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The magnetic fields of peculiar A and B stars in open clusters

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Abstract. This paper discusses our recent efforts to observe magnetic fields in a large sample of A and B stars in a number of open clusters. The aim of this project is to obtain a statistically significant sample of magnetic Ap and Bp stars, for which we can characterise the magnetic field structures and chemical abundances, and for which we have reasonably well-determined *masses and ages.* We expect that this sample will provide valuable constraints on the evolution of magnetic fields and chemical peculiarities in these stars.

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 classification spectra. The chemically anomalous stars form several roughly homogeneous classification groups: 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.

The two subgroups of Ap-Bp stars and 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 field 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 of photometric brightness (in typical photometry bands such as U, B, V), spectrum, and magnetic field strength. When more than one characteristic varies, all vary with exactly the same period, and with a fixed phase relation among variables. The periods are in the range of 0.5 d up to some decades. Furthermore, the observed projected rotation velocity $v_{\rm e} \sin i$ is closely related to the period; the smaller $v_\mathrm{e} \sin i$ is, the longer the period. It was realized long ago that the period of variability is the rotation period, and this realization led to the phenomenological "oblique rotator model", in which the variations are due to an inhomogeneous distribution of elements and magnetic field vector over the stellar surface, which lead to variations in the observed quantities as the star rotates. Usually the dipolar overall structure of the field is 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 very longest period 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 recent Poprad meeting on A stars (Zverko et al. 2004).

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) 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, and the lack of correlation between the field strength $\langle B \rangle$ and rotation rate, all suggest that the field is a fossil left from (at least) the pre-main sequence phase.

- Why do Ap stars have fields 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 very satisfactory answer to this question yet.

- 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)?

  If the field is a fossil, there should be ohmic decay plus distortion and amplification due to stellar structure changes. Can this idea be tested in some way?

2 Observational study of Ap evolution

2.1 Field magnetic stars

A large number of field (main sequence) 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, we also do not know the 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 an 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 as well as several age bins, with at least a few stars in each 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 first glance to be a fairly straight-forward problem, especially since the tremendous success of the Hipparcos satellite, which has provided hundreds 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 Diagramme. This would furnish a sizable sample of stars with known magnetic and abundance properties which can be binned by mass and age. With the resulting sample, we could look for statistical trends in 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.

In fact, this kind of study has already been done by two groups. A first study was carried out by Hubrig et al. (2000), using a rather small sample of field magnetic Ap stars, essentially only ones for which the ratio of field strength to $v_{\rm e} \sin i$ is large enough that they have visibly split lines. More recently, this study has been repeated by Kochukhov & Bagnulo (2006), for a considerably larger sample, including most of the field stars for which both accurate Hipparcos parallaxes and useful field strength estimates are available. In both cases the authors have placed the stars of their samples in the HR diagramme as accurately as possible, and then tried to discern evolutionary trends in field strength through the main sequence lifetime of the stars studied.

Hubrig et al. (2000) have argued that their data support a very surprising result, namely that in lower mass ($M \leq 3M_\odot$) magnetic Ap stars, *fields do not appear at the surface of the stars until about 30% of the main sequence lifetime has elapsed.* This result is disputed by Kochukhov & Bagnulo (2006) on the basis of their larger sample of Ap stars, but as the Hubrig et al. conclusion raises fundamental questions (see below), it would be valuable to test it farther.

Is the conclusion of Hubrig et al. consistent with other things we believe that we understand about magnetic Ap stars? One major problem raised by their result concerns rotation of Ap stars. As mentioned above, the rotation periods of these stars are typically a factor of ten longer than the rotation periods of normal A and B stars, and in some cases hundreds or thousands of times longer. These stars are in general *not* members of close binary systems, so that is not the origin of their slow rotation. Instead, it is generally believed (see Stępień 2000) that this angular momentum is lost during the pre-main sequence phase of the star's formation, when strong magnetic coupling with the accretion disk and outflowing wind allow the star to brake more efficiently than most stars do. This model of slowing not only explains the generally slow rotation of Ap stars, but also accounts for the fact that the slowest rotators are virtually always relatively low mass stars: the length of time spent as a pre-main sequence star rises rapidly as the mass decreases, so the lowest mass stars have the longest time in which to shed angular momentum. If the magnetic field only emerges for the first time well into the main sequence phase, then this picture makes no sense, and we are left with no plausible explanation of the slow rotation of magnetic Ap stars. Hence we need to carefully test the conclusion of Hubrig et al.

There are important uncertainties associated with efforts to place magnetic Ap stars in the HR Diagramme. A 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 $T_{\rm e}$'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 $T_{\rm e}$. Thus, at present, we really ought to consider that effective temperatures of magnetic Ap stars are uncertain by perhaps as much as 500 K. This is quite a lot larger than the uncertainty assumed by Hubrig et al (2000), and it could be a systematic effect, raising most or all $T_{\rm e}$ values.

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). Sometimes even obsolete bolometric corrections such as that of Schmidt-Kaler (reproduced in Lang 1992) are used; Hubrig et al. used the Schmidt-Kaler BC, again introducing a systematic error. We have recently derived a new BC for Ap and Bp stars, which is systematically smaller than the one for normal stars. Even with this new result, 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 Diagramme. 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 ±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 Diagramme (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 Diagramme positions are usually only accurate enough to decide on whether a given star is in the first or second half of its main sequence life.

2.2 Cluster magnetic stars

It is certainly desirable to obtain more accurate ages than this. 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 mas accuracy not only for the Hipparcos Input Catalogue stars, but also for the 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 FORS1 on the ESO VLT, and ESPaDOnS at the Canada-France-Hawaii telescope. FORS1 is a low-dispersion multi-object spectrograph with optional polarisation optics, which has been 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 can 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 FORS1, in spite of the fact that the CFHT has only 20% of the 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; Thompson et al. 1987). However, there are certainly not enough observations of cluster and association Ap stars available in the literature to study the evolution of fields using such stars. A new survey was required.

Bagnulo et al. (2006) have used FORS1 to carry out a major survey of probable Ap stars in more than 30 open clusters. The goal of this survey is 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) have been observed with a median uncertainty of about 80 G. Fields have been detected in 41 of the observed stars; for 36 of these stars this is the first reported detection.

This survey has 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 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 FORS1 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.

One particularly interesting star that was found during the course of this survey is star number 334 in the very young (2–3)$\cdot 10^6$ yr) cluster NGC 2244 in the Rosette Nebula, which had a measured $\langle B_z \rangle$ value of about 9 kG, the second highest value ever found in a non-degenerate star. This star has $V \approx 13$, and is the faintest main sequence star in which a field has ever been detected (Bagnulo et al. 2004). It appears otherwise to be typical Si-rich, He-weak Bp star.

3.2 Discussion of results

For the stars observed in the survey of Bagnulo et al. (2006), and the stars available from the literature, 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 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 diagramme, 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 (Landstreet et al. 2007).

The analysis of this data set is not yet completed, but we do have a number of preliminary results.

- 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 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 $\langle B_z \rangle$ seems to decline somewhat with increasing star age in each mass interval. This is consistent with the results of Kochukhov & Bagnulo for field stars. The decline is also consistent with flux conservation as stellar radius expands during main sequence evolution.

- Contrary to the proposal of Hubrig et al. (2000), a substantial number of stars which have gone through less than 30% of their main sequence lifetimes are found to exhibit magnetic fields. This was already demonstrated by an early result of our survey, in which a strong field was detected in the star HD 66318, a star which has completed only about $16 \pm 5\%$ of its main sequence lifetime (Bagnulo et al. 2003). This result is also consistent with the results of Poehnl et al. (2003) and of Kochukhov & Bagnulo.

- 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 stars. It is not known at present why the cluster sample is deficient in such stars.

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. We expect that this 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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