Detecting Magnetic Fields of Upper-Main-Sequence Stars With FORS1 at ANTU

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During the night between 22 and 23 March 2001, the VLT unit telescope ANTU was pointed to a 6th-magnitude A-type star to obtain several low-resolution spectra in circular polarisation with FORS1. Two nights later, the same exercise was repeated selecting a second A-type star of similar magnitude. The outcome of this experiment was the firm detection of a magnetic field in an upper-main-sequence star, HD 94660. It is the first time that a VLT unit telescope was (successfully) used to detect magnetic fields in non degenerate stars.

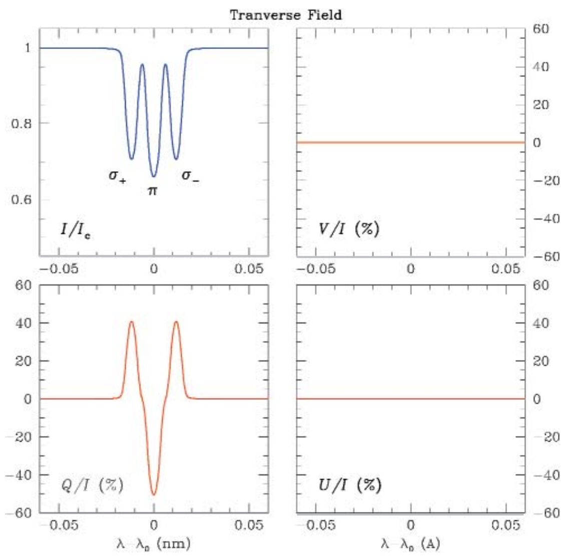
We will start with a quick overview about observations of stellar magnetic fields, and we will outline the theoretical fundamentals of magnetic diagnostic techniques. Then we will describe our experiment with the VLT and discuss which perspectives our results open for the observations of stellar magnetic fields with large telescopes.

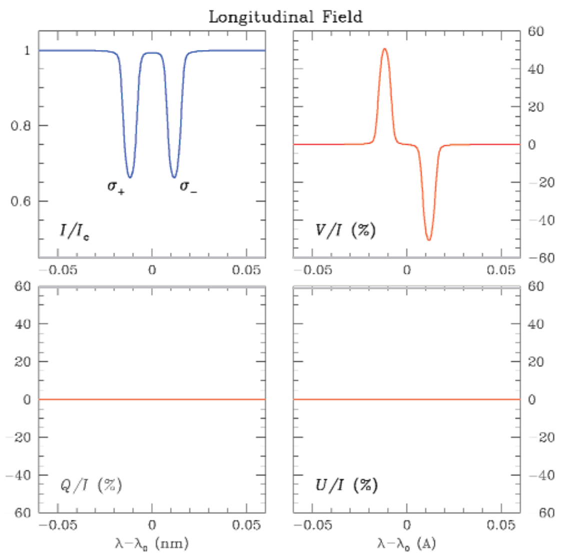
1. Some History

Magnetic fields have been firmly detected in many objects of the Hertzsprung-Russell diagram. In historical order, obviously first comes the Sun, with the discovery made by Hale (1908) that sunspots are characterised by a magnetic field up to a few kG. The first detection of a magnetic field in a star other than the Sun was made 40 years later, with the observations of the Ap star 78 Vir by Babcock (1947). A decade later, it was clear that most of the chemically peculiar stars of the upper main sequence are characterised by a magnetic field organised on a large scale, with a typical strength of a few hundred up to a few ten thousand G (Babcock 1958). Ap stars are still the

The Zeeman Effect on Spectral Lines

Let us assume that a spectral line is formed in presence of a magnetic field perpendicular to the line of sight. The classical interpretation of the *Zeeman effect* describes an atomic oscillator split into two σ components at frequencies $\nu_0 \pm \nu_L$, and into a π component at frequency ν_0, where ν_0 is the unperturbed frequency of the oscillator, and ν_L is the Larmor frequency. The σ components appear polarised in the direction perpendicular to the magnetic field vector, the π component is polarised in the direction parallel to the magnetic field. In case of a longitudinal field, the spectral line will be split into two σ components at frequencies $\nu_0 \pm \nu_L$, circularly polarised in opposite directions. Above some critical regime, about 1 MG, the quadratic Zeeman effect becomes important, and line formation can be explained only in terms of quantum-mechanics. For $B > 50$ MG, magnetic field and Coulomb forces are of comparable strength, and only few numerical calculations have been performed to explore the physics of line formation in this regime. These complications should be taken into account for objects such as (some) magnetic white dwarfs, or cataclysmic variables, but can be safely neglected in non degenerate stars. For a 10 kG magnetic field, the Stokes profile of a *metallic* line originated by a single stellar surface element appears as in the left lower panels for a transverse field, and as in the right lower panels for a longitudinal field. Stokes *I* represents the well-known 'intensity', Stokes *V* measures the circular polarisation, Stokes *Q* and *U* the linear polarisation. Typically one prefers to plot the ratio Stokes *V/I*, *Q/I*, and *U/I*, i.e., we normalise the polarisation to the intensity (sometimes the continuum intensity), and we express this ratio in percent units, as in these panels. Note that for a transverse field, the circular polarisation is zero (left panels). Note also the different signs of Stokes Q in the π and σ components – which correspond to a linear polarisation parallel to the field in the π components, and perpendicular to the field in the σ components. (The fact that Stokes *U* is null depends uniquely on the reference system adopted for the measurement of the linear polarisation.) For a longitudinal field (right panels), the linear polarisation is zero.





For a field vector arbitrarily oriented, the line components are 'elliptically' polarised, see for instance the top panels on page 33, which refer to a 10 kG field tilted at an angle of 45° with respect to the line of sight, and with an azimuth angle of 30°.

most popular targets for studying stellar magnetic fields (except the Sun, of course): their strong and smooth field produces a signal of polarisation on the spectral lines that can relatively easily be detected even through disk-integrated observations. In comparison, the value of the disk-averaged solar magnetic field is extremely low: from 3 G at solar minimum to 20 G at solar maximum. Most of it is concentrated in discrete magnetic elements of mixed polarity, so that the net, disk-averaged component of the field along the line of sight is much smaller than those values. In particular, the circular polarisation of spectral lines due to several magnetic flux tubes of different polarities would mostly cancel out if the sun were observed as a star. Most main-sequence late-type stars have probably a solar-like magnetic morphology, which as such escaped all attempts of detection until the eighties, when Robinson et al. (1980) detected a phenomenon of magnetic intensification in the spectral lines of ξ Boo A and 70 Oph A.

Amongst the objects outside the main sequence, magnetic white dwarfs are the ‘easiest’ targets: as in the Ap stars, the magnetic field of white dwarfs is generally characterised by a smooth morphology, but with a strength which can measure up to several hundred megagauss! However, white dwarfs are very faint objects (typically V > 13), therefore only middle- and large-size telescopes are suitable for their observations. The first detection of a magnetic white dwarf was made 30 years ago (Kemp et al. 1970), and large surveys have been carried out in the last decade (Schmidt & Smith 1995; Putney 1997).

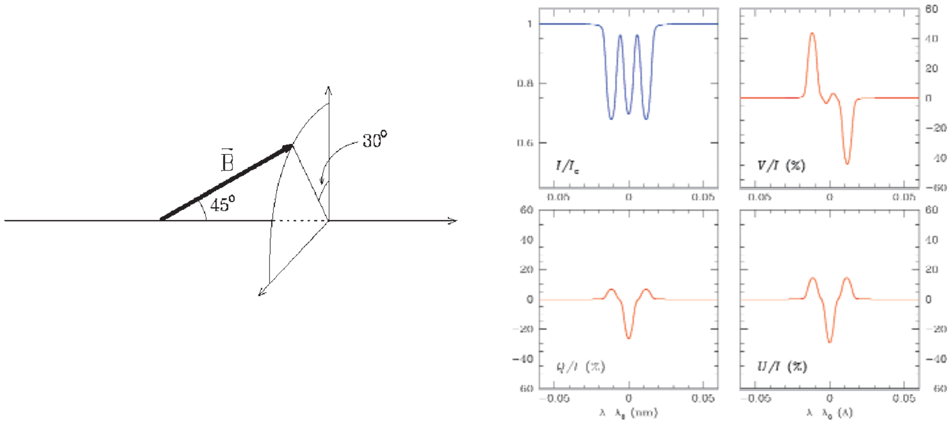
Thanks to refined studies of magnetic intensification of spectral lines, or the use of more modern and exotic techniques such as the LSD (this means Least Square Deconvolution, Donati et al. 1997), magnetic fields are nowadays commonly observed also in pre-main-sequence stars, and in various evolved objects such as RS CVn stars.

As we will show next, the VLT has also the capability of playing a central role in the studies of stellar magnetic fields, not only for observations of extremely faint objects that would be simply invisible to middle-size-class telescopes, but also for highly sensitive detections of magnetic fields in relatively bright stars.

2. Theoretical and Observational Basis

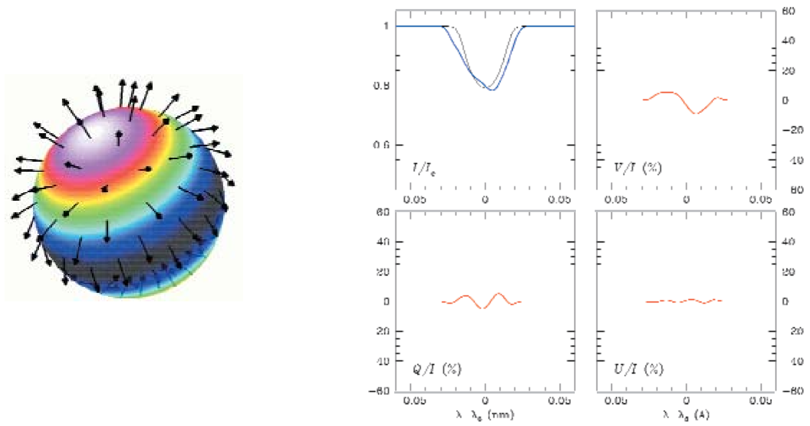
The most direct method for detection of magnetic fields in non degenerate stars is based on the analysis of the Zeeman effect in the Stokes parameters of the spectral lines.

Spectral lines formed in presence of a magnetic field may be split into several (polarised) components. In the optical range, the Zeeman splitting is of the order of about 1 km s^{-1} per kG, which means for instance that the splitting of spectral lines of a star characterised by a mean field strength of 10 kG is comparable to the effect of rotational broadening if the star rotates with projected rotational equatorial velocity $v \sin i$ = 10 km s^{-1}. It is clear that rotational broadening is going to wash out



The stellar case is a bit more complicated, as one has to integrate the contributions from all stellar surface elements, taking into account a magnetic field which changes across the stellar surface: the polarisation signal is noticeably diluted, since contributions to the polarisation signal coming from different stellar regions tend to cancel out. The right panels in the figure below show the Stokes profiles calculated for a 10 kG dipole oriented as shown in the left panel, and for a star that rotates with $v \sin i$ = 10 km s^{-1}. Note that Zeeman splitting in Stokes *I* is washed out by the rotational broadening, whereas polarisation in spectral lines can typically be observed in stars that rotate with $v \sin i$ up to a few tens of km s^{-1}. (In faster rotators, also Stokes *Q*, *U*, and *V* become ‘invisible’.) For ‘real’ magnetic morphologies, which are in general much more complex than the dipolar one, detection of stellar magnetic fields may be quite challenging!

Note that the Zeeman effect is also responsible for a broadening of the spectral lines, which depends upon the magnetic strength, but – to first order, not on the field orientation. The contributions from different stellar regions do *not* cancel out, and spectral lines formed in presence of a magnetic field appear always slightly broader than what expected in the same physical conditions but without magnetic field. (For comparison, the black thin solid line represents the spectral line formed without the presence of a magnetic field.)



One of the worst enemies of the polarisation in spectral lines is the instrumental blurring. The Stokes profiles shown in the figure would be considerably smeared out if they where observed with a spectral resolution as low as 40,000 (!) and would be reduced to a level nearly consistent with noise at spectral resolutions lower than 10000. High resolution is mandatory for spectropolarimetry of metallic lines. Clearly, for Hydrogen lines, the resolution requirements are considerably relaxed.

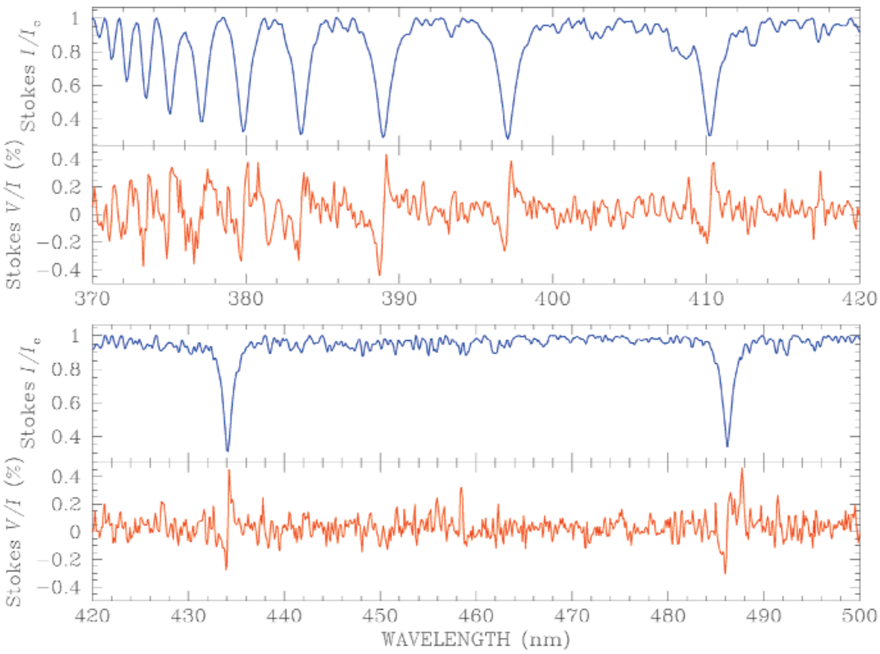


Figure 1: The polarised spectrum of the magnetic Ap star HD 94660.

the Zeeman splitting in most stars, except those that are very slow rotators and which possess a very strong magnetic field. Although these kinds of objects do exist, and Zeeman splitting has been detected indeed in several magnetic Ap stars (see Mathys et al. 1997), most magnetic stars can be disclosed as such only through the use of polarimetric techniques. (The Zeeman effect on spectral lines is illustrated in the box below.)

Indeed, most of our knowledge of stellar magnetic fields comes from the detection of *circular* polarisation of metallic lines. The theory of line formation in a magnetic field shows that the measurement of the first-order moment of Stokes V about the line centre of metallic lines is proportional to the component of the magnetic field along the line of sight averaged over the stellar disk, i.e., the *mean longitudinal magnetic field* (e.g., Mathys 1991; this technique is equivalent to the measurement of the splitting of a spectral line observed in both senses of circular polarisation, which is what Babcock did in his pioneering work in the 50's). An extensive campaign of spectropolarimetry of Ap stars was carried out by Mathys (1991) at ESO with CASPEC at the 3.6-m telescope. Since CASPEC was decommissioned, no high-resolution spectroscopy in circular polarisation is currently possible at ESO.

An alternative technique for the detection of stellar magnetic fields was developed in the 70's by Angel & Landstreet (1970; see also Borra & Landstreet 1980), based on the detection of circular polarisation on the Hydrogen Balmer lines (and in some hot stars, also He Balmer lines). The H Balmer lines are so broad that they can be easily detected even at low resolution. In fact, what for instance Borra & Landstreet (1980) used was rather a *photopolarimetric* technique, which made use of two 5 Å wide filters centred on the wings of the Hβ. Similarly to the measurement of the first-order moment of Stokes V about the line centre, the measurement of the difference between the circular polarisation observed in the red and blue wings of Hβ permits one to derive the mean longitudinal field. In principle, we thought the same technique could be used with a low-resolution spectropolarimeter such as FORS1, with which, in addition, several Balmer lines could have been observed. In the past, spectropolarimetry of the Hα and Hβ Balmer lines was repeatedly applied for detection of strong magnetic fields of white dwarfs. The question was whether the same technique could have been used for detection of weaker stellar fields, such as those of magnetic Ap stars. The theoretical examples shown in the box refer to sharp metallic lines, and do not account for instrumental blurring. What happens with the (very broad) H lines observed at the low resolution of FORS1 ?

Under reasonable approximations, one can show that for H lines

$$\frac{V}{I} = 4.67 \times 10^{-13} \lambda^2 \frac{\mathrm{d}I}{\mathrm{d}\lambda} \frac{1}{I} \langle B_z \rangle \qquad (1)$$

where *I* is the usual (unpolarised) intensity, *V* is the Stokes parameter which measures the circular polarisation, λ is the wavelength expressed in Å, and $\langle B_z \rangle$ is the mean longitudinal field expressed in G. The precision of this expression is certainly arguable, the reader can find more details e.g., in Mathys (1989). However, there is no doubt that it does permit us to give a first rough estimate of the longitudinal field $\langle B_z \rangle$ – caution should be used however for detailed modelling purposes. A simple numerical exercise shows where the major problems come from. Take a star with a 1 kG longitudinal field, be aware that for H Balmer lines of A and B stars $\mathrm{d}I/\mathrm{d}\lambda \times 1/I$ is typically < 0.1Å^{-1}, and find that the expected value of the circular polarisation is about 0.1%. This means that for a firm detection of a 1 kG magnetic field, we need to count at least 10^6 photons. For a 100 G field we expect a polarisation of 0.01%, i.e., we want to obtain a S/N ratio of 10^4! Clearly, such a S/N ratio need not be per pixel, but integrated over the direction perpendicular to the dispersion, and over all the various observed Balmer lines. With the GRISM 600B (which covers the interval range between 3450 and 5900 Å, i.e., including all Balmer lines from Hβ on), the signal that we want to detect is spread over approximately 10^3 pixels. Therefore, we estimated that 10^5 was the order of magnitude of photons per pixel that we should try to reach – something safely possible by setting the readout mode to low gain, and with the help of multiple exposures. (Multiple exposures are anyway mandatory in polarimetric mode: to minimise the effect of cross-talk, exposures have to be taken with the retarder waveplate set at different angles.)

3. Results

Thanks to DDT 266.D-5649, we were able to test this technique with FORS1 at ANTU. The observations were carried out with the Grism 600B. With a 0.4 arcsec slit we obtained a spectral resolution of about 2000. As a target for our experiment we selected a well studied magnetic Ap star, HD 94660, which is known to have a very long rotational period (≃ 2800 d) and a moderately strong magnetic field. For comparison, we also decided to observe a non magnetic star of similar spectral type and magnitude, HD 96441. Figure 1 shows the observed spectrum of HD 94660 in 'natural' light (Stokes *I*), normalised to the (pseudo) continuum, together with the spectrum of the circular polarised radiation. The S/N as measured from the rms around the continuum is about 1500 per pixel (binned in the direction perpendicular to the dispersion). A dozen Balmer lines are clearly visible, and what looks like noise is due in fact to the contributions of many metallic lines: it should be recalled that chemically peculiar stars are characterised by overabundances (with respect to the solar case) of iron peak and rare-earth elements. All H Balmer lines appear clearly polarised up to a maximum level of about 0.4%. Note the characteristic S-shape of Stokes V profiles of Balmer lines; the fact that the circular polarisation is negative in the blue wings and positive in the red wings tells us that the mean longitudinal field is negative, i.e., points away from the observer.

Like Stokes *I*, also Stokes *V* looks very noisy. A fraction of the 'noise' is probably due to the polarisation coming from the metallic lines, as it appears clear from a comparison with the observations of HD 96441, the non-polarised star that was selected for a comparative test (see Fig. 2). Here the signal of circular polarisation is consistent with a null detection, and what we see in Stokes *V* is real noise.

A more quantitative overview of the results of our experiment is shown in Figure 3. A least-square technique was used to derive the longitudinal field via Eq. (1), allowing also for a constant contribution of instrumental polarisation. The validity of Eq. (1) is in fact limited to unblended H lines. Clearly, our spectrum includes zillion metallic lines, many of them blended with H lines. Still, Eq. (1) was empirically shown to be a reasonable assumption. We first applied a least-square technique including *all* data points (i.e., including all H Balmer lines and all metallic lines); then we repeated the calculations considering only the wavelength intervals around the Balmer lines. The results from the two experiments were found consistent among themselves, and for HD 94660 we derived a longitudinal field of –2110 ± 50 G (Figure 3 refers to the H Balmer lines only). This value is fully consistent with what is known from

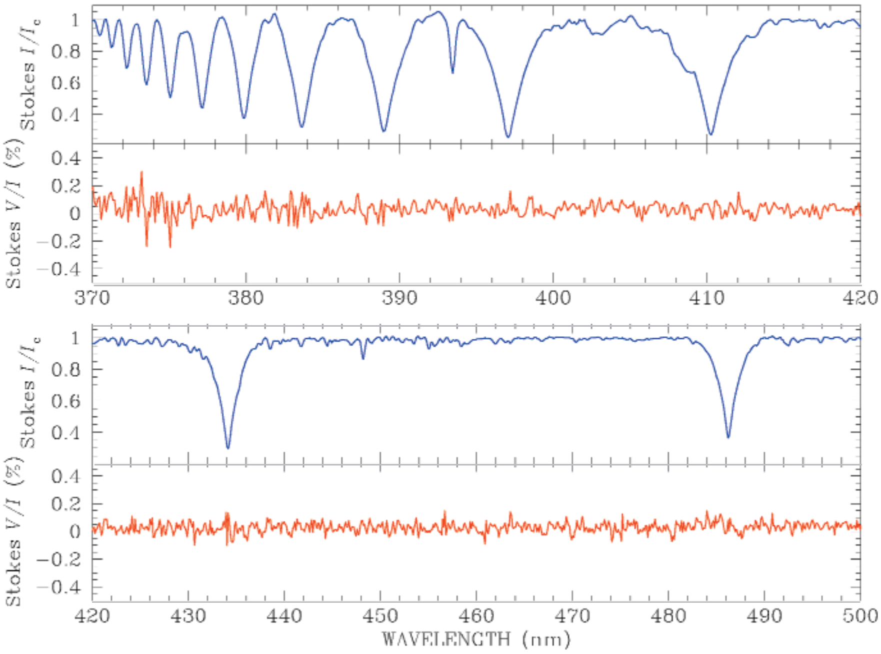


Figure 2: The unpolarised spectrum of the non magnetic A star HD 96441.

previous studies of the same star. As a matter of fact, Balmer lines dominate the observed Stokes *I* and Stokes *V*. However, the *real* error associated to our estimate of $\langle B_z \rangle$ *is* probably larger than the *formal* error obtained via the least-square technique: it should be recalled that Eq. (1) permits us to obtain the mean $\langle B_z \rangle$ only as a first approximation. The estimate of the mean longitudinal field of HD 96441 was found consistent with zero. The contribution due to instrumental polarisation was found about –0.03 %.

4. A Comparison with the Previous Techniques

The magnetic target selected for our experiment was a very bright star: V = 6. Our choice was due to the fact that most of the known magnetic stars are very bright. Clearly, the actual exposure time was very short (about 30 seconds, split in several exposures). We roughly estimate that 200–300 G fields can be detected with an exposure time of about 2 hours in a 13th magnitude star. (The limit magnitude that we can reach

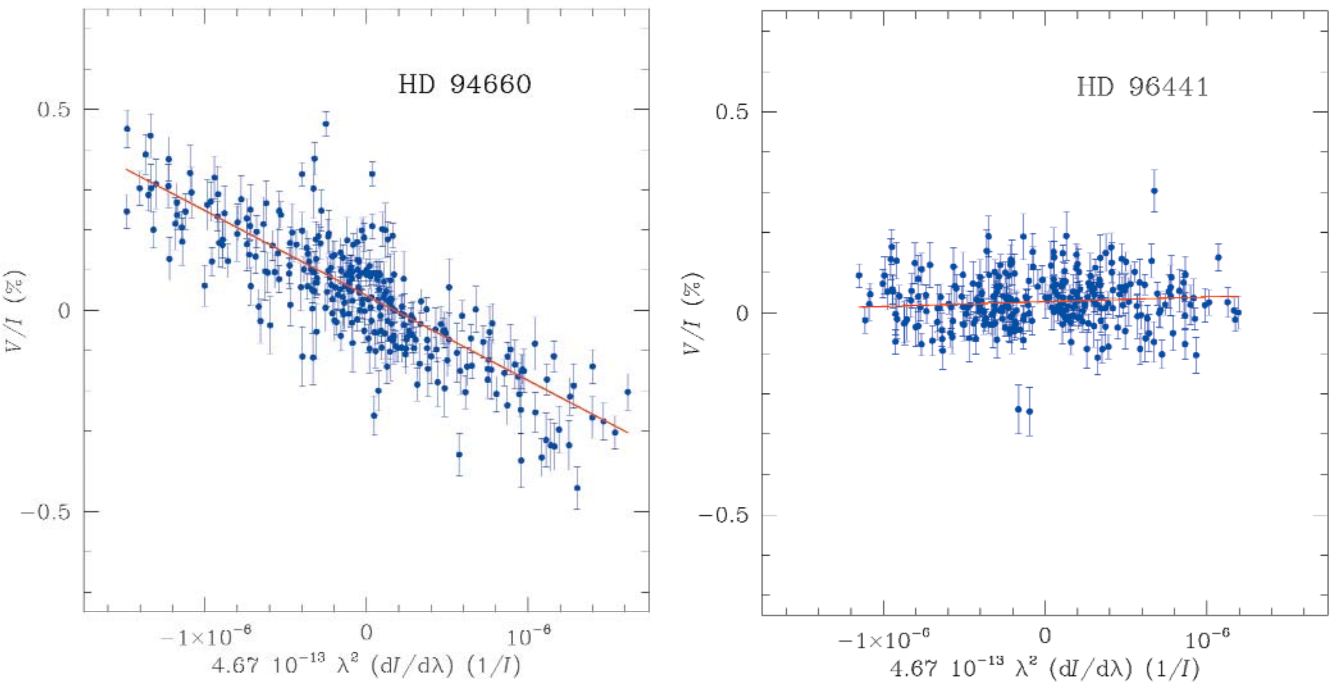


Figure 3: The slope of the red line (obtained via a least-square technique to the observed data) is proportional to the stars' mean longitudinal field. For the magnetic star HD 94660 (left panel) we measured $\langle B_z \rangle$ = –2110 ± 50 G. For the non magnetic star HD 96441 (right panel) there is no magnetic field detection.

is in fact strictly related to the precision that we want to obtain: stronger field can be detected in fainter stars.)

Practically, what is the advantage of using FORS1 + ANTU to detect stellar magnetic fields, compared to the use of the previous techniques at the small- and middle-size-class telescopes? Do we just save telescope time and/or observe fainter stars?

Compared to the photopolarimetric technique of Hβ, the capability of observing several Balmer lines reflects in a substantial gain in terms of S/N, thus in terms of limit magnitude of the star that one wants to observe, even assuming an identical size for the collecting area.

A proper comparison with the technique based on high-resolution spectropolarimetry of metallic lines is less straightforward. With this technique, and in the cooler early-type stars, one can easily detect hundred metallic lines, thus obtaining a very high S/N per pixel is not a critical issue. One could suspect that the sole advantage of using FORS1 at the VLT is due to the large collecting area of the telescope, and that high-resolution spectropolarimetry of metallic lines would be still the best-choice to study stellar magnetic fields. This is certainly true for detailed *modelling* of magnetic fields in *slower* rotators, but low-resolution spectropolarimetry of H Balmer lines will remain the best-choice for *surveys* of magnetic stars, and for studying magnetic field's *faster* rotators, even when high-resolution spectropolarimetric capabilities will be available at the large-size-class telescopes.

The polarisation of H Balmer lines is well detectable also in relatively fast rotators, maybe up to 150 km s^{-1}. This represents a major advantage with respect to high-resolution spectropolarimetry of metallic lines, a technique which can successfully be applied only to stars that rotate with $v \sin i$ < 30–40 km s^{-1}. Furthermore, the multi-object capability of *FORS1 is* available also in spectropolarimetric mode, which may substantially increase the efficiency of the telescope time.

On the whole, the use of a technique based on *low-resolution* spectropolarimetry on large-size-class telescopes such as FORS1 at the VLT opens the very interesting opportunity to study magnetic fields in upper main sequence stars fainter and faster rotating that it was possible before. Why do we care about this possibility?

5. Scientific Applications

Chemically peculiar stars do not represent a restricted class of objects, but a consistent fraction of all upper main sequence stars – about 20%. Understanding their physics is a compulsory step in order to have a comprehensive view of general stellar physics and evolution. For the time being, the physics of the atmospheres of magnetic Ap stars is far from being well understood. We believe that their chemical anomalies result from the influence of the magnetic field on the diffusing ions, possibly in combination with the influence of a weak, magnetically-directed wind (Michaud 1970; Babel 1992). The magnetic field is itself probably a fossil remnant, either of a field swept up by the star during formation, or possibly generated during pre-main-sequence evolution. In fact, it is unknown *when* the magnetic field of these stars forms. Does the magnetic field characterise their entire life on the main sequence, or does the magnetic field pop up at the surface at some stage? The results of some studies suggest that the magnetic fields and chemical anomalies in Ap stars originated at the moment when young Ae/Be stars arrive on the zero-age line, when the gaseous dust envelopes surrounding them dissipate and accretion ceases, i.e., magnetic Ap stars form at the ZAMS. On the other hand, Hubrig et al. (2000) have recently argued that magnetic stars are concentrated toward the centre of the main sequence band (for stellar masses ≤ 3 $M_\odot$). Summarising, there are no firm conclusions about the role played by the magnetic field in the evolution of Ap stars (nor other non-peculiar stars). We do not know either whether all Ap stars pass through a magnetic phase, or just some of them. This is due mainly to a single difficulty: due to their weird spectral energy distributions, it is not possible to locate Ap stars on a precise position along the main sequence strip (and hence derive their ages). Systematic errors seem to be very important. This is also illustrated by recent studies using Hipparcos data (Gomez et al. 1998; Hubrig et al. 2000) which draw apparently contradictory conclusions about the general evolutionary state of magnetic A stars.

The use of a FORS1 at the VLT opens the possibility to search for magnetic stars in open clusters, sampling the stellar evolution across the main sequence, and correlating the presence of magnetic fields with age. This is a task that has been unsuccessfully attempted in the past, being virtually out of reach of small and middle-size telescopes. With FORS1 used in multi-object spectropolarimetric mode it may become a feasible and interesting research field.

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Colour composite of the spiral galaxy M83 in the visible. This mosaic is a composite of WFI images taken in the B, V, and R filters (3 × 200 sec in each filter). It shows the structure of the spiral galaxy M83 in great detail, especially its regions of active star formation and clusters. Such deep wide-field images of nearby galaxies are also very valuable for the search of low-surface-brightness companions to the central galaxy and of faint tidal structures in its outer regions. This colour composite was constructed by D. Froebrich and A. Scholz at Thüringer Landessternwarte Tautenburg from test data taken by J. Eislöffel and R. Mendez. ▶