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Evolutionary estimates for 10 magnetic Ap stars calculated from their rigid rotator geometries

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Abstract. I present estimates of the evolutionary states (effective temperatures, masses, radii, luminosities and ages) of 10 magnetic Ap stars, and subsequent constraints on the evolution of magnetic fields in these objects.

Using rotational axis inclinations ($\sin i$) reported by Leroy et al. (1996), combined with apparent rotational velocities ($v \sin i$) and rotational periods ($P_{\rm rot}$) obtained from a variety of sources, the radii of these stars have been calculated assuming rigid rotation. From the positions of these objects in the radius-effective temperature ($\log\left(\frac{R}{R_\odot}\right) - \log T_{\rm eff}$) plane I obtain their evolutionary states using the model evolutionary calculations by Schaller et al. (1992).

The stars in this study span the entire width of the main sequence, showing no tendancy to cluster near the ZAMS or the TAMS. In this respect these results are consistent with the conclusion of North (1993) (who reports that the Ap (CP2) stars appear to be distributed uniformly along the width of the main sequence) and inconsistent with that of Hubrig & Mathys (1994) (who suggest that the magnetic Ap stars may be near the end of their main sequence life).

When the magnetic field strengths of these stars are graphed versus the fraction of main sequence evolution completed, no correlation is evident. However, it is of interest to note that strong magnetic fields do exist in Ap stars at all evolutionary states (from the ZAMS to the TAMS), and that more than 70% of the stars discussed in this paper have polar magnetic field strengths between 3 and 6 kG. A similar graph of the magnetic axis obliquity angle β of each star versus age shows that intermediate values of β exist for stars as old as 10^9 y. This indicates that, if β does evolve toward asymptotic values as suggested by Mestel et al. (1981), the timescale for this evolution is quite long, at least for stars with $\sim$ 5 kG surface magnetic fields and rotational periods near 10 days.

Key words: stars: chemically peculiar – stars: evolution – stars: magnetic field – stars: temperatures – stars: rotation

1. Introduction

The many phenomena associated with the magnetic Ap stars remain some of the most perplexing mysteries in stellar physics. The presence of multi-kilogauss magnetic fields in their atmospheres, coupled with chemical abundances which vary by orders of magnitude both within a given Ap star's atmosphere and from star to star, shows quite clearly that interesting (and poorly understood) physical processes operate within these stars.

An understanding of the origin of these phenomena (and subsequent constraints on the responsible physics) demands data concerning the evolutionary state (i.e. the HR diagram position) of these objects. Not only does this offer us basic data (masses, radii, luminosities and ages), it furthermore enables us to determine any correlation which may exist between evolutionary state and peculiarity. A number of methods exist with which we can determine these evolutionary states.

Detailed studies of Ap stars in spectroscopic and speckle binaries (see Abt et al. 1968, Bonsack 1976, Oetken & Orwert 1984, and Wade et al. 1996) can provide useful constraints on the evolutionary states of these objects. However, as very few of these systems are currently known, the amount of information available via this technique is quite limited.

Ap stars belonging to open clusters and associations offer us another alternative for obtaining evolutionary data (see Hubrig & Schwan 1991, North 1993 and Hubrig & Mathys 1994). Since distances to these clusters are presumably known via the moving cluster method or main sequence fitting, the absolute magnitudes of member stars are easily determined. Taken along with their effective temperatures, this allows the evolutionary states of any Ap members to be calculated. While this method shows promise in principle, in practice it is notoriously difficult to determine membership of individual stars in open clusters.

Another technique employs the fact that magnetic, rotating Ap stars exhibit specific polarization variability which can be, to first order, modeled as an oblique rotating magnetic dipole (see Landstreet 1988, Landstreet et al. 1989). Fitting this model to combined circular and linear polarization measurements furnishes three parameters, which are determined uniquely. The first two are the angle between the magnetic dipole axis and the stellar rotational axis (generally denoted by β) and the polar strength of the magnetic dipole (generally denoted by $B_{\rm d}$). While these parameters are quite useful to those studying the magnetism in these objects, they are of little value in determining their evolutionary states. However, the third parameter which is furnished by the model is the inclination of the stellar rotational axis to the observer's line-of-sight. Since the rotational periods of these objects are in general well known (from the rotational modulation of various observables), and their apparent rotational velocities ($v \sin i$) can be measured, we can determine their radii from straightforward relations provide by rigid rotation. If we furthermore infer their effective temperatures, evolutionary states can be determined.

Results generally agree that the magnetic Ap stars (as well as the other classes of peculiar A and B-type stars[1]) are main sequence objects. Their position within the main sequence is somewhat a matter of controversy, and has been addressed in a number of studies. Two of these studies, by Hubrig & Schwan (1991) and Hubrig & Mathys (1994), attempted to derive physical parameters for 5 Ap stars which they had determined to be members of the Hyades and UMa superclusters. They concluded that all of these stars had completed a significant fraction of their main sequence evolution, and that A stars possibly become magnetic near the end of core hydrogen burning. However, North (1993) presented a extensive photometric study of peculiar stars in open clusters, and concluded that the frequency of Ap stars is essentially constant along the width of the main sequence.

In this study I employ the rigid rotation technique to derive evolutionary estimates for a sample of magnetic Ap stars for which the results of polarization measurements have recently become available. In Sect. 2, I describe quantitatively the rigid rotation technique, and the input data which I use to calculate the radii of the stars under consideration. In Sect. 3, I briefly describe the results for each object, and compare my results with any obtained previously. Finally, in Sect. 4, I discuss the implications of these results on our understanding of the origin of the phenomena (particularly the magnetic fields) which we observe in the magnetic Ap stars.

2. Calculation of the evolutionary state of magnetic Ap stars via the rigid rotation technique

To determine the evolutionary states of the stars included in this study I have calculated their radii and effective temperatures, and thereby located them on the radius-effective temperature plane. By adopting a model for stellar evolution (that described by Schaller et al. 1992) I have furthermore inferred their masses, luminosities and ages.

The radius of a spherical, rotating star with rotational period $P_{\rm rot}$ (in days), apparent rotational velocity $v \sin i$ (in km s^{-1}) and inclination angle i of its rotational axis to the line of sight is given by

$$\frac{R}{R_\odot} = \frac{P_{\rm rot}\ v \sin i}{50.6 \sin i}. \tag{1}$$

Historically, application of this expression to individual stars has been hampered by lack of data concerning i. However, as described in Sect. 1, applying the oblique rotator model to a magnetic Ap star for which both circular and linear polarimetry is available furnishes a unique (and generally quite precise) value for this angle. Using inclination angles published recently by Leroy et al. (1996) and Wade et al. (1996) and applying this technique, I have calculated radii for the 10 Ap stars listed in Table 1 (wherein are also listed the rotational periods, inclination angles and apparent rotational velocities necessary for calculation of the radii). When coupled with the effective temperatures of these stars (also listed in Table 1), these data determine a unique position for each star in the radius-effective temperature plane.

I have transformed the theoretical luminosity-effective temperature evolutionary tracks for solar metallicity calculated by Schaller et al. (1992) to the radius-effective temperature plane using the simple expression

$$\log \frac{R}{R_\odot} = \frac{1}{2} \log \frac{L}{L_\odot} - 2 \log \frac{T_{\rm eff}}{T_{\rm eff\odot}}. \tag{2}$$

The transformed evolutionary tracks, as well as the positions of the stars considered in the study, are shown in Fig. 1.

Table 1. Input data concerning the Ap stars included in this study. Sources are provided in Sect. 3.

HD designation	$P_{\rm rot}$ (days)	$v \sin i$ (km s^{-1})	i (°)	$T_{\rm eff}$ (K)
4778	2.56	34 ± 3	70 ± 15	9180 ± 300
24712	12.46	6 ± 2	140 ± 5	7330 ± 140
62140	4.29	23 ± 3	90 ± 5	7900 ± 330
71866	6.80	14 ± 4	110 ± 5	8760 ± 100
80316	2.09	32 ± 5	60 ± 15	8070 ± 230
98088	5.90	27 ± 3	85 ± 5	8610 ± 700
108662	5.06	20 ± 3	55 ± 15	10000 ± 490
115708	5.08	13 ± 2	130 ± 15	7510 ± 230
118022	3.72	10 ± 4	25 ± 5	9250 ± 270
137909	18.49	3.5 ± 1.5	160 ± 5	7730 ± 380

3. Comments on individual stars

The literature was searched extensively for effective temperatures and apparent rotational velocities. In the following comments, unless stated otherwise, where several precise values of $T_{\rm eff}$ or $v \sin i$ were available these values were averaged to obtain a more representative value, and the standard deviation was used as a measure of the related uncertainty.

[1] This includes the He-strong and He-weak SiSrTi stars in which magnetic fields are also routinely observed, and the Ap HgMn, Am, λ Boo and He-weak PGa stars, in which magnetic fields have generally not been detected.

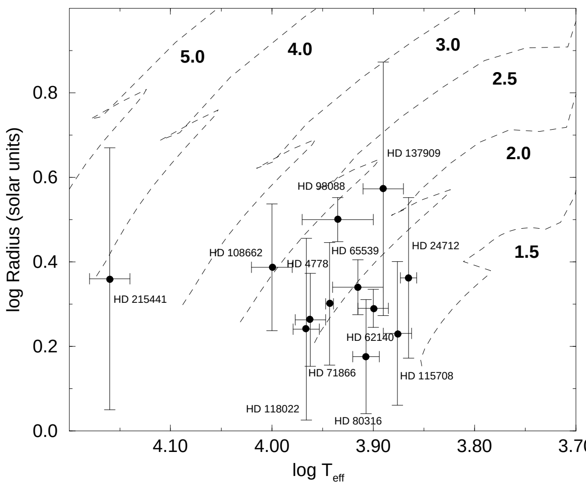

Fig. 1. Positions of programme stars in the $\log\left(\frac{R}{R_\odot}\right) - \log T_{\rm eff}$ plane. Evolutionary tracks are labelled in solar masses.

Table 2. Evolutionary results. For completeness I also include the results for HD 65339 (53 Cam; Landstreet 1988) and HD 215441 (Babcock's star; Landstreet et al. 1989)

HD designation	Radius ($R_\odot$)	Mass ($\mathscr{M}_\odot$)	Luminosity ($L_\odot$)	Age (10^8 y)
4778	$1.83^{+0.58}_{-0.36}$	2.1 ± 0.2	21^{+21}_{-9}	2.5
24712	$2.30^{+1.14}_{-0.91}$	1.8 ± 0.3	14^{+19}_{-9}	11.1
62140	$1.95^{+0.26}_{-0.15}$	$1.8^{+0.2}_{-0.1}$	13^{+7}_{-3}	7.9
65339	2.30 ± 0.4	2.0 ± 0.3	25^{+12}_{-8}	6.8
71866	$2.00^{+0.67}_{-0.61}$	2.1 ± 0.3	21^{+18}_{-11}	4.1
80316	$1.53^{+0.63}_{-0.38}$	$1.7^{+0.1}_{-0.2}$	9^{+11}_{-4}	5.2
98088	$3.16^{+0.39}_{-0.36}$	$2.4^{+0.3}_{-0.2}$	49^{+35}_{-22}	5.6
108662	$2.44^{+1.14}_{-0.63}$	2.6 ± 0.4	53^{+85}_{-29}	2.8
115708	$1.70^{+0.92}_{-0.48}$	$1.7^{+0.3}_{-0.2}$	8^{+14}_{-4}	5.9
118022	$1.74^{+1.05}_{-0.71}$	2.1 ± 0.4	20^{+37}_{-14}	1.5
137909	$3.74^{+3.32}_{-2.01}$	$2.2^{+0.8}_{-0.5}$	45^{+147}_{-37}	8.5
215441	2.60 ± 1.2	3.9 ± 1	63^{+95}_{-38}	0.3

3.1. HD 4778

The inclination $i = 70° \pm 15°$ is taken from Leroy et al. (1996) and the period $P_{\rm rot} = 2\overset{\rm d}{.}56$ from Leroy (1995). Values of $v \sin i$ from Hensberge et al. (1991) (35 $\rm km\,s^{-1}$; calculated from the line width given in Babcock (1958), calibrated to $v \sin i$) and Abt & Morrell (1995) (33 $\rm km\,s^{-1}$) result in an adopted $v \sin i = 34 \pm 3$ $\rm km\,s^{-1}$ (where a reasonable value for the uncertainty has been assumed). The effective temperature of 9180 ± 300 K is from the Geneva photometry in Hauck & North (1982) and Geneva photometry-effective temperature calibrations in Hauck & North (1993). These characteristics place HD 4778 quite close to the ZAMS.

3.2. HD 24712

The inclination $i = 140° \pm 5°$ is taken from Leroy et al. (1996) and the period $P_{\rm rot} = 12\overset{\rm d}{.}46$ from Leroy (1995). No accurate value of $v \sin i$ had been published for this slow rotator. Using a high-resolution ($\lambda/\Delta\lambda = 10^5$) optical spectrum of this star obtained using the ESO CAT+CES by Mathys (1996) I have determined the effective temperature $T_{\rm eff} = 7330 \pm 140$ K and apparent rotational velocity $v \sin i = 6 \pm 2$ $\rm km\,s^{-1}$by comparison with synthetic spectra computed using the LTE line-synthesis programme ZEEFIT (Landstreet 1988). The effects of a dipolar magnetic field with polar strength 4500 G and magnetic axis obliquity $\beta = 147° \pm 5°$ (consistent with the circular and linear polarization variations) were also included in the synthesis. For the temperature determination I compared observed lines of Fe I and Fe II with synthesized lines, assuming model atmospheres with surface gravities consistent with the HR diagram position of the star at a number of assumed temperatures. The temperature determined in this manner is consistent with the Geneva photometry temperature of 7110 K (Hauck & North 1982, 1983), that reported by Mathys et al. (1996) (7400 K; calculated from the Strömgren photometry calibration of Moon & Dworetsky 1985), that reported by Renson et al. (1991) (7230 K) and that reported by Kupka et al. (1994) (7500 K; from $\rm H\gamma$ and metal line syntheses). The derived apparent rotational velocity is basically consistent with previous results (Renson et al. 1991 (7 $\rm km\,s^{-1}$), Kupka et al. 1994 ($<$ 5 $\rm km\,s^{-1}$), Abt & Morrell 1995 ($<$ 10 $\rm km\,s^{-1}$)).

Kurtz & Martinez (1993) have employed the pulsation amplitudes of this roAp star to determine its position on the HR diagram, and determine it to be a 1.6 $\mathscr{M}_\odot$ star which has completed a considerable fraction ($>$ 50%) of its evolution along the main sequence. My estimate is completely consistent with this result.

3.3. HD 62140 (49 Cam)

The inclination $i = 110° \pm 5°$ is taken from Leroy et al. (1996), the period $P_{\rm rot} = 4\overset{\rm d}{.}29$ from Leroy (1995). Reports of $v \sin i$ in the literature from Abt & Morrell (1995) (18 $\rm km\,s^{-1}$), Bonsack et al. (1974) (22 $\rm km\,s^{-1}$) and Wolff (1976) (30 $\rm km\,s^{-1}$) result in $v \sin i = 23 \pm 3$ $\rm km\,s^{-1}$. The effective temperature $T_{\rm eff} = 7900 \pm 330$ K is calculated from Geneva photometry (7570 K; Hauck & North 1982, 1983) and the temperature reported by Mathys et al. (1996) (8230 K; calculated from the Strömgren photometry calibration of Moon & Dworetsky 1985). These characteristics indicate that 49 Cam has completed about 50% of its main sequence evolution.

3.4. HD 71866

The inclination $i = 95° \pm 5°$ is taken from Leroy et al. (1996) and the period $P_{\rm rot} = 6\overset{\rm d}{.}80$ from Leroy (1995). The adopted $v \sin i = 14 \pm 4$ $\rm km\,s^{-1}$ is calculated from the results of Hensberge et al. (1991), who give $v \sin i = 12$ $\rm km\,s^{-1}$ (calculated from the line width given by Babcock (1958), calibrated to

$v \sin i$), and Wolff (1976), who gives 17 $\mathrm{km\,s^{-1}}$. The effective temperatures available in the literature are from Geneva photometry (8665 K; Hauck & North 1982, 1983) and the UV energy distribution (8850 K; Adelman (1985)), and result in an adopted $T_{\rm eff}$ = 8760 $\pm$ 100 K. These characteristics indicate that HD 71866 has completed less than half of its main sequence evolution.

3.5. HD 80316

No value of $v \sin i$ has previously been published for this poorly studied roAp star. Using an optical spectrum ($\lambda/\Delta\lambda = 7 \times 10^4$; Mathys 1996) of this star I have determined the apparent rotational velocity $v \sin i = 32 \pm 5$ $\mathrm{km\,s^{-1}}$ using a spectrum synthesis procedure similar to that used for HD 24712. Since no magnetic field measurements of this star have been published, I have not included magnetic effects in the spectrum synthesis. However, since this star rotates fairly rapidly, magnetic broadening of the spectral lines should introduce a negligible error into measurements of $v \sin i$ (errors due to line blending are considerably more important). Effective temperatures reported in the literature are from Geneva photometry (7840 K; Hauck & North 1982, 1983) and that reported by Mathys et al. (1996) (8300 K; calculated from the Strömgren photometry calibration of Moon & Dworetsky 1985). The adopted effective temperature is $T_{\rm eff}$ = 8070 $\pm$ 230 K.

Photometry (Manfroid & Mathys 1986, Kurtz (1990)) and broadband linear polarimetry (Leroy 1995) show that two possible rotational periods exist: $P_{\rm rot}$ = $4\overset{\rm d}{.}18$ or $P_{\rm rot}$ = $2\overset{\rm d}{.}09$. According to Kurtz (1990, 1996), the rotational splitting of the pulsation frequencies of HD 80316 determine different values of the quantity $\tan i \tan \beta$ (based on the oblique pulsator model, or OPM) depending on which rotational period one selects. For $P_{\rm rot}$ = $2\overset{\rm d}{.}09$, Kurtz (1990) obtains $\tan i \tan \beta$ = 1.23, whereas for $P_{\rm rot}$ = $4\overset{\rm d}{.}18$, Kurtz (1996) finds $\tan i \tan \beta$ to be very large, implying that either i or β (or both) is near 90°. Since Leroy's (1995) linear polarization measurements also provide constraints on i and β, can we rule out one of the (*a priori*) acceptable rotational periods using this information?

For $P_{\rm rot}$ = $2\overset{\rm d}{.}09$, Leroy's (1995) linear polarization measurements trace a single loop in the Q-U plane. Using the $\tan i \tan \beta$ = 1.23 constraint provided by the OPM (Kurtz 1990) and the computed linear polarization variations for magnetic dipoles by Landolfi et al. (1993), Leroy et al. (1996) obtain i = 60° $\pm$ 15° and β = 35° $\pm$ 15°. The radius implied by these values of $P_{\rm rot}$ and i is R = 1.5 $R_\odot$, reasonable for a star with this temperature near the ZAMS.

For $P_{\rm rot}$ = $4\overset{\rm d}{.}18$, Leroy's (1995) linear polarization measurements trace a double loop in the Q-U plane, with both loops similar in size. The OPM requires that either i or β (or both) is near 90° (Kurtz 1996). The computed linear polarization models of Landolfi et al. (1993) match the observed linear polarization variation (Leroy 1995) for only a very limited range of (i, β) consistent with the OPM requirement: $60° \leq \beta \leq 90°$ and $i \leq 30°$.

For $P_{\rm rot}$ = $4\overset{\rm d}{.}18$ and $i \leq 30°$, we obtain a radius for HD 80316 of $R \geq 4.5$ $R_\odot$. Such a radius places HD 80316 at the end of core hydrogen burning or within the Hertzsprung gap, presumably an unlikely scenario[2].

Since the radii which correspond to the two possible rotational periods above clearly imply quite different surface gravities for HD 80316 ($\log g$ = 3.6 for $P_{\rm rot}$ = $4\overset{\rm d}{.}18$ and $\log g$ = 4.3 for $P_{\rm rot}$ = $2\overset{\rm d}{.}09$), I have attempted to estimate $\log g$ for this star using Strömgren photometry and the grids published by Moon & Dworetsky 1985. Using values of Strömgren β and c_0 indices (Martinez & Kurtz 1995) I find $\log g$ = 4.2. Since the typical photometric errors translate into an uncertainty of about 0.1 dex in surface gravity, this effectively rules out the larger radius, and therefore the longer rotational period. Based on this analysis I adopt $P_{\rm rot}$ = $2\overset{\rm d}{.}09$ and i = 60° $\pm$ 15°.

Clearly, further direct investigation of the rotational period of this star should be pursued, and circular polarization measurements should be obtained.

3.6. HD 98088

HD 98088 is an SB2, and the evolutionary estimate clearly refers to the Ap component. The inclination i = 85° $\pm$ 5° is from Leroy et al. (1996) and the period $P_{\rm rot}$ = $5\overset{\rm d}{.}90$ from Leroy (1995). Reported rotational velocities are from Abt & Morrell (1995) (31 $\mathrm{km\,s^{-1}}$) and Wolff (1976) (25 $\mathrm{km\,s^{-1}}$), and I adopt $v \sin i$ = 27 $\pm$ 3 $\mathrm{km\,s^{-1}}$. The effective temperature $T_{\rm eff}$ = 8610 $\pm$ 700 K is calculated from Geneva photometry (7910 K; Hauck & North 1982, 1983) and Hγ profile fitting (9300 K; Abt et al. (1968)). These characteristics indicate that HD 98088 has completed most of its main sequence evolution. The mass which we infer ($2.4^{+0.3}_{-0.2}$ $\mathcal{M}_\odot$) is consistent with the estimate of Abt et al. (1968), who find the Ap component of this binary to have a mass of 2.2 $\pm$ 0.5 $\mathcal{M}_\odot$.

3.7. HD 108662 (17 Com)

The inclination i = 55° $\pm$ 15° is taken from Leroy et al. (1996) and the period $P_{\rm rot}$ = $5\overset{\rm d}{.}06$ from Leroy (1995). There appears to be no clear consensus about the apparent rotational velocity of this object, with values from 10 to 22 $\mathrm{km\,s^{-1}}$ reported in the literature. However, Rice & Wehlau (1994) performed Doppler imaging on this star, employing $v \sin i$ of 20 $\mathrm{km\,s^{-1}}$. Such a careful analysis of the line profile variations is far more likely to produce an accurate $v \sin i$ than most other methods; I have therefore adopted this value. Effective temperatures reported are from Geneva photometry (9530 K; Hauck & North 1982, 1983) and the optical energy distribution (10500 K; Wolff 1967). I adopt $T_{\rm eff}$ = 10000 $\pm$ 490 K. These characteristics indicate that HD 108662 has completed about half of its main sequence evolution.

[2] Although Kurtz & Martinez (1993) and Mathys et al. (1996) both find that the roAp stars, while still main sequence stars, are generally evolved and lie well above the ZAMS.

3.8. HD 115708

The inclination $i = 130° \pm 15°$ and period $P_{\rm rot} = 5^{\rm d}\!.08$ are taken from Wade et al. (1996). No value of $v \sin i$ had been published for this object. Using an optical spectrum of this star (Mathys 1996) I have determined the effective temperature $T_{\rm eff} = 7510 \pm 230$ K and apparent rotational velocity $v \sin i = 13 \pm 2$ km s^{-1} using a spectrum synthesis procedure identical to that used for HD 24712. The effects of a dipolar magnetic field with polar strength 5000 G and magnetic axis obliquity $\beta = 77° \pm 6°$ (consistent with the circular and linear polarization variations) were also included in the synthesis. The spectroscopic effective temperature is consistent with the Geneva photometry temperature of 7520 K (Hauck & North 1982, 1983) and that reported by Mathys et al. (1996) (7620 K; calculated from the Strömgren photometry calibration of Moon & Dworetsky 1985). These characteristics indicate that HD 115708 has a mass below 2 $\mathcal{M}_\odot$, and that it has probably completed less than 50% of its main sequence evolution.

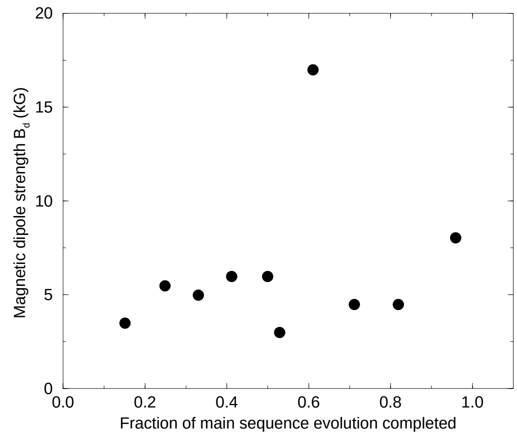

Fig. 2. Polar magnetic field strength $B_{\rm d}$ versus fractional main sequence evolutionary state for the magnetic Ap stars listed in Table 3. Typical uncertainties are about ±10% in $B_{\rm d}$, and about ±0.2 in fractional evolution. Babcock's star is out of range, with $B_{\rm d}$ = 65.0 kG.

3.9. HD 118022 (78 Vir)

The inclination $i = 25° \pm 5°$ is taken from Leroy et al. (1996), the period $P_{\rm rot} = 3^{\rm d}\!.72$ from Leroy (1995). Wolff & Preston (1978), Abt et al. (1972) and Abt & Morrell (1995) all agree that $v \sin i$ is 10 km s^{-1}: this value has been adopted. The effective temperatures reported in the literature are from Geneva photometry (9063 K; Hauck & North 1982, 1983), the optical energy distribution (9690 K (Wolff 1967) and 9250 K (Monier 1993)) and the UV energy distribution (9000 K; Adelman (1985)). I adopt $T_{\rm eff} = 9250 \pm 270$ K. These characteristics indicate that 78 Vir probably lies near the ZAMS, and has almost certainly completed less than 50% of its main sequence evolution. These results are not consistent with the evolutionary estimate of Hubrig & Schwan (1991), who, based on their conclusion that 78 Vir is a member of the UMa supercluster, find this star to be approaching the end of core hydrogen burning.

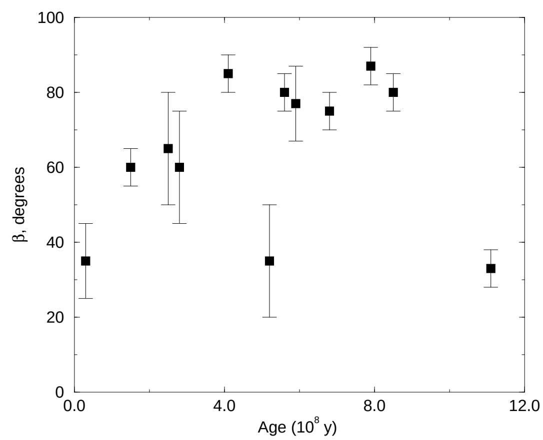

Fig. 3. Obliquity angle β of the magnetic field axis with respect to the rotational axis versus age for the magnetic Ap stars listed in Table 3. Typical age uncertainties are about $1 - 2 \times 10^8$ y.

3.10. HD 137909 (β CrB)

This well-studied Ap star is a member of a speckle binary. The inclination $i = 160° \pm 5°$ is from Leroy et al. (1996), the period $P_{\rm rot} = 18^{\rm d}\!.49$ from Leroy (1995). I adopt $v \sin i = 3.5 \pm 1.5$ km s^{-1}(Wade 1996) for the apparent rotational velocity, inferred from modeling the profile variability of magnetically-split lines in high-resolution ($\lambda/\Delta\lambda = 10^5$) optical spectra of this star. The effective temperatures reported in the literature are from Geneva photometry (7430 K; Hauck & North 1982, 1983), the optical energy distribution (7750 K (Farragiana & Gerbaldi 1993), the UV energy distribution (8350 K; Adelman (1985)) and that reported by Mathys et al. (1996) (7400 K; calculated from the Strömgren photometry calibration of Moon & Dworetsky 1985). The adopted effective temperature is $T_{\rm eff} = 7730 \pm 380$ K. The resultant characteristics permit rather a large range of possibilities for the evolutionary state of β CrB (due chiefly to its low $v \sin i$). However, this star is probably very close to the end of its main sequence lifetime, a result consistent with the conclusions of Oetken & Orwert (1984) and Hubrig & Mathys (1994).

4. Discussion and conclusions

It is clear that each of the stars included in this study has a strong magnetic field, since each exhibits continuum linear polarization and most have had spectral line circular polarization detected, each of which varies (to first order) in the fashion predicted by an oblique rotating magnetic dipole (Leroy et al. 1996). As the majority of these stars do not appear to be near the end of their main sequence lifetimes, magnetism in these stars cannot be a result of the impending onset of the end of core hydrogen burning. This conclusion of Hubrig & Mathys (1994) is not supported by these results.

There are, however, good reasons to expect systematic changes in the magnetic fields of these stars as they evolve along

Table 3. Magnetic field strengths, obliquity angles (transformed from the $0° - 180°$ scale of Leroy et al. (1996) to the more conventional $0° - 90°$ scale) and ages for the stars included in this study. As discussed in the text, the models a ssume a dipolar magnetic field geometry with polar strength B_d. Also included are HD 65339 (53 Cam) and HD 215441 (Babcock's star).

HD designation	Age (10^8 y)	Fractional Age	B_d (kG)	Source for B_d	β (°)	Source for β
4778	2.5	0.25	5.5	Bohlender (1989)	65	Leroy et al. (1996)
24712	11.1	0.71	4.5	Preston (1972)	33	Leroy et al. (1996)
62140	7.9	0.50	6.0	Landstreet (1996)	87	Leroy et al. (1996)
65339	6.8	0.61	17.0	Landstreet (1988,1996)	75	Landstreet (1988)
71866	4.1	0.41	6.0	Babcock (1958)	85	Leroy et al. (1996)
80316	5.2	0.29	-	-	35	Leroy et al. (1996)
98088	5.6	0.82	4.5	Babcock (1958)	80	Leroy et al. (1996)
108662	2.8	0.53	3.0	Preston et al. (1969)	60	Leroy et al. (1996)
115708	5.9	0.33	5.0	Wade et al. (1996)	77	Wade et al. (1996)
118022	1.5	0.15	3.5	Borra & Landstreet (1980)	60	Leroy et al. (1996)
137909	8.5	0.96	8.0	Mathys (1991)	80	Leroy et al. (1996)
215441	0.3	0.20	65.0	Landstreet et al. (1989)	35	Landstreet et al. (1989)

the main sequence. While several possible modes of field evolution exist, the most straightforward mode is the decrease in the surface magnetic field strength which accompanies the expansion of the star as it evolves. If we assume that magnetic flux is conserved, the surface magnetic field strength of a star will decrease as

$$B_\mathrm{S}(R) = B_0 \left(\frac{R_0}{R}\right)^2, \qquad (3)$$

where R_0 and B_0 are the ZAMS radius and surface magnetic field strength of the star, respectively.

Since all but one of the stars included in this study have had their longitudinal magnetic field variations measured, simple magnetic models can be fit to these data assuming the i and β angles given by Leroy et al. (1996). I have fit pure magnetic dipoles to the longitudinal field variations of each of the stars listed in Table 3, and graphed in Fig. 2 the polar strength of each model versus the age of the star in question, as a fraction of its total main sequence lifetime. While no trend is evident, it is of interest to note that:

- Strong magnetic fields exist in A stars at all stages of their main sequence evolution.
- All but 3 of the stars listed in Table 3 have magnetic field strengths B_d between 3.0 and 6.0 kG (although it should be kept in mind that these stars populate the high-field tail of the distribution, and are not representative of the "average" magnetic Ap star).

A number of authors have proposed models for magnetic field evolution which make specific predictions about how the magnetic obliquity β should change as Ap stars evolve. In particular, Mestel et al. (1981) predict evolution of β toward asymptotic values of either 0° or 90° on timescales as short as 10^5 y and as long as 10^{10} y, depending upon initial rotation rate and magnetic field geometry.

In Table 3 I list values of β reported by Landstreet (1989), Wade et al. (1996) and Leroy et al. (1996), and in Fig. 3 these values have been graphed versus the ages of the stars. The absence of stars with low β (near the bottom of Fig. 3) is at least in part due to a selection effect, since detection of magnetic stars using broadband linear polarization measurements (from which the majority of this sample is drawn) tends to systematically exclude stars with small β. We can therefore make no conclusions regarding the lack of data with $\beta < 30°$. However, Fig. 3 does show that intermediate values of β do exist for evolved stars (note the well-constrained point in Fig. 3 for HD 24712, located at [Age, β]=[11.1×10^8 y, 33°]). This suggests that, if β does evolve toward asymptotic values, the timescale for this evolution is considerably longer than 10^9 y for stars with $\sim$ 5 kG surface magnetic fields and rotational periods near 10 days.

That magnetic Ap stars exist across the entire width of the main sequence (and the inclusion of the results of Bonsack (1976) for the SB2 HD 55719, and those of Wade et al. (1996) for the SB2 HD 59435 only strengthens this conclusion) argues against any model which connects the source of their magnetic fields to a particular phase of main sequence evolution. The pre-main sequence should continue to be where we look in order to discover the most primitive information about the magnetic Ap stars.

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References

Abt H.A., Conti P.S., Deutsch A.J., Wallerstein G., 1968, ApJ 153, 177
Abt H.A., Chaffee F.H., Suffolk G., 1972, ApJ 175, 779
Abt H.A. & Morrell N.I., 1995, ApJS 99, 135
Adelman S.J., 1985, PASP 97, 970
Babcock H.W. 1958, ApJ 128, 228
Bohlender D.A. 1989, A&A 220, 215

Bonsack W.K., 1976, ApJ 209, 160
Bonsack W.K., Pilachowski C.A., Wolff S.C., 1974, ApJ 187, 265
Borra E.F. & Landstreet J.D. 1980, ApJS 42, 421
Faraggiana R. & Gerbaldi M., 1993, in *Peculiar Versus Normal Phenomena in A-Type and Related Stars*, IAU Colloquium 138, ASP Conference Series Vol. 44, M.M. Dworetsky, F. Castelli and R. Faraggiana (eds.), p. 169
Hauck B. & North P., 1982, A&A 114, 23
Hauck B. & North P., 1993, A&A 269, 403
Hensberge H., Van Rensbergen W. and Blomme R., 1991, A&A 249, 401
Hubrig S. & Schwan H., 1991, A&A 251, 469
Hubrig S. & Mathys G., 1994, Astron. Nachr. 315, 343
Kupka F., Ryabchikova T., Bolgova G., Kuschnig R., Weiss W.W., Mathys G., Le Contel J.M., in *Chemically Peculiar and Magnetic Stars*, Astronomical Institute, Slovak Academy of Sciences, Tatranská Lomnica, p. 130
Kurtz D.W., 1990, MNRAS 242, 489
Kurtz D.W., 1996, MNRAS, in press.
Kurtz D.W. & Martinez P., 1993, in *Peculiar Versus Normal Phenomena in A-Type and Related Stars*, IAU Colloquium 138, ASP Conference Series Vol. 44, MM. Dworetsky, F. Castelli and R. Faraggiana (eds.), p. 561
Kupka F., Ryabchikova T., Bolgova G., Kuschnig R., Weiss W.W., Mathys G., Le Contel J.M., 1994, in *Chemically Peculiar and Magnetic Stars*, Astronomical Institute, Slovak Academy of Sciences, J. Zverko & J. Ziznovsky (eds.), p. 130
Landolfi M., Landi Degl'Innocenti E., Landi Degl'Innocenti M., Leroy J.-L., 1993, A&A 272, 285
Landstreet J.D., 1988, ApJ 326, 967
Landstreet J.D., 1989, ApJ 344, 876
Landstreet J.D., 1996, private communication.
Landstreet J.D., Barker P.K., Bohlender D.A., Jewison M.S., 1989, ApJ 344, 876
Leroy J.-L., 1995, A&AS 114, 79
Leroy J.-L., Landolfi M., Landi Degl'Innocenti E., 1996, A&A 311, 513
Manfroid J. & Mathys G., 1986, A&AS 64, 9
Martinez P. & Kurtz D.W., 1995, Ap&SS 230, 29
Mathys G., 1991, A&AS 89, 121
Mathys G., 1996, private communication.
Mathys G., Kharchenko N., Hubrig S., 1996, A&A 311, 901
Mestel L., Nittman J., Wood W.P., Wright G.E.A., 1981, MNRAS 195, 979
Monier R., 1993, in *Inside the Stars*, IAU Colloquium 137, ASP Conference Series Vol. 40, W.W. Weiss & A. Baglin (eds.), p. 156
Moon T.T. & Dworetsky M.M., 1985, MNRAS 217, 305
North P., 1993, in *Peculiar Versus Normal Phenomena in A-Type and Related Stars*, IAU Colloquium 138, ASP Conference Series Vol. 44, MM. Dworetsky, F. Castelli and R. Faraggiana (eds.), p. 577
Oetken L. & Orwert R., 1984, Astron. Narchr. 305, 317
Preston G.W., 1972, ApJ 175, 465
Preston G.W., Stepien K., Wolff S.C. 1969, ApJ 156, 653
Renson P., Kobi D., North P., 1991, A&AS 89, 61
Rice J.B. & Wehlau W.H., 1994, A&A 291, 825
Schaller G., Schaerer D., Meynet G., Maeder A., 1992, A&AS 96, 269
Wade G.A., Neagu E., Landstreet J.D., 1996, A&A 307, 500
Wade G.A., 1996, in *Stellar Magnetism*, Russian Academy of Sciences, Yu.V. Glagolevskij & I.I. Romanyuk (eds.), in press.
Wade G.A., North P., Mathys G., Hubrig S., 1996, A&A 314, 491
Wolff S.C., 1967, ApJS 15, 21
Wolff S.C., 1976, in *Multiperiodic Variable Stars*, Konkoly Observatory, Budapest, L. Detre (ed.), p. 43
Wolff S.C. & Preston G.W., 1978, ApJS 37, 371

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