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Evolution of the Magnetic Fields of Magnetic Ap Stars During the Main Sequence Phase

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Abstract. This paper discusses the results of our survey of magnetic fields among Ap stars that are members of open clusters. Such stars are unlike field Ap stars in that they have relatively well–determined ages, both absolutely (in years) and as a fraction of the main sequence lifetime elapsed. By measuring the fields of such stars once or a few times per star, we can estimate the RMS longitudinal field strength of each star, and study how this quantity varies with age through the 10^8 to 10^9 yr of main sequence life. Dividing our sample of some 80 stars into mass bins of $2-3$, $3-4$, and $4-5\,M_\odot$, we find that both the typical field strength and the total magnetic flux, emerging from the surface of stars decline on time scales that are a modest fraction of the main sequence lifetime in each of the three mass bins.

Key words: stellar magnetic fields – upper main sequence stars – open clusters

1 Introduction

About 10% of A and B main sequence stars show peculiar atmospheric chemistry, sufficiently peculiar that the anomalies relative to stars of approximately solar chemical composition are readily seen in the classification spectra. The chemically anomalous stars form several roughly homogeneous classification groups are: Am stars, which range from about F0 to A0 and show a modest excess of iron peak elements; Ap and Bp stars, which range between about F0 and B3, and show very substantial excesses of Cr and rare earths in cooler stars, changing gradually to excess Si and deficient He in hotter stars; HgMn stars, in the range between A0 and B6, which show large excesses of a small number of elements such as P, Mn, Ga, and Hg; He–weak stars, in the range between about B8 and B3, with clearly deficient He for their effective temperatures; and He–strong stars, near B2, whose principal anomaly is strongly overabundant He.

Magnetic fields in such stars may be directly detected by observation of the Zeeman effect in the stellar spectrum. This effect leads to readily detectable circular polarisation in spectral line profiles, and in the special case of a very small projected rotation velocity $v_\mathrm{e} \sin i$ (less than a few km/s) and a particularly large field (some kG) the spectral lines are seen to split into multiple components. Searches for stellar magnetism have shown that certain subgroups of the chemically peculiar A and B stars, namely the Ap–Bp stars, the He–strong stars, and some of the He–weak stars, are found to host readily detectable magnetic fields, usually in the range between $3 \cdot 10^2$ and $3 \cdot 10^4$ G. These fields appear to have a relatively simple global structure. Usually the fields are topologically dipolar, although the detailed structure can vary considerably. These are the stars that will be discussed in this paper.

These magnetic Ap and Bp stars have a number of other characteristics by which they differ from other peculiarity groups, and from normal A and B stars. Most are periodically variable in one or more photometric brightness (in typical photometry bands, such as U, B, V), spectral line shape and strength, and magnetic field strength. When more than one characteristics varies, all vary with exactly the same period, and with a fixed phase relation among variables. The observed periods cover the enormous range of $0\overset{\mathrm{d}}{.}5$ up to some decades. Furthermore, the observed projected rotation velocity $v_{\mathrm{e}} \sin i$ is closely related to the period; the smaller the $v_{\mathrm{e}} \sin i$ the longer the period. It was realized decades ago (Deutsch, 1958) that the period of variability is in fact the rotation period, and this realization led to the phenomenological "oblique rotator model", in which the observed variations are understood as consequences of an inhomogeneous and non–axisymmetric distribution of elements and magnetic field vector over the stellar surface, which lead to variations in the observed quantities as the star rotates. In particular, the dipolar overall structure of the field is usually not aligned with the rotation axis of the star; this is the origin of the "oblique" in "oblique dipole rotator".

The rotation periods of magnetic Ap and Bp stars are several times longer than those of typical A and B stars; these stars typically have only about 10 or 20% of the specific angular momentum of normal main sequence stars of similar mass. The most slowly rotating stars have less than 0.1% of the normal specific angular momentum of normal stars.

For recent reviews concerning many of the points summarized above, consult the volume from the Poprad meeting on A stars (Zverko et al., 2004), and the meeting in Vienna on peculiar A and B stars (Paunzen & Netopil, 2008).

The existence of rather large, and globally fairly simple magnetic fields in some main sequence stars, but apparently not in others (field measurements of some of the brightest normal A and B stars give upper limits of some tens of G only: see for example Shorlin et al., 2002, and Aurière et al., 2007, 2010) raises a number of fundamental questions, to which some provisional answers have been proposed, but which are still not definitively settled.

- What is the nature of magnetic fields found in Ap and Bp stars? How are they produced?

  The long–term stability, simple structure, lack of activity (such as X–rays, flares, and coronal UV emission lines), and the lack of correlation between the field strength $\langle B \rangle$ and rotation rate all suggest that the field is *not* due to a currently active dynamo, like that of the Sun and sun–like stars, but is a fossil left from some previous evolutionary state, perhaps the pre-main sequence phase, or possibly even the initial contraction from the interstellar medium.

- Why do Ap stars have magnetic fields covering most or all of the stellar surface, while other A and B stars do not, or at most have fields some orders of magnitude weaker than those of Ap and Bp stars?

  There is no satisfactory answer to this question yet. Perhaps internal circulation currents (Eddington–Sweet circulation) submerge the fields of normal stars, while fields above some limiting strength can resist being swept inside the star and remain visible in the Ap stars.

- How does the magnetic field evolve as the star evolves (more specifically, how does the field evolve during the pre–main sequence and main sequence stages of the star's life?

  There is no convincing previous observational evidence relevant to this question. Theoretically, we think that if the field is a fossil, there should be ohmic decay, plus field evolution driven by any large-scale flows (such as the Eddington–Sweet circulation) within the star, plus distortion and amplification due to overall stellar structure changes. Can this idea be tested observationally in some way?

2 Observational Study of Ap Evolution

2.1 Field Magnetic Stars

A large number of main sequence field Ap and Bp stars have been studied in some detail. For many we have rotation periods, overall magnetic field structure and strength, abundances of a number of elements and even simple models of the patchy distribution of some elements. However, in general we either do know the ages of these stars, or do not know them with useful precision. For many of these magnetically well studied stars, we also do not know the distance, luminosity, or mass particularly accurately either. For any particular star in this well–studied sample what we frequently know is that at some *unknown time* in the main sequence life of a star of *uncertain mass*, a magnetic Ap star can have the observed field structure and surface chemistry.

If we were able to determine the mass and age (both absolute and "fractional" — the fraction already elapsed of the main sequence lifetime of that star) of a large number of Ap stars with known magnetic fields and chemistry, these stars would provide new clues about the evolution of magnetic fields and abundance patterns, and could be used to test evolution theories of Ap stars. Is this practical?

We need to determine masses, ages, and fractional ages for a substantial sample of Ap stars, since each star is only a snapshot of evolution, and these stars, even at a single mass, clearly have a *distribution* of such properties as field strength. A substantial sample might be $50-100$ stars, because we would like to divide the sample into at least three or four mass bins that sample the full range of evolution from the ZAMS to TAMS, with at least a few stars in each mass bin. There are enough well studied stars in the field to provide a sample of adequate size — but can we get masses and ages for these stars?

This seems at a first glance to be a fairly straight–forward problem, especially since the tremendous success of the Hipparcos satellite, which has provided many tens of parallaxes of Ap and Bp stars that are accurate to ±10 or 20%. The obvious method to use is to determine $T_{\rm e}$ from photometry, and $\log(L/L_{\odot})$ from apparent magnitude, bolometric correction, and distance, for a large sample of field stars. One then uses the results of standard evolution models such as those of the Geneva group to determine mass and absolute and fractional age from the observed positions in the theoretical HR Diagram. This would furnish a sizable sample of stars with known mass and known magnetic and abundance properties which can be binned by mass and age. With the resulting sample, we could look for statistical trends in the field strength, chemical abundances, rotation periods, etc.

We would expect that such a sample would provide a number of really valuable hints about how both stellar magnetism and the associated abundance anomalies evolve through the main sequence lifetime of a star. In turn, this should also provide valuable constraints on the mechanisms proposed for field origin and evolution, for the development of chemical peculiarities, and so on.

Unfortunately, there are important uncertainties, associated with efforts to place field magnetic Ap stars in the HR Diagram. The first problem concerns the effective temperature calibrations. There are *no* magnetic Ap stars with fundamentally determined temperatures (i.e. based on measured angular diameters and fluxes). Instead, we must adapt calibrations obtained for normal A and B stars to Ap stars. However, it is well known that, compared to a normal star of similar Paschen continuum slope, Ap stars are usually deficient in flux in the Balmer continuum. Furthermore, in general, even model atmospheres with tuned abundances have not been successful at reproducing these peculiar energy distributions, although such models are often extremely good for normal stars (see for example Fitzpatrick & Massa, 1999). In this circumstance, a number of empirical corrections have been developed (e. g. Lanz, 1984; Stępień & Dominiczak, 1989; Hauck & Kuenzli, 1996) which have generally concluded that effective temperatures of Ap stars are a few hundred K lower than those of normal stars of similar photometric colours. This generally shared opinion has led people to guess that Ap T_e's may be deduced from colours with uncertainties similar to those of normal stars, of the order of $2-300$ K for A and B stars.

However, this calibration has been questioned recently by Khan & Shulyak (2006), who find, using the best available models of magnetic Ap stars (computed with LLModels, their own code) that the Paschen continuum slope of peculiar magnetic stars is very similar to that of normal stars of the same T_e. Thus, at present, we really ought to consider that effective temperatures of magnetic Ap stars are uncertain by perhaps as much as 500 K.

Similarly, the value of $\log(L/L_\odot)$ is uncertain by more than simply the distance uncertainty. This value is deduced with the aid of a bolometric correction (BC), usually the one for normal stars (see Code et al., 1976; Malagnini et al., 1986). We have recently derived a new BC for Ap and Bp stars, which is systematically smaller than the one for normal stars. To complicate matters, it appears that the BC for Ap stars of a given T_e probably varies from star to star. Even with this improved BC, we estimate that values of $\log(L/L_\odot)$ with good parallaxes are uncertain by about ± 0.1 dex.

These uncertainties in turn lead to significant age uncertainties when the stars are placed in the HR Diagram. The problem is particularly acute for stars near the beginning of their main sequence life, as the isochrones are quite close together, and a typical error box can easily result in an age uncertainty of the order of one–quarter of the main sequence lifetime, although the uncertainty in mass is relatively small, only perhaps $\pm 10\%$. A further important source of age uncertainty is the fact that we do not know the bulk composition (particularly the metallicity, Z) of any particular Ap star. Since evolution tracks and isochrones of models of various Z values are displaced with respect to one another in the HR Diagram (see Schaller et al., 1992; Schaerer et al., 1993), this leads to further age uncertainty; in fact, we find that for field Ap stars, ages determined from HR Diagram positions are usually at best only accurate enough to decide whether a given star is in the first or second half of its main sequence life.

2.2 Cluster Magnetic Stars

To study evolution through the main sequence phase it is essential to obtain more accurate ages. This can be accomplished, especially for stars early in their main sequence lifetimes, by studying magnetic Ap stars in open clusters, for which age uncertainties are typically of the order of 0.2 dex, or less than a factor of two. This means that for very young stars (say 10^7 years old), the uncertainty relative to the full main sequence lifetime (which for A0 stars is of the order of $3 \cdot 10^8$ yr) is only a few percent, rather than roughly 50%. Note that this advantage diminishes as one looks at stars which are near the cluster turnoff, so that they have ages similar to that of the cluster. In this limit, the age uncertainty is similar for cluster members and for field stars with good parallaxes.

Two important recent advances have made cluster Ap stars accessible in interesting numbers. The first is the new proper motions from the Hipparcos project, which has generated proper motions with mass accuracy not only for the Hipparcos Input Catalogue stars, but also for roughly 2 million stars detected with the guide system, now publicly available as the Tycho–2 catalogue (Høg et al., 2000). These new proper motions are fairly complete to fainter than $V \sim 10$, making them powerful discriminants of cluster membership for A stars out to distances of several hundred parsecs. This fact makes it possible to confirm or reject membership of magnetic Ap stars in dozens of clusters, so that a usefully large sample of magnetic stars may be gathered. In parallel, observations with Geneva and especially Δa photometry (see Maitzen, 1993) have made identification of probable magnetic Ap stars much more efficient by allowing easy selection of good candidate stars.

The second advance is the presence of high–efficiency spectropolarimeters on large telescopes. Two important recent additions to the previously available instruments (such as the Main Stellar Spectrograph on the SAO 6–m telescope) are the FORS1 (now replaced by FORS2) on the ESO VLT, and ESPaDOnS at the Canada–France–Hawaii telescope. FORS is a low–dispersion multi–object spectrograph with optional polarisation optics, which is found to be very efficient for magnetic measurements (see Bagnulo et al., 2002). It primarily relies on detecting fields through the Balmer lines, but has a resolving power which is just high enough that it could also detect the Zeeman polarization in the metallic spectrum, although with substantially reduced efficiency. In contrast, ESPaDOnS is a single–object high–resolution spectrograph specifically designed for spectropolarimetry, which has a very wide wavelength coverage. For field measurements of sharp–lined stars, ESPaDOnS is able to fully exploit the information content in the metallic spectrum, and for such stars, it is even more efficient at detecting fields than the FORS, in spite of the fact that the CFHT has only 20% of the collecting surface area of an 8–m telescope.

3 Magnetic Fields in Cluster Stars

3.1 New Observations

A few previous surveys have observed a small number of cluster stars, and also a substantial sample of stars in the Ori OB1 and Sco OB2 associations (Borra, 1981; Glagolevskij et al., 1987; Thompson et al., 1987). However, there are certainly not enough observations of cluster and association Ap stars available in the literature to study reliably the evolution of fields using such stars. A new survey was required.

Bagnulo et al. (2006) used FORS1 to carry out a major survey of probable Ap stars in more than 30 open clusters. The goal of this survey was to obtain a significant sample of detected magnetic stars of relatively well-known age. Almost 100 candidate Ap stars (stars identified as probable Ap's on the basis of photometric indices or classification spectra, and probable cluster members) were observed with a median uncertainty of about 80 G. Fields were detected in 41 of the observed stars; for 36 of these stars this was the first reported detection.

This survey required a lot of work (particularly on the part of Bagnulo and Mason) to develop robust and reliable reduction techniques for the data. The success of this effort is shown by the fact that no field was detected in any of the roughly 160 non–Ap stars observed during the survey, which shows clearly that this method of field measurement is not prone to spurious field detections. Furthermore, Bagnulo et al. have shown that for stars in which a field is detected from the Zeeman signature in Balmer lines, it is often possible (when the star observed has a rich spectrum of strong lines) to detect the Zeeman signature in the low–resolution metallic spectrum. The field measurement, obtained from the metallic spectrum is generally in good agreement with that from the Balmer lines except for a few large fields (above about 1 kG), for which the weak–field approximation used in data analysis breaks down for metal lines. Thus the metallic spectrum can often be used to confirm or reject a marginal detection in Balmer lines.

It is clear from our work that FORS is capable of obtaining field measurements with a standard error of the order of 30 or 40 G if enough exposures are made, although achieving this error level requires *very* careful reduction. It is not known at present if the instrument is capable of achieving still lower uncertainties, or if this floor is set by instrumental instabilities or remaining unidentified reduction difficulties.

More recently, the survey has been extended to cover more northern cluster stars, and particularly a number of low–mass Ap stars near the end of their lifetimes, using the ESPaDOnS spectropolarimeter at the Canada–France–Hawaii telescope (Landstreet et al., 2008). This instrument is a cross–dispersed echelle spectrograph with a polarisation analyser that can be used to obtain any or all of the Stokes parameters with resolving power $R = 65\,000$, so that for stars with many sharp lines, the uncertainties can (realistically) be as low as a few G, and fields can be detected through the non–zero profile of V across spectral lines even if the longitudinal field is very close to zero.

3.2 Discussion of Results

For the stars observed in the survey of Bagnulo et al. (2006) and Landstreet et al. (2007, 2008, and a few stars available from the literature (e. g. Bohlender et al., 1993; Kudryavtsev et al., 2006), we have re–examined cluster membership on the basis of the best available parallaxes, proper motions, radial velocities, and photometry. The data now available are usually sufficient to decide whether a star is a probable cluster member or not. For cluster members, we then determine effective temperatures from the available *uvby* and Geneva photometry, using the calibrations of Stępień & Dominiczak (1989) and of Hauck & Künzli (1996). Luminosities are found from cluster distance moduli and apparent magnitudes, together with a new set of bolometric corrections specifically for Ap and Bp stars. We are then able to place the stars in the HR Diagram, and compare their positions to standard evolution tracks and isochrones (e. g. Schaller et al., 1992), using the cluster ages to constrain the range of allowed absolute and fractional ages, and obtain reasonably precise masses (Landstreet et al., 2007, 2008).

The available sample of more than 80 stars for which we have either field detections or good upper limits, all probable cluster members and probable Ap stars, is large enough to divide into mass bins. We have good age sampling for the mass range $2 - 5\,M_{\odot}$, and enough stars to define three mass bins: $2 - 3\,M_{\odot}$, $3 - 4\,M_{\odot}$, and $4 - 5\,M_{\odot}$. We characterise the field of each star by the root–mean–square (RMS) value $\langle B_{\rm rms} \rangle$ of the longitudinal field averaged over the available observations. Using this index, we are able with this sample to examine the statistical variation of the field strength and magnetic flux distributions with respect to both age in years and fractional age. The results are discussed in detail in Landstreet et al. (2008).

The main results of this study are the following:

- The sample of known magnetic stars which are probable clusters is now sufficient for a useful statistical analysis. The present sample is rich in relatively young stars, reflecting the fact that typical cluster and association lifetimes are smaller than the main sequence lifetimes of A stars. The sample is also rich in relatively massive Bp stars, reflecting the fact that young clusters still have many of their more massive members.

- The median field strength $\langle B_{\rm rms} \rangle$ found is somewhat larger for stars of more than $3\,M_{\odot}$ than for lower mass stars. This is consistent with the results of Thompson et al. (1987) for Sco OB2 and with Kochukhov & Bagnulo (2006) for field stars.

- The mean field strength $\langle B_{\rm rms} \rangle$ clearly declines strongly with increasing star age in each mass interval. This is particularly clear in the right–hand panels where fractional age is used as the abscissa. This conclusion is consistent with the results of Kochukhov & Bagnulo for field stars, but is a considerably stronger result. Interestingly, the time scale for the field to decline is a small fraction of the main sequence lifetime for each of the mass bins, so that the time scale is considerably smaller for the bin with the largest masses compared to the other bins.

- The mean flux also declines with stellar age in each mass bin, with about the same time scale as the field strength. It appears that magnetic flux is not conserved during the main sequence life of a star.

- The observed fields are clearly largest at and near the ZAMS. All the particularly large fields in our sample are found in stars near the ZAMS.

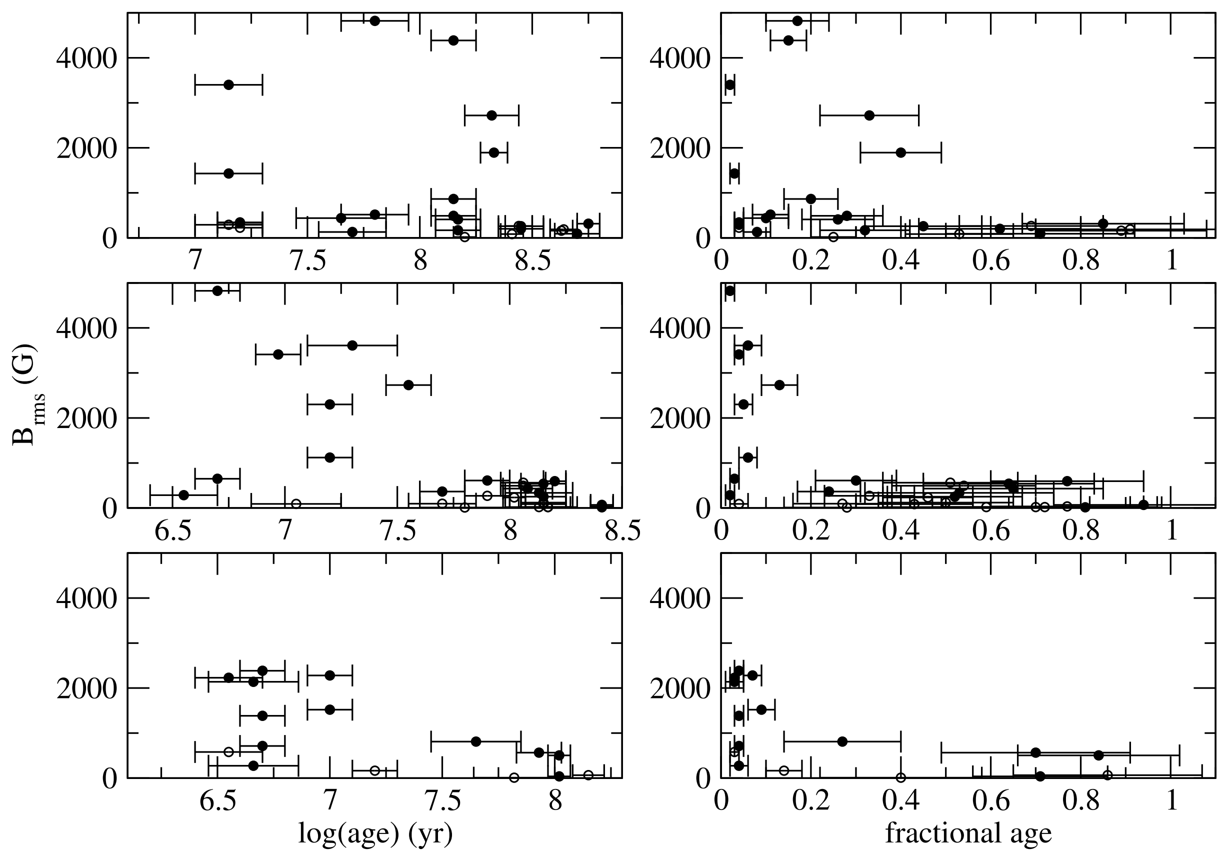

Figure 1: This figure shows the currently estimated values of $\langle B_{\rm rms}\rangle$ as functions of logarithmic stellar age (left) and of fractional age (right) for three mass bins, from top to bottom $2-3\,M_\odot$, $3-4\,M_\odot$, and $4-5\,M_\odot$. Filled symbols are stars for which a field is definitely detected; open symbols are probable magnetic Ap stars in which no field has yet been detected. The right–hand limit of each of the panels using log (age) as abscissa is near the main sequence lifetime for stars in that mass range. In the bottom pair of panels, one point (for NGC 2244–334) has such a large field ($\langle B_{\rm rms}\rangle = 9.52$ kG) that it is off scale (at $\log t = 6.4 \pm 0.10$ and $\tau = 0.02 \pm 0.01$ respectively).

- However, hardly any stars in our new sample have masses of less than about $2\,M_\odot$, in spite of the fact that magnetic Ap stars occur in the field with masses down to about $1.6\,M_\odot$ (see Kochukhov & Bagnulo, 2006); the roAp stars are all such low–mass Ap stars. It is not known at present why the cluster sample is deficient in such stars.

How do these results compare to theoretical expectations?

- We expect the global field to decrease in strength with age even if flux is conserved, because the star expands in radius by about a factor of two during its main sequence lifetime.

- However, if no Ohmic decay or other field "destruction" occurs, the product $\langle BR^2\rangle$, which is a rough measure of the magnetic flux passing through the stars, should be approximately conserved. In fact this quantity decreases with age, on about the same time scale as the field strength, so the field is dissipating — or at least decreasing at the surface — somehow.

- The statistical decrease in stellar magnetic flux does not seem to be due to simple Ohmic decay — it occurs too rapidly compared to the expected decay time of a few Gyr. Perhaps

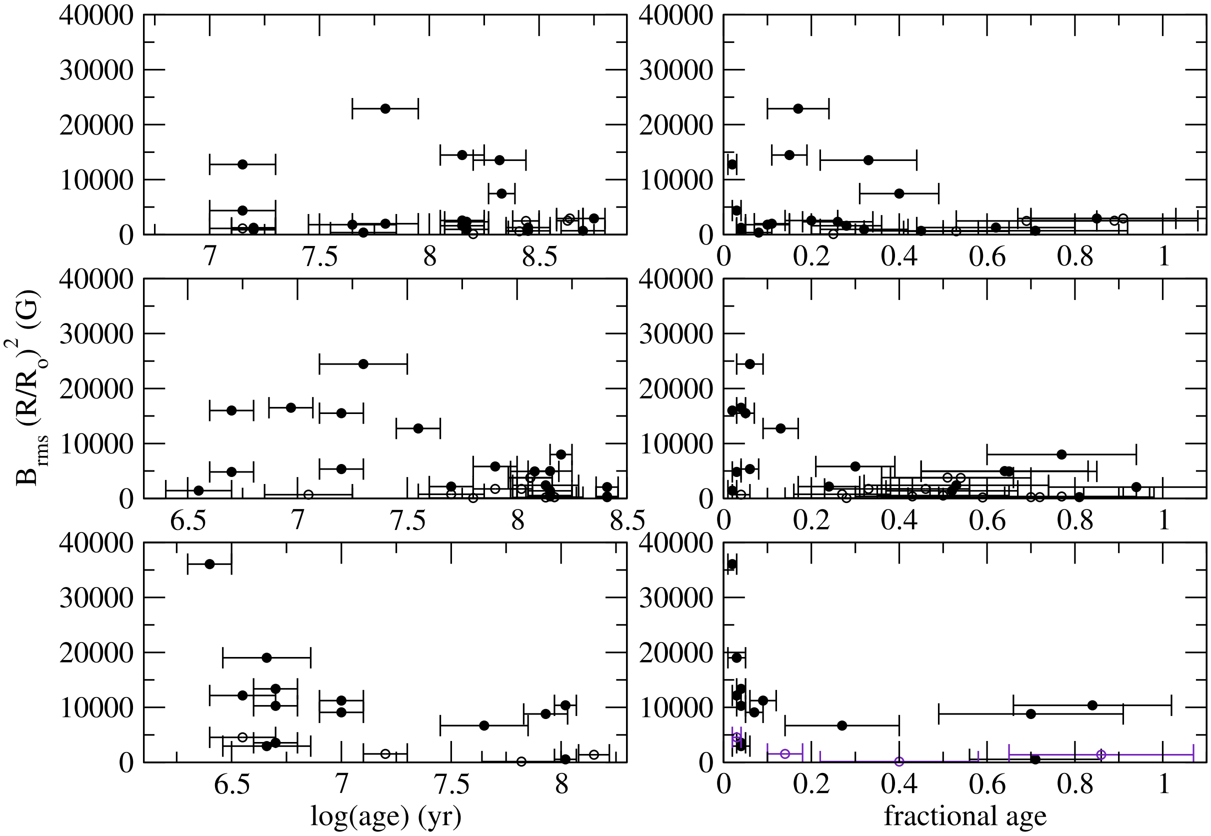

Figure 2: This figure shows the estimated values of normalised emergent magnetic flux $\sim\langle B_{\rm rms}\rangle\cdot(R/R_\odot)^2$ as functions of logarithmic stellar age (left) and of fractional age (right) for three mass bins. Apart from the quantity plotted, this figure has the same structure as Figure 1.

the field readjusts slowly due to large–scale flows inside the star, or to the shrinking size of the stellar core.

The next step in this programme will be to study the evolution of atmospheric chemical patterns with age thorough the main sequence life of the stars in our cluster-association sample. This requires fairly high–resolution spectra and significant modelling for each star. We will start with the ESPaDOnS spectra and other spectra that are available from various archives, and also carry out further spectroscopic observations of Ap stars in the clusters we have studied. We expect that this project will provide valuable clues about the long–term operation of the sorting and mixing mechanisms that operate inside such stars, and that lead to the remarkable variety of Ap abundance patterns observed.

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