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The search for magnetic fields in two Wolf–Rayet stars and the discovery of a variable magnetic field in WR 55

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ABSTRACT

Magnetic fields in Wolf–Rayet (WR) stars are not well explored, although there is indirect evidence, e.g. from spectral variability and X-ray emission, that magnetic fields should be present in these stars. Being in an advanced stage of their evolution, WR stars have lost their hydrogen envelope, but their dense winds make the stellar core almost unobservable. To substantiate the expectations on the presence of magnetic fields in the most-evolved massive stars, we selected two WR stars, WR 46 and WR 55, for the search of the presence of magnetic fields using FORS 2 spectropolarimetric observations. We achieve a formally definite detection of a variable mean longitudinal magnetic field of the order of a few hundred gauss in WR 55. The field detection in this star, which is associated with the ring nebula RCW 78 and the molecular environment, is of exceptional importance for our understanding of star formation. No field detection at a significance level of 3σ was achieved for WR 46, but the variability of the measured field strengths can be rather well phased with the rotation period of 15.5 h previously suggested by *FUSE* (*Far Ultraviolet Spectroscopic Explorer*) observations.

Key words: techniques: polarimetric – stars: individual: WR 46 – stars: individual: WR 55 – stars: magnetic field – stars: massive – stars: Wolf–Rayet.

1 INTRODUCTION

In the modelling of massive stars, specific aspects, especially the role of magnetic fields, remain not well understood, implying large uncertainties in the star's evolutionary path and ultimate fate. Previous observations indicate that probably about 7 per cent of O-type stars with masses exceeding $18\,M_\odot$ and about 6 per cent of early B- and O-type stars have measurable, mostly dipolar magnetic fields (e.g. Grunhut et al. 2017; Schöller et al. 2017). Theoretical models suggest that O stars with strong magnetic field detections may be related to magnetars with $B \approx 10^{15}$ G (e.g. Thompson, Chang & Quataert 2004). Thus, it is important to detect magnetic fields in Wolf–Rayet (WR) stars, which are descendants of massive O stars and direct predecessors of compact remnants. WR stars are highly chemically evolved massive stars that have lost their hydrogen envelope and now expose their former stellar core. However, their dense winds make the stellar surface almost unobservable.

Magnetic fields in WR stars are currently not sufficiently explored, in spite of the fact that there is indirect evidence, e.g. from spectral variability and X-ray emission, that magnetic fields are present in WR star atmospheres (e.g. Michaux et al. 2014). Previous theoretical work of Gayley & Ignace (2010) predicted a fractional circular polarization of a few times 10^{-4} for magnetic fields of about 100 G. Using high-resolution spectropolarimetric observations with ESPaDOnS at the Canada–France–Hawaii Telescope, de la Chevrotiére et al. (2014) reported marginal magnetic field detections for WR 134, WR 137, and WR 138, corresponding to magnetic field strengths of about 200, 130, and 80 G, respectively, and an average upper limit of about 500 G for the non-detections in other stars. As the line spectrum in WR stars is formed in the strong stellar wind, the detection of magnetic fields in these stars is difficult. Doppler shifts due to wind velocities of a few thousand km s^{-1} lead to broadening of the emission lines. When observing WR stars with high-resolution spectropolarimeters, their broad spectral lines extend over adjacent orders, making it necessary to adopt order shapes to obtain the best continuum normalization.

As immense line broadening is not an impediment in low-resolution spectroscopy, Hubrig et al. (2016) used the FOcal Reducer low dispersion Spectrograph in spectropolarimetric mode (FORS 2; Appenzeller et al. 1998) mounted on the 8-m Antu telescope of the European Southern Observatory's Very Large Telescope (VLT) on Cerro Paranal/Chile to search for weak magnetic fields in a number of WR stars.

The obtained FORS 2 polarimetric spectra allowed Hubrig et al. (2016) to measure a mean longitudinal magnetic field $\langle B_z\rangle = 258 \pm 78$ G in the cyclically variable and X-ray emitting WN5 star WR 6 at a significance level of 3.3σ. Notably, the two Of?p stars HD 148937 and CPD -28° 5104 are clearly magnetic and were detected as magnetic for the first time in FORS 2 observations at significance levels of 3.1σ and 3.2σ, respectively (Hubrig et al. 2008, 2011). Keeping this in mind, the detection of a magnetic field in WR 6 at a significance level of 3.3σ indicates that a magnetic field

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is likely present in this star. Spectropolarimetric monitoring of WR 6 revealed $\langle B_z \rangle$ variations of a sinusoidal nature, which is indicative of a predominantly dipolar magnetic field structure (Hubrig et al. 2016; see fig. 1, left-hand side). The field appeared to be reversing, with the extrema detected at rotation phases 0 and 0.5.

In the sample of spectropolarimetrically studied WR stars by Hubrig et al. (2016), WR 6 was the only target showing X-ray emission and cyclical variability due to the presence of corotating interacting regions (CIRs), which are formed out of the interaction between high- and low-velocity flows as the star rotates (e.g. St-Louis et al. 1995). CIRs were detected in spectroscopic time-series observations of only a few massive stars (e.g. Mullan 1984). It was suggested that CIRs are related to the presence of magnetic bright spots, which are indicators of the presence of a global magnetic field (e.g. Ramiaramanantsoa et al. 2014).

To substantiate expectations on the presence of magnetic fields in the most-evolved massive stars, we have searched for magnetic fields in two other promising targets, WR 46 (=HD 104994) and WR 55 (=HD 117688), which, similar to WR 6, show CIRs (e.g. Chené & St-Louis 2011). These stars are accessible from the VLT and have never been observed with spectropolarimetry in the past.

WR 46 is a WN3p star (Hamann et al. 2019), with relatively strong O IV λ3811 and λ3834 emission lines. It is very hot and compact ($T_{\rm eff} = 112.2$ kK, $R = 1.4\,{\rm R}_\odot$), and also bright in X-rays, possessing a hard component in its X-ray emission (Gosset et al. 2011), which may indicate the magnetic nature of WR 46. According to Hénault-Brunet et al. (2011), WR 46 is known to exhibit a very complex variability pattern. The different periods and time-scales observed in the past suggest the presence of multiple periods, including dominant and secondary periods (see fig. 1 in their work). To explain the short-term variability of this star, different scenarios were evoked, including the possibility of a close binary or non-radial pulsations (e.g. Veen et al. 2002a; Veen, Van Genderen & van der Hucht 2002b). Using observations with the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*), Hénault-Brunet et al. (2011) found significant variations on a time-scale of $\sim$8 h. This period is close to the photometric and spectroscopic periods previously reported by other authors. Hénault-Brunet et al. (2011) also reported the detection of a second significant peak, just slightly weaker, corresponding to $P = 15.5 \pm 2.5$ h.

WR 55 is a significantly cooler ($T_{\rm eff} = 56.2$ kK) WN7 star with hydrogen deficiency and belongs to the WNE subclass, like WR 6 (Hamann, Gräfener & Liermann 2006). However, its radius, $R = 5.2\,{\rm R}_\odot$, is larger compared to the radius of WR 6 with $R = 3.2\,{\rm R}_\odot$. A highly significant level of spectroscopic variability of about 10 per cent was discovered by Chené & St-Louis (2011). So far, no periodicity search was carried out for this star. Cappa et al. (2009) investigated the distribution of molecular gas related to the ring nebula RCW 78 around WR 55 and concluded that this star is responsible not only for the ionization of the gas in the nebula, but also for the creation of the interstellar bubble. Their analysis indicates that the star formation in this region is induced by the strong wind of WR 55. Thus, the discovery of a magnetic field in this target would be of exceptional interest for star formation theories.

As WR stars are characterized by spectra showing very broad emission lines, the determination of their magnetic fields is usually based on the calculation of the mean longitudinal magnetic field, i.e. of the line-of-sight field component, using circularly polarized light. To search for magnetic fields in WR 46 and WR 55, we obtained several randomly timed distributed low-resolution spectropolarimetric observations using FORS 2 (Appenzeller et al. 1998), installed at the ESO/VLT. In the following, we give an overview of our

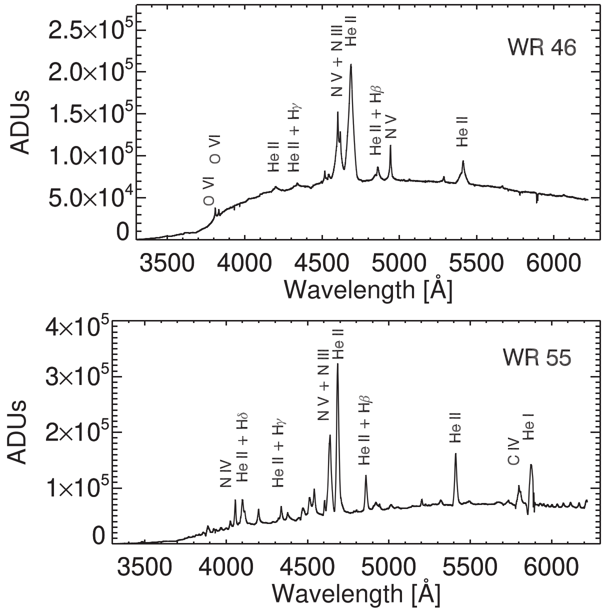

Figure 1. FORS 2 Stokes *I* spectra of WR 46 and WR 55. Spectral line identification is based on the work of Hamann et al. (2006) and is shown above the line profiles.

spectropolarimetric observations, describe the data reduction, and discuss the results of the magnetic field measurements.

2 DATA REDUCTION AND RESULTS OF THE MAGNETIC FIELD MEASUREMENTS

To maximize the field detection probability and to avoid missing the magnetic field due to an unfavourable viewing angle in certain rotation phases, FORS 2 observations of both targets were obtained on several different epochs to sample different rotation phases. Seven spectropolarimetric observations of WR 46 were obtained in service mode, one observation on 2016 March 14 and six observations from 2020 January 16 to February 21. For WR 55, we obtained five observations from 2020 February 13 to March 10. The last observation of WR 55 recorded on March 10 was not completed, probably due to bad weather conditions, and was therefore used only for the inspection of spectral variability.

The FORS 2 multimode instrument is described in detail by Appenzeller et al. (1998). GRISM 600B and the narrowest available slit were used to obtain a spectral resolving power of $R \sim 2000$. The method to assess the presence of a magnetic field using FORS 1/2 spectropolarimetric observations was previously presented by us in a number of publications (e.g. Hubrig et al. 2004a, b, 2020; Hubrig, Schöller & Kholtygin 2014; Schöller et al. 2017, and references therein). The ordinary and extraordinary beams were extracted using standard IRAF procedures as described by Cikota et al. (2017). The wavelength calibration was carried out using He–Ne–Ar arc lamp exposures.

The spectral appearance of the WN stars WR 46 and WR 55 in the FORS 2 spectra is presented in Fig. 1. The spectra of WN stars are dominated by helium and nitrogen lines. The WN3p star WR 46 is characterized by the presence of strong N V and He II lines and the absence of hydrogen. The 'p' stands for peculiar and denotes the presence of unusually strong O VI λ3811 and λ3834 emission lines, the relatively strong N V λ4604 line, and relatively weak C IV λ5801 and λ5812 lines (e.g. Conti & Massey 1989).

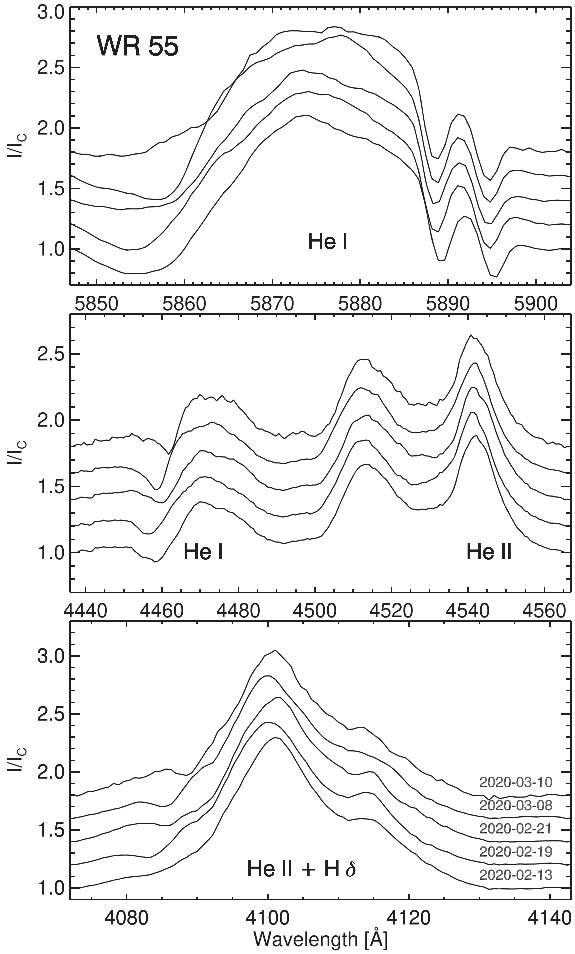

Figure 2. FORS 2 Stokes *I* spectra showing variability of different spectral lines. The spectra obtained at different epochs are offset vertically for better visibility. Spectral line identification is based on the work of Hamann et al. (2006).

Table 1. Longitudinal magnetic field values obtained for WR 46 and WR 55 using FORS 2 observations. In the first column, we show the modified Julian dates of mid-exposures, followed by the corresponding signal-to-noise ratio (*S*/*N*) of the FORS 2 Stokes *I* spectra measured close to 4686 Å. The measurements of the mean longitudinal magnetic field using the Monte Carlo bootstrapping test and using the null spectra are presented in columns 3 and 4. All quoted errors are 1σ uncertainties.

MJD	*S*/*N*	$<B_z>$ (G)	$<B_z>_N$ (G)
		WR 46	
57461.3213	2339	− 199 ± 88	46 ± 81
58864.2960	1477	342 ± 154	− 68 ± 146
58885.1674	1845	35 ± 94	− 62 ± 109
58885.2627	2046	− 43 ± 99	− 7 ± 97
58892.1191	1189	268 ± 194	81 ± 173
58898.3843	1905	23 ± 93	− 41 ± 115
58900.1569	1088	− 112 ± 160	23 ± 179
		WR 55	
58892.2058	2388	205 ± 58	− 16 ± 55
58898.3492	2579	− 378 ± 85	− 2 ± 78
58900.2075	2168	56 ± 80	63 ± 82
58916.3059	2386	4 ± 66	− 16 ± 57
58918.2531	533		

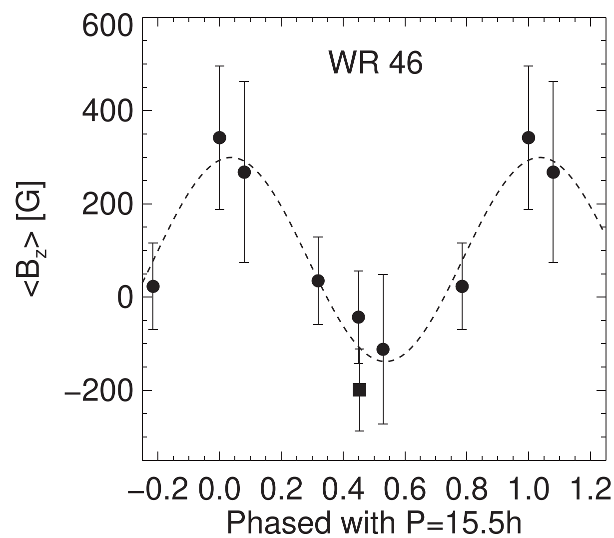

Figure 3. Longitudinal magnetic field measurements of WR 46 carried out using low-resolution FORS 2 spectropolarimetric observations and phased with the period of 15.5 h. The overplotted dashed curve corresponds to the sinusoidal fit. The filled square corresponds to the observation obtained in 2016.

While previous observations of WR 46 clearly showed the presence of variability in photometry and spectroscopy, the variability of WR 55 was studied only once by Chené & St-Louis (2011) using spectra in the spectral range of 5200–6000 Å obtained with the 1.5-m telescope of the Cerro Tololo Inter-American Observatory. The authors reported for this star a highly significant level of variability of up to 10 per cent of the line intensity. As we show in Fig. 2, spectral line variability is also detected in our FORS 2 Stokes *I* spectra of this star.

Our longitudinal magnetic field measurements for both WR stars are presented in Table 1. For WR 46, the values for the longitudinal magnetic field $\langle B_z\rangle$ show change of polarity, with the strongest mean longitudinal magnetic field of positive polarity $\langle B_z\rangle = 342 \pm 154$ G at a significance level of 2.2σ and the strongest field of negative polarity $\langle B_z\rangle = -199 \pm 88$ G at a significance level of 2.3σ. Since significant photometric and spectroscopic variations on a time-scale of ∼8 h were reported in previous studies of this star, assuming that this periodicity is caused by rotational modulation, we tested the distribution of the measurement values over this period. We do not find any hint for sinusoidal modulation, which is expected for a large-scale organized dipole field structure. However, as we show in Fig. 3, rotation modulation is indicated in our data, if we use the period of 15.5 h suggested by Hénault-Brunet et al. (2011). Due to the large uncertainty of this period, only the measurements obtained in 2020 are fitted by a sinusoid. The older measurement obtained in 2016 and marked by the filled square appears (purely coincidentally) slightly shifted from the expected negative field extremum. Interestingly, our period analysis by fitting a sinusoid to the measurements obtained in 2020, indicates almost the same rotation period $P_{\rm rot} = 15.53 \pm 0.14$ h. Obviously, the fidelity of the 15.5 h period needs to be confirmed with a long-term extensive data set.

For WR 55, the values for the longitudinal magnetic field $\langle B_z\rangle$ show change of polarity with the highest field values $\langle B_z\rangle = -378 \pm 85$ G at a significance level of 4.4σ and $\langle B_z\rangle = 205 \pm 58$ G at a significance level of 3.5σ. In view of the importance of the field detection at a significance level of 4.4σ, we decided to carry out a consistency check using a different spectral extraction. The parallel and perpendicular beams in the observations at this epoch were extracted using a MIDAS based pipeline developed and coded by T. Szeifert. More details on this pipeline can be found in Hubrig et al. (2014). The result of this measurement, $\langle B_z\rangle = -334 \pm 77$ G, is fully compatible with the measurement $\langle B_z\rangle = -378 \pm 85$ G within the error bars.

The simplest model for the magnetic field geometry in stars with globally organized fields is based on the assumption that the studied stars are oblique dipole rotators, i.e. their magnetic field can be approximated by a dipole with the magnetic axis inclined to the rotation axis. Unfortunately, the rotation axis inclination i for WR stars is undefined because of their dense winds, making the measurement of the projected rotation velocity $v \sin i$ using broad emission lines impossible. Since the rotation period and the limb-darkening are also unknown for WR 55, we can only estimate for this star a minimum dipole strength of $\sim$1.13 kG using the relation $B_{\rm d} \geq 3| < B_{\rm z} >_{\rm max}|$ (Babcock 1958).

3 DISCUSSION

While it is quite certain that magnetic fields play a decisive part in massive star evolution, spectropolarimetric observations of WR stars, which are descendants of massive O stars, are still very scarce. WR stars are usually rather faint, and, in addition, their line spectra are formed in the strong stellar wind, with the wind broadening of the emission lines up to a few thousand km s^{-1}. Both WR 46 and WR 55 are faint with visual magnitudes $m_{\rm v} \geq 10.9$, and have never been observed spectropolarimetrically in the past. Using FORS 2 observations of these targets, we undertook the first study of their magnetic nature.

The strongest mean longitudinal magnetic field for WR 46 was measured at a significance level of 2.2σ at the positive field extremum and at the level 2.3σ close to the negative field extremum. Only for WR 55, we achieve formally definite detections, $<B_z> = -378 \pm 85$ G at a significance level of 4.4σ and $<B_z> = 205 \pm 58$ G at a significance level of 3.5σ. However, we should not forget that we determine the magnetic field in the line-forming regions. In a WR wind, these are located far out and not at the stellar surface. Different lines originate from different wind zones and thus sample different field strengths. Thus, the method we apply for the measurements gives results only for field strengths in the locations where the lines are formed. It is expected that the surface values of the magnetic field are significantly stronger than the field measured in the wind lines (de la Chevrotiére et al. 2013).

With respect to the confidence of the field detection, a recent detailed comparison between our analysis technique and an independent analysis from another team showed that the measurement results agree well within expected statistical distributions (Schöller et al. 2017). This gives us high confidence about the accuracy of our longitudinal magnetic field measurements. Importantly, detections at a level lower than 3σ seem to be genuine in several studies, where the longitudinal magnetic field values show a smooth modulation over the rotation period, comparable with those found for the magnetic Of?p stars HD 148937 and CPD -28° 2561 (Hubrig et al. 2008, 2011, 2013, 2015). Not one of the detections reported in these investigations reached a significance level of 4σ.

The first detection of the presence of a magnetic field in WR 55 makes this star the best candidate for long-term spectropolarimetric monitoring. Further spectropolarimetric time series will substantiate the magnetic nature of WR 55 and will allow to set tighter boundaries to its magnetic field strength. The temporal variations of the measured longitudinal magnetic fields should be used to ascertain the rotation/magnetic period of WR 55 and determine for the first time the geometry of the global magnetic field in a WR star.

Furthermore, the detection of the magnetic field in WR 55 associated with the ring nebula RCW 78 and its molecular environment is of exceptional importance for our understanding of star formation. According to Cappa et al. (2009), WR 55 is responsible not only for the ionization of the gas in the nebula, but also for the creation of the interstellar bubble. The presence of star formation activity in the environment of this nebula suggests that it may have been triggered by the expansion of the bubble.

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DATA AVAILABILITY

The FORS 2 data from 2016 are available from the ESO Science Archive Facility at http://archive.eso.org/cms.html. The data from 2020 will become available in March 2021 at the same location and can be requested from the author before that date.

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