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Evolution of Global Magnetic Fields in Main Sequence A and B Stars

J. D. Landstreet,[1] S. Bagnulo,[2] V. Andretta,[3] L. Fossati,[4] E. Mason,[5] J. Silaj,[1] and G. A. Wade[6]

[1]*Department of Physics & Astronomy, University of Western Ontario, London, ON, Canada N6A 3K7*

[2]*Armagh Observatory, College Hill, Armagh BT61 9DG, Northern Ireland*

[3]*INAF - Osservatorio Astronomico di Capodimonte, salita Moiariello 16, 80131 Napoli, Italy*

[4]*Institut für Astronomie, Universität Wien, Türkenschanzstr. 17, A-1180 Wien, Austria*

[5]*European Southern Observatory, Alonso de Cordova 3107, Vitacura, Santiago, Chile*

[6] *Department of Physics, Royal Military College of Canada, P.O. Box 17000, Station 'Forces', Kingston, Ontario, Canada K7K 7B4*

Abstract. Some main sequence A and B stars ("magnetic Ap stars") possess kG-strength global fields of simple geometry. These fields are expected to evolve during the main sequence lifetime of the stars due to ohmic decay, large-scale circulation flows, and the changing stellar structure caused by stellar evolution. We are attempting to obtain useful observational constraints on field evolution by observing the fields of a large sample of magnetic Ap stars in open clusters, from which we derive stellar ages. Our data to date indicate that the fields of these stars decline with stellar age more rapidly than would be expected from magnetic flux conservation as the stars expand with evolution.

1. Introduction

Among middle main sequence A and B stars we find a few percent that have strong global magnetic fields. Such stars are known as "magnetic Ap stars". Their fields are roughly dipolar in overall topology, with characteristic field strengths of order 10^2 to $3\,10^4$ G. The observed fields are associated with specific atmospheric abundance anomalies which are (roughly) functions of effective temperature $T_{\rm eff}$. Among A stars the typical anomalies include overabundant Cr and rare earth elements, while for late B stars one finds underabundant He and (often) overabundant Si. Some magnetic early B stars have overabundant He.

In most cases, the brightness as measured in various photometric bands, the spectral line shapes and equivalent widths, and the magnetic field, vary periodically, all with the same period, which may have any value between about

0.5 d and several decades. It is found that the period of variation is inversely correlated with $v_e \sin i$. The extremely large range of periods cannot be produced by any reasonable pulsation mechanism; the relationship between short periods and high $v_e \sin i$ then indicates clearly that the observed periods are rotation periods.

The fact that a magnetic Ap star varies as it rotates shows that its atmospheric composition (and the magnetic field) are functions of position on the surface; the observed variations are simply due to seeing different parts of the stellar surface as the star rotates. This conceptual picture is known as the "oblique rotator model".

An interesting peculiarity of magnetic Ap stars is that typically they only have about 0.1 times the normal specific angular momentum of an A or late B star, and in a small fraction of cases may have as little as 10^{-4} of the specific angular momentum of a normal A star.

2. Magnetic Field Evolution

The observed magnetic fields are believed to be produced by large-scale electrical currents deep in the stellar interior. Because of the very large size and high electrical conductivity of a star, the ohmic decay time for such fields is of the order of 10^{10} yr. The observed fields do not show any variations other than those due to rotation of the underlying star, and it is widely thought that the fields are not being currently generated by a stellar dynamo, but are relics of a previous stage of evolution. This idea is known as the "fossil field hypothesis". The fields may even be the remnants of the weak interstellar field that threaded the these stars as they formed from interstellar gas and dust, amplified by the contraction of the gas and the entrained field lines.

Such fields should evolve with time due to ohmic decay of the underlying electrical current systems that support the fields, due to large-scale hydrodynamic flows ("meridional circulation") in the interior of the star which advect field lines, and due to the global structural changes (particularly, an expansion in radius by a factor of order two) that occur in the star during main sequence evolution. However, at present there are virtually no clear observational constraints on field evolution through the main sequence phase. This situation arises because the only way to observe field evolution is through studying a sample of magnetic Ap stars of various ages to try to detect statistical trends. Such a study requires a statistical knowledge of field strength distributions for stars of various ages. Until recently, no significant sample of stars with magnetic field data and well determined ages existed. We are currently carrying out a large survey to obtain such a sample.

3. Fields of Ap Stars of Known Ages

To describe the evolution of a star through the mains sequence stage of evolution, it is convenient to assign both absolute age (in yr) and "fractional ages", the fraction of the main sequence lifetime of the star that has already elapsed. Determination of the fractional age of a star requires determination of its mass; then comparison with computed evolution tracks of appropriate bulk chemistry provides the main sequence lifetime of the star, from which the fractional age (actual age divided by main sequence lifetime) may be determined.

Magnetic data are available for a large sample of stars in the field around the Sun. Ages for such stars may be estimated by placing these stars in the Hertzsprung-Russell diagram and comparing the positions with theoretical evolution tracks and isochrones. Such comparisons have recently become significantly more precise than in the past due to improved parallaxes from the Hipparcos project, which in turn lead to improved luminosities. However, effective temperatures of magnetic Ap stars are still fairly uncertain, as is the appropriate bulk composition to use for the theoretical models from which to deduce mass and age. As a result, the age determinations of field stars are still frustratingly imprecise; at best one can assign a given star to the first or second half of its main sequence life (Bagnulo et al. 2006).

Much more accurate ages can be obtained for stars in the early phases of mains sequence evolution if they are member of open clusters. Until recently, little was known about such stars beyond tentative identification of a substantial number of candidate magnetic Ap stars by classification spectroscopy (e.g. Abt 1979) and by use of photometric indices, particularly the Δa index (Maitzen 1993). However, two major advances have made it practical to study fields in cluster Ap stars. (1) The Hipparcos mission, and especially the Tycho-2 project (Høg et al. 2000a,b), have provided accurate parallaxes and especially proper motions that greatly facilitate the identification of members and non-members of open clusters. (2) The new generation of high-efficiency spectropolarimeters on large telescope, especially FORS1 on the ESO VLT and ESPaDOnS on the CFHT, have made it practical to survey the magnetic fields of a usefully large sample of magnetic Ap stars that are members of open clusters, by increasing the useful limiting magnitude of measurements from about $m_V \sim 6$ to $m_V \sim 10$. Note that FORS1 has the advantage of much larger collecting area, but that ESPaDOnS has much higher spectral resolving power (65 000 compared to about 2 000), a difference which makes ESPaDOnS measurements even more precise than FORS1 measurements for the same time on target if the star observed has a rich spectrum of sharp lines.

We are currently carrying out a major survey of fields in cluster Ap stars using these two instruments. Our observations are able to produce measurements of the line-of-sight magnetic field component (the mean longitudinal field $\langle B_z \rangle$) with standard errors mostly below 100 G even in stars of $m_V \sim 10$. This sensitivity is partly due to the high efficiency of the spectropolarimeters and the large aperture of the telescopes, but also because we are able to combine the Zeeman polarisation signal from many spectral lines, which in some cases dramatically reduces the measurement uncertainty compared to single-line measurements (Bagnulo et al. 2006; Landstreet et al. 2007).

4. Results and Conclusions

Figure 1 shows some of the results of our survey so far. In the top two panels we display the RMS average of the measured mean longitudinal field values $\langle B_z \rangle$ for each star in our sample, as a function of stellar fractional age (each sample includes only measurements with standard errors of order 10^2 G or so to avoid

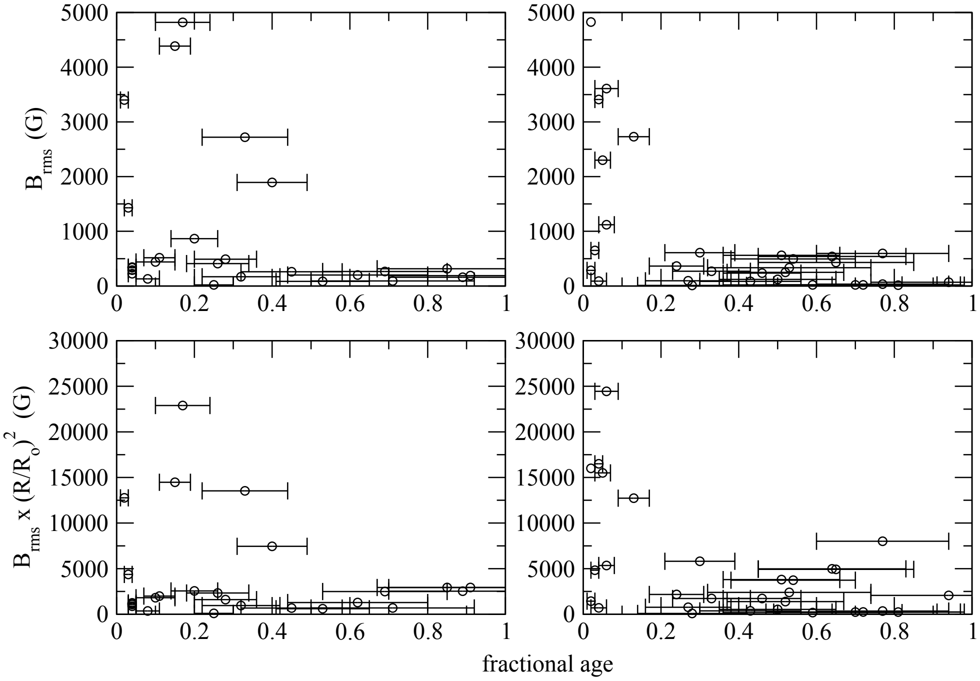

Figure 1. This figure summarises some of the results of the cluster Ap star survey. In two mass bins (2 – 3 $M_\odot$, left column; 3 – 4 $M_\odot$, right column) we show the RMS value $B_{\rm rms}$ of the sample of longitudinal field measurements $\langle B_z \rangle$ available at present for each star (top row) and the normalised emergent flux estimate $B_{\rm rms}(R/R_\odot)^2$ (bottom row). It is clear that in each mass bin, large $B_{\rm rms}$ field values are present only near the ZAMS and that the observed typical fields decrease with increasing fractional age. Similarly, the net emergent flux declines with increasing stellar fractional age.

inflating the value of $B_{\rm rms}$ with inaccurate measurements). In the left column we show results for the mass bin 2 – 3 $M_\odot$, and in the right column for the mass bin 3 – 4 $M_\odot$. In the lower row the two plots (for the same two mass bins) show a normalised proxy of the magnetic flux emerging from the stellar surface, $B_{\rm rms}(R/R_\odot)^2$. The results for the mass bin 4 – 5 $M_\odot$ are very similar to those shown here (Landstreet et al. 2007, 2008).

Notice that with the absolute age of each cluster having an uncertainty of order 0.1 – 0.2 dex, the uncertainty in fractional age is considerably smaller for small fractional ages than for large ones; the use of cluster ages for stars permits very precise fractional age determinations near the ZAMS.

Several conclusions may be drawn from the present data, assuming that a sample of stars of various ages is a suitable proxy for a sample of stars observed at a number of times during their main sequence evolution.

- Magnetic fields are detected in stars from all ages from the ZAMS to the TAMS. These fields are apparently already present when the stars reach the ZAMS stage of evolution.

- The observed field strengths appear to decline with increasing fractional age, in qualitative agreement with idea that the expansion in radius during the main sequence, combined with approximate flux conservation, should lead to smaller fields in more evolved main sequence stars.

- However, even the estimated emergent flux appears to decline with increased age. That is, the field strength estimated by $B_{\rm rms}$ decreases with stellar age more rapidly than would be required by magnetic flux conservation.

It is clear that studies of magnetic Ap stars in open clusters and associations can provide a sample of such stars with sell-determined ages, and thus can furnish extremely valuable information about the evolution of both the surface magnetic fields and the atmospheric chemistry. We are currently extending our survey of such stars, and beginning to study their surface chemistry in order to obtain constraints on the evolution of chemical peculiarity with time during the long period ($10^8 - 10^9$ yr) that such stars spend on the main sequence.

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References

Abt, H.A. 1979, ApJ, 230, 485
Bagnulo, S., Landstreet, J. D., Mason, E., et al. 2006, A&A, 450, 777
Høg, E., Fabricius, C., Makarov, V. V., et al. 2000a, A&A, 355, L27
Høg, E., Fabricius, C., Makarov, V. V., et al. 2000b, A&A, 357, 367
Landstreet, J. D., Bagnulo, S., Andretta, V., et al. 2007, A&A, 470, 685
Landstreet, J. D., Silaj, J., Andretta, V., et al. 2008, A&A, 481, 465
Maitzen, H. M. 1993, A&AS, 102, 1