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A search for magnetic Ap stars in young open clusters using the ESO VLT*

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Abstract.

We report results of an ongoing search for magnetic Ap stars in young open clusters using the ESO VLT and FORS1 spectropolarimeter. New magnetic field detections have been obtained for 19 stars, including a -9 kG magnetic field detected in the very young Rosette Cluster member NGC 2244-334 (a longitudinal field intensity second only to that of Babcock's star). In particular, we demonstrate robust exceptions to the proposal that Ap stars acquire their magnetic fields only after completing a substantial fraction of their main sequence evolution.

Key words: stars: magnetic fields – stars: chemically peculiar – open clusters – methods: observational

1 Introduction

About 10% of main sequence A- and B-type stars exhibit organised magnetic fields with typical strengths of about 1 kG. It is unknown when the magnetic field of these stars appears, e.g. during star formation, during the pre-main sequence phase, or during early main sequence evolution. Recently, Hubrig et al. (2000) examined the H-R diagram positions of resolved-line and other strongly magnetic Ap stars. Based on these results, they proposed that magnetic fields in lower-mass ($M < 3\ M_{\odot}$) Ap stars *do not appear until 30% of main sequence evolution is complete.* In other words, they proposed that either (i) the mechanism responsible for the generation of their magnetic fields did not become active, or (ii) that magnetic fields remained buried inside the stellar envelope, until a substantial fraction of the main sequence evolution was complete.

This primary result of Hubrig et al. (2000) has been cited as an important new constraint on models of magnetic field origin and evolution by theoreticians at conferences in Santiago (2001), Uppsala (2002), and Mmabatho (2003). Notwithstanding the enthusiastic reception by some theoreticians, this proposal provokes surprise in the light of other, apparently contradictory, results:

- Analysis of a large sample of Ap stars by Gomez et al. (1998), exploiting HIPPARCOS parallaxes, finding Ap stars to be distributed across the *full width* of the main sequence.
- Direct detections of magnetic fields in many higher-mass Bp stars at early stages of evolution in young associations like Ori and Sco-Cen.
- Earlier works by I.M.Kopylov, P.North, etc., along with more recent results (e.g. Pöhnl et al. 2003) identifying classical Ap star members of young open clusters, suggesting CP phenomena are exibited at relatively early stages of main sequence evolution.

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* This paper is based on data obtained at the European Southern Observatory VLT.

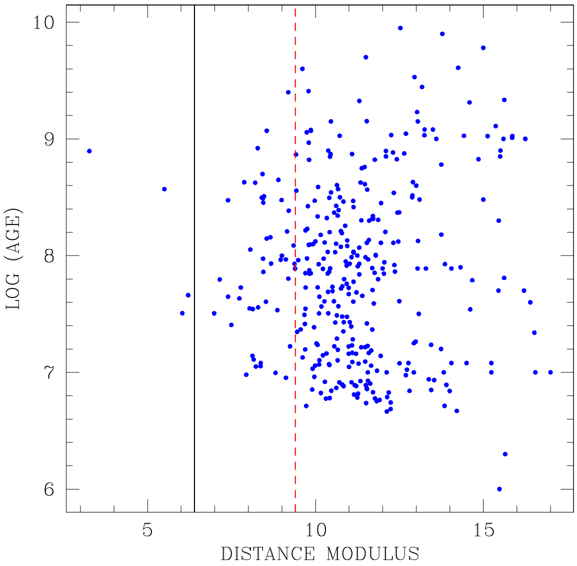

Figure 1: *Distribution of open clusters in the* log Age – *Distance Modulus plane. The solid line shows the limiting distance modulus for low-resolution spectropolarimetry with a 3.6 m telescope, while the dashed line shows the corresponding limit for an 8 m class telescope.*

Thus, we are presented with two contradictory conclusions based on high-quality data and careful analysis. How can this be resolved? Much of this ambiguity can be attributed to a single difficulty: due to their peculiar spectral energy distributions, it is very difficult to determine the HR diagram position of most magnetic A and B stars with sufficient accuracy so as to obtain their detailed position on the main sequence (and hence their ages). By contrast, it is often possible to obtain accurate ages of open clusters. Therefore, surveying open clusters with A and B star members allows us to determine their ages in a manner independent of the stellar spectrum. Such a strategy benefits from modern large telescopes and high-resolution spectroscopy.

This poster describes a project using FORS1 at the ESO VLT to perform spectropolarimetry of A and B stars in open clusters, in an attempt to correlate the presence of magnetic phenomena with stellar age.

2 Why an 8 m telescope?

In Fig. 1 we illustrate the distribution of open clusters as a function of age and distance modulus (using data obtained from the WEBDA database[1]). Fig. 1 demonstrates that only 4 open clusters are accessible to spectropolarimetric study with a 3.6 m telescope (such as the ESO 3.6 m telescope at La Silla, or the Canada-France-Hawaii telescope). On the other hand, an 8 m class telescope such as the ESO VLT can perform a spectropolarimetric study of a sample of clusters more than 10 times larger. Moreover, the ages of the clusters in this accessible sample span the full range of interesting ages, from very young clusters like NGC 2244 (the Rosette Nebula cluster, with log Age = 6.9), to older clusters, such as NGC 3114 (log Age = 8.1).

3 FORS1 at the VLT

FORS1 (FOcal Reducer and Spectrograph) is a low-resolution spectrograph and spectro-imager with polarimetric capabilities, currently mounted on the Antu unit telescope of the ESO VLT. FORS1 can provide low-resolution ($R \sim 1000 - 2000$) Stokes I and V spectra spanning the Balmer series from Hα to the Balmer limit.

As has been demonstrated by Bagnulo et al. (2002), longitudinal magnetic fields can be inferred with high precision ($\sim 20 - 100$ G) from these spectra using the well-known weak-field relation:

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[1] `http://obswww.unige.ch/webda/webda.html`

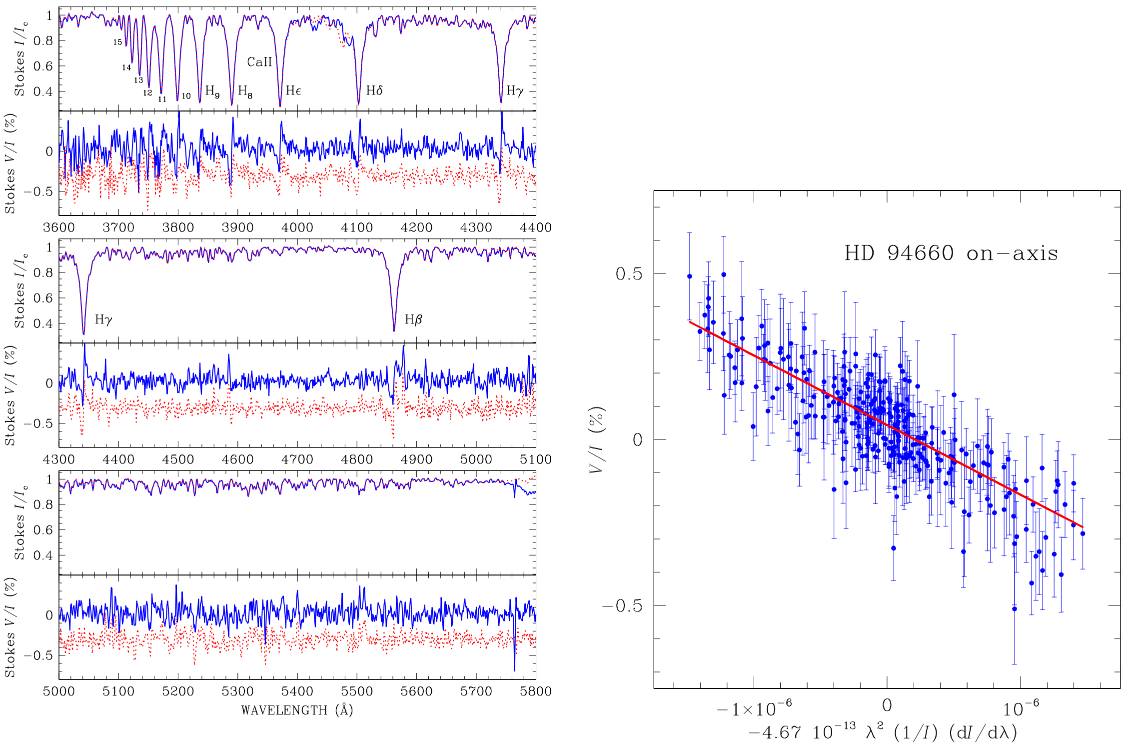

Figure 2: *Detection and diagnosis of a −2.1 kG magnetic field in the bright Ap star HD 94660 using FORS1 (Bagnulo et al. 2002).*

$$\frac{V}{I} = g_{\rm eff}\ \Delta\lambda_z\ \lambda^2\ \frac{1}{I}\ \frac{{\rm d}I}{{\rm d}\lambda}\ \langle {\rm B_z}\rangle\ + V_0/I_0; , \tag{1}$$

where g_{eff} is the effective Landé factor, V is the Stokes parameter which measures the circular polarization, I is the usual (unpolarized) intensity, λ is the wavelength, $\Delta\lambda_z$ is a constant and $\langle {\rm B_z}\rangle$ is the mean longitudinal field expressed in G. In A and B stars, for spectral lines of iron-peak elements (which have intrinsic widths around $\sim 3\ {\rm km\,s^{-1}}$), the weak-field regime typically holds only for magnetic strengths less than about 1 kG. Hydrogen lines are characterised by a much greater intrinsic broadening than metallic lines, and the weak-field approximation can be reasonably adopted for magnetic strengths up to a few tens of kG. An additional advantage is that the H Balmer lines are so broad that they can be easily detected even at low resolution.

Assuming $0.8''$ seeing, the approximate exposure time-uncertainty relation of FORS1 working as a Balmer-line Zeeman analyser is given by (Bagnulo et al. 2002):

$$t = 20 \times 10^{(V-6)/2.5}(100/\sigma)^2, \tag{2}$$

where V is the visual magnitude, σ is the desired 1σ error bar expressed in G, and t is the required exposure time in seconds. This relation results in a 20 second shutter time in order to detect a 300 G field in a V=6 star ($\sigma = 100$ G); a 3.5 hour shutter time to detect a 300 G field in a V=13 star ($\sigma = 100$ G); and a 2 minute shutter time to detect a 3 kG field in a V=13 star ($\sigma = 1$ kG). These calculations illustrate the utility of the FORS1/VLT combination for detecting both the weakest and strongest field present in Ap stars.

4 The open cluster survey

To date, we have obtained 149 circularly polarised spectra in 12 open clusters ranging in age from $\log t < 6.5$ to 8.1, in 2 FORS1 runs. A third FORS1 run has also been allocated, as well as UVES runs aimed at acquiring complementary high-resolution spectroscopy of identified magnetic candidates.

Of the targets observed, 110 are spectral type A and B main sequence stars, and 35 were previously identified CP stars. From this sample we have obtained 21 firm new magnetic field detections at $> 3\sigma$.

Table 1:

Open Cluster	$\log t$	$m - M$	No. of observed A and B stars	No. of observed known Ap stars	No. of magnetic detections
Ori B Ass. c	6.6	8.16	13	9	4
NGC 2244	<6.5	12.28	3	1	1
NGC 2169	7.07	10.75	5	1	1
NGC 2343	7.10	10.50	17	0	0
NGC 2232	7.35	7.76	1	1	1
NGC 2451	7.65	7.57	4	3	2
IC 2391	7.66	6.24	2	2	2
NGC 2422	7.86	8.67	2	2	1
NGC 3228	7.93	8.77	11	0	0
NGC 5662	7.97	10.11	7	2	1
NGC 6087	7.98	10.31	2	1	1
NGC 2516	8.05	8.38	38	9	4
NGC 3114	8.09	10.02	5	4	3
TOTAL			110	35	21

The clusters observed and the detection statistics are summarised in Table 1. In Fig. 3 we represent our sample results as observed longitudinal field strength B_z versus the detection significance $z = |B_z/\sigma_B|$. In this diagram, significant field detections of strong fields sit at the upper right (and are represented by filled symbols), while null detections lie below the 3σ dashed line (typically at the lower left of the figure). As can be seen in this figure, a number of significant detections of very strong fields have been obtained, with intensities of B_z in excess of 1 kG.

Throughout the remainder of this paper, we will describe magnetic and complementary spectroscopic results obtained for two of the 21 stars detected. These targets are outstanding for the super-strong magnetic fields that they exhibit, and for their especially early main sequence evolutionary stages.

5 Discovery of super-strong magnetic fields in 2 Ap young stars

5.1 HD 66318

Results for HD 66318 are described in detail by Bagnulo et al. (2003).

HD 66318 was classified by Hartoog (1976) as an A0p SrCrEu star, a spectral classification almost always associated with the presence of a detectable magnetic field. It was found by Maitzen & Hensberge (1981) that the Δa photometric index of HD 66318 is very large, indicating that this star is extremely peculiar. It is a *bona fide* member of the open cluster NGC 2516. In this star, we detect a super-strong longitudinal magnetic field $B_z = +4.5 \pm 0.2$ kG. This detection is illustrated in Fig. 4.

Using the available (de-reddened) photometry, various independent calibrations yield an effective temperature of 9200 ± 200 K. Based on this temperature and the cluster age of 113 Myr, HD 66318 has a mass of $2.1 \pm 0.1\ M_\odot$, and has completed only $16 \pm 5\%$ of its main sequence evolution (where the uncertainty includes both that due to the error in the cluster age and that due to uncertainty in the effective temperature). This result contradicts the hypothesis of Hubrig et al. (2000) that magnetic fields only appear in Ap stars after about 30% of the main sequence lifetime has elapsed.

Follow-up using the ESO Coudé Echelle Spectrograph on the 3.6 m telescope at La Silla produced a single high-resolution spectrum covering the entire visible region. This spectrum immediately revealed that HD 66318 has very sharp lines, and hence a very low value of $v \sin i$ (at most a few km s^{-1}), and that almost every line in the spectrum is strongly and obviously split into several components by the Zeeman effect. The field deduced from the splitting in this spectrum (see Fig. 5) is about 14.5 kG. Again this places HD 66318

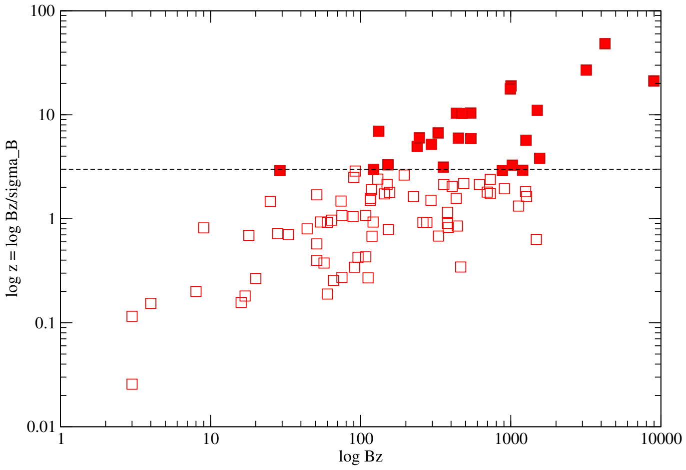

Figure 3: *Results from the Open Cluster Survey. This figure shows definite detections of strong fields (characterised by large values of the detection significance* z *and the absolute field strength* $\langle B_z \rangle$*) at upper right.*

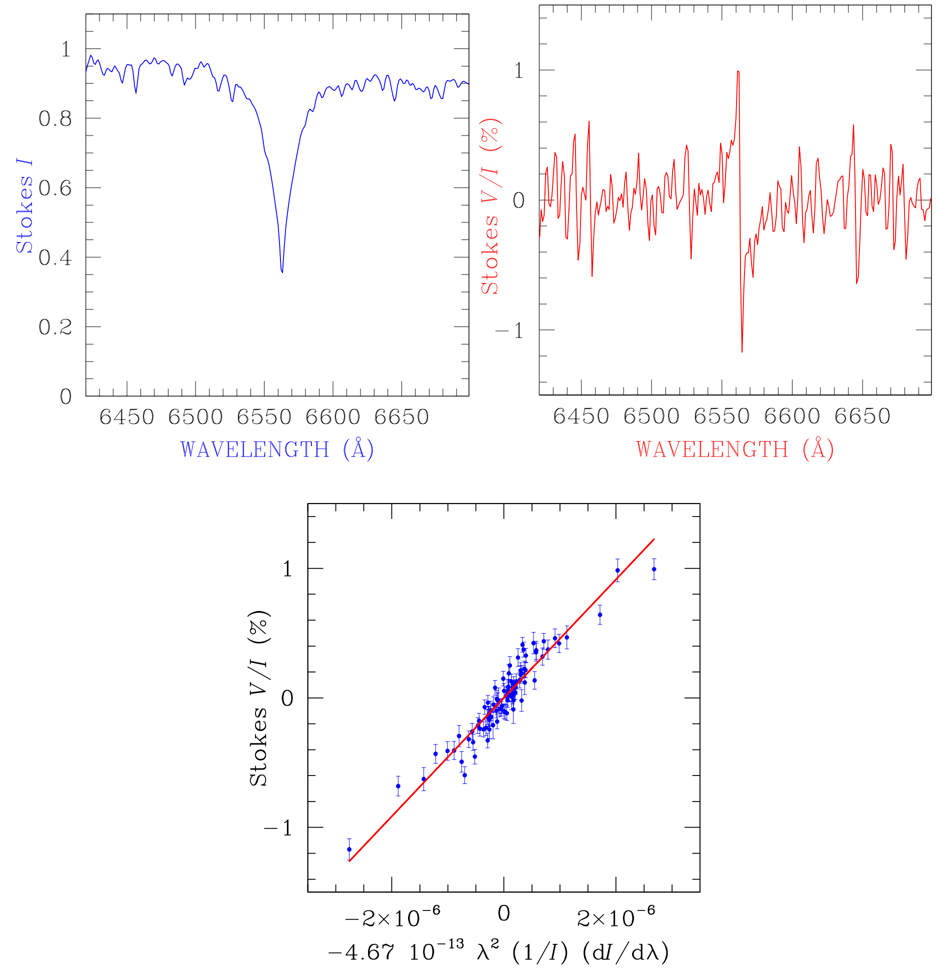

Figure 4: *Detection of a 4.5 kG longitudinal magnetic field in HD 66318.* Upper frames – *FORS1 Hα Stokes I (left) and V (right) profiles.* Lower frame – *regression according to Eq. (1), giving the longitudinal magnetic field.*

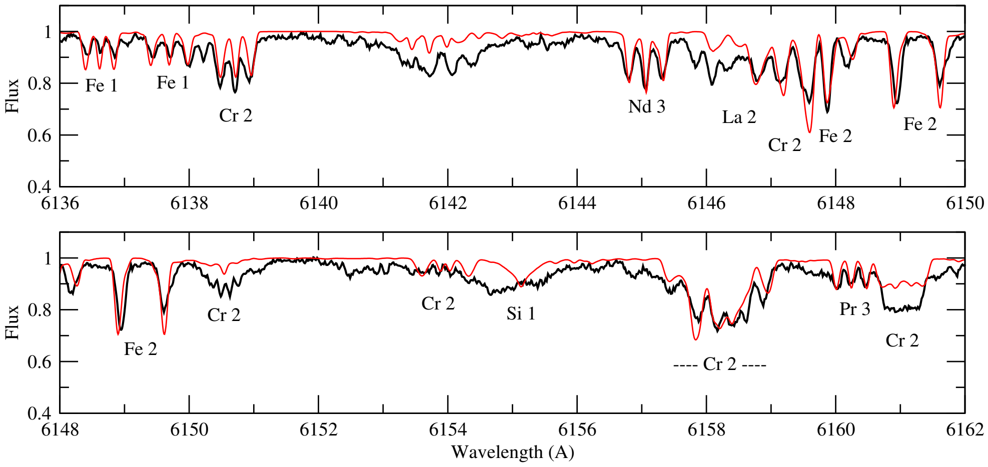

Figure 5: *High-resolution spectrum of HD 66318 obtained using the Coudé Echelle Spectrograph (CES) of the 3.6 m ESO telescope at La Silla.* Thick curve – *observed spectrum.* Thin curve – *synthetic spectrum including a 14.5 kG surface magnetic field and adjusted abundances. Note the magnetic splitting.*

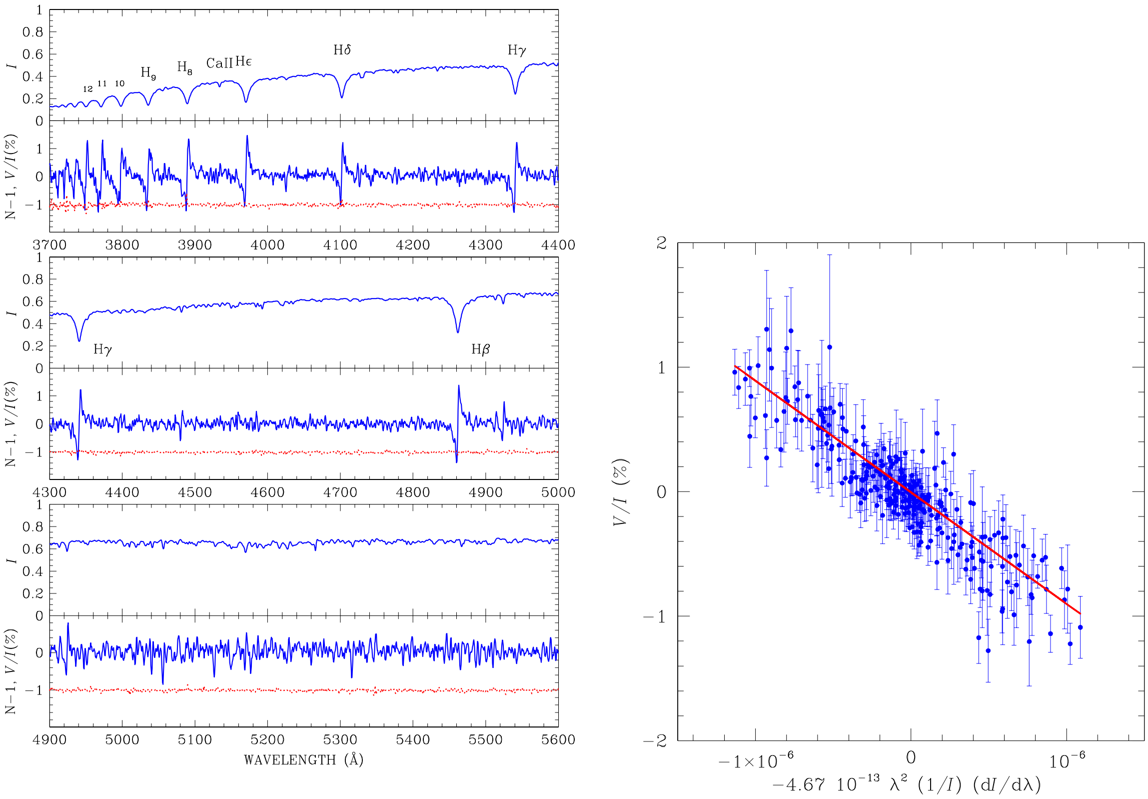

Figure 6: *Detection of a −9 kG longitudinal magnetic field in NGC 2244-334.* Left – *FORS1 Stokes I and V spectrum showing strong circular polarisation profiles associated with all Balmer series lines.* Right – *regression providing diagnosis of the longitudinal magnetic field according to Eq. (1).*

among the magnetic Ap stars with the largest values of the surface field; as a comparison, note that only five of the 42 stars with measured values of the surface field listed by Mathys et al. (1997, Table 2) sometimes exhibit values of the mean field modulus as large as that of HD 66318.

Magnetic spectrum synthesis (see Fig. 5) yields approximate mean vertically-integrated and disc-integrated abundances for various elements. We find that HD 66318 is indeed strongly chemically peculiar: O is underabundant by > 1 dex, Si is enhanced by at least 1 dex and vertically stratified, Fe, Ti, and Cr are enhanced by 1.5–4.5 dex and stratified, and La II appears to be enhanced by as much as 4 dex.

5.2 NGC 2244-334

Results for NGC 2244-334 are described in detail by Bagnulo et al. (2004).

NGC 2244-334 was included in our cluster sample due to the discovery by Hensberge et al. (1998), using synthetic Δa photometry, that this star is strongly peculiar Ap-Bp member of the young open cluster NGC 2244 (the Rosette nebula cluster). The open cluster itself is estimated to be less than $3 \cdot 10^6$ y old, and is one of the youngest open clusters known. In this star, we detect a super-strong longitudinal magnetic field $B_z = -9.0 \pm 0.2$ kG, *the second-largest longitudinal magnetic field ever detected in a non-degenerate star.* This detection is illustrated in Fig. 6.

Using the available (de-reddened) photometry, we obtain an effective temperature of 15000 ± 1000 K. Based on this temperature and the cluster age, NGC 2244-334 has a mass of $4.0 \pm 0.5\ M_\odot$, and has completed less than $2 \pm 1\%$ of its main sequence evolution. Although this result does not expressly contradict the hypothesis of Hubrig et al. (2000), it does illustrate that very strong magnetic fields can exist in Ap/Bp stars at the very earliest stages of main sequence evolution, virtually from birth on.

Follow-up of this detection was conducted using the UVES spectrograph, producing a single high-resolution spectrum over the entire visible window. Unlike the spectrum of HD 66318, in the spectrum of NGC 2244-334 we observe lines extensively broadened by rotation ($v \sin i = 50$ kms^{-1}). Abundances could nevertheless be obtained using magnetic spectrum synthesis. Again, NGC 2244-334 is found to be strongly peculiar, with He underabundant by 1.5 dex, Si overabundant by somewhat less than 1 dex and possibly stratified, and Fe, Cr, Ti overabundant by 0.8–2 dex.

6 Conclusions

In this paper we have described the motivation, procedure and preliminary results of a survey of magnetic Ap stars in open clusters using the FORS1 spectropolarimeter on the ESO VLT.

We have found that FORS1 on the VLT represents a superb tool for studying evolutionary aspects of stellar magnetism.

We have identified firm examples of unevolved main sequence Ap/Bp stars hosting strong surface magnetic fields, in contradiction of the hypothesis of Hubrig et al. (2000).

We can conclude that surface magnetism in A and B stars can appear very early in their evolution, and that chemical peculiarity accompanies the appearance of these fields. This supports the proposal that their magnetic fields are generated pre-main sequence.

The results of Hubrig et al. (2000) must be tested. Simultaneously, the Open Cluster Survey will be continued in order to study the characteristics of stellar magnetism across the full width of the main sequence.

These results provide motivation for a high-precision search for strongly magnetic *pre-main sequence Ap/Bp stars* to be initiated.

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