Evolution of Magnetic Fields in Stars Across the Upper Main Sequence: Results from Recent Measurements with FORS 1 at the VLT

S. Hubrig

*European Southern Observatory, Casilla 19001, Santiago 19, Chile*

P. North

*Laboratoire d’Astrophysique de l’Ecole Polytechnique Fédérale de Lausanne, Observatoire, CH-1290 Chavannes-des-Bois, Switzerland*

T. Szeifert

*European Southern Observatory, Casilla 19001, Santiago 19, Chile*

**Abstract.** We rediscuss the evolutionary state of upper main sequence magnetic stars using a sample of Ap and Bp stars with accurate Hipparcos parallaxes and definitely determined longitudinal magnetic fields. FORS 1 at the VLT in spectropolarimetric mode has been used to carry out a systematic search for magnetic fields in chemically peculiar stars whose magnetic field has never been studied before. We confirm our previous results obtained from the study of Ap and Bp stars with accurate measurements of the mean magnetic field modulus and mean quadratic magnetic fields that the distribution of the magnetic stars of mass below $3 \, M_\odot$ differs significantly from that of normal stars in the same temperature range. Normal A stars occupy the whole width of the main sequence, without a gap, whereas magnetic stars are concentrated towards the centre of the main-sequence band. We show that, in contrast, higher mass magnetic Bp stars may well occupy the whole main-sequence width.

1. **Introduction**

To properly understand the physics of upper main sequence stars it is particularly important to identify the origin of their magnetic fields. Two main streams of thought have been followed: one according to which the stars have acquired their field at the time of their formation or early in their evolution (what is currently observed is then a fossil field), and the other according to which the field is generated and maintained by a contemporary dynamo. Recently, we found that magnetic fields appear only in stars of mass below $3 \, M_\odot$ if they have already completed at least approximately 30% of their main-sequence lifetime ([Hubrig, North & Mathys](#2000ApJ...532..449H)). The absence of stars with strong magnetic fields close to the ZAMS might be seen as an argument against the fossil field theories. Yet, the whole sample under study contained only 33 magnetic stars with accurate measurements of the mean magnetic field modulus or mean quadratic magnetic fields from spectra taken in unpolarized light. For these stars
the mean magnetic field modulus which is the average over the stellar disk of the modulus of the magnetic vector has been derived through the measurement of the wavelength separation of resolved magnetically split components of spectral lines. The mean quadratic field has been diagnosed from the consideration of the differential magnetic broadening of spectral lines. Our study suffered from a selection effect: our sample contained a high fraction (about 2/3) of stars with rotation periods longer than 10 days, while the majority of the periods of magnetic stars fall between 2 and 4 days.

The goal of our program currently scheduled on the VLT with FORS 1 in spectropolarimetric mode is to carry out a systematic search for longitudinal magnetic fields in about 100 upper main sequence chemically peculiar stars with good Hipparcos parallaxes in a wider range of masses whose magnetic field has been never or only poorly studied before, and with a distribution of rotation periods more representative of that of all Ap and Bp stars. The mean longitudinal magnetic field is the average over the stellar disk of the component of the magnetic vector along the line of sight and is derived from measurements of wavelength shifts between right and left circular polarization. Here we present the first results of our study of the evolution of the magnetic field across the main sequence obtained from the knowledge of the longitudinal magnetic fields and the accurate position of these stars in the H-R diagram. To better constrain our results on the origin of the magnetic field in Ap and Bp stars we enlarged our data sample by including in this study also the data for stars with accurate Hipparcos parallaxes and longitudinal fields reliably measured in previous studies by different authors. The measurements of these additional stars are compiled in the paper of Bychkov et al. (2003).

2. Basic data

The General Catalogue of Ap and Am stars (Renson et al. 1984) includes 2875 Ap stars showing abnormal enhancement of one or several elements in their atmospheres. Although Hipparcos parallaxes have been measured for about 940 Ap and Bp stars, only 371 of them have been measured at a low parallax error of $\sigma(\pi)/\pi < 0.2$. Currently 149 Ap stars have reliably measured longitudinal fields ranging from hundreds of Gauss to dozens of kG (Romanyuk & Kudryavtsev 2001). But only for 62 stars with measured magnetic fields the parallax error is less than 20%. Half of these stars have in addition accurate measurements of the mean magnetic field modulus and mean quadratic magnetic field and have been used in our previous study of the evolutionary state of magnetic stars. The mean field modulus and mean quadratic magnetic field are, by definition, much less aspect-dependent than the longitudinal field and, thus, they characterize the intrinsic stellar magnetic field much better. The observations also show that their variations are most often of low amplitude. However, longitudinal field measurements represent the standard method of searching for magnetic fields in different types of stars, and all models of the geometry and detailed structure of the magnetic fields of these stars have been constrained using longitudinal field measurements. The distribution of the other half of the stars for which longitudinal fields in the H-R diagram have been reliably measured is shown in Fig. 1 (left).
Evolution of Magnetic Fields

3. Analysis and results

It is obvious from Fig. 1 that magnetic stars of mass below $3M_\odot$ are only rarely found close to the zero-age main sequence, supporting the view that magnetic Ap stars are observed only in a restricted range of evolutionary states. The majority of the rotational periods of the studied stars fall between 2 and 4 days,
and there is no indication that the distribution of these stars in the H-R diagram is different than that of very slowly rotating magnetic stars.

By contrast, the stars of higher mass seem to fill the whole width of the main-sequence band. However, we should note that for Bp stars the effective temperatures derived from photometry are not in good agreement with the spectral classification (Hubrig, North & Mathys 2000). Because of the extremely anomalous energy distribution and large variations of their spectra, the calibration of the photometric temperature indicators are frequently questioned. The goal of our future work is to try to resolve these inconsistencies by detailed spectroscopic studies of these stars. While a few double-lined spectroscopic binary systems containing an Ap star of mass below $3M_\odot$ are currently known, the rate of binaries is much smaller among magnetic Bp stars (Gerbaldi et al. 1985), and only one double-lined eclipsing binary with a Bp component, namely AO Vel, is known to date. The evolutionary state of this star is currently under study by P. North.

Because of the strong dependence of the longitudinal field on the rotational aspect, its usefulness to characterise actual field strength distributions is limited, but this can be overcome, at least in part, by repeated observations to sample various rotation phases, hence various aspects of the field. Three observations per star should be the strict minimum to be able to apply in a meaningful way the kind of statistics we use to confirm the detection of a field from longitudinal field measurements based on the rms longitudinal field strength computed from all the measurements (see eqn. 1) and a reduced chi-square statistics.

$$\langle B_l^2 \rangle^{1/2} = \left( \frac{1}{n_1} \sum_{i=1}^{n_1} B_{li}^2 \right)^{1/2}$$

(1)

In Fig. 2 (left) the rms longitudinal field strength is plotted against the age (expressed as a fraction of their total main-sequence lifetime) of stars with magnetic fields already known from previous studies. Only one or two measurements are currently available for the stars observed with FORS 1. Some of them show mean longitudinal fields below the $3\sigma$ level and it still must be established if all of them have detectable magnetic fields. The measured longitudinal fields in the stars observed with FORS 1 as a function of the complete fraction of main-sequence life are presented in Fig. 2 (right).

It is clearly seen from Fig. 2 that magnetic fields become observable in the lower mass stars only after they have completed a significant fraction of their life on the main sequence, more than 30%. Our results also show that stronger magnetic fields tend to be found in hotter, younger (in terms of the elapsed fraction of main-sequence life) and more massive stars. Hubrig, North & Mathys (2000) have already reported about the existence of such a trend in their study of the evolutionary state of magnetic Ap stars.

Certainly, further systematic studies of magnetic fields in Ap and Bp stars should be conducted with a view to derive unambiguous results about the origin of the magnetic fields of the Ap and Bp stars. Only a few double-lined spectroscopic binary systems containing a magnetic Ap star are currently known, and in all the studied systems the Ap components have already completed a significant fraction of the main-sequence life. As far as the membership of Ap stars
Evolution of Magnetic Fields

Figure 2. Left: The rms longitudinal field strength as a function of the completed fraction of main-sequence life for stars with reliably measured longitudinal fields. Right: The mean longitudinal field versus age for the stars observed with FORS 1. Asterisks correspond to the stars of mass above $3M_\odot$ whereas diamonds distinguish stars of lower mass.

in distant open clusters is concerned, we should keep in mind that such studies are mostly based upon photometry and upon radial velocity determinations. However, criteria for assessing cluster membership based on photometry cannot be applied to peculiar stars straight away, in which strong backwarming effects lead to an anomalous energy distribution, thus affecting the position of the star in colour–magnitude diagrams. 12 stars in our sample are known members of nearby open clusters of different ages and have very accurate Hipparcos parallaxes. They are very promising candidates for our study and the measurements of their magnetic fields will allow us to put more stringent constraints on the origin of the magnetic fields. The study of these stars is currently under way.

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