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Astronomy & Astrophysics

Magnetic field measurements of O stars with FORS 1 at the VLT*

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ABSTRACT

Context. The presence of magnetic fields in O-type stars has been suspected for a long time. The discovery of these fields would explain a wide range of well documented enigmatic phenomena in massive stars, in particular cyclical wind variability, Hα emission variations, chemical peculiarity, narrow X-ray emission lines, and non-thermal radio/X-ray emission.

Aims. To investigate the incidence of magnetic fields in O stars, we acquired 38 new spectropolarimetric observations with FORS 1 (FOcal Reducer low dispersion Spectrograph) mounted on the 8-m Kueyen telescope of the VLT.

Methods. Spectropolarimetric observations were obtained at different phases for a sample of 13 O stars. Ten stars were observed in the spectral range 348−589 nm, HD 36879 and HD 148937 were observed in the spectral region 325−621 nm, and HD 155806 was observed in both settings. To prove the feasibility of the FORS 1 spectropolarimetric mode for the measurements of magnetic fields in hot stars, we present in addition 12 FORS 1 observations of the mean longitudinal magnetic field in θ^1 Ori C and compare them with measurements obtained with the MuSiCoS, ESPaDOnS, and Narval spectropolarimeters.

Results. Most stars in our sample, which were observed on different nights, show a change of the magnetic field polarity, but a field at a significance level of 3σ was detected in only four stars, HD 36879, HD 148937, HD 152408, and HD 164794. The largest longitudinal magnetic field, $\langle B_z \rangle = -276 \pm 88$ G, was detected in the Of?p star HD 148937. We conclude that large-scale organized magnetic fields with polar field strengths larger than 1 kG are not widespread among O-type stars.

Key words. polarization – stars: early-type – stars: atmospheres – magnetic fields

1. Introduction

Massive stars usually end their evolution with a final supernova explosion, producing neutron stars or black holes. The initial masses of these stars range from ~9−10 $M_\odot$ to 100 $M_\odot$ or more, which correspond to spectral types earlier than about B2. Magnetic O stars of mass higher than 30 $M_\odot$ and their WR descendants were suggested to be progenitors of magnetars (Gaensler et al. 2005). In contrast to the case of Sun-like stars, the magnetic fields of stars on the upper main sequence (Ap/Bp stars), white dwarfs, and neutron stars are dominated by large spatial scales and remain unchanged on yearly timescales. In each of these classes, there is a wide distribution of magnetic field strengths, but the distribution of magnetic fluxes appears to be similar in each class, with maxima of $\Phi_{\rm max} = \pi R^2 B \approx 10^{27-28}$ G cm^2 (Reisenegger 2001; Ferrario & Wickramasinghe 2005), arguing for a fossil field whose flux is conserved along the path of stellar evolution. Braithwaite & Spruit (2004) confirmed through simulations that there are stable MHD configurations that might account for long-lived, ordered fields in these types of stars.

However, very little is known about the existence, origin, and role of magnetic fields in massive O and Wolf-Rayet stars. The lack of information is especially disturbing because magnetic fields may have paramount influence on the stellar evolution of high-mass stars. Maeder & Meynet (2005) examined the effect of magnetic fields on the transport of angular momentum and chemical mixing, and found that the potential influence on the evolution of massive stars is dramatic.

Indirect observational evidence for the presence of magnetic fields are the many unexplained phenomena observed in massive stars, which are thought to be related to magnetic fields. One of the main indications that massive stars have magnetic fields is the cyclic behavior on a rotational timescale observed in the UV wind lines (e.g. Henrichs et al. 2005). Other indications are variability observed in the H and He lines (Moffat & Michaud 1981; Stahl et al. 1996; Rauw et al. 2001), narrow X-ray emission lines (Cohen et al. 2003; Gagné et al. 2005) and the presence of non-thermal radio emission (Bieging et al. 1989; Scuderi et al. 1998; Schnerr et al. 2007).

Direct measurements of the magnetic field strength in massive stars using spectropolarimetry to determine the Zeeman splitting of the spectral lines are difficult, since only a few spectral lines are available for these measurements, which are usually strongly broadened by rapid rotation. To date, a magnetic field

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has only been found in the three O stars, θ^1 Ori C, HD 155806, and HD 191612 (Donati et al. 2002; Hubrig et al. 2007; Donati et al. 2006a) and in a handful of early B-type stars (Henrichs et al. 2000; Neiner et al. 2003a,b,c; Hubrig et al. 2006; Donati et al. 2006b; Hubrig et al. 2007). In this paper, we present measurements of magnetic fields in 13 O type stars using FORS 1 at the VLT in spectropolarimetric mode. Our observations and the data reduction are described in Sect. 2, the obtained results in Sect. 3, and their discussion is presented in Sect. 4.

2. Observations and data reduction

The major part of the observations reported here were carried out between March and August of 2005 in service mode at the European Southern Observatory with FORS 1 mounted on the 8-m Kueyen telescope of the VLT. This multi-mode instrument is equipped with polarization analyzing optics, comprising super-achromatic half-wave and quarter-wave phase retarder plates, and a Wollaston prism with a beam divergence of 22″ in standard resolution mode. Eleven O-type stars were observed in 2005 with the GRISM 600B in the wavelength range 3480–5890 Å to cover all hydrogen Balmer lines from Hβ to the Balmer jump. Their selection was based on the extensive study of wind variability in O and B stars using the IUE data archive by ten Kulve (2004), anomalous X-ray behavior and brightness. The spectral types of the studied stars are listed in Table 1 and the observed FORS 1 spectra in integral light are presented in Fig. 1. The observation of HD 36879 was obtained at the beginning of September 2007 and two more observations, one for the star HD 148937 and another one for the star HD 155806, were obtained at the end of March 2008. These observations were carried out with the GRISM 600B and a new mosaic detector with blue optimized E2V chips, which was installed in FORS 1 at the beginning of April 2007. It has a pixel size of 15 μm (compared to 24 μm for the previous Tektronix chip) and higher efficiency in the wavelength range below 6000 Å. With the new mosaic detector and the grism 600B, we are also able to cover a much larger spectral range, from 3250 to 6215 Å.

Twelve observations of the magnetic O star θ^1 Ori C, distributed over the rotational period, were obtained in 2006 with GRISM 600R in the wavelength range 5240–7380 Å. In all observations, the narrowest slit width of 0.″4 was used to obtain a spectral resolving power of $R \sim 2000$ with GRISM 600B and $R \sim 3000$ with GRISM 600R.

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

$$\frac{V}{I} = -\frac{g_{\rm eff} e \lambda^2}{4\pi m_e c^2} \frac{1}{I} \frac{{\rm d}I}{{\rm d}\lambda} \langle B_z \rangle, \quad (1)$$

where V is the Stokes parameter, which measures the circular polarization, I is the intensity in the unpolarized spectrum, $g_{\rm eff}$ is the effective Landé factor, e is the electron charge, λ is the wavelength expressed in Å, m_e the electron mass, c the speed of light, ${\rm d}I/{\rm d}\lambda$ is the derivative of Stokes I, and $\langle B_z \rangle$ is the mean longitudinal field expressed in Gauss. To minimize the cross-talk effect, we executed the sequence +45−45, +45−45, +45−45 etc. and calculated the values V/I using:

$$\frac{V}{I} = \frac{1}{2} \left\{ \left(\frac{f^{\rm o} - f^{\rm e}}{f^{\rm o} + f^{\rm e}} \right)_{\alpha=-45^\circ} - \left(\frac{f^{\rm o} - f^{\rm e}}{f^{\rm o} + f^{\rm e}} \right)_{\alpha=+45^\circ} \right\}, \quad (2)$$

where α denotes the position angle of the retarder waveplate and $f^{\rm o}$ and $f^{\rm e}$ are ordinary and extraordinary beams, respectively.

Table 1. Target stars discussed in this paper. Spectral types are from Maíz-Apellániz et al. (2004), $v \sin i$ values are taken from Howarth et al. (1997). For two stars, HD 135240 and HD 167771, not considered by Howarth et al. (1997), the $v \sin i$ values are from the Bright Star Catalogue (Hoffleit & Jaschek 1991). The $v \sin i$ value for HD 148937 was recently reported by Nazé et al. (2008).

HD	Other name	V	Spectral type	$v \sin i$ [km s^{-1}]
36879	BD+21 899	7.6	O7 V(n)	163
112244	HR 4908	5.3	O8.5 Iab(f)	147
135240	δ Cir	5.1	O7.5 III((f))	189
135591	HR 5680	5.3	O7.5 III((f))	78
148937	CD−47 10855	6.8	O6.5 f?p	45
151804	HR 6245	5.2	O8 Iaf	104
152408	HR 6272	5.9	O8: Iafpe	85
155806	HR 6397	5.6	O7.5 V[n]e	91
162978	63 Oph	6.2	O7.5 II((f))	86
164794	9 Sgr	5.9	O4 V((f))	70
167263	16 Sgr	6.0	O9.5 II-III((n))	99
167771	HR 6841	6.5	O7 III:(n)((f))	90
188001	9 Sge	6.2	O7.5 Iaf	93

Stokes I values were obtained from the sum of the ordinary and extraordinary beams. To derive $\langle B_z \rangle$, a least-squares technique was used to minimize the expression

$$\chi^2 = \sum_i \frac{(y_i - \langle B_z \rangle x_i - b)^2}{\sigma_i^2} \quad (3)$$

where, for each spectral point i, $y_i = (V/I)_i$, $x_i = -\frac{g_{\rm eff} e \lambda_i^2}{4\pi m_e c^2} (1/I \times {\rm d}I/{\rm d}\lambda)_i$, and b is a constant term that, assuming that Eq. (1) is correct, approximates the fraction of instrumental polarization not removed after the application of Eq. (2) to the observations. During the commissioning of FORS 1, this instrumental polarization term was found to be wavelength independent. A wavelength-dependent instrumental polarization would also be visible in the V/I spectra, but we do not see anything like this in the data. For each spectral point i, the derivative of Stokes I with respect to the wavelength was evaluated following

$$\left(\frac{{\rm d}I}{{\rm d}\lambda} \right)_{\lambda=\lambda_i} = \frac{N_{i+1} - N_{i-1}}{\lambda_{i+1} - \lambda_{i-1}}, \quad (4)$$

where N_i is the photon count at wavelength λ_i. Since noise strongly influences the derivative, we interpolate the data after spectrum extraction with splines. In our calculations, we assumed a Landé factor $g_{\rm eff} = 1$ for hydrogen lines. We use 23 lines of He I, He II, C III, C IV, N II, N III, and O III in our analysis. The average Landé factor of these lines for measurements carried out with GRISM 600B is $g_{\rm eff} = 1.07$ and the average Landé factor of these lines for measurements carried out with GRISM 600R is $g_{\rm eff} = 1.02$. More details of the observing technique are given by Bagnulo et al. (2002) and Hubrig et al. (2004a,b).

Longitudinal magnetic fields were measured in two ways: using only the absorption hydrogen Balmer lines or using the entire spectrum including all available absorption lines of hydrogen, He I, He II, C III, C IV, N II, N III and O III. The lines that show evidence for emission were not used in the determination of the magnetic field strength (see Sect. 3). The feasibility of longitudinal magnetic field measurements in massive stars using FORS 1 in spectropolarimetric mode was demonstrated by studies of early B-type stars (e.g., Hubrig et al. 2006, 2007, 2008). In Fig. 2, we demonstrate the excellent potential of FORS 1 for

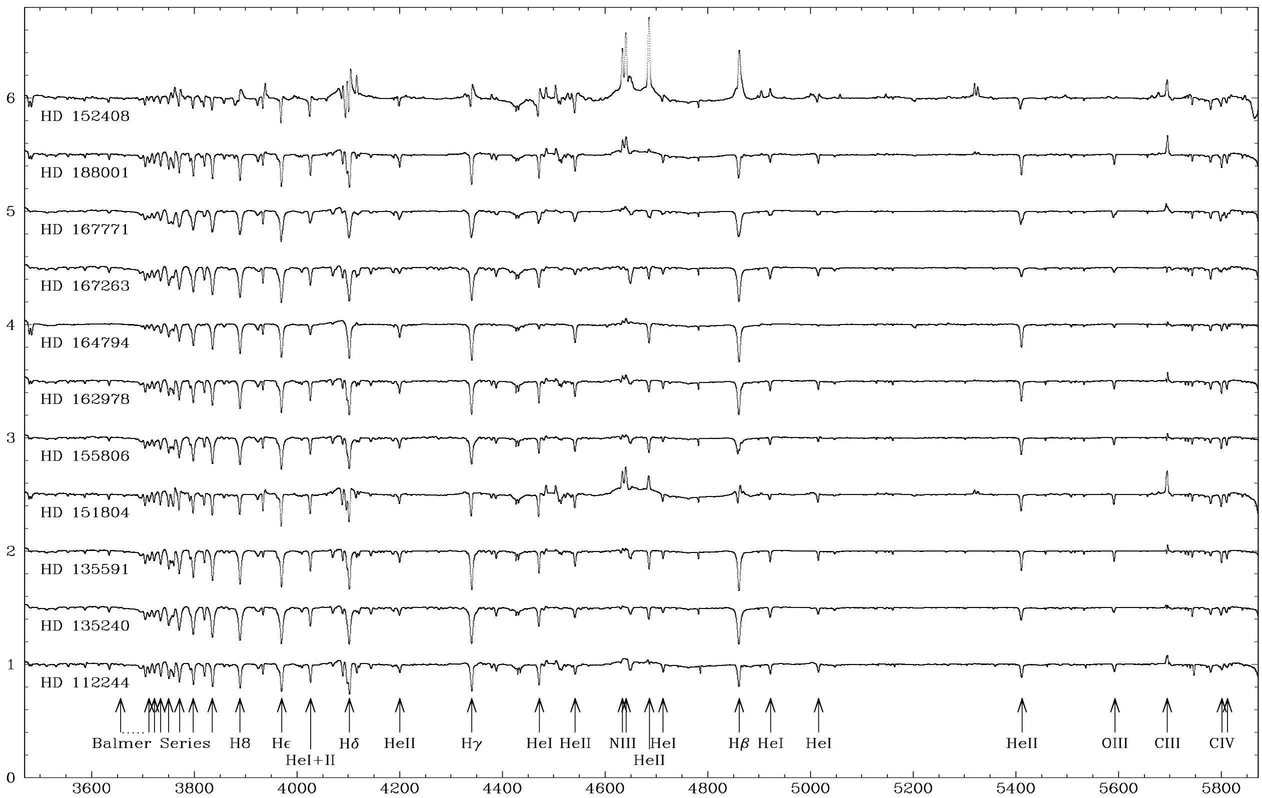

Fig. 1. Normalized FORS 1 Stokes I spectra of O-type stars observed in 2005. Well known spectral lines have been indicated by the arrows, all Balmer lines from the Balmer jump to Hβ are visible. The spectra were offset from 1 by multiples of 0.5 for clarity.

measuring magnetic fields in the star θ^1 Ori C, which was the first O-type star with a detected weak magnetic field varying with the rotation period of 15.4 days. The open symbols represent previous magnetic field measurements by other authors. It is obvious that the FORS 1 measurements are sufficiently accurate, showing a smooth sinusoidal curve in spite of the phase gap between 0.60 and 0.88. The values for the measured longitudinal magnetic field in different rotational phases are presented in Table 2.

However, our observations determine a magnetic geometry that differs from the one deduced by Wade et al. (2006). The maxima and minima of the measured longitudinal field and the phases of the field extrema appear to be different. We are unaware of any systematic shift between FORS 1 measurements and measurements with other spectropolarimeters. We periodically observe well-studied magnetic stars with known variation curves and our measurements are usually in good agreement with those obtained with other instruments. On the other hand, the reason for a difference is understandable since Wade et al. (2006) used only three metal lines, O III 5592, C IV 5801, and C IV 5811 to obtain their results. The profiles of these lines exhibit clear variations, which could be signatures of an uneven distribution of these elements over the stellar surface (see e.g. Reiners et al. 2000). Such an uneven element distribution of metal lines will affect the line-of-sight component of the magnetic field integrated over the stellar surface. A different set of lines is of special relevance for magnetic field measurements only where a few lines are used. If the distribution of spots of different elements on the stellar surface is related to the magnetic field geometry (as is usually found in classical magnetic Ap and Bp stars where certain elements are concentrated at magnetic poles and other elements along the stellar magnetic equator), magnetic field measurements using the lines of different elements will produce different magnetic field strengths, depending on the location of the elemental spots on the stellar surface. With FORS 1 we use for the measurements all absorption lines belonging to various chemical elements together, and therefore might sample the magnetic field more uniformly over the observed hemisphere.

Without further detailed high-resolution studies of polarized line profiles of different elements, it is currently not obvious which set of measurements is closer to the true longitudinal magnetic field of θ^1 Ori C. Assuming an inclination of the rotation axis to the line-of-sight of $i = 45°$ (Wade et al. 2006), our modeling of the longitudinal field variation constrains the dipole magnetic field geometry of θ^1 Ori C to be $B_{\mathrm{d}} \approx 1100$ G and β to be close to 90°, where B_{d} is the dipole intensity and β is the obliquity angle.

3. Results

Due to the strong dependence of longitudinal magnetic field on rotational aspect, its usefulness in characterizing actual magnetic field strength distributions depends on the sampling of the various rotation phases, and hence various aspects of the magnetic field. All targets were observed on three or four different nights. As mentioned before, the exceptions were the stars HD 36879 and HD 148937, which we were able to observe only once. Apart from HD 148937, which has a rotation period of seven days (Nazé et al. 2008), no exact rotation periods are known for the other stars in our sample, and it is certainly not possible to characterize the magnetic field topology with only a few measurements. We would like to emphasize on the other hand that since

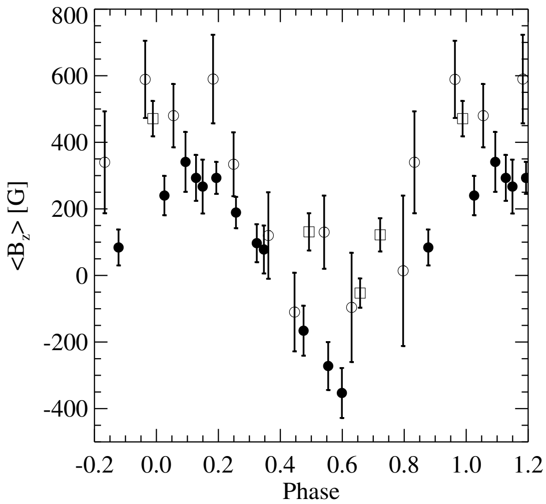

Fig. 2. $\langle B_z \rangle$ vs. the rotation phase for θ^1 Ori C. Open circles: observations by Wade et al. (2006) with MuSiCoS. Open squares: observations by Petit et al. (2008) with ESPaDOnS and Narval. Filled circles: our FORS 1 measurements. For one measurement of θ^1 Ori C presented by Petit et al. (2008) the phase 0.05 seems to be erroneous. Using the HJD of the observations presented in their Table 1, we calculate the phase 0.99.

Table 2. Magnetic field measurements of θ^1 Ori C with FORS 1. Phases are calculated according to the ephemeris of Stahl et al. (1996), JD = 2 448 833.0 + 15.422 E. All quoted errors are 1σ uncertainties.

MJD	Phase	$\langle B_z \rangle$ [G]
54 107.221	0.0257	240 ± 59
54 108.272	0.0939	341 ± 90
54 109.127	0.1494	267 ± 81
54 112.174	0.3469	78 ± 72
54 114.149	0.4750	−166 ± 75
54 116.057	0.5987	−353 ± 75
54 155.062	0.1279	293 ± 69
54 156.072	0.1933	293 ± 48
54 157.051	0.2569	189 ± 47
54 158.086	0.3239	97 ± 57
54 177.064	0.5545	−272 ± 72
54 182.048	0.8777	84 ± 54

the existence of magnetic fields in O stars has been suspected for a long time for many compelling reasons, including theoretical developments, discovery of these fields is of great importance, and subsequent detailed studies will help to explain a wide range of well documented enigmatic phenomena in massive stars.

Normalized FORS 1 Stokes I spectra of all targets observed in 2005, and the identification of the strongest spectral lines are presented in Fig. 1. Compared with lower mass stars, fewer lines were available to measure the magnetic field and the metal lines are not strong. Even the strongest hydrogen lines have a maximum depth of only about 40% below the continuum, since they are intrinsically weaker than in B and A type stars. P Cygni profiles and pure emission lines are visible in all stars apart from HD 167263, which shows a weak emission only in the C III line at 5696 Å (only marginally visible at the resolution provided in this paper). This C III line is in emission in the spectra of all studied stars. As we emphasized in the previous section, the lines that show evidence for emission were not used in the determination of the magnetic field strength. Most of these lines are wind-formed and may have very different polarization signatures.

Table 3. Longitudinal magnetic fields measured with FORS 1 in 13 O-type stars. All quoted errors are 1σ uncertainties.

HD	MJD	$\langle B_z \rangle_{\rm all}$ [G]	$\langle B_z \rangle_{\rm hydr}$ [G]	Comment
36879	54 345.389	**180 ± 52**	109 ± 74	ND
112244	53 455.193	34 ± 55	15 ± 62	
	53 475.177	41 ± 43	1 ± 60	
	53 483.104	9 ± 78	−4 ± 79	
135240	53 475.246	65 ± 83	86 ± 111	
	53 487.263	−37 ± 62	−12 ± 72	
	53 553.103	−65 ± 63	−45 ± 78	
135591	53 487.243	−118 ± 57	−142 ± 62	
	53 553.081	110 ± 54	116 ± 61	
	53 571.081	−8 ± 62	−20 ± 71	
148937	54 550.416	**−276 ± 88**	−145 ± 104	ND
151804	53 476.369	−151 ± 90	−87 ± 96	
	53 571.025	68 ± 65	91 ± 73	
	53 596.061	82 ± 46	66 ± 48	
152408	53 556.216	**−89 ± 29**	−112 ± 57	ND
	53 571.104	−91 ± 46	−93 ± 75	
	53 596.081	46 ± 34	32 ± 60	
155806	53 476.401	−80 ± 132	−216 ± 141	
	53 532.283	*−115 ± 37*	*−119 ± 50*	PD
	53 532.306	−29 ± 44	−35 ± 70	
	53 556.235	−184 ± 88	−160 ± 93	
	54 549.403	93 ± 68	54 ± 88	
162978	53 556.260	−50 ± 49	−56 ± 86	
	53 595.116	91 ± 81	73 ± 84	
	53 604.144	80 ± 83	60 ± 89	
164794	53 520.357	−114 ± 66	−111 ± 75	
	53 594.119	**211 ± 57**	147 ± 72	ND
	53 595.096	−165 ± 75	−139 ± 77	
167263	53 594.142	−24 ± 91	−54 ± 96	
	53 595.015	−19 ± 41	−29 ± 49	
	53 596.112	29 ± 53	37 ± 61	
167771	53 520.377	5 ± 79	11 ± 85	
	53 594.241	92 ± 46	78 ± 73	
	53 595.066	−31 ± 54	−16 ± 88	
188001	53 520.434	117 ± 65	100 ± 65	
	53 594.208	−35 ± 50	−53 ± 55	
	53 595.149	−35 ± 36	−32 ± 57	
	53 597.149	−95 ± 48	−163 ± 70	

The results of our magnetic field measurements are presented in Table 3. In the first two columns, we provide the HD numbers of the targets and the modified Julian dates at the middle of the exposures. The measured mean longitudinal magnetic field $\langle B_z \rangle$ using all absorption lines is presented in Col. 3. The measured mean longitudinal magnetic field, $\langle B_z \rangle$ using all hydrogen lines in absorption, is listed in Col. 4. All quoted errors are 1σ uncertainties. In Col. 5, we identify new detections by ND. We note that all claimed detections have a significance level of at least 3σ, determined from the formal uncertainties that we derive. These measurements are indicated in bold face.

Four stars of our sample, HD 36879, HD 148937, HD 152408, and HD 164794, show evidence for the presence of a weak magnetic field in the measurements using all spectral absorption lines. The uncertainties in the mean longitudinal field determination is obtained from the formal uncertainty in the linear regression of V/I versus the quantity $-\frac{g_{\rm eff} e}{4\pi m_e c^2} \lambda^2 \frac{1}{I} \frac{{\rm d}I}{{\rm d}\lambda} \langle B_z \rangle + V_0/I_0$. For measurements obtained from

Balmer lines only, the mean uncertainty ranging from 49 to 141 G is generally higher than for measurements using all absorption lines for which the uncertainty can be as small as 29 G. These results are easily understandable since the robustness and accuracy of the spectropolarimetric observations increase with the number of spectral lines used in the measurements. In previous studies, the uncertainty in the FORS 1 measurements was shown to be as low as 13 G in late A spectral types with numerous strong absorption lines (e.g. Kurtz et al. 2008).

The stars HD 36879 and HD 148937 were observed only once and their magnetic fields were detected at the 3.5 and 3.1σ level, respectively. Since the rotation period of HD 148937 is known (Nazé et al. 2008), the $v \sin i$ value is relatively low and a comparatively strong magnetic field is detected, this star should clearly be of highest priority for future spectropolarimetric observations over the rotation period to study its magnetic field topology. In Table 3, the second observation of HD 152408 reveals a magnetic field at almost 2σ level, and the third observation of HD 164794 shows a magnetic field at 2.2σ level. We should note that the marginal detections of the magnetic field for HD 152408 and HD 164794 on these observing nights can naturally be explained by the strong dependence of the longitudinal magnetic field on the rotational aspect. In the case of θ^1 Ori C, of the ten magnetic field measurements presented by Wade et al. (2006), only four measurements have values larger than 3σ, and among the four measurements of Petit et al. (2008) only one measurement is at a high significance level. Among our 12 observations of θ^1 Ori C, four measurements could be considered as marginal detections. However, all measurements plotted over the rotational phase of 15.4 d can be described well by a sine fit that characterizes a dipole magnetic field of a certain pole strength and inclination to the rotational axis.

Interestingly, most stars in our sample observed repeatedly during different nights show a change in polarity. The star HD 188001, which was observed on four different nights, shows one 2.3σ detection obtained from Balmer lines and a 2σ detection was achieved using all absorption lines. The magnetic field of the star HD 135591 was observed at 2.1σ and 2σ levels on two different nights using all absorption lines. Both stars appear to be good candidates for future magnetic field measurements. The star HD 155806 was already observed once with FORS 1 using GRISM 1200g in the framework of the ESO service program 075.D–0507 by Hubrig et al. (2007), who reported the presence of a weak mean longitudinal field, $\langle B_z \rangle = -115 \pm 37$ G. For convenience, the previously published measurement is presented in the same table in italics and marked as PD (previous detection). Four new measurements with the GRISM 600B indicate a polarity change, although all are marginal detections. The first measurement is in addition of large uncertainty because of bad weather conditions during the service observations. One of the measurements reveals a longitudinal magnetic field at the 2.1σ level: $\langle B_z \rangle = -184 \pm 88$ G. Although we do not detect magnetic fields for other O-type stars at a 3σ level, it is still possible that some host magnetic fields, but that these fields remain undetected due to high measurement uncertainties. We note that further observations of improved accuracy are necessary to measure a reliable upper limit on the strength of their longitudinal magnetic fields.

Appendix A provides a brief overview of the previous knowledge of the stars with a magnetic field detection at 3σ level. A few notes are also given on HD 155806 for which the presence of a magnetic field was reported by Hubrig et al. (2007).

4. Discussion

Stellar magnetic fields have been discovered for a wide range of spectral types (see Charbonneau & MacGregor 2001). In late-type stars, dynamos active in the convective layers are believed to generate the observed magnetic fields. In earlier type stars, which have radiative envelopes, large-scale magnetic fields of the order of a kilogauss were discovered in Ap/Bp stars, but the precise origin of these fields is not yet known (Charbonneau & MacGregor 2001; Braithwaite & Nordlund 2006). About 10% of main-sequence A and B stars are slowly rotating, chemically peculiar, magnetic Ap and Bp stars and among their descendants, white dwarfs, 10% have high magnetic fields. The magnetic fields in magnetic white dwarfs could be fossil remnants of the main-sequence phase, consistent with magnetic flux conservation (Ferrario & Wickramasinghe 2005). If we assume that massive stars behave like Ap and Bp stars, then for a magnetic field detection probability of 10%, an O star sample should consist of a larger number of unbiased targets, including stars in clusters and the Galactic field at different ages, in different Galactic metallicity zones, and with different rotational velocities and surface composition. As we mentioned in Sect. 2, our sample is biased in the sense that it is restricted to O-type stars exhibiting wind variability, anomalous X-ray behavior, and brightness variations.

Still, this is the first time that magnetic field strengths were determined for such a large sample of stars, with an accuracy comparable to the errors obtained for the three previously known magnetic O-type stars, θ^1 Ori C, HD 155806, and HD 191612. For the magnetic Of?p star HD 191612, Donati et al. (2006a) measured a magnetic field of $\langle B_z \rangle = -220 \pm 38$ G, by averaging a total of 52 exposures obtained over 4 different nights. This is similar to our typical errors of a few tens of G. We have found four new magnetic O-type stars, which have different spectral types, luminosity classes, and behavior in various observational domains (see Appendix A). It raises the question if O-type stars are magnetic in different evolutionary states. The study of the evolutionary state of one of the Galactic Of?p stars, HD 191612, indicates that it is significantly evolved with an ~O8 giant-like classification (Howarth et al. 2007). The youth of the most carefully studied magnetic O-type star θ^1 Ori C and the older age of the Of?p star HD 191612 suggest that the presence of magnetic fields in O-type stars is unrelated to their evolutionary state. On the other hand, θ^1 Ori C appears to have a stronger magnetic field in comparison to that of HD 191612, indicating that the magnetic field could be a fossil remnant. Considering different size of radii due to the different evolutionary state and assuming conservation of the magnetic surface flux, the magnetic field strength is expected to decrease by a factor proportional to the square of the ratio of their radii. Some support for the fossil magnetic field origin arises also from the comparative study of magnetic fields of early B-type stars at different ages by Briquet et al. (2007). This work revealed that the strongest magnetic fields appear in the youngest Bp stars, compared to weaker magnetic fields in stars at advanced ages.

It is notable, that the current analyses of Nazé et al. (2008) and Nazé et al. (in preparation) suggest slower rotation than usually observed in O-type stars and nitrogen enhancement in both other Of?p stars, HD 108 and HD 148937. Their multiwavelength studies indicate rotation periods of ~55 yr for HD 108 and 7 d for HD 148937. Also, NLTE abundance analyses of early B-type stars by Morel et al. (2008) and Hunter et al. (2008) confirm that slow rotators often have peculiar chemical enrichments. It is remarkable that the observational data collected by

Morel et al. (2008) highlight significantly a higher incidence of magnetic fields in stars with nitrogen excess and boron depletion. Clearly, future studies are required to determine the efficiency of various indirect indicators of the presence of magnetic fields in the atmospheres of hot stars.

Although it was possible to recognize a few hot magnetic stars as being peculiar on the basis of their spectral morphology, prior to their field detection (Walborn 2006), the presence of a magnetic field can also be expected in stars of other classification categories. Our measurements of 13 O-type stars indicate that magnetic fields are possibly present in stars with very different observed properties in visual, X-ray and radio domains. Future magnetic field measurements will constrain the conditions controlling the presence of magnetic fields in hot stars, and the implications of these fields on their mass-loss rate and evolution.

Since no longitudinal magnetic fields stronger than 300 G were detected in our study (apart from θ^1 Ori C) we suggest that large-scale, dipole-like, magnetic fields with polar field strengths higher than 1 kG are not widespread among O type stars. Stars more massive than about 9 $M_\odot$ become neutron stars or black holes. A significant fraction of newborn neutron stars are strongly magnetized, with typical fields of $\sim 10^{12}$ G, and fields of up to $\sim 10^{15}$ G in the magnetars. Simple conservation of magnetic flux would imply field strengths of at least $(5\,R_\odot/10\,\mathrm{km})^{-2} \times 10^{12}$ G $\simeq 10^1$ G as a minimum for their progenitors. This is similar to the minimum field strength required to explain the wind variability observed in the UV (several 10^1 G), as can be concluded from numerical simulations of wind behavior in early-type stars (ud-Doula & Owocki 2002). Our measurements have a typical accuracy of a few tens of G and it is possible that weak magnetic fields are present in the atmospheres of the other stars in our sample, but remain undetected until the measurement uncertainties are significantly improved.

As we mention in Sect. 2, a new mosaic detector with blue optimized E2V chips was installed in FORS 1 in 2007. To achieve the highest possible signal-to-noise (S/N) ratio – as required for accurate measurements of stellar magnetic fields – the (200 kHz, low, 1×1) readout mode is used, which can provide a S/N ratio of more than 1000 with only one single sub-exposure. Our tests indicate that by using a sequence of 8−10 sub-exposures, we can attain far higher accuracies of 10−20 G. The typical uncertainties presented in Tables 2 and 3, at the time of our observations, before this CCD upgrade were of the order of 40 to 70 G.

In the absence of further direct magnetic measurements, it is unclear whether more complex, smaller scale fields play a role in the atmospheres of O-type stars. In the case of a more complex magnetic field topology, the longitudinal magnetic field integrated over the visible stellar surface will be smaller (or will even cancel) and not be easily detected with the low-resolution FORS 1 measurements, which only allow detection of magnetic fields that have a large-scale organization. However, high resolution spectropolarimeters should be able to detect such complex field configurations using high signal-to-noise observations of the Zeeman effect in metal lines (e.g. Donati et al. 2006b).

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Appendix A: Brief notes on stars with possible evidence of a magnetic field

A.1. HD 36879

This star has a classification O7 V(n) according to the Galactic O Star Catalogue (Maíz-Apellániz et al. 2004). It exhibits peculiar narrow emission features in the Si IV line profiles $\lambda\lambda$1394, 1403 Å detected by Walborn & Panek (1984a,b). The authors noted that these emission features are strongly variable in IUE spectra obtained four days apart. Otherwise, this star has been only marginally studied, mainly due to its quite rapid rotation.

A.2. HD 148937

Only three Galactic Of?p stars are presently known: HD 108, HD 148937, and HD 191612. No attempt has yet been made to measure the magnetic field of HD 108. The search for a magnetic field in HD 191612 was motivated by very unusual, large, periodic spectral variations found previously by Walborn et al. (2003) and resulted in $\langle B_z \rangle = -220 \pm 38$ G, measured with ESPaDOnS (Donati et al. 2006a). An extensive multiwavelength study of HD 148937 was recently carried out by Nazé et al. (2008), who detected small-scale variations of He II 4686 and Balmer lines with a period of 7 days and an overabundance of nitrogen by a factor of 4 compared to the Sun.

A.3. HD 152408

This star is a member of NGC 6231 and was classified as O8 Iafpe or WN9ha by Walborn & Fitzpatrick (2000). Observational studies of wind and photospheric variability were performed by Colley (2003) and Prinja et al. (2001). The interesting fact is that Prinja et al. (2001) discovered that the line profile behavior was clearly not erratic, but instead organized into sequential, localized episodes of enhanced and/or reduced flux, that migrated in velocity as a function of time. They also demonstrated that systematic variability is present in absorption lines formed in the photospheric layers of this star, and suggested that the presence of a magnetic field, in particular, may provide significant variation in the mass-flux and thus also account for the fluctuations discovered in the central regions of the Hα emission line. A medium-resolution spectropolarimetric study of the Hα emission line by Harries et al. (2002) indicated that the continuum polarization agrees well with the local interstellar polarization pattern. However, there appears to be some evidence of a position angle rotation in combination with a magnitude enhancement across Hα.

A.4. HD 155806

The star HD 155806 was classified as O7.5 V[n]e by Walborn (1973), but was reclassified by Negueruela et al. (2004) as O7.5 IIIe based on the strength of its metallic features. A strong variability in its Balmer lines and small-scale variations in Si IV and He I lines were detected in FEROS and UVES spectra retrieved from the ESO archive (Programs 073.C−0337, 073.D−0609, 075.D−0061, and 266.D−5655). Spectral profile variations of Hα and Hβ lines are presented in Fig. A.1 and those of the He I 5016 Å and Si IV 4089 Å lines in Fig. A.2.

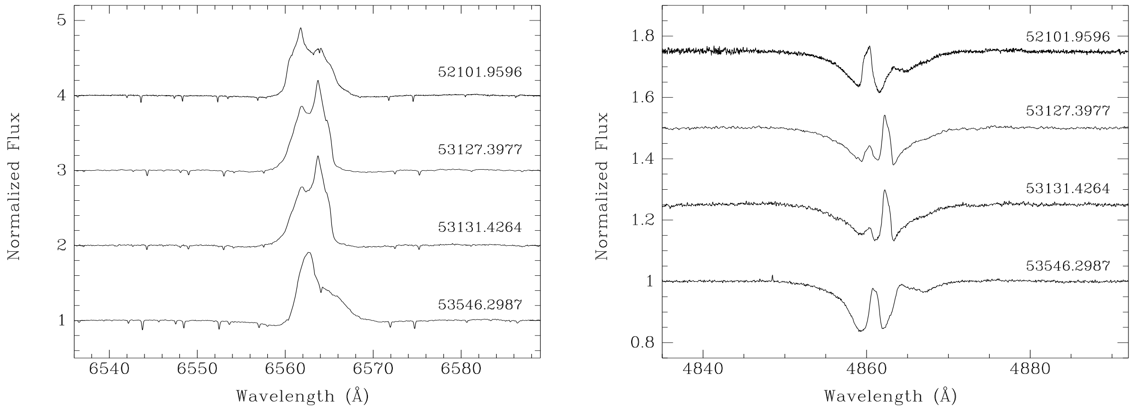

Fig. A.1. Spectral profile variability in the Balmer Hα and Hβ lines of the FEROS and UVES spectra of HD 155806. The spectra are labeled with their modified Julian dates.

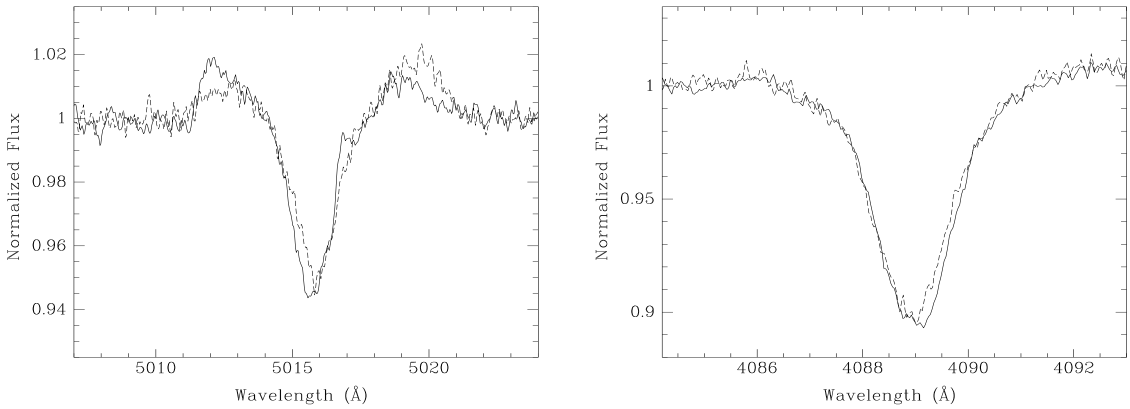

Fig. A.2. Small-scale variations of the He I 5016 Å and Si IV 4089 Å lines in the spectra of HD 155806 obtained on the modified Julian dates 53 127.40 (solid line) and 53 546.30 (dashed line).

A.5. HD 164794

This star has a classification O4 V((f)) according to the Galactic O Star Catalogue (Maíz-Apellániz et al. 2004), exhibiting weak N III emission and strong He II λ4686 absorption. It is a well-known non-thermal radio emitter and, according to van Loo et al. (2006), the most likely mechanism is synchrotron emission from colliding winds, implying that all O stars with non-thermal radio emission should be members of binary or multiple systems. Hints of a wind-wind interaction were indeed detected in the X-ray domain (Rauw et al. 2002). A long-term study of its binary nature and spectrum variability is presently being undertaken by our Belgian colleagues (see preliminary results in Rauw et al. 2005).

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