ca II. The secondary star spectrum is known to show Am star characteristics and as the determination of its elemental abundances is very uncertain (Wahlgren et al. 1994) we excluded this binary system from the spectral analysis.

Besides  $\chi$  Lupi, three other program stars (HD 35548, HD 158704, and HD 193452) are known to have very close visual companions. Unfortunately, little is known about their companions other than their fainter, and presumably cooler, nature in most cases. Spectral lines from the companions have been detected in our data only for the star HD 158704. Therefore, for this star the parameters of the atmospheric model are particularly uncertain. For the other two stars the flux distribution of cool companions has a smaller influence at shorter wavelengths, where the atmospheric parameters  $T_{\text{eff}}$  and gravity are determined from photometric indices, than at the red wavelengths of the lines studied. Using synthetic spectra representing the coolest HgMn stars, we estimate that a 5% contribution to the total flux from a companion would lead to an error of approximately 1 mÅ in interpreting the measured equivalent width as from a single star. It should be noted that the three stars in our program (HD 175640, HD 178065, HD 186122) with the largest observed relative intensification, as measured by both the Gaussian and integration techniques, are not known to have companions.

#### 4. Discussion

The comparison of the relative intensification measurements for the features at  $\lambda 6147.7$  and at  $\lambda 6149.2$  in HgMn stars with the calculations of synthetic spectra suggests

that at least three HgMn stars, HD 175640, HD 178065 and HD 186122, very likely possess a magnetic field. These stars have the largest observed  $\Delta W/\overline{W}$ , and measurements performed by the Gaussian and integral methods show mutually consistent results. It was shown in the past that  $\Delta W/\overline{W}$  is generally not a monotonic function of magnetic-field strength and depends upon various parameters (e.g., aspect-angle of magnetic field, microturbulence, Fe abundance) (Takeda 1991). Mathys & Lanz (1992) examined an empirical correlation between  $\Delta W/\overline{W}$  and magnetic field for magnetic Ap stars with magnetically split lines and found an approximately linear relation over a limited range of field strength. They have shown that this relation cannot be extrapolated linearly from weak to strong fields. Therefore, the magnitude of the observed relative intensifications of the two Fe II lines at  $\lambda 6147.7$  and at  $\lambda 6149.2$  cannot be used directly to derive a value for magnetic field strength in HgMn stars. On the other hand, the theoretical computations of Takeda (1991) for the hot Am star  $\alpha$  Peg, which has a relative intensification  $\Delta W/\overline{W} = 0.052$  (Mathys & Lanz 1990), showed that for this difference between equivalent widths of  $\lambda 6147.7$  and  $\lambda 6149.2$  the most probable value for the magnetic field strength,  $H$ , would be  $H \sim 2\text{--}3$  kG. Theoretical  $\Delta W/\overline{W}$  vs.  $H$  relations were also applied to cool Ap stars of the Sr–Cr–Eu type studied by Adelman (1973). The surface magnetic-field strengths for these stars were estimated from the resolved Zeeman-split doublets or by use of the technique of differential broadening (Preston 1971). Most of the observed data showed the same tendency of  $\Delta W/\overline{W}$  vs.  $H$  as that of the theoretical curves (Takeda 1991). Therefore, the finding of a magnetic field  $H \sim 2\text{--}3$  kG in  $\alpha$  Peg would suggest that three HgMn stars in our sample may have a field that is larger than 2 kG.

Unfortunately, all but one of our HgMn stars were observed on a single occasion and therefore we cannot assess at this stage the possible variability of these fields and determine their structure. An interesting area for future

research would therefore be to study the possible variations of these magnetic fields from very high-quality data.

To better understand the nature of HgMn stars, further searches for magnetic fields are necessary. The unambiguous detection of magnetic fields in HgMn stars would extend the weak field detection beyond the realm of the Am stars, for which evidence exists for three stars.  $\alpha$  Peg has a magnetic field of the order of 2 kG and two other stars, HD 29173, and HD 195479A, are likely to possess a magnetic field of about the same strength (Lanz & Mathys 1993). It also raises speculation that differences in observed spectral anomalies between the HgMn-Am and Bp-Ap star sequences are not a matter of magnetic versus non-magnetic, but rather between stars that possess complex versus dipole magnetic fields, respectively. A straightforward continuation in the study of magnetic fields in HgMn stars would be to apply the moment technique to look for possible differential broadening of spectral lines having different magnetic sensitivities (Mathys 1995; Mathys & Hubrig 1997), or the multi-line Stenflo-Lindgren (1977) technique, which can be very powerful if it is applied to a suitable sample of spectral lines. Magnetic field detections in HgMn stars might also be valuably attempted through the observation of linear polarization in spectral lines. Such observations should prove especially appropriate to probe the possibility that the field has a topology such that it appears primarily transversal, with sufficient large-scale organization, as would be the case, for instance, of a toroidal field.

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## References

- Adelman S.J., 1973, ApJ 183, 95  
 Adelman S.J., 1994, MNRAS 266, 97  
 Babcock H.W., 1958, ApJS 3, 141  
 Blackwell, D.E., Shallis, M.J., Simmons, G.J., 1980, A&A 81, 340  
 Brage, T. Proffitt, C.R., Leckrone, D.S., 1999, ApJ 512, in press  
 Castelli F., 1998, colors available at <http://cfaku5.harvard.edu>  
 Conti P.S., 1970, ApJ 159, 723  
 Conti P.S., 1970, ApJ 160, 1077  
 Conti P.S., 1969, ApJ 156, 661  
 Fuhr, J.R., Martin, G.A., Wiese W.L., 1988, J. Phys. Chem. Ref. Data 17, Suppl.4.  
 Griffin R.F., Griffin R.E.M., 1979, Procyon Atlas  
 Hubrig S., Castelli F., Mathys G., 1999, A&A 341, 1999  
 Kurucz, R.L., 1988, Trans. IAU, XXB, In: M. McNally, (ed.), Dordrecht:Kluwer, p. 168  
 Kurucz R.L., 1993, Kurucz CD-ROM No. 18. SYNTHES Spectrum Synthesis Programs and Line Data, (Cambridge: SAO)

- Kurucz R.L., 1995, Kurucz CD-ROM No. 23, (Cambridge: SAO)  
 Landstreet J.D., 1992, A&AR 4, 35  
 Lanz T., Mathys G., 1993, A&A 280, 486  
 Mathys G., 1990, A&A 232, 151  
 Mathys G., 1995, A&A 293, 746  
 Mathys G., Lanz T., 1990, A&A 230, L21  
 Mathys G., Lanz T., 1992, A&A 256, 169  
 Mathys G., Hubrig S., 1995, A&A 293, 810  
 Mathys G., Hubrig S., 1997, A&AS 124, 475  
 Mermilliod J.C., Mermilliod M., Hauck B., 1997, A&AS 124, 349  
 Migdalek J., 1976, Canadian J. Phys. 54, 2272  
 Moon T.T., 1985, Commun. Univ. London Obs. 78  
 Moon T.T., Dworetzky M.M., 1985, MNRAS 217, 305  
 Murakawa, K., 1932, Sci. Pap. Inst. Phys. Chem. Res. Tokyo 18, 299  
 Preston G.W., 1971, ApJ 164, 309  
 Reader, J., Sansonetti, C.J., 1986, Phys Rev A 33, 1440  
 Renson P., 1991, Catalogue Général des Etoiles Ap et Am. Institut d'Astrophysique – Université de Liège  
 Stenflo J.O., Lindgren L., 1977, A&A 59, 367  
 Strömgren B., 1966, ARA&A 4, 433  
 Takada-Hidai M., Jugaku J., 1992, PASP 104, 106  
 Takeda Y., 1991, Publ. Astron. Soc. Japan 43, 823  
 Wahlgren G.M., Adelman S.J., Robinson R.D., 1994, ApJ 434, 349