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Evolution of global magnetic fields in main sequence A and B stars

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Abstract. The (presumably fossil) magnetic fields in magnetic Ap stars are expected to evolve as the stars pass through the main sequence. Virtually no observational evidence currently constrains this process, because ages of field Ap stars cannot be determined accurately at present. To provide data about field evolution as a function of age, we are studying the fields of Ap stars in clusters. It is found that the fields, and probably the emergent magnetic flux, decline with increasing age for Ap stars in the range of 2 – 5 $M_\odot$.

Key words: stars: chemically peculiar – stars: evolution – stars: magnetic fields – open clusters and associations: general

1. Introduction

Magnetic fields are found in essentially all well-established Ap stars of the SrCrEu, Cr and Si stars, and in the Sr-Ti and Si classes of He-weak Bp stars. These fields show none of the usual symptoms of contemporary dynamo-generated fields, such as irregular short-term variability or great spatial intermittency, and they are generally thought to be fossil fields, based on flux left in the star from epochs of stellar evolution before the main sequence. In fact, the fields may be the remnants of the interstellar magnetic field trapped in the star during the early stages of star formation.

Even if the field is a fossil, it is expected to vary with time within a single star as the star evolves. Evolution of field strength and structure is expected as a consequence of (a) ohmic decay of the field, due to the finite electrical conductivity of the stellar plasma; (b) internal fluid flows in the star, such as the "meridional" circulation driven by stellar rotation, and (c) as a consequence of the structure changes that occur in a star as stellar evolution progresses (for example, the radius of a star increases by a factor of order two during the main sequence phase). These processes are understood to some extent, but as always, theoretical modelling benefits greatly from comparisons with observations.

However, at present there are essentially no reliable observational constraints on field evolution during a star's life as a luminous object, beyond the plausible idea that the fields of magnetic white dwarfs may be the fossil remnants of the fields of the magnetic Ap stars. There is no useful observational information about the evolution of field strength or structure during the main sequence phase, even though this is the longest stage of evolution before collapse.

We are trying to provide constraints on field evolution by measuring the fields in a large sample of Ap stars of known ages, from which we are beginning to see clear trends for the field strength with stellar age.

2. Measuring ages of Ap stars

To describe evolution across the main sequence, it is very useful to obtain both the absolute ages of stars, and the "relative" or "fractional" ages (ratio of actual age to main sequence lifetime).

One method of obtaining stellar ages is to use the observed effective temperature $T_{\rm eff}$ (determined from photometry or spectroscopy) and the luminosity $L/L_\odot$ (derived for example from apparent brightness, bolometric correction, and an accurate parallax). These quantities are plotted in a colour-magnitude or Hertzsprung-Russell diagram, where they are compared with theoretical isochrones. This method has been used to estimate ages for a large sample of Ap stars in the field by Hubrig *et al.* (2000) and by Kochukhov and Bagnulo (2006).

It is found that the inferred stellar masses are reasonably precise. However, the deduced ages are not very accurate, particularly for the first half of main sequence evolution when the structure of the star changes rather little, because there are important uncertainties in this method. There is an unavoidable uncertainty in the bulk chemical composition(s) to use in the theoretical isochrones (because the surface abundances of magnetic Ap stars are certainly not representative of the the bulk composition); and the values of $T_{\rm eff}$ are significantly more uncertain for magnetic Ap stars than for normal stars, because *no* fundamental values are available for calibration. As a result of the usual uncertainties plus these two additional factors, using this method, in general one can determine little more than whether a star is in the first or second half of its main sequence life. Diagrams explaining this difficulty can be found in Bagnulo *et al.* (2006, hereafter Paper I).

In contrast, much more accurate ages (both relative and absolute) can be derived for stars which are members of open clusters, for which the age can be derived either by fitting an isochrone to the whole cluster main sequence, or by the positions in the HR diagram of pre-main sequence stars.

Three important recent developments have made the use of cluster ages practical for the study of Ap star ages.

- The Hipparcos mission (ESA 1997) has led directly to an enormous increase in the number of accurate parallaxes available, and the data from this mission and from earlier positions studies have yielded the Tycho and Tycho-2 proper motion catalogues (Høg *et al.* 2000). These data together have made it possible to assign cluster membership much more securely than in the past for several tens of open clusters (e.g. Robichon *et al.* 1999; Baumgardt *et al.* 2000; Dias *et al.* 2001).
- Many new Ap star candidates in clusters have been identified by Δa photometry (Maitzen, 1983) and by Geneva photometry (Cramer, Maeder 1979); greatly simplifying the task of identifying stars to study. Because magnetic measurements are very resource-intensive, it is of great value to have a good pre-selection of stars.
- Finally, we now have access to a new generation of sensitive and powerful spectropolarimeters on large telescopes, including FORS1 at ESO's VLT (Bagnulo *et al.*, 2002) and ESPaDOnS on the CFHT (Landstreet *et al.*, 2008). These instruments make it possible to measure fields with usefully small standard errors (less than $\sim 10^2$ G) in stars of $m_V \lesssim 10$ in reasonable amounts of time, thus making it practical to survey magnetic stars in dozens of open clusters compared to the few that were accessible with the earlier generation of instruments.

As a consequence of these enabling factors, we have been able to carry out a survey of magnetic fields in more than 100 magnetic Ap stars in more than 40 open clusters (Paper I; Landstreet *et al.*, 2007). This has mainly been done using FORS1, but a significant part of the survey has also been carried out with ESPaDOnS. (Note that FORS1 uses is a rather low resolution spectropolarimeter, with $R \sim 2000$, while for ESPaDOnS $R \sim 65\,000$; as a result, ESPaDOnS can measure fields in stars with small $v_{\rm e} \sin i$ and rich spectra more accurately than FORS1 in spite of the unfavorable difference in telescope aperture.)

Absolute ages of clusters stars, of course, have the same precision as the cluster ages. Using the typical dating method of isochrone fitting, cluster ages are usually determined with a relative precision of the order of 0.1 to 0.3 dex ($\pm 30\%$ up to approximately a factor of 2), independent of the actual age of the cluster. Thus the fractional age of stellar members is very well determined for stars that have main sequence ages much longer than the cluster age; in other words, the precision of fractional ages for cluster stars is *best* for stars near the ZAMS. As we look at older and older clusters, up to ages near the main sequence lifetime of a magnetic Ap star, the relative uncertainty in the absolute age does not grow systematically, but the precision of the fractional age decreases, until near the TAMS fractional ages of cluster stars are similar in precision to those of field stars near the TAMS (for similar assumptions about uncertainties due to the poorly determined T_{eff} values and bulk chemistry of Ap stars).

3. Results from the open cluster survey

We make the reasonable assumption that field measurements of a sample of stars of different ages observed at a single time is approximately equivalent to observing the time evolution of fields in a fixed sample of stars. We have measured and found in the literature enough accurate field measurements of cluster Ap stars to have useful statistical samples of field evolution of stars in the mass ranges $2 - 3\,M_{\odot}$, $3 - 4\,M_{\odot}$, and $4 - 5\,M_{\odot}$. All three mass ranges give similar results, which we illustrate by showing the variation of RMS field (the RMS value of all available mean longitudinal field strength $\langle B_z \rangle$ having standard errors of order 10^2 G or less) with stellar fractional age in Fig. 1 for the mass intervals $2 - 3\,M_{\odot}$and $3 - 4\,M_{\odot}$..

The field strength evolution plot for $4M_{\odot} \leq M \leq 5M_{\odot}$ is similar to the upper panel of Fig. 1 (Landstreet *et al.*, 2008).

The following conclusions emerge from this study:

- In all three mass ranges, a number of stars are found with fractional ages close to zero. It is clear that detectable surface fields are present from the ZAMS onwards. Similarly, a significant number of stars with ages near the TAMS are present in our sample; fields apparently persist until the end of the main sequence life.
- Stars of small fractional age are found with large RMS fields B_{rms}. The largest RMS fields reach several kG. However, no RMS fields above 1 kG are found for stars of large fractional age, although our sample of such stars is now adequate to detect such fields if they occur with the frequency of large fields among relatively young stars.
- Low RMS fields (below about 1 kG, corresponding to an upper limit of the order of 4 or 5 kG in mean field modulus) occur for all fractional ages.
- The presence of large fields near the ZAMS and their absence near the TAMS is qualitatively compatible with the field decrease expected due to the global expansion of a star (by about a factor of 2 in radius) as it evolves from the ZAMS to the TAMS. However, the decline in field strength occurs too near the ZAMS (for $M > 3M_{\odot}$) for this to be the only explanation. Furthermore, when we plot the quantity $B_{\mathrm{rms}}R^2$ (a proxy for the total magnetic flux emerging from the surface of a star) as a function of absolute or fractional age, we find that the flux declines with age in all three mass bands.

It is now clear that observations of magnetic fields in Ap/Bp stars which are members of open clusters have become quite practical, and that such observa-

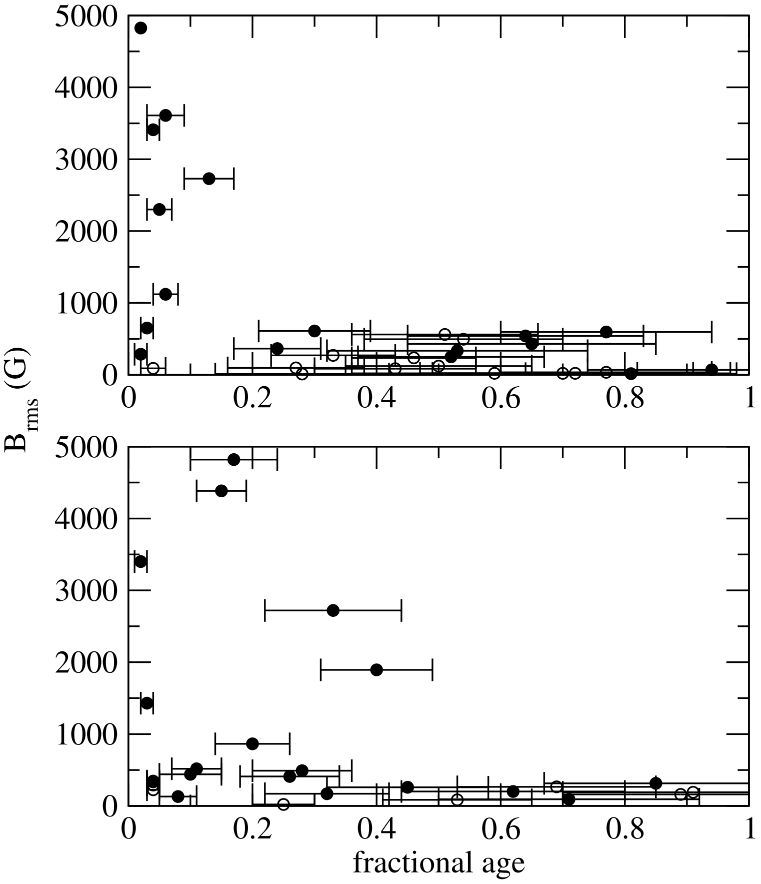

Figure 1. RMS field characterising stars with masses in the interval $2M_{\odot} \le M \le 3M_{\odot}$ (lower panel) and $3M_{\odot} \le M \le 4M_{\odot}$ (upper panel) as functions of stellar fractional age (= cluster age/main sequence lifetime). Filled circles refer to stars in which fields have been definitely detected; open circles to field measurements which have so far provided upper limits. Error bars on fractional age include both uncertainty in cluster age, and in the main sequence lifetime of the star arising from uncertain stellar parameters.

tions are already providing extremely interesting information about the evolution of surface magnetic fields in such stars. We are continuing our programme of observations, and are also starting to model intensity spectra of cluster Ap stars in order to better define observationally the evolution of atmospheric chemistry with age in these extremely interesting objects.

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References

Baumgardt, H., Dettbarn, C., Wielen, R.: 2000, *Astron. Astrophys., Suppl. Ser.* **146**, 251

Bagnulo, S., Szeifert, T., Wade, G.A., Landstreet, J.D., Mathys, G.: 2002, *Astron. Astrophys.* **389**, 191

Bagnulo, S., Landstreet, J.D., Mason, E., Andretta, V. Silaj, J., Wade, G.A.: 2006, *Astron. Astrophys.* **450**, 777

Cramer, N., Maeder, A.: 1979, *Astron. Astrophys.* **78**, 305

Dias, W.S., Lépine, J.R.D., Alessi, B.S.: 2001, *Astron. Astrophys.* **376**, 441

ESA: 1997, *The Hipparcos and Tycho Catalogues,* ESA SP-1200

Høg, E., Fabricius, C., Makarov, V.V., Bastian, U., Schwekendiek, P., Wicenek, A., Urban, S., Corbin, T., Wycoff, G.: 2000, *Astron. Astrophys.* **357**, 367

Hubrig, S., North, P., Mathys, G.: 2000, *Astron. Astrophys.* **539**, 352

Kochukhov, O., Bagnulo, S.: 2006, *Astron. Astrophys.* **450**, 763

Landstreet, J.D., Bagnulo, S., Andretta, V., Fossati, L., Mason, E., Silaj, J., Wade, G.A.: 2007, *Astron. Astrophys.* **470**, 685

Landstreet, J.D., Silaj, J., Andretta, V., Bagnulo, S., Berdyugina, S.V., Donati, J.-F., Fossati, L., Petit, P., Silvester, J., Wade, G.A.: 2008, *Astron. Astrophys.*, submitted

Maitzen, H.M.: 1993, *Astron. Astrophys., Suppl. Ser.* **102**, 1

Robichon, N., Arenou, F., Mermilliod, J.-C., Turon, C.: 1999, *Astron. Astrophys.* **345**, 471