A search for magnetic fields in cool sDB stars

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1 Introduction

Horizontal branch (HB) stars of clusters and their field equivalents, the subdwarf B and O (sDB and sDO) stars, represent a challenge for stellar evolution theory. While they are all known to burn He in their centre, the evolutionary scenario leading to sDB and sDO stars is not well established. It is not well understood either why there are such relative differences as observed in the number of blue or extremely blue HB stars from one cluster to the other. While metallicity is part of the explanation, it cannot account for the diversity of HB branch morphologies observed. Reviews of typical characteristics of HB stars in clusters are presented in the works of Moehler (2001) and Moehler & Sweigart (2006). In those globular clusters where HB stars have $T_{\text{eff}} > 11,000$ K are present, they have been observed to have 180 metal abundances very different from those of the red giant (RG) branch stars of the same clusters, while the HB stars with $T_{\text{eff}} < 11,000$ K have the same abundances as RG branch stars. For instance, 6 of the 7 HB stars of M15 with $T_{\text{eff}} > 11,000$ K observed by Behr et al. (1999) (see their Fig. [1]) have [Fe/H] larger by a factor of 50 than all cooler HB stars and the RG branch stars.

Similar results were obtained in many other clusters (Behr et al. 2000a, Behr 2003, Moehler et al. 2000, Fabbian et al. 2005, Pace et al. 2006). Furthermore, the hotter HB stars rotate more slowly than the cooler ones that show no abundance anomalies (Behr et al. 2000a, 2000b, Recio-Blanco et al. 2002).

The abundance anomalies in those hot HB stars are believed to be caused by atomic diffusion, radiative accelerations leading for instance to the observed Fe overabundances (Michaud et al. 2008). The link with atomic diffusion is strengthened by the observed slow rotation, a feature which is also a characteristic of Ap and HgMn stars and is required to allow the slow diffusion processes to be effective. Similar statements can be made for the sDB stars, for which both abundance anomalies of heavy elements associated with diffusion processes (Geier et al. 2010, Michaud et al. 2011) and very slow rotation velocities are usually the norm (Edelmann 2003). However the reason why very blue HB and sDB stars rotate slowly is not known. Some suggestions have been made but are not generally accepted.

Magnetic fields are believed to be responsible for the slow rotation of Ap stars, but the origin of the slow rotation of HgMn stars is also unknown. Could the presence of a magnetic field differentiate slowly rotating blue HB stars with $T_{\text{eff}} > 11,000$ K and abundance anomalies from the red HB stars with the same composition as the RG stars? Most sDBs and sDOs are also believed to have abundance anomalies caused by atomic diffusion. Gravitational settling of He...
is important in most of them except for some of the sdOs where, in some cases, He is more abundant than H.

In the past, magnetic fields of up to 1450 G were detected at significance levels ranging from 4 to 12 \( \sigma \) in four sdB and two sdO stars by O’Toole et al. (2005). A variable magnetic field (from \( \sim 0 \) to 10 kG) was observed by Valyavin et al. (2006) in the sdO star Feige 34. Magnetic fields of \( -1680 \) G in an sdO star and varying between \(-1300\) and \(1750\) G in the sdOB star Feige 66 were observed by Elkin (1996). Magnetic fields have now been observed in all sdO and sdB stars in which they were looked for with an error bar lower than 1000 G. Only upper limits had been observed for Feige 86 and one sdO by Borra et al. (1983) but the error bars are compatible with the more recent observations. All these stars have effective temperatures close to or greater than 30,000 K. It then appears likely that magnetic fields of kG order are present in most if not all sdO and hot HB stars. To our knowledge, there has been no attempt so far to detect magnetic fields in cool sdBs or in HB stars of globular clusters. While sdOs, sdBs and hot HB stars probably do not all have exactly the same evolutionary scenario, the fact that they all burn He in their centre and the presence of diffusion-caused anomalies suggests that they are strongly linked. It seems plausible that magnetic fields may be an important factor for all of them. Establishing the presence or absence of such fields will provide important clues about their potential role in slowing these stars down. This could for instance be done through magnetic fields forcing iso-rotation during their preceding evolution, as magnetic fields have been suggested to do for the solar radiative interior (Charbonneau & MacGregor 1993). To test the hypothesis that the observed abundance anomalies of sdOs, sdBs and hot HB stars reflect the presence of magnetic fields in these stars, we conducted a systematic search for magnetic fields in field sdB stars with \( T_{\text{eff}} < 30,000 \) K.

2 Observations and magnetic field measurements

We obtained FORS 2 longitudinal magnetic field measurements of ten sdB stars over three consecutive nights, from 28 to 31 August 2009. Measurements of each star were based on a sequence of observations with the following positions of the retarder waveplate: \(+45\), \(-45\), \(+45\), \(-45\), etc. We used grism 600B and a slit width of 0\(\prime\)4 to achieve a spectral resolving power of \( R \approx 2000 \). The observations were performed using the readout mode (100 kHz, high, 1x1).

Most of the stars in our sample were observed on each night to check the magnetic field variability. More details on the observing technique with FORS 1 can be found elsewhere (e.g., Hubrig et al. 2004a, 2004b, and references therein).

The mean longitudinal magnetic field, \( \langle B_z \rangle \), was derived using

\[
\frac{V}{I} = \frac{g_{\text{eff}} e \lambda^2}{4 \pi m_e c^2} \frac{1}{I} \frac{dI}{d\lambda} \langle B_z \rangle,
\]

where \( V \) is the Stokes parameter that measures the circular polarisation, \( I \) is the intensity in the unpolarised spectrum, \( g_{\text{eff}} \) is the effective Landé factor, \( e \) is the electron charge, \( \lambda \) is the wavelength, \( m_e \) the electron mass, \( c \) the speed of light, and \( dI/d\lambda \) is the derivative of Stokes \( I \).
The longitudinal magnetic field was measured in two ways: using only the absorption hydrogen Balmer lines or using the entire spectrum including all available absorption lines. In Fig. 1 we present FORS 2 integral spectra for all observed targets together with the well-studied Pop II halo B-type star Feige 86 with $T_{\text{eff}} = 16430$ K, in which we searched for a magnetic field in May 2011. As we mention above, only upper limits have been obtained for Feige 86 by Borra et al. (1983). It is however possible that Feige 86 exhibits more similarity with HgMn stars than with sdB stars, as it shows He and Hg isotopic anomalies (Hubrig et al. 2009).

Our measurements of magnetic fields in ten sdB stars together with the observations of the classical Ap star HD 142070 (used as a standard star) are shown in Table 1. The first two columns list the object name and the modified Julian date of mid-exposure, followed by the measured longitudinal magnetic field $\langle B_z \rangle_{\text{all}}$ using the whole spectrum. In columns 4 and 5 we give the rms field $\langle B_z \rangle_{\text{all}}$ and the reduced $\chi^2$. Columns 6 to 8 list $\langle B_z \rangle_{\text{hyd}}$, $\langle B_z \rangle_{\text{hyd}}$, and $\langle \chi^2/n \rangle_{\text{hyd}}$ for the measurements using hydrogen lines.

In order to minimize the risk of apparent non-detection in some of the targets of our sample, due to fortuitous null observations of the longitudinal field close to the phases where it reverses its sign, stars were observed at two to four different epochs. The rms field is defined as:

$$\langle B_z \rangle = \left( \frac{1}{n} \sum_{i=1}^{n} \langle B_z \rangle_i^2 \right)^{1/2},$$

and the reduced $\chi^2$ as

$$\chi^2/n = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{\langle B_z \rangle_i}{\sigma_i} \right)^2,$$

where $n$ is the number of measurements of the considered star, $\langle B_z \rangle_i$ is the $i$-th such measurement and $\sigma_i$ is its uncertainty.

Figure 2 shows the three measurements of the mean longitudinal magnetic field of the Ap star HD 142070 that we obtained from consideration of its whole spectrum, together with the measurements of Mathys et al. (in preparation), based on CASPEC spectropolarimetric observations. The good agreement between the two datasets confirms the quality of the longitudinal field determinations achieved from...
FORS 2 observations and indicates that the order of magnitude of their quoted uncertainties is correct.

3 Discussion

In no star do our measurements reveal the presence of 1-2 kG fields. Our ability to detect weaker fields is limited by the accuracy of the measurements, as a result of the faintness of the studied stars and of the readout mode that was used. In only one case, SB 290, the longitudinal field determined at one of three epochs is formally significant at a level greater than 3σ. For this star, the reduced χ² of the three measurements that were performed also supports the reality of a detection at a confidence level greater than 99%. However, this conclusion depends critically on the correctness of the adopted measurement uncertainty; if the latter was only slightly underestimated (by 20% for the measurements based on all absorption lines), it would be invalidated. Thus measurements at more epochs and with better accuracy are needed to confirm the presence of a magnetic field in SB 290.

On the other hand, no significant longitudinal field was detected in Feige 86 in our recent spectropolarimetric observations of May 2011. The measurements resulted in ⟨Bz⟩all = 55 ± 49 G.

In conclusion, this study shows that large-scale organised magnetic fields of kG order are not generally present in sdB stars with Teff < 30 000 K. Yet it leaves open the possibility that these stars may have fields of a few hundred Gauss, with in particular a tantalising, although marginal, detection in one of them, SB 290. A firmer conclusion will require additional observations of higher quality.

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