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A magnetic model for the Ap star HD 192678 *

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Abstract. We present a magnetic model for the A2pCr star HD 192678 based upon modeling of new and previously published longitudinal magnetic field measurements, surface field measurements, broadband linear polarimetry and unpolarized high-resolution spectra.

The limitations of the classical dipole oblique rotator model are clearly detectable in the case of HD 192678. An oblique rotating dipole is not capable of simultaneously reproducing the surface field variations and the broadband linear polarization variations.

Line profile variations of the Fe II $\lambda\,6149.2$ Zeeman doublet may be consistent with a dipole field whose pole-to-equator modulus ratio has been decreased by about 20%. However, this is uncertain since it relies critically on the amount of microturbulence present, about which we have little information. Excess broadening of Fe II $\lambda\,6149.2$ is apparent which appears to be neither rotational nor microturbulent in origin, and may be indicative of small photospheric regions of high field strength.

Our magnetic model for HD 192678 consists of an oblique rotating dipole with modified field line inclinations. The polar field strength of the dipole is 6.8 ± 0.2 kG, with $i = 173°\pm5°$ and $\beta = 120°\pm7°$. This model contains a region of open field lines near the magnetic equator, a recurring feature in magnetic models of a number of Ap stars (Leroy et al. 1995b).

Key words: polarization – stars: chemically peculiar – stars: individual: HD 192678 – stars: magnetic fields

1. Introduction

We have undertaken magnetic modeling of HD 192678 ($m_{\rm V} = 7.4$) as part of a programme aimed at investigating the magnetic field structure of Ap stars through analysis of combined circular and linear polarization measurements.

HD 192678 was first classified as A4p by Babcock (1958). He reported a sharp-lined metallic spectrum with outstanding lines of Cr, and weak Mg II $\lambda\,4481$. From modeling of the energy distribution in the Paschen continuum, Stepien and Dominiczak (1989) calculate an effective temperature for HD 192678 of 9000 K, indicating a spectral type of A2. Hill et al. (1976) have observed this star to be photometrically nonvariable.

Babcock (1958) reported a 2 kG longitudinal magnetic field of positive polarity from one photographic observation. A surface field of 4.6 kG was reported by Preston (1971).

2. Observations, reductions and period analysis

2.1. Longitudinal field

Longitudinal magnetic field measurements of HD 192678 have been acquired at both the Special Astrophysical Observatory (SAO) of the Russian Academy of Sciences, and at the Elginfield Observatory of the University of Western Ontario (UWO).

SAO measurements (Glagolevskij et al. 1986) were obtained from photographic spectra acquired during 1981 at the 6 metre telescope of the Russian Academy of Sciences. Spectra were obtained on Kodak IIaO plates using an achromatic circular polarization analyzer with a reciprocal linear dispersion of 9 Å/mm. Further information on the equipment and observing technique is available in Glagolevskij et al. (1986).

UWO measurements were acquired at the 1.2 metre UWO telescope using a photoelectric Balmer line Zeeman analyzer. This instrument measures the fractional circular polarization in the wings of Hβ at ± 5.0 Å from line centre. The quantity thus measured is linearly related to the longitudinal magnetic field. A more detailed description of the instrument and observing technique is given by Landstreet (1980).

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* Based on observations acquired at l'Observatoire de Haute Provence, Saint-Michel-l'Observatoire, France.

All available longitudinal field measurements are presented in Table 1, tabulated together for convenient access. All the data agree that the longitudinal field is about +1.5 kG, and varies only mildly at most. A period search of these data from 0.1 to 100 days reveals only one significant period at $13.^{\rm d}049 \pm 0.^{\rm d}012$, with strong sidelobes at $10.^{\rm d}61$ and $16.^{\rm d}72$. The best fit to these measurements with a first-order sinusoid with a period of $13.^{\rm d}049$ has a reduced χ^2 of 3.2, while the reduced χ^2 of a horizontal straight line fit to the longitudinal field data is 5.0.

Table 1. Journal of longitudinal field observations of HD 192678. Phases are calculated from the ephemeris cited in the text and σ_B is the 1 standard deviation uncertainty.

JD-244 0000	Phase	$B_l \pm \sigma_B$ (G)	Observatory
4590.113	0.309	1640 ± 170	SAO
4712.426	0.365	1100 ± 145	SAO
4720.434	0.613	1680 ± 150	SAO
4775.355	0.170	1410 ± 100	SAO
4777.293	0.472	1320 ± 90	SAO
4778.316	0.631	1040 ± 110	SAO
4779.508	0.817	1240 ± 110	SAO
4860.195	0.387	1600 ± 90	SAO
4860.223	0.392	1230 ± 80	SAO
4890.168	0.057	1990 ± 120	SAO
4890.184	0.060	1350 ± 90	SAO
4918.152	0.417	1510 ± 80	SAO
9882.730	0.884	1250 ± 250	UWO
9883.715	0.038	1640 ± 220	UWO

2.2. Surface field and Fe II $\lambda\,6149.2$ *line profiles*

As part of a search for Ap stars with magnetically split lines, HD 192678 was included in the survey for slowly rotating stars with strong magnetic fields (Mathys and Lanz 1992). This investigation revealed a mean surface field of about 4.8 kG, with a variation of a few hundred gauss.

Surface field measurements were made from CCD spectra acquired at the 1.5 metre telescope of l'Observatoire de Haute Provence (OHP) using the AURELIE spectrograph and Thomson "barrette" ($\lambda/\Delta\lambda = 6 \times 10^4$) and at the 0.9 metre telescope of the Kitt Peak National Observatory (KPNO) using the coudé spectrograph and Echelle grating ($\lambda/\Delta\lambda = 10^5$). The surface field strength was inferred by measuring the separation of the components of the Fe II $\lambda\,6149.2$ Zeeman doublet. A more detailed description of this technique is given by Mathys (1990).

There is a systematic difference between those surface fields inferred from OHP spectra and those inferred from KPNO spectra. The most plausible explanation for this offset is a linear polarization effect. To bring all measurements to the same scale, 163 G (equal to the difference between the means of the OHP and KPNO measurements) has been subtracted from all surface fields inferred from OHP spectra.

Fig. 1. Surface field (circles) and longitudinal field (squares) measurements of HD 192678. Superimposed on the observations are the computed variations for the pure dipole model (dashed curves) and the modified dipole model (solid curves) described in the text.

The surface field measurements (34 in total) were obtained between JD 2448166 and JD 2449582. These are to be published separately (Mathys et al. 1996) and are consistent with Preston's (1971) report of a 4.6 kG surface field. A period search of these measurements from 0.1 to 100 days reveals significant periods at $5.^{\rm d}6237 \pm 0.^{\rm d}004$ and $6.^{\rm d}4185 \pm 0.^{\rm d}004$. The reduced χ^2 of the best first-order sinusoid fits to the surface field data with these periods are 2.1 and 2.6, respectively. The reduced χ^2 of a straight-line fit to the data is 5.0.

Both the surface field and longitudinal field data are shown in Fig. 1, phased according to the ephemeris described below.

2.3. Broadband linear polarization

Broadband linear polarimetry of HD 192678 was acquired at the Pic du Midi Observatory using the "Sterenn" polarimeter at the Cassegrain focus of the 2 metre Bernard Lyot telescope. The observations, first published by Leroy (1995), are shown in Fig. 3, phased according to the ephemeris described below. The solid curve is a least-squares $3^{\rm rd}$-order harmonic fit ($\chi^2/\nu = 1.6$). These data, obtained between JD 2448513 and JD 2449688, overlap strongly with the surface field measurements. A period search of the linear polarization variations reveals one significant period at $6^{\mathrm{d}}.4186 \pm 0^{\mathrm{d}}.002$, which is consistent with the $6^{\mathrm{d}}.4185 \pm 0^{\mathrm{d}}.004$ period found in the surface field variations. The linear polarization data are completely inconsistent with the $13^{\mathrm{d}}.049 \pm 0^{\mathrm{d}}.012$ period revealed from the analysis of the longitudinal field measurements and the $5^{\mathrm{d}}.6237 \pm 0^{\mathrm{d}}.004$ period revealed from the analysis of the surface field measurements. This indicates that these periods are almost certainly spurious. Thus we have adopted $6^{\mathrm{d}}.4186 \pm 0^{\mathrm{d}}.002$ as the rotation period of HD 192678. In Fig. 2 the surface field measurements are shown, phased with this period. It is clear that the surface field shows real variation with this period, and has a non-zero amplitude. It should be noted that because the dates of acquisition of the surface field and linear polarization measurements overlap, the relative phase of these datasets is almost independent of our choice of best period around $6^{\mathrm{d}}.418$.

All data have therefore been phased according to the ephemeris JD $= 2449113.24 + 6^{\mathrm{d}}.4186$ E, where the surface field maximum has been chosen as phase 0.0. The longitudinal field data reveal no clear variation with this period. The reduced χ^2 of the best sine curve fit of the longitudinal field measurements with this period is 5.1, essentially the same as that of a straight-line fit to the data. It is thus apparent that we are not detecting the variation of the longitudinal field, and so only a very modest amplitude of variation is possible. This suggests that the photographic measurement uncertainties may be underestimated, and are likely closer to 200 G (Preston 1969).

Fig. 2. Surface field measurements of HD 192678, phased according to the ephemeris described in the text.

3. Toward a model of the magnetic field

3.1. A pure oblique dipole model

An oblique rotating dipole is an obvious choice as an initial magnetic model for HD 192678 – the characteristic sinusoidal variation is evident in the surface field, the $Q-U$ diagram shows the double-loop structure which is known to be reproducible by an oblique rotator (Landolfi et al. 1993), and the Fe II $\lambda\,6149.2$ line profiles exhibit variation in the relative strengths of the red and blue components which indicate a global-scale variation in field strength.

The classical oblique rotating dipole is a 3 parameter model. The two geometric parameters, the inclination i of the stellar rotation axis to the observer's line-of-sight and the obliquity β of the dipole symmetry axis to the rotation axis, may be retrieved from the combination of longitudinal field measurements and broadband linear polarization measurements (Leroy et al. 1995a). Briefly, i and β may be determined uniquely, given knowledge of two quantities, for a magnetic field dominated by the dipole component. It will be shown that although somewhat approximate, this assumption is consistent to first order with all of the available data.

The first quantity necessary is the ratio r of the lesser longitudinal field extremum to the greater longitudinal field extremum:

$$r = \begin{cases} B_l^{\max}/\,B_l^{\min} & \text{if } |B_l^{\max}| < |B_l^{\min}| \\ B_l^{\min}/\,B_l^{\max} & \text{if } |B_l^{\min}| < |B_l^{\max}|. \end{cases}$$

Due solely to the $\pm 0^{\mathrm{d}}.002$ uncertainty associated with the adopted period, there is an uncertainty of about 0.25 periods in the phase of the SAO longitudinal field data relative to the remaining data. However, since we are unable to detect the variation in the longitudinal field, we effectively have no information about its phase. Nevertheless, it is clear that the longitudinal field variation is confined to a few hundred gauss. Fig. 1 indicates that r is greater than 0.75 (and ≤ 1.0, by definition). Based on our measurements of the longitudinal field, we adopt the value $r = 0.87 \pm 0.12$.

Also necessary is the quantity s, calculated from the first- and second-order Fourier coefficients of the Q/I and U/I variations of the linear polarization:

$$s = \frac{1 - P_1/P_2}{1 + P_1/P_2},$$

where the q_is and u_is in the expression for P_1 and P_2,

$$P_1 = q_1^2 + q_2^2 + u_1^2 + u_2^2$$

and

$$P_2 = q_3^2 + q_4^2 + u_3^2 + u_4^2,$$

Fig. 3. Broadband linear polarization measurements of HD 192678. The solid curves are least-squares 3$^{\rm rd}$-order harmonic fits. The reduced χ^2 is 1.6.

are taken from a Fourier decomposition of the polarization data,

$$Q/I \approx q_0 + q_1 \cos f + q_2 \sin f + q_3 \cos 2f + q_4 \sin 2f$$

and

$$U/I \approx u_0 + u_1 \cos f + u_2 \sin f + u_3 \cos 2f + u_4 \sin 2f,$$

where f is the angular rotational phase.

We calculate $s = 0.87 \pm 0.1$ from the best fit of the Q/I and U/I variations.

From these values of r and s, employing the relations between i and β, r and s given by Leroy et al. (1995a) we find $i = 175° \pm 5°$ and $\beta = 140° \pm 10°$. Note that i and β must be greater than 90° due to the clockwise direction of the polarization diagram (Leroy et al. 1995a).

The geometric parameters may alternatively be calculated from the longitudinal field and surface field observations. A magnetic field modeling programme developed by two of us (JDL and GW) calculates the longitudinal and surface field variations expected for given values of i and β assuming a very general magnetic field geometry. Assuming a pure dipole field and the direction of rotation implied by the linear polarization data, we find via this method $i = 173° \pm 5°$, $\beta = 135° \pm 10°$, in very good agreement with the values calculated above. The necessary polar strength for the dipole (the third parameter in this model) is $B_p = 6.5$ kG ± 0.2 kG.

As can be seen in Fig. 1 (dashed curves), the agreement between the observed and computed surface field and longitudinal field variations for this model is quite good (although we recall that the longitudinal field curve contains no phase information). In Fig. 4 the linear polarization measurements are plotted versus phase and versus one another. [1] The solid curves in Fig. 4 are the computed polarization variations for this model, calculated as per the method of Landolfi et al. (1993). With a reduced χ^2 of 9.4, it is evident that the agreement between the observed and computed linear polarizations is not very good for this model. It is important to recall that because the surface field measurements and the broadband linear polarization measurements were secured during almost the same period of time, no phase ambiguity exists between these two datasets. Thus, the disagreement between the linear polarization variations and the oblique rotating dipole model with the nearest approach of the magnetic pole to the line-of-sight occurring simultaneously with surface field maximum shows unambiguously that the magnetic field of HD 192678 contains deviations from an oblique dipole.

3.2. A modified oblique dipole model

To improve the agreement between our model and the observations, modifications are necessary. A choice must be made as to how the model should be altered. In this

[1] These data differ from those shown in Fig. 3 in that the constant (0$^{\rm th}$-order) terms in the harmonic fits have been subtracted from each measurement. These constant terms are interpreted as interstellar polarization and are irrelevant to the modeling procedure.

Fig. 4. Linear polarization measurements of HD 192678. The solid curve is the computed variation for the pure dipole model described in the text. The reduced χ^2 is 9.4.

sense we are fortunate, since we have in our longitudinal field, surface field and linear polarization measurements three quantities which are highly independent insofar as small changes in the field are concerned. For example, local modifications of the field modulus affect the computed surface field curve quite strongly, while having little effect on the computed longitudinal field or linear polarizations (Leroy et al. 1995b). Local modifications of the field direction (i.e. the orientation of field lines) affect the linear polarizations quite strongly, the longitudinal field mildly, and have no effect on the surface field.

We have made modifications to the field line inclinations in our oblique dipole model using the method described by Leroy et al. (1995b). This is accomplished via an inversion/residues-minimization technique which allows rotations of field lines within the meridian plane in a band $\pm 36°$ wide about the magnetic equator. Because any magnetic model would not seem particularly credible if the $\nabla \cdot \mathbf{B} = 0$ condition were violated, these field line modifications are described by spherical harmonics which are symmetric about the magnetic equator. This choice has an additional advantage – it limits the number of unknown coefficients to be recovered via the inversion process, thereby decreasing the likelihood of spurious magnetic structures.

Because uniqueness is always a concern in underdetermined problems, we make futher efforts to restrict valid solutions. As is typical in inversion techniques, we adopt a penalty function (Leroy et al. 1995a) which restricts solutions to the coarsest possible spatial resolution consistent with the observations. The residues minimization involves a phase-space search based on the simulated annealing method, from which the best-fit coefficient solution is found. In addition, i and β may also be varied, thereby allowing for improvement of the geometric oblique rotator parameters.

We have computed field line inclination modifications via this method for HD 192678. The resultant linear polarization variations are shown in Fig. 5. With an average reduced χ^2 of 2.9, this modified oblique dipole model is a significant improvement over the pure dipole. This model predicts a localized region of magnetic field lines (at the magnetic equator) which tend to open outwards. The magnetic field geometry is shown in Fig. 6 and the region of open field lines has been circled. The adopted values of i, β and B_p for the modified model are $i = 173° \pm 5°$, $\beta = 120° \pm 7°$ and $B_p = 6.8$ kG $\pm$ 0.2 kG. The longitudinal field and surface field variations for the modified dipole model are shown in Fig. 1 (solid curves). The values of the coefficients in the spherical harmonic expansion which describes the modifications to the field line inclinations, as well as a subroutine which computes the magnetic field geometry therefrom, are available by contacting JLL.

3.3. Synthesis of Fe II $\lambda\,6149.2$

No significant additional information about the magnetic field structure of HD 192678 appears to be contained in the longitudinal field, surface field or linear polarization data. The Fe II $\lambda\,6149.2$ line profiles may offer something

Fig. 5. Linear polarization measurements of HD 192678. The solid curve is the computed variation for the modified dipole model described in the text. The reduced χ^2 is 2.9.

Fig. 6. Magnetic field geometry of HD 192678 based on the modified dipole model discussed in the text. The point at which the rotation axis intersects the surface of the star is indicated with a small circle, while the larger circle indicates the region of open field lines.

further. Although these data were acquired chiefly as a tool for surface field measurement, their availability motivated us to attempt to model them. To ensure a homogeneous data set, we have modeled only profiles from spectra acquired at OHP.

Line profile modeling of the Fe II $\lambda\,6149.2$ Zeeman doublet was performed using ZEESYNTH, an LTE line synthesis programme for modeling spectra of magnetic Ap stars developed by JDL (Landstreet et al. 1989) and modified by GW. This programme is designed to calculate radiative transfer in all four Stokes parameters for a stellar atmosphere permeated by a very general magnetic field. The disk-integrated synthetic line profiles, which are computed at a number of phases, are broadened using a Gaussian instrumental profile and ultimately compared with the observations.

The ATLAS9 model atmosphere assumed for the HD 192678 line synthesis has an effective temperature of 9000 K and $\log g = 4.0$ (Stepien and Dominiczak 1989).

The formation of Fe II $\lambda\,6149.2$, which occurs under partial Paschen-Back effect, is thoroughly described by Mathys (1990). The partial Paschen-Back effect is mild in the case of surface fields with strengths similar to those of HD 192678, and serves to introduce an asymmetry into the local profile. We have modeled this line assuming only Zeeman effect, which predicts a symmetric local profile. Based on the results of Mathys (1990) it is not expected that the exclusion of the partial Paschen-Back effect has affected the modeling at any significant level.

Several observed profiles, phased according to the adopted ephemeris, are shown in Fig. 7 as the dashed curves. The model profiles, computed assuming the modified dipole model described in Sect. 3.2 and a projected equatorial rotation velocity $V_e \sin i = 4.0\ \mathrm{km\,s^{-1}}$ are the superimposed solid curves. It should be noted that, while our modified field line inclinations have been included in the computations, they have little affect on the resulting profiles.

This model reproduces the gross variability of the line profiles quite well. The observed and computed profile variations, due primarily to rotational Doppler effect combined with the magnetic pole crossing the stellar disk, are accurately phased relative to one another. This shows that the profiles are consistent with a nearest approach of the magnetic pole to the line-of-sight occurring at surface field maximum. Nevertheless, obvious discrepancies are apparent between observation and calculation.

The source of these discrepancies is currently ambiguous. As can be seen in Fig. 8, reducing the pole-to-equator ratio of the dipole field strength in the modified dipole model by about 20% (either by multiplying the dipole field strength by the Y_2^0 spherical harmonic, or by introducing a colinear octupole with a polar strength of about -2 kG) serves to improve the agreement between observation and computation. Introducing this modification decreases slightly the amplitude of variation of the computed surface field, while leaving the other computed parameters virtually unchanged. We can achieve a similar level of agreement using the original modified dipole model, reducing our assumed $V_e \sin i$ to $2.0\ \mathrm{km\,s^{-1}}$ and adding $1.5\ \mathrm{km\,s^{-1}}$ of microturbulent broadening. Unfortunately, our spectra do not contain the appropriate unblended lines with which one might choose between these two possibilities. For the moment, this ambiguity must remain unresolved.

Even with the good agreement in Fig. 8, there is still one feature of the observed profiles which is systematically underreproduced in the computations – the total breadth of the profiles. Our experimentation has shown that this does not appear to be due to rotational or microturbulent broadening. This excess broadening is quite possibly magnetic, and may indicate that small regions of enhanced field strength exist in the photosphere of HD 192678. This could be verified by determining whether the widths of magnetically insensitive lines are well reproduced by our model.

4. Conclusion

We have developed a magnetic model for HD 192678 based on longitudinal and surface field measurements, broadband linear polarization measurements and high-resolution unpolarized spectra. This is the largest database ever used in constructing a stellar magnetic model. We began with an oblique rotating dipole phased such that the closest approach to the line-of-sight of the positive magnetic pole occurred at surface field maximum. Discrepancies between the observed and computed broadband linear polarizations motivated us to explore models with magnetic field line orientations which were modified from those of a dipole. Our result consists of an oblique rotating dipole with polar strength $B_p = 6.8\ \mathrm{kG} \pm 0.2\ \mathrm{kG}$, a rotation axis inclined to the line-of-sight by an angle $i = 173^\circ \pm 5^\circ$ and with an obliquity of the magnetic axis to the rotation axis of $\beta = 120^\circ \pm 7^\circ$. Simultaneous agreement of the observed and computed surface field and linear polarization variations requires a localized equatorial region (a "patch") in which the magnetic field line inclinations tend to extend outward as compared to those of a pure dipole.

Because the surface field and broadband linear polarization measurements were secured during the same period of time, the relative phase of these observations is not affected by the $0\overset{\mathrm{d}}{.}002$ uncertainty in the rotation period of HD 192678. Thus, we consider our detection of magnetic deviations from an oblique rotating dipole to be quite definite.

In addition, our modeling of the line profile variations of the Fe II $\lambda\,6149.2$ Zeeman doublet shows that line broadening is present whose source is neither rotation nor microturbulence. This may be indicative of small regions of strong magnetic field in the photosphere of HD 192678. This could be verified by determining whether the widths

Fig. 7. Observed Fe II $\lambda\,6149.2$ line profiles. The solid curves are the computed profiles assuming the modified dipole model, the atmospheric parameters described in the text and $V_e \sin i = 4.0\ \mathrm{km\,s^{-1}}$.

Fig. 8. Observed Fe II $\lambda\,6149.2$ line profiles. The solid curves are the computed profiles assuming the modified dipole model with the pole-to-equator field strength ratio decreased by 20%, the atmospheric parameters described in the text and $V_e \sin i = 4.0\ \mathrm{km\,s^{-1}}$.

of magnetically insensitive lines are well reproduced by our model. Our profiles may also be consistent with a dipole field whose pole-to-equator modulus ratio has been decreased by about 20%. This is uncertain however, since we can achieve the same level of agreement by reducing the projected rotational velocity and introducing a small ($1.5\ \mathrm{km\,s^{-1}}$) microturbulent broadening. Testing whether a curve-of-growth analysis is consistent with our assumed microturbulence should solve this problem. In any case, it is evident that the issues discussed in this paragraph are coupled, and should be resolved with this in mind.

The additional constraint on the transverse field geometry which is imposed by broadband linear polarimetric measurements is chiefly responsible for the recent detection of the limitations of classical magnetic models in a significant number of cases (e.g. β CrB and 49 Cam (Leroy et al. 1995a), HD 71866 (Bagnulo et al. 1995), 53 Cam (Leroy et al. 1995b)). Another factor is the recent accumulation of high-precision surface field observations for a large number of stars (Mathys et al. 1996). With these improvements in techniques and precision we are beginning to develop a more sophisticated picture of the magnetic fields of Ap stars.

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