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No weak magnetic field detected in the variable HgMn star α Andromedae*

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Abstract.
High-S/N, phase-distributed circular polarisation spectra of the variable HgMn star α And provide no evidence of any photospheric magnetic field, with an upper limit for oblique dipolar fields of 280 G (approximately the equipartition field at $\log \tau_{5000} = 0.0$). We therefore propose that the variability of the Hg λ3984 line and the inferred nonuniform distribution of Hg (reported by Adelman et al. 2002) most plausibly result from a separation mechanism unrelated to the presence of a magnetic field.

Key words: stars: magnetic fields – stars: individual: α And

1 Introduction

Although Ap HgMn stars have generally been found to show no clear evidence of variability (e.g. Adelman 1998) or magnetic fields (Shorlin et al. 2002), Adelman et al. (2002) reported convincing evidence that the bright, well-established HgMn star α Andromedae A (HD 358) exhibits clear (> 30%) variability of the equivalent width of the Hg II λ3984 line profile.

The Hg line variations observed by Adelman et al. (2002) were consistent with a period of 2.38236 ± 0.00011 days, a value in good agreement with the rigid rotation period $P = 2.53 \pm 0.4$ days (Ryabchikova et al. 1999) calculated using the measured $v \sin i$ of 52 ± 2 km/s, the inferred rotational axis inclination $i = 74^\circ$ and the stellar radius $R = 2.7 \pm 0.4\ R_\odot$.

Interpreting the Hg line profile variability as the consequence of rotational modulation of a nonuniform photospheric abundance distribution, Adelman et al. (2002) inverted the variations using the Doppler Imaging technique to recover a map of the Hg surface distribution. The distribution is characterised by a strong (~ 4.5 dex) enhancement of the Hg abundance in the *rotational* equatorial regions, from about -30° to $+30^\circ$ rotational latitude. The equatorial Hg enhancement appears to be structured into a series of three or four spots of very high abundance, distributed approximately uniformly in longitude, connected by "bridges" of somewhat lower Hg abundance.

In the atmospheres of classical Ap stars, magnetic fields seem to be a necessary ingredient in the production of nonuniform surface abundance distributions. Could the inferred nonuniform surface distribution of Hg imply that α And is a magnetic HgMn star? In this paper we explore this hypothesis using new high-S/N polarisation observations, well-distributed according to the rotational ephemeris of Adelman et al. (2002).

* Based on observations obtained using the MuSiCoS spectropolarimeter at the Pic du Midi Observatory, France.

Table 1: Journal of MuSiCoS spectropolarimetric observations of α And. Phases are calculated according to the ephemeris of Adelman et al. (2002: JD $= 2449279.6898 + (2.38236 \pm 0.00011) \cdot$ E.)

UT Date	HJD	Phase
12 dec 00	2451891.32	0.23769
24 jun 03	2452815.65	0.22582
26 jun 03	2452817.65	0.06532
04 jul 03	2452825.64	0.41914
07 jul 03	2452828.65	0.68469
09 jul 03	2452830.64	0.51790
09 jul 03	2452830.65	0.52210
09 jul 03	2452830.66	0.52630
10 jul 03	2452831.65	0.94185
10 jul 03	2452831.66	0.94605
10 jul 03	2452831.67	0.95025
11 jul 03	2452832.65	0.36160
12 jul 03	2452833.60	0.76037
17 jul 03	2452838.60	0.85913
17 jul 03	2452838.61	0.86332
17 jul 03	2452838.62	0.86752
18 jul 03	2452839.61	0.28308
18 jul 03	2452839.62	0.28727
19 jul 03	2452840.59	0.69443
19 jul 03	2452840.60	0.69863
19 jul 03	2452840.61	0.70283
26 jul 03	2452847.64	0.65368
26 jul 03	2452847.65	0.65788
26 jul 03	2452847.66	0.66208

2 Observations

To search for a magnetic field in α And, in June-August 2003 23 new high-S/N Stokes V spectra of α And were obtained using the MuSiCoS spectropolarimeter (Baudrand & Böhm 1992, Donati et al. 1999) on-board the 2m TBL at Pic du Midi Observatory. The spectra were reduced using the ESpRIT reduction package (Donati et al. 1997).

Least-Squares Deconvolution (LSD; Donati et al. 1997, Wade et al. 2000a) was employed to extract high-precision mean Stokes I and V profiles from the spectra. For the extraction we have employed a specially-designed HgMn line mask (see, e.g., Shorlin et al. 2002) calculated for an effective temperature of 14000 K (Ryabchikova et al. 1999). The typical S/N of the extracted Stokes V mean profiles is 10^4. The journal of observations is reported in Table 1.

Fringes are apparent in the reduced Stokes V spectra of α And, with amplitudes of order 0.2% and wavelengths larger than about 4 Å. Preliminary fringe removal was performed using the wavelet transform procedure described by Monin et al. (in preparation).

After fringe removal, LSD profiles obtained within ± 0.05 days of each other were averaged, finally resulting in 13 sets of Stokes I and V LSD profiles that were employed for all of the following analysis.

3 Constraints on the photospheric magnetic field

We find that no Stokes V signatures are detected within any of the 13 final LSD line profiles, with 3σ upper limits from 0.015% to 0.035%.

Longitudinal magnetic fields were inferred from each of the Stokes I and V profile sets, using the first-order moment method described by Donati et al. (1997) and Wade et al. (2000b). The resultant measurements have associated 1σ uncertainties from 29–98 G, and a median uncertainty of 45 G. We detect no significant longitudinal magnetic field or field variation.

To place an upper limit on the strength of any photospheric magnetic field present, we have calculated synthetic Stokes I and V LSD profiles, using the polarized line synthesis code Zeeman2 (Landstreet 1988, Wade et al. 2001), and assuming a triplet Zeeman pattern and the mean Landé factor and wavelength appropriate to the α And line mask (the accuracy of such a modelling procedure has been demonstrated by e.g. Donati et al. 2001). We performed calculations for a large grid of magnetic field models and compared the Stokes V profile rotational variation predicted by each model with the observed Stokes V phase variation. Over 3000 individual models were calculated for pure dipolar and pure linear quadrupolar fields of various geometries; equivalently over 27300 comparisons were made between observed and calculated profiles. Note that although very few magnetic upper main sequence stars exhibit obviously quadrupolar magnetic fields, these solutions were calculated in order to test the robustness of the upper limits we determine.

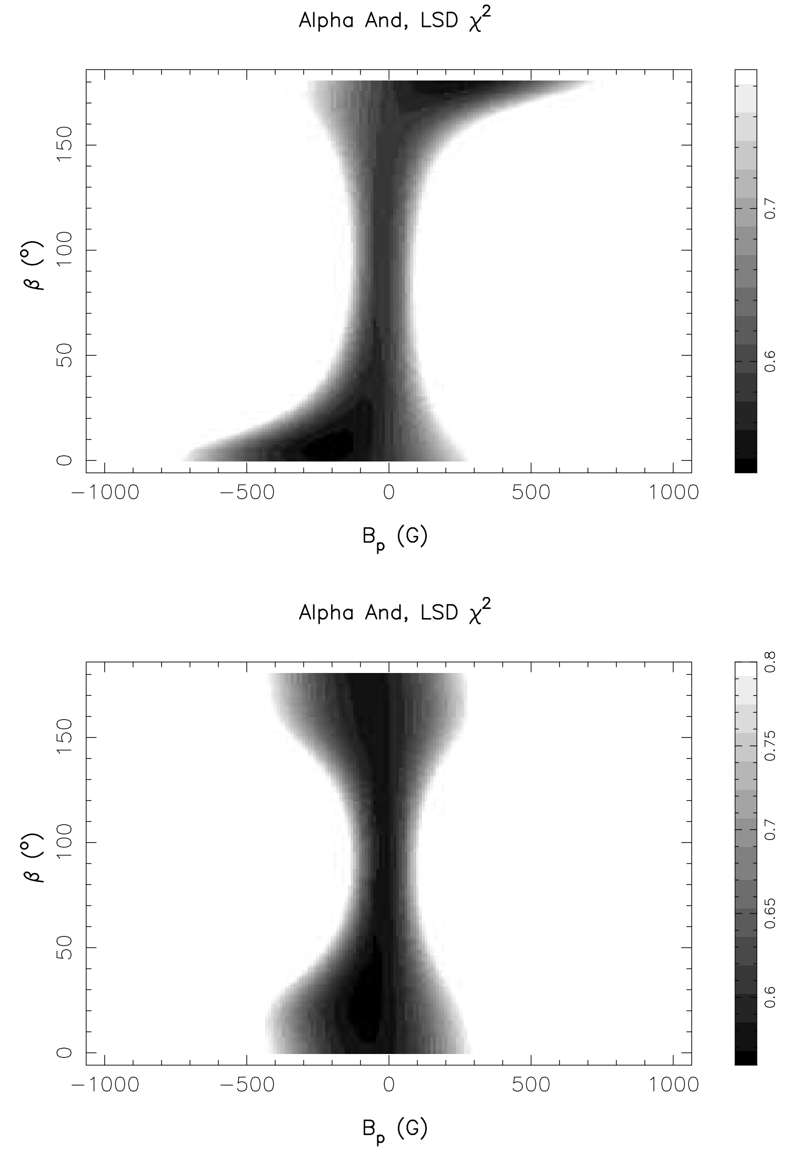

Figure 1: *Reduced χ^2 of the model/data comparison for dipole (top) and quadrupolar (bottom) fields, as a function of the polar field strength B_p and the obliquity between the rotational axis and the magnetic field symmetry axis β. A rotational axis inclination of $i = 74°$ has been assumed for all models. Dark regions correspond to models consistent with the observations, while white regions correspond to models incompatible with the observations at more than 99.9% confidence.*

The values of the summed reduced χ^2 for each model/data comparison are shown in Fig. 1 as a function of the model magnetic field polar strength B_p and obliquity β. Calculated Stokes V profiles consistent with the observations are obtained only for dipolar fields weaker than 600 G and for quadrupolar fields weaker than 400 G. Moreover, the strongest field solutions are consistent with the observations only for magnetic fields nearly aligned with the stellar rotational axis (obliquities close to zero or 180°). Aligned magnetic fields tend to be characteristic of magnetic A stars with long rotational periods (Landstreet & Mathys 2000), whereas oblique magnetic fields tend to be characteristic of magnetic A stars with short periods (like α And). If we consider only solutions with significant obliquity ($30^\circ < \beta < 150^\circ$), we find that any magnetic fields present in the photosphere of α And should be weaker than about 280 G if the field is dipolar, and weaker than 380 G if the field is quadrupolar. Note that these values are strict upper limits at $> 99.9\%$ confidence for this range of β.

Let us now restrict our discussion to the more plausible case of the predominantly dipolar magnetic field. In the atmosphere of α And, at $\log\tau_{5000} = 0.0$, the equipartition field strength (for which the magnetic and thermodynamic energy densities are approximately equal) is $B_\mathrm{eq} = \sqrt{12\pi nkT} \simeq 260$ G. This is approximately equal to the upper limit derived for any dipolar field that might be present, and so we can state that *our data rule out the presence of any oblique dipolar field stronger than the equipartition field strength.* Furthermore, if we believe that a magnetic field of at least this order is required to produce and support horizontal abundance nonuniformities (as appears to be the case for Ap stars, Auriere et al., this conference), then *an oblique dipolar magnetic field cannot be responsible for the nonuniform distribution of Hg of α And, at least in atmospheric layers around* $\log\tau_{5000} = 0.0$.

Parenthetically, we also comment that although we have performed no quantitative modeling of tangled magnetic fields in this study (fields such as those exhibited by active late-type stars such as HR 1099, e.g. Petit et al. 2003), the fact that such fields are detected in LSD profiles of similar quality in a sample of late-type stars using the MuSiCoS spectropolarimeter implies that similar fields are not present in the photosphere of α And. This result is fully consistent with the conclusions of Shorlin et al. (2002), who using high-S/N Stokes V profiles found no evidence for any tangled magnetic fields in a sample of 74 A and B type stars.

A comparison between the sample of the final observed LSD profiles and the predictions of 500 G dipolar magnetic field with $\beta = 90^\circ$ is shown in Fig. 2.

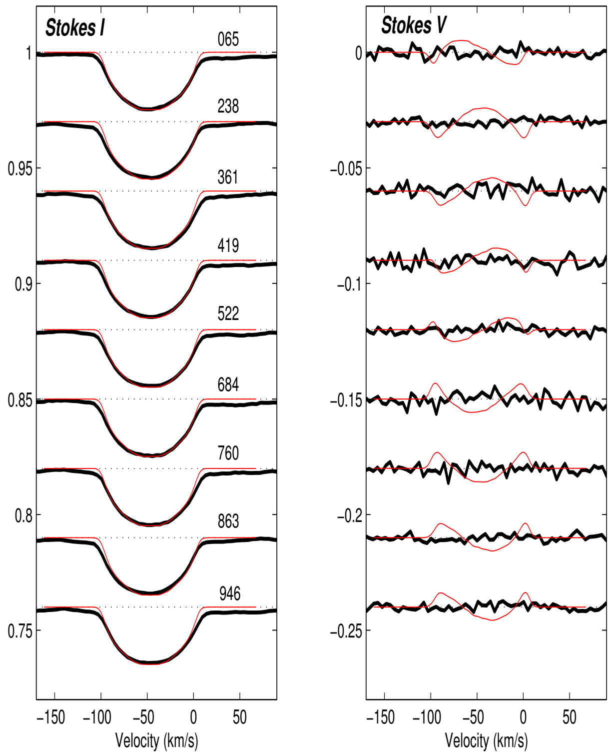

Figure 2: *Stokes I and V profiles for $\beta = 90^\circ$ and $B_\mathrm{d} = 500$ G.* Thick lines — *observed LSD profiles.* Thin lines — *calculated profiles.*

4 Implications

We stress that α And represents the only convincing example of a HgMn star which shows intrinsic line profiles variability, making it an important testbed for theories describing the formation of abundance nonuniformities. If the nonuniform surface Hg distribution does not result from the presence of a magnetic field, what is its origin?

One possibility is that the nonuniform abundance distribution is supported via interaction with the star's binary companion. As reported by Ryabchikova et al. (1999), the HgMn star α And is orbited by a lower-mass companion, in a highly eccentric orbit with a period of 96.7 days. At apastron, the stars are separated by 1.12 AU (approximately 45 diameters of the HgMn star), whereas at periastron they are separated by only 0.32 AU (approximately 12 stellar diameters). We speculate that variable tidal interaction (with a period equal to one-half of the orbital period, or 48.4 days) between the two components might excite nonradial waves in the surface layers of the stars, producing mixing at selective longitudes (perhaps extrema of the surface wave), and relative stability at other longitudes (possibly nodes). Although this hypothesis is totally speculative, we point out that it naturally explains the concentration of Hg in the rotational equator, if the rotational and orbital axes of the system are aligned. A low-order surface wave might also explain the apparently equal 90° spacing in longitude of the Hg spots (although only three spots are obvious in the maps of Adelman et al. (2002; at longitudes of 90, 180 and 270 degrees), taking into account nonuniform phase sampling and uncertainties in interpreting the abundance scaling in the published maps, a fourth spot could plausibly exist at longitude 360°). Because the orbital period of the α And system is not an integral multiple of the rotational period of the HgMn star, one would expect that a tidally-induced surface inhomogeneity would change with time, probably on timescales of order the orbital period. Such changes might correspond to a precession of the surface abundance pattern. Oleg Kochukhov has recently reported (Kochukhov 2003) that in fact tentative evidence for variations in the structure of the Hg map do exist.

A second possibility (suggested by John Landstreet (2003)) is that α And does indeed host a magnetic field, but which is weaker than the local equipartition field in layers around $\log \tau_{5000} = 0.0$. However, because of the exponential decrease of the gas density with height in the outer layers of the star, such a field could in fact be stronger than the equipartition field in atmospheric layers around (say) $\log \tau_{5000} = -3$ (where $B_{\rm eq}$ is only a few tens of G). If the Hg concentration and nonuniformities were confined to these high layers (as, for example, in the cases of other HgMn stars like 3 Cen A, Sigut et al. 2000), then even a very weak magnetic field could be responsible. Although plausible, such a hypothesis raises some interesting questions regarding the stability of weak magnetic fields. In particular, could a magnetic field weaker than the equipartition field in layers with $\log \tau_{5000} = 0.0$ (and therefore subject to distortion by flows in those layers) survive disruption to produce nonuniformities in the upper photosphere?

5 Conclusions

High-S/N, phase-distributed circular polarisation spectra of the variable HgMn star α And have been obtained using the MuSiCoS spectropolarimeter at Pic du Midi Observatory. No evidence of any magnetic field has been detected, leading to the following conclusions: α And does not host a dipolar or quadrupolar photospheric magnetic field substantially stronger than the equipartition threshold. Nor does it host tangled magnetic fields with characteristics similar to those of active late-type stars (e.g. RS CVn systems or FK Com stars). We therefore conclude that the variability of the Hg λ3984 line, and the inferred nonuniform distribution of Hg, most plausibly result from a separation mechanism unrelated to the presence of a magnetic field.

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References

Adelman S.J., 1998, Astron. Astrophys. Suppl. Ser., **132**, 93
Adelman S.J., Gulliver A.F., Kochukhov O., Ryabchikova T.A., 2002, Astrophys. J., **575**, 449
Baudrand J., Böhm T., 1992, Astron. Astrophys., **259**, 711
Donati J.F., Semel M., Carter B.D., Rees D.E., Cameron A.C., 1997, Mon. Not. R. Astron. Soc., **291**, 658
Donati J.-F., Catala C., Wade G.A., Gallou G., Delaigue G., Rabou P., 1999, Astron. Astrophys. Suppl. Ser., **134**, 149

Donati J.-F., Wade G.A., Babel J., Henrichs H.F., de Jong J.A., Harries T., 2001, Mon. Not. R. Astron. Soc., **326**, 1265

Kochukhov O., 2003, private communication

Landstreet J.D., 1988, Astrophys. J., **326**, 967

Landstreet J.D. & Mathys G., 2000, Astron. Astrophys., **359**, 213

Landstreet J.D., 2003, private communication

Petit P., Donati J.-F., Wade G.A., Auriere M. et al., 2003, submitted to Mon. Not. R. Astron. Soc.

Ryabchikova T.A., Malanushenko V.P., Adelman S.J., 1999, Astron. Astrophys., **351**, 963

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

Sigut T.A.T., Landstreet J.D., Shorlin S.L.S., 2000, Astrophys. J., **530**, 895

Wade G.A., Donati J.-F., Landstreet J.D., Shorlin S.L.S., 2000a, Mon. Not. R. Astron. Soc., **313**, 823

Wade G.A., Donati J.-F., Landstreet J.D., Shorlin S.L.S., 2000b, Mon. Not. R. Astron. Soc., **313**, 851

Wade G.A., Bagnulo S., Kochukov O., Landstreet J.D., Piskunov N., Stift M.J., 2001, Astron. Astrophys., **374**, 265