Detection of anomalous element distribution in the extremely slowly rotating magnetic O9.7 V star HD 54879

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ABSTRACT

The O9.7 V star HD 54879 is currently the only massive magnetic star whose magnetic field geometry and rotation period are not constrained. Over the last three years, we gathered additional observations of this star, obtained using various instruments at several astronomical facilities with, the aim to constrain the rotation period and the magnetic field geometry. The new data include the first full Stokes vector observations with the PEPSI spectropolarimeter, installed at the Large Binocular Telescope. The acquired spectropolarimetric observations show a very slow magnetic field variability related to the extremely slow rotation of HD 54879, which is also indicated in a dynamical spectrum, displaying variability of the Hα line. The most intriguing result of our study is the discovery of differences in longitudinal magnetic field strengths measured using different LSD masks containing lines belonging to different elements. It is the first time that such a differential analysis of the field strength in dependence of the used lines is carried out for a magnetic O-type star. Since the LSD Stokes I profiles of the studied O, Si, and He line masks remain stable over all observing epochs, we conclude that the detection of different field strengths using lines belonging to these elements is related to the different formation depths, with the He lines formed much higher in the stellar atmosphere compared to the silicon and the oxygen lines, and NLTE effects. Our numerical magnetospherical model suggests the presence of enhanced gas density that fills the volume inside the field lines close to the star.

Key words: stars: individual: HD 54879 – stars: early-type – stars: atmospheres – stars: variables: general – stars: magnetic fields

1 INTRODUCTION

The origin of the magnetic fields in massive stars is an important problem that is not solved yet. A strong support in favour of a scenario that magnetic fields in massive stars may be generated by strong binary interaction, i.e. in stellar mergers, or during a mass transfer or common envelope evolution, was presented in the recent work of Frost et al. (2021), who studied the properties of the massive double-lined system containing the magnetic Of?p star HD 148937. Using multiwavelength observations, they reported about the age discrepancies of the binary components in the system HD 148937, consistent with the primary component being a rejuvenated merger product. The spectral Of?p classification is described by Walborn (1972). Five such stars were identified in our Galaxy and magnetic fields were detected in all of them.

To answer the principal question on the possible origin of magnetic fields in massive stars, it is important not only to build trustworthy statistics on the occurrence of magnetic fields, but also on their topology at different evolutionary stages. During the last two decades, a considerable number of O-type stars have been investigated for magnetic fields, and as a result, about a dozen magnetic O-type stars are presently known (e.g. Grunhut et al. 2017; Schöller et al. 2017). The most recent detection of a magnetic field in an O-type star dates already seven years back: the presence of a magnetic field in the O9.7V star HD 54879 was reported by Castro et al. (2015), using a combination of FOcal Reducer low dispersion Spectrograph (FORS2; Appenzeller et al. 1998) and high-resolution HARPSpol (the High Accuracy Radial velocity Planet Searcher in polarimetric mode; Snik et al. 2008) observations. For this 4 Myr old star, the authors detected a ∼ 600 G longitudinal magnetic field with a lower limit of the dipole strength of ∼ 2 kG. Despite of several subsequent studies (e.g. Hubrig et al. 2020, and references therein), HD 54879 currently remains the only massive magnetic star whose magnetic field geometry and rotation period are not constrained. The reason for this is related to the extremely slow rotation of this star: based on

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the variability of the Hα line intensity and the longitudinal magnetic field, Hubrig et al. (2020) concluded that the rotation period is probably longer than 9 yr. Although magnetic O-type stars are known as a class of slowly rotating magnetic massive stars, the extremely slowly rotation of HD 54879 with the second longest rotation period after the Of?p star HD 108 with a rotation period of about 50–60 yr (Næs et al. 2001), makes it an important target for studies of the impact of the magnetic field on the physical processes taking place in stellar atmospheres and inside of stars.

New spectroscopic and spectropolarimetric material has been acquired over the last years using various instruments belonging to different astronomical facilities. In this work, they are used to study the properties of HD 54879 and to put constraints onto the rotation period, the field strength, and the field geometry. In this article, we describe the observations in Section 2 and in Section 3 we present the results of the magnetic field measurements and the analysis techniques, and put constraints onto the rotation period and the most probable configuration of the magnetic field geometry. In Section 4, we report on the field strength differences detected using for the measurements lines belonging to different elements, followed by a discussion of the current status of the numerical simulations, the binarity status, and short-term variability in Sections 5, 6, and 7. Finally, we discuss the obtained results in Section 8.

2 OBSERVATIONS

The observations used in our analysis of the properties of HD 54879 were obtained with several European Southern Observatory (ESO) instruments installed at the Very Large Telescope (VLT) on Cerro Paranal, Chile: the FOcal Reducer low dispersion Spectrograph in spectropolarimetric mode (FORS 2; Appenzeller et al. 1998), the Ultraviolet and Visual Echelle Spectrograph (UVES; Dekker et al. 2000), and the beam combining instrument Precision Integrated-Optics Near-infrared Imaging ExpeRiment (PIONIER; Le Bouquin et al. 2011) on the Very Large Telescope Interferometer (VLT; e.g. Schöller et al. 2007). Further, we used the Potsdam Echelle Polarimetric and Spectroscopic Instrument (PEPSI; Strassmeier et al. 2015) at the 2 × 8.4 m Large Binocular Telescope (LBT) in Arizona to record high-resolution spectra in circular and linear polarized light. Additionally, we downloaded two archive spectropolarimetric observations recorded with the Echelle SpectroPolarimetric Device for the Observation of Stars (ESPaDOnS; Donati et al. 2006) installed at the Canada-France-Hawaii Telescope (CFHT). In the following subsections, we describe the data acquired with these instruments. Finally, we have used the FORS 2, HARPSpol, and ESPaDOnS data already presented by Hubrig et al. (2020).

2.1 FORS 2

Two new spectropolarimetric observations of HD 54879 with FORS 2 were obtained on 2020 September 20 and November 15 in the framework of the programme 0106.D-0250(A) executed in service mode at UT1 of the VLT. Similar to observations presented previously by Hubrig et al. (2020), both FORS 2 observations were recorded with the GRISM 600B and the narrowest available slit width of 0′′.4 to obtain a spectral resolving power of $R \approx 2,000$ within the observed spectral range from 3250 to 6215 Å. Further, a non-standard readout mode with low gain (200kHz, 1×1, low) was used, providing a broader dynamic range and hence allowing us to reach a higher signal-to-noise ratio (S/N) in the individual spectra. The position angle of the retarder waveplate was changed from +45° to −45° and vice versa every second exposure. This is done to minimize the cross-talk effect and to cancel errors from different transmission properties of the two polarized beams. Moreover, the reversal of the quarter-wave plate compensates for fixed errors in the relative wavelength calibrations of the two polarized spectra. The wavelength calibration was carried out using He-Ne-Ar arc lamp exposures. The ordinary and extraordinary beams were extracted using standard IRAF procedures, as described by Cikota et al. (2017).

2.2 UVES

Two spectra were recorded on 2020 October 11 and November 25 with UVES mounted on UT2 of the VLT within the framework of the programme 0106.D-0250(B). The obtained spectra have a resolving power $R \approx 80,000$ in the blue arm and $R \approx 110,000$ in the red arm. The spectra cover the wavelength ranges 3756–4982 Å and 5690–9459 Å and were reduced by the ESO Phase 3 UVES pipeline.

2.3 Interferometric observations with PIONIER

HD 54879 was observed with the beam combining instrument PIONIER on 2018 November 30 in the framework of the programme 0102.D-0234(C). PIONIER combines four beams in the H-band, either from the 8.2 m Unit Telescopes (UTs), or, as in this case, from the 1.8 m Auxiliary Telescopes (ATs), which leads to visibilities on six different baselines, as well as four closure phase measurements, simultaneously. PIONIER was used without a dispersive element, to enhance the sensitivity for this rather faint target. For brighter objects, the instrument can also operate in a low resolution spectroscopic mode to carry out measurements at five different wavelengths within the H-band, improving the UV-coverage. The observations of HD 54879 were carried out on the AT configuration A0-G1-J2-K0.

2.4 PEPSI

We used the Potsdam Echelle Polarimetric and Spectroscopic Instrument (PEPSI) at the 2 × 8.4 m Large Binocular Telescope (LBT) in Arizona to obtain circular and linear polarized spectra of HD 54879. The spectrograph and its spectropolarimetric capabilities have been described in detail by Strassmeier et al. (2015). The polarimetric mode has a spectral resolution of $R \approx 130,000$. The observations were obtained on 2020 December 6 and cover two wavelength regions: the crossdisperser II covers the wavelength range 4236–4770 Å and the crossdisperser IV 5391–6288 Å. Retarder angles of 45° and 135° were set to record the Stokes V spectra, whereas the Foster prism position angles 0° and 90° with respect to

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1 http://www.eso.org/rm/api/v1/public/releaseDescriptions/163
the North were used to obtain Stokes $Q$, then 45° and 135° to obtain Stokes $U$. The exposure time for each subexposure accounted for 5 min.

The data reduction was done using the software package SDSS4PEPSI (“Spectroscopic Data Systems for PEPSI”) based on Ilyin (2000), and described in detail by Strassmeier et al. (2018). It includes bias subtraction and variance estimation of the source images, master flat field correction for the CCD spatial noise, scattered light subtraction, definition of échelle orders, wavelength solution for the ThAr images, optimal extraction of image slices and cosmic spike elimination, normalisation to the master flat field spectrum to remove CCD fringes and the blaze function, a global 2D fit to the continuum, and the rectification of all spectral orders into a 1D spectrum.

2.5 ESPaDOnS

Recently, two ESPaDOnS polarimetric spectra with a spectral resolution of $R \approx 65,000$ obtained on 2019 March 15 and September 17 became publicly available. We downloaded these already reduced spectra from the CFHT archive.

3 CONSTRANING THE ROTATION PERIOD OF HD 54879 AND ITS MAGNETIC FIELD GEOMETRY

According to previous studies, HD 54879 is expected to have a rotation period of the order of several years (Kupka et al. 1997; Hubrig et al. 2009, 2020). To determine the periodicities in magnetic massive O-type stars, not only long-term monitoring of the variability of the longitudinal magnetic field, but also of the variability of equivalent widths of the Ho and He ii 4686 lines, which are dominated by stellar wind material in the stellar magnetosphere, is usually used (e.g. Stahl et al. 2008).

3.1 Searching for periodicity using measurements of the longitudinal magnetic field

The procedure for the measurement of longitudinal magnetic fields using low-resolution FORS 1/2 spectropolarimetric observations is described e.g. in Hubrig et al. (2004a, b, and references therein). The results of our measurements are listed in Table 1. To obtain robust estimates of the standard errors, we also carried out Monte Carlo bootstrapping tests (e.g. Steffen et al. 2014).

To measure the longitudinal magnetic field $\langle B_z \rangle$ from the high-resolution spectropolarimetric observations, we employed, similarly to the work of Hubrig et al. (2020), the least-squares deconvolution (LSD) technique, allowing us to achieve a much higher $S/N$ in the polarimetric spectra. For the details of this technique and of the calculation of the Stokes $I$ and Stokes $V$ parameters, we refer to the work of Donati et al. (1997). The line masks were constructed using the Vienna Atomic Line Database (VALD3; Kupka et al. 2011) and the stellar parameters $T_{\text{eff}} = 30.5 \, \text{kK}$ and $\log g = 4.0$ reported by Shenar et al. (2017). Given the shorter wavelength coverage of the PEPSI spectra compared to the spectral coverage of the HARPS and ESPaDOnS spectra, we had to modify our line masks by removing the spectral lines not covered by PEPSI. Consequently, we re-measured the field values also in the polarimetric spectra from the previous analysis by Hubrig et al. (2020).

| MJD | $S/N$ | $\langle B_z \rangle_{\text{all}}$ (G) | $\langle B_z \rangle_{\text{hyd}}$ (G) | $\langle B_z \rangle_{\text{N}}$ (G) |
|-----|------|-----------------|-----------------|-----------------|
| 59122.37 | 2205 | $-275 \pm 95$ | $-424 \pm 144$ | $-51 \pm 87$ |
| 58169.26 | 2130 | $-291 \pm 103$ | $-649 \pm 147$ | $68 \pm 106$ |

The measurements using the line mask optimised for the PEPSI spectral wavelength coverage containing metal and He lines and those using the line mask containing exclusively metal lines are listed in the first four columns in Table 2 along with the spectropolarimeter identification and the modified Julian dates for the middle of each exposure. In all cases, the false alarm probability is less than $10^{-6}$. According to Donati, Semel, & Rees (1992), a Zeeman profile with false alarm probability (FAP) $\leq 10^{-5}$ is considered as a definite detection, $10^{-5} < \text{FAP} < 10^{-3}$ as a marginal detection, and FAP $> 10^{-3}$ as a non-detection. In this table, we also indicate the number of lines in each line mask, and the mean effective Landé factors and the mean wavelengths used for the normalisation for the line mask. The calculated LSD Stokes $I$ and Stokes $V$ profiles for each observing epoch are presented in Figs. A1–A5 in the Appendix.

The distribution of the measured mean longitudinal magnetic field values using spectra obtained with different spectropolarimeters as a function of MJD is presented in Fig. 1. While the mean longitudinal magnetic field measured in metal lines using the HARPS spectra in 2014 April showed a strength of about $-569 \, \text{G}$, the field strength values were gradually decreasing over the subsequent years and changed their polarity from negative to positive around 2019. The strongest longitudinal field with a positive polarity of about $50 \, \text{G}$ was measured using the line mask with metal lines on the night of 2019 March 15. The measurements on 2019 September 17 showed that the field values reversed the sign again, showing negative polarity and reaching a field strength of about $-300 \, \text{G}$ in our last observations with PEPSI on 2020 December 6. The distribution of the field strengths measured on the low-resolution FORS 2 polarimetric spectra shows a larger dispersion of the data points, but is roughly similar to that of the measurements using high-resolution spectropolarimetric observations. We observe that FORS2 field strengths from using only the hydrogen lines are in absolute values higher than those using the entire spectra. This effect is already visible in previous studies of a number of magnetic early B-type stars (e.g. Hubrig et al. 2009, 2017).

Generally, magnetic massive O- and B-type stars exhibit a smooth, single-wave variation of the longitudinal magnetic field during the stellar rotation cycle. The approximately sinusoidal variation of $\langle B_z \rangle$ and the ratio of the values of the
\[\langle B_z \rangle \] extrema in previously studied stars suggest that there is an important component of the field that is dipolar. Assuming that the magnetic field of HD 54879 has a pure dipolar configuration and that the negative field extremum is indeed around $-570 \text{ G}$ and not at a lower value, we fitted a cosine curve to the observed distribution of data points obtained from the high-resolution spectropolarimetric observations and determined a stellar rotation period of 7.2 yr. Certainly, further monitoring of the magnetic field variability is needed to determine the rotation period with more confidence. The result of our fitting procedure is presented in the lower panel of Fig. 1 by a dark dashed green cosine curve corresponding to the 7.2 yr rotation period.

This simple cosine curve presenting the variability of the \[\langle B_z \rangle \] values as a function of the rotation phase has an amplitude $A(B_z) = 280 \pm 10 \text{ G}$ and a mean value $\langle B_z \rangle = -250 \pm 10 \text{ G}$. Using the values from the fit of the longitudinal magnetic field over the rotation period, one can determine a minimum dipolar magnetic field strength $B_d$ of 1950 G, using a limb darkening parameter of 0.2. As we do not know the inclination of the star and cannot estimate it due to HD 54879’s long rotation period, we cannot determine the actual dipolar field strength, which e.g. would be around 6 kG for an inclination $i$ of 10°. As already discussed by Järvinen et al. (2021), magnetic studies of several O-type stars indicate that only one magnetic pole is well visible while the star rotates, implying that the magnetic field structure over the fraction of their invisible surface remains unconstrained.

As the mean longitudinal magnetic field is defined as the average over the visible stellar hemisphere of the line-of-sight component of the magnetic vector, only the availability of all four Stokes parameters ($I$, $V$, $Q$, and $U$) permits a study of the longitudinal and transversal field components to determine the real topology of stellar magnetic fields. That is, to prove whether massive stars possess dipole-like fields or more complex fields with contributions from higher-order harmonics. Measurements of linear polarization are also a powerful means to study asymmetries in stellar winds. Since HD 54879 possesses a magnetosphere (e.g. Hubrig et al. 2020), a study of the variability of the linear polarization in photospheric and wind sensitive lines is of great importance to investigate the field geometry and circumstellar environment. However, no high-resolution linear polarization measurements were carried out for any magnetic O-type star so far.

In Fig. 2 we present the first PEPSI observations of the full Stokes vector for HD 54879. These observations were carried out with the LBT in binocular mode in the night of 2020 December 6. At that epoch, the strength of the longitudinal magnetic field was about $-300 \text{ G}$. However, despite our expectations, no linear polarization signatures were discovered in the PEPSI spectra, which were recorded at a $S/N$ of about 500 in the corresponding Stokes $I$ spectra. In this figure we show the PEPSI spectra for all four Stokes parameters and their null spectra in the vicinity of two spectral lines, the HeI line at 5875.6 Å, which is sensitive to the circumstellar environment, and the photospheric line SiIII at 5739.7 Å. The asymmetrical profile of the HeI 5876 triplet presented in Fig. 2 can indicate the presence of an asymmetrical wind. A similar asymmetrical line profile is also detected in the HeI 7065 triplet. On the other hand, we cannot exclude that due to the presence of the magnetosphere around HD 54879, the red side of the line profiles of the HeI 5876 and HeI 7065 lines may be partially filled in with emission: these lines appear in emission in the spectra of the Of?p star NGC1624-2, which has the strongest magnetic field among O type stars, with a dipole strength $\geq 16 \text{ kG}$ (Järvinen et al. 2021), and their intensity varies in phase with that of the emission line HeI 4686, sensitive to the circumstellar environment.

Unfortunately, the line most dominated by the magnetospheric wind material, Hα, is not covered in the PEPSI spectra presented here. Therefore, we plan to record the circumstellar lines Hα, Hβ, and HeII at 4686 Å, sensitive to the stel-
anomalous element distribution in HD 54879

3.2 Searching for periodicity using spectroscopic data

Previous studies of magnetic massive stars indicated that the presence of variable emission in Hα and the He ii line at 4686 Å is indicative of circumstellar structures around magnetic O-type stars and related to their magnetospheres. Further, a correlation exists between the absolute value of the mean longitudinal magnetic field and the strength of these emissions in the sense that the strongest emissions appear at phases of maximum absolute value of the mean longitudinal magnetic field. While the He ii λ4686 line profile in the spectra of HD 54879 is observed exclusively in absorption, the emission line profiles of Hα are highly variable, changing between a triple-peak and a double-peak emission line profile, indicating a composite structure of the surrounding circumstellar material (e.g. Hubrig et al. 2020).

In the left panel of Fig. 3, we present all available high-resolution spectroscopic observations of the Hα line, including the two most recent UVES observations, as a dynamical spectrum phased with the period of 7.2 yr. The displayed Hα profiles recorded in the UVES observations show lower emission levels than the Hα profile observed in the HARPS spectrum obtained in 2014 (Fig. 3, middle panel), when the maximum longitudinal magnetic field strength was observed. In the right panel we show only a few Hα line profiles recorded with ESPaDOnS resembling the most recent UVES observations. The presented differences in the emission levels of the line profiles indicate that we are probably a couple of years away from the epoch that allows the best visibility of the negative magnetic pole.

The variability of the equivalent widths (EWs) of the circumstellar emission line Hα and the He ii λ4686 line, sensitive to stellar wind material, is frequently used to constrain the rotation period in magnetic O-type stars (e.g. Stahl et al. 2008). In Fig. 4 the EWs of these two lines are plotted as a function of MJD. As can be seen in this figure, the EWs of the Hα and He ii λ4686 lines were the strongest at the epoch of the best visibility of the negative magnetic pole. The EW values measured using ESPaDOnS spectra appear systematically lower compared to those using HARPS spectra. This can be due to the presence of scattered light or the lower resolution of the ESPaDOnS spectra with $R \approx 65,000$, while the spectral resolution of the HARPS spectra is about 110,000.

Figure 1. Upper panel: Distribution of the mean longitudinal magnetic field $\langle B_z \rangle$ values of HD 54879 as a function of MJD between the years 2014 and 2021. The lighter colours represent low-resolution data that were published in Hubrig et al. (2020). Darker colours are used to present the new measurements. Open circles indicate FORS2 measurements obtained using the entire spectrum and open triangles measurements where only the hydrogen lines were used. All high-resolution data have been re-analysed due to different wavelength coverage. Open squares and filled stars indicate measurements using HARPS and ESPaDOnS high-resolution spectropolarimetric observations and are based on the line mask with metal lines. The measurement obtained using the PEPSI spectra is indicated by a magenta diamond. Lower panel: As above, but showing only the $\langle B_z \rangle$ obtained from high-resolution observations. The dashed dark green line shows a cosine curve with the period of 7.2 yr.

Figure 2. The four Stokes parameters and their null profiles for two individual lines, He i at 5875.6 Å and Si iii at 5739.7 Å, in PEPSI observations obtained on 2020 December 6. In the spectra recorded in circular polarized light, clear Zeeman signatures are detected for both lines whereas the spectra recorded in linear polarized light appear flat.
showed that these stars form to study the profiles show also short term variability, already mentioned in the previous work by Hubrig et al. (2020). Middle panel: The variability of the Hα profiles in HARPS, ESPaDOnS, and UVES spectroscopic observations. Right panel: A few ESPaDOnS observations of Hα profiles showing similarity with the profiles from our recent UVES observations.

Figure 4. Variability of the Hα and He ii 4686 lines observed on the available high-resolution HARPS, ESPaDOnS, UVES, and PEPSI spectra. As the Hα line exhibits a very complex variable line profile, to calculate the EWs, the integration was carried out over the most variable part of the line profile between 6559 and 6566 Å.

Considering the distribution of the measurements shown in Fig. 4, it appears that the EWs of both lines show an increase during the most recent UVES and PEPSI observations, but further monitoring is necessary to confirm this trend. Additionally, we observe a rather large scatter in the EW values in the ESPaDOnS spectra during the period between MJDs 57740 and 58130, when the longitudinal magnetic field was decreasing from −250 to −105 G. According to Hubrig et al. (2020), the Hα lines in the spectra of HD 54879 show variability on time scales of weeks and even hours. It is possible that this variability is related to the wind or the immediate environment of the star. The impact of the magnetic field of HD 54879 on its wind characteristics was discussed in detail by Hubrig et al. (2019), who used the NIRVANA magnetohydrodynamical (MHD) code (Ziegler 2011) to study the distribution of the trapped gas within the magnetosphere and in particular the presence of outbursts. Their simulations showed that outside of the confinement radius, gas still concentrates in elongated structures along the magnetic field lines, but is ejected away from the star in episodic outbursts.

4 FIELD STRENGTH DIFFERENCES IN MEASUREMENTS FROM DIFFERENT ELEMENTS

The NIRVANA MHD simulations of the slowly rotating magnetic O-type stars NGC 1624-2 (Järvinen et al. 2021) and HD 54879 (Hubrig et al. 2020) showed that these stars form dynamical magnetospheres, in which material flows along closed magnetic field loops from both magnetic poles, colliding near the magnetic equator and then falling back on to the stellar surface, leading to complex flows in the magnetosphere. The study of the strongly magnetic Of?p star NGC 1624-2 by Järvinen et al. (2021) showed opposite variability of the hydrogen and helium emission lines in comparison to the variability of the photospheric absorption lines He i λ4713 and C iv λ5801. The emission lines become stronger when the magnetically confined cooling disc around the magnetic equator is seen closer to face-on, while the emission contribution is reduced when the cooling disc is seen closer to edge-on. The photospheric absorption lines appear stronger when the cooling disc is seen closer to edge-on. The photospheric absorption lines appear weaker when the cooling disc is seen closer to edge-on. The photospheric absorption lines appear weaker when the cooling disc is seen closer to edge-on. The photospheric absorption lines appear weaker when the cooling disc is seen closer to edge-on. In that study, an interesting fact was reported with respect to the LSD magnetic field measurements using a line mask with photospheric absorption lines including the Si lines, or a line mask without the Si lines. The measured magnetic field strength became lower if the Si lines were included in the line mask. To explain these measurements, it was suggested that Si is inhomogeneously distributed on the stellar surface with a region of Si concentration located in the vicinity of the magnetic
In the last three columns and we show in the left and in the middle panel the stellar wind fractionation and Si lines, and by He I lines. The measurements using these three masks are listed in Table 2 in the last three columns and their distribution as a function of MJD is presented in Fig. 5 along with the measurements using line masks for all lines and metal lines, which include spectral lines with and without known Landé factors.

The observed trends of the longitudinal magnetic field strengths with elapsed time obtained using different masks appear qualitatively similar, but remarkable differences in the measurements using the individual line masks, in particular for the He mask, are well visible on a few epochs. The dispersion in field strengths is noticeably large at the epochs close to the best visibility of the negative magnetic field pole. The measured field strength $\langle B_z \rangle$ using the He lines is systematically lower than the field strength measured using the other masks and the field strength $\langle B_z \rangle$ using the O lines is systematically higher than the field strengths obtained using the Si lines. Interestingly, a similar behaviour was recently reported for the rapidly oscillating Ap star HD 166473 (Järvinen et al. 2020), for which a dispersion in field strengths was found to be remarkably large in the regions close to the magnetic field poles. However, HD 166473 is a pulsating star showing a strong vertical abundance stratification of iron peak and rare earth elements. For such stars, the existence of a relation between the magnetic field strength and its orientation and vertical element stratification is expected.

In Fig. 6 we show in the left and in the middle panel the time evolution of the LSD Stokes $V$ and $I$ profiles calculated for all line masks. The LSD Stokes $V$ profiles change their shape in accordance with the measured longitudinal magnetic strengths. The magnetic field has most of the time a negative polarity, with the exception of 2019 March 15, when the field is clearly positive. We observe crossover profiles on 2019 September 17, when the magnetic field changes polarity (see also the plots in Appendix A). A description of the crossover effect can be found in the work of Mathys (1995).

Despite the clear variability of the LSD Stokes $V$ profiles, the LSD Stokes $I$ profiles in all line masks constructed for the analysis of HD 54879, remain stable over all observed epochs from 2014 to 2020 (middle panel of Fig. 6), and only weak profile changes in the line cores are observed (right panel of Fig. 6). This is in contrast to the behaviour of the Stokes $I$ profiles in Ap and Bp stars. An inspection of the line cores indicates a clear separation between the core depths recorded with ESPaDOnS and those recorded with HARPS and PEPSI. The different depths clearly visible in the overplotted line cores in the spectra obtained using different spectropolarimeters are probably caused by the much lower spectral resolution of ESPaDOnS compared to the spectral resolution of HARPS and PEPSI. As we show in Fig. 7, the differences in core depths can also be due to the presence of scattered light in the ESPaDOnS spectropolarimeter. In this figure we show ESPaDOnS, HARPS, and PEPSI observations of the spectral region containing the Zeeman doublet Fe II at 6149.25 Å in the spectra of γ Equ. Since this star with very sharp lines has an extremely long rotation period of at least 95.5 yr (Bychkov, Bychkova & Madej 2016), no significant changes in the line profiles are expected over a couple of years. Again, we observe markedly lower depths of the

![Figure 5. Distribution of the mean longitudinal magnetic field values $\langle B_z \rangle$ calculated for the different epochs listed in Table 2 using different line masks. As in Fig. 1, the dashed dark green line shows a cosine curve based on measurements using only metal lines with the period of 7.2 yr.](image-url)
Figure 6. Overplotted LSD Stokes $V$ profiles (left panel) and LSD Stokes $I$ profiles (middle panel) computed using high-resolution polarimetric spectra recorded with HARPS (dotted lines), ESPaDOnS (solid lines) and PEPSI (dashed lines). In the right panel we plot the line cores of the Stokes $I$ profiles at an enlarged scale for better visibility of the differences between the observations obtained at different epochs. On the top of this figure, we present the dates of the observations and the identification of the lines used.

Figure 7. Observations with ESPaDOnS, HARPS, and PEPSI of the spectral region containing the Zeeman doublet Fe ii at 6149.25 Å in the spectra of $\gamma$ Equ.

line profiles recorded with ESPaDOnS compared to the line depths recorded with HARPS and PEPSI.

Because of the different depths between the ESPaDOnS spectra and the higher resolution HARPS and PEPSI spectra, the differences in the line cores have to be considered separately. A most obvious conclusion with respect to the degree of variability follows from the consideration of the Si lines, which show the largest depth differences in higher and lower resolution spectra, followed by the He lines. The O lines appear to be the most stable lines. Further, we observe a trend for lower core depths to appear in observations carried out in 2014 and 2019, i.e. at epochs when $\langle B_z \rangle$ is the strongest or when $\langle B_z \rangle$ is around zero.

On the surface of magnetic He-rich early-B type stars analyses of the inhomogeneous element distribution usually indicate the presence of He spots located close or around the magnetic poles and a high concentration of Si spots located close to the magnetic equator (e.g. Hubrig et al. 2017). As the O9.7 V star HD 54879 is hotter than the magnetic early-B type stars, the stellar wind fractionation scenario predicting an enrichment of helium at the poles, which is dependent on the ionization of H and He in the stellar wind (Hunger & Groote 1999), is not expected to work in O-type stars usually showing higher mass-loss rates (Vink, de Koter & Lamers 2000). According to Krtička (2014), early-B type stars have line driven winds with mass-loss rates of the order of $10^{-9} M_\odot \text{yr}^{-1}$. This mass loss rate, as suggested by Porter & Skouza (1999), presents a maximum value to enable the stellar wind fractionation to operate. On the other hand, the empirical mass-loss rate estimation in HD 54879 by Shenar et al. (2017) using the two most prominent wind features, the resonance lines C iv $\lambda\lambda$1548, 1551, and Si iv $\lambda\lambda$1394, 1403 recorded with Hubble Space Telescope UV observations, showed a much lower mass-loss rate than the theoretical estimates for early B-type stars by Krtička (2014), namely $10^{-10.2} M_\odot \text{yr}^{-1}$.
Still, as we do not detect noteworthy variability in the Stokes $I$ line profiles belonging to O, Si, and He, the stellar wind fractionation scenario may not seem to be plausible and another interpretation for the detection of different magnetic field strengths measured for different elements needs to be found. As mentioned above, previous studies of magnetic O-type stars report line profile variability belonging to different elements with the rotation period (e.g. Stahl et al. 2008; Wade et al. 2015; Järvinen et al. 2021). This variability is interpreted not in the context of variations of the chemical abundance, but as due to variable contamination by circumstellar matter. However, the detected stability of the Stokes $I$ line profiles calculated for different line masks in the spectra of HD 54879 indicates that the studied spectral lines are not strongly affected by emission from the stellar wind or material trapped in the magnetosphere, suggesting that the circumstellar environment of this star is less dynamic compared to other magnetic O-type stars. One of the logical explanations for the detection of different magnetic field strengths measured using lines belonging to O, Si, and He might be that the lines of these elements are formed at different atmospheric heights. We cannot exclude that also Non-Local Thermodynamic Equilibrium (NLTE) effects play a role in the line formation of the considered elements, causing changes in their equivalent widths. According to Zboril et al. (1997), who estimated the quantitative NLTE effects on the equivalent widths of He lines for model atmospheres with an effective temperature of 15000 K and 30000 K, the strength of the He I lines increases when the NLTE effects are taken into account. Studies of NLTE effects were predominantly carried out in the past for He-rich magnetic early B-type stars. As an example, González et al. (2019) reported that in their study of the strongly magnetic binary HD 96446 the weak Si II lines become significantly weaker in NLTE, while O II, strong Si III and weak Si IV lines become stronger.

5 NUMERICAL MODEL OF THE STELLAR MAGNETOSPHERE

Current numerical models based on standard magnetohydrodynamics can make predictions for the mass distribution around the star, but not for concentrations of specific elements. The different field strengths found for different elements can therefore not be explained by these models. Assuming a dipolar field with a polar field strength of 2 kG, the star is expected to be surrounded by an extensive magnetosphere. This is confirmed by numerical simulations. We have rerun the model described in Hubrig et al. (2019) with a full polar field strength of $B_0 = 2$ kG and $\dot{M}_0 = 10^{-9} M_\odot \text{yr}^{-1}$. Figure 8 shows the field structure and density distribution. While far away from the star the magnetic field is stretched out by the wind and becomes a split monopole, the magnetic field is dominant in the immediate vicinity of the star and the dipole structure is preserved. This implies a $1/r^3$ dependence of the magnetic field strength on the distance from the stellar surface. The smaller field strength found for He places it way above the photosphere.

As Fig. 8, shows, the gas flowing from the star escapes almost freely at the polar caps, while there is a buildup of gas from the magnetic equator to mid-latitudes. However, we observe near the star a region of enhanced gas density that fills the volume inside the field lines up to rather high latitudes. It is thus possible that this region of enhanced gas density is the source of the He lines for which we measure lower longitudinal field strengths. To make detailed predictions about a possible stratification of elements in the magnetosphere, a multi gas approach would be needed. This is beyond the scope of the current paper, but might be addressed in the future with the latest version of the NIRVANA code.

Figure 9 shows the mass loss rate as a function of time for the model shown in Fig. 8. The time series shown in the figure has been computed by integrating the mass flux over all latitudes and averaging over the outer 25 per cent of the simulation box. After the initial phase, the mass loss rate oscillates around a value close to the value of $3 \times 10^{-10}$ solar masses per year.
6 BINARITY

It is not clear yet whether HD 54879 is a member of a binary or multiple system. Hubrig et al. (2020) discussed the radial velocity (RV) measurements presented in the literature supplemented by own measurements using the LSD Stokes I spectra calculated for HARPS and ESPaDOnS observations. The new RV measurements using the newly recorded ESPaDOnS, UVES, and PEPSI spectra indicate a possible increase in RV by about 300 m s$^{-1}$ between 2018 January and 2020 December. The plot with literature and our own measurements is presented in Fig. 10. The oldest measurement (Boyajian et al. 2007) in this plot is based on observations obtained with the Kitt Peak National Observatory (KPNO) Coudé feed telescope. The following literature values (Castro et al. 2015) are based on data obtained either with the Fibre-fed Echelle Spectrograph (FIES) at the Nordic Optical telescope or with the Fiber-fed Extended Range Optical Spectrograph (FEROS) at the ESO 2.2 m telescope.

Both Hipparcos and Gaia’s second data release (GDR2; Gaia Collaboration 2016, 2018) data do not raise a binarity flag. On the other hand, HD 54879 was included in the study by Kervella et al. (2019), who analysed the proper motions of stars presented in the Hipparcos catalogue (van Leeuwen 2007) and GDR2 data. According to this study, HD 54879 shows a proper motion anomaly, indicating the presence of a companion.

We also made use of archival VLTI observations with PIONIER (Le Bouquin et al. 2011) to explore whether HD 54879 has a companion. We reduced the PIONIER data with the pnDRS pipeline (Le Bouquin et al. 2011). To determine the transfer function applied to calibrate the squared visibility amplitudes and the closure phases of the science target, the pnDRS pipeline uses the diameters listed in the JSDC catalog (Chelli et al. 2016) for the interferometric calibrator star, which is observed before and after the science target.

We looked for potential companions, utilizing the Python tool candid², developed by Galletme et al. (2015). candid performs a search on an adaptive grid with a spacing that will allow it to find the global minimum in $\chi^2$. For assessing the significance of a companion detection, not only the reduced $\chi^2$ is considered, but also the number of degrees of freedom. We scrutinized the distance range from 1.6 to 40 mas around the primary, which, given the 0.8633 mas Gaia parallax of HD 54879, corresponds to projected linear separations from 2 to 46 au. candid did not find any companion to HD 54879 up to 3.5 magnitudes fainter than the primary star in the search area.

7 SHORT-TERM SPECTRAL VARIABILITY

Blomme et al. (2011) reported that early-type O stars typically show stochastic low-frequency variability (SLF), whereas late-type O and early-type B stars typically show coherent pulsation modes and suggested that the transition between these types of variability takes place at a spectral type around O8. Recently, Burssens et al. (2020) studied the variability of 98 massive O and B stars using the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015) Sections 1-13 observations and reported the possible detection of coherent $p$ and $g$ modes in a number of main-sequence stars with spectral types in the range O4.5-O9.5, including HD 54879. The authors concluded that the dominant periodicity detected in TESS observations does not agree with constraints on the rotational period of HD 54879, hence some other mechanism must be responsible.

Spectral variability on a short-time scale in HD 54879 was investigated by Järvinen et al. (2017) using subexposures with different integration times in high-resolution HARPS spectropolarimetric observations. The analysis of these observations indicated distinct changes in line profiles belonging to different elements and taking place on timescales corresponding to the duration of the individual subexposures of the order of 15–45 min. However, although distinct variability was detected, the level of the variability amplitude was rather low, between 0.2 and 0.5 per cent. As of today, the only magnetic O-type star showing pulsating variability using photometric observations is NGC 1624-2. Using TESS two minute cadence data, Kurtz et al. (2020) detected three significant low-frequency peaks probably corresponding to coherent $g$ mode pulsations. The presence of short-term spec-

² https://github.com/amerand/CANDID

Figure 9. Mass loss rate in units of solar masses per year averaged over the outer 25 per cent of the simulation box vs. time.

Figure 10. Radial velocity measurements of HD 54879 between 2000 and 2020 compiled from the literature and supplemented by measurements on the spectra obtained with HARPS, ESPaDOnS, UVES, and PEPSI. Our own measurements are carried out using LSD Stokes I profiles calculated with the mask containing metal lines.
Figure 11. LSD Stokes $I$ profiles calculated for individual ESPaDOnS subexposures observed at different epochs. The profiles calculated using oxygen lines are shown on the left, those using aluminium and silicon lines are shown in the middle and on the right. The upper panels show the overplotted LSD Stokes $I$ profiles calculated for individual subexposures with the mean profiles indicated by red lines. In the lower panels we show the differences between the LSD Stokes $I$ profiles for each subexposure and the mean profiles. We also indicate the date of the observation and the length of each subexposure.
trol variability in HD 54879 was also discussed in the study by Hubrig et al. (2019), who reported that several line profiles show distinct radial velocity shifts in FORS2 spectra.

Since we have now more extensive spectroscopic material at our disposal, to test the presence of spectral variability on short time scales of the order of minutes, we used all available high-resolution ESPaDOnS spectropolarimetric observations, consisting each of four subexposures recorded with integration times between 8 and 15 min, which are even shorter than the subexposure integration times with HARPS. As Järvinen et al. (2017) reported the strongest variations – of up to 0.5 per cent – in line profiles calculated from HARPS spectra using exclusively silicon lines, we compared the variability amplitude of the silicon lines with the variability of line profiles belonging to the elements oxygen and aluminium. The line mask for oxygen used in this test included fourteen O iii lines, that for Al four Al iii lines, and the silicon mask included five Si iii and two Si iv lines. The LSD profiles calculated for these masks for all individual ESPaDOnS subexposures are presented in Fig. 11. The lowest amplitude of variability is detected in oxygen lines with an intensity amplitude in the range between 0.07 and 0.24 per cent. The least variable LSD line profiles belong to the first data set from 2014 November 9, whereas the most variable profiles are observed in the data set from 2017 January 5. The aluminium and silicon lines show stronger variability with amplitudes 0.21–0.36 per cent and 0.15–0.26 per cent, respectively. The lowest amplitude for aluminium was again detected in the first data set obtained on 2014 November 9, whereas the LSD silicon profiles were least variable in 2017 September 11. The strongest variability amplitude is observed in the Al lines in the data set from 2019 March 3 and that for the Si lines in the data set from 2018 January 10. To conclude, the amplitude of the line profile variability is slightly different for different elements, but is always below 0.5 per cent.

8 DISCUSSION

In agreement with previous studies of HD 54879 (Shenar et al. 2017; Hubrig et al. 2019, 2020), our recently acquired spectropolarimetric observations show a very slow magnetic field variability related to the extremely slow rotation of HD 54879. The extremely slow rotation of this star is also indicated in our dynamical spectrum, displaying the variability of the Hα line. From the end of 2017 to the end of 2019, we were observing the star at rotational phases with the best visibility of the magnetic equator, leading to a low positive (Bz) value around 50 G in 2019 March. At the end of 2020, the field strength decreased to about −300 G, measured in the LSD Stokes V spectra calculated for metal lines. The strongest field in HD 54879 of the order of −570 G was observed in 2014, but it is not clear yet whether this field strength indeed represents the extremum of the field of negative polarity or if the field will reach an even higher strength when the full rotation cycle is covered by future spectropolarimetric observations.

The question on the presence of a companion to HD 54879 is still an open important issue in view of the scenario that magnetic fields in massive stars may be generated by strong binary interaction and a recent report by Frost et al. (2021) that the primary component of the magnetic Of?p star HD 148937 is most likely a rejuvenated merger product. Our radial velocity study indicates that if HD 54879 is indeed a binary member, the orbital period should be very long. As of today, only the study of Kervella et al. (2019), who detected a proper motion anomaly, indicates the possible presence of a companion.

The most intriguing result of our study is the discovery of differences in longitudinal magnetic field strengths measured using different LSD masks containing lines belonging to different elements. It is the first time that such a differential analysis of the field strengths in dependence of the used lines is carried out for a magnetic O-type star. While in magnetic Ap and Bp stars chemical elements have different distributions across the stellar surface and sample the magnetic field topology in different manners, the presence of chemical spots is not expected in O-type stars with radiatively driven winds. Interestingly, conspicuously differing field strengths measured using individual lines belonging to different elements were reported for the strongly magnetic Of?p star NGC 1624-2 by Wade et al. (2012). Although the authors noticed that their measurements exhibit a scatter larger than predicted by the standard deviations, they attempted to explain the differences in the measurements by difficulties of establishing the position of the centre of gravity in the relatively noisy spectra.

In our study of HD 54879 remarkable differences in the measurements using line masks for the elements O, Si, and He are detected on a few epochs close to the best visibility of the negative magnetic field pole: the field strengths using the He lines systematically lower than the field strengths measured using other masks and the field strengths using the O lines are systematically higher than the field strengths measured using the Si lines. In contrast to the usually observed variability of the Stokes I profiles in Ap and Bp stars showing surface patchiness, the LSD Stokes I profiles of the studied line masks remain stable over all observed epochs from 2014 to 2020, and are not noteworthy contaminated by emission from the stellar wind or material trapped in the magnetosphere. Thus, we conclude that the elements O, Si, and He are not uniformly distributed over the stellar surface of HD 54879, but that the formation of their spectral lines takes place at different atmospheric heights, with He lines formed much higher in the stellar atmosphere compared to the Si and O lines. Interestingly, Castro et al. (2015) considered the abundances of carbon, nitrogen, oxygen, silicon, and magnesium of HD 54879 and reported that they are slightly lower than solar, but comparable within the errors. Martins et al. (2015) studied the carbon, nitrogen, and oxygen abundances in 74 massive O-type stars, also including seven O stars with known magnetic fields in the sample, and concluded that their surface abundances do not deviate from other non-magnetic O-type stars. They did not take into account a potential vertical abundance stratification.

Obviously, the detected element stratification has to be considered in the context of the dynamic competition between the outward forces of radiation pressure and the channeling and confinement of an outflowing wind by the large-scale organized magnetic field. Future magnetohydrodynamical simulations have to include chemical gradients in the wind plasma to explain the detected vertical abundance stratification of different elements in hot stars possessing dynamical magnetospheres. We also discuss the possible contribution of
NLTE effects, causing changes in the equivalent widths of lines belonging to different elements. Obviously, NLTE modeling should be implemented in the line forming calculations in studies of vertical element stratification in O-type stars.

Short-term spectral variability is certainly present in the high-resolution spectropolarimetric observations of HD 54879, but the variability amplitude in the normalised intensity is rather low, not higher than 0.5 per cent. Pulsations in massive stars are commonly associated with coherent pulsation modes triggered by an opacity mechanism operating in the Z-bump, relating to iron-peak elements (e.g., Dziembowski, Moskalik, & Pamyatnykh 1993; Miglio, Montalán & Dupret 2007). Asteroseismological studies allowing to directly access stellar interiors gained momentum in recent years due to the availability of photometric TESS data. The vertical abundance stratification of different elements in magnetized atmospheres is a known phenomenon and was well-documented for Bp stars and, in particular, for rapidly oscillating Ap (roAp) stars (e.g., Hubrig & González 2007; Cowley et al. 2001). While the reason for stratification in roAp stars is related to the existence of a non-standard temperature gradient in the pulsating atmospheric layers, the origin of the element stratification in magnetic Bp stars and HD 54879 is not clear. On the other hand, since Burssens et al. (2020) reported on the detection of low-frequency variability in the TESS photometric data of several magnetic massive stars including HD 54879, it is possible that pulsations can affect the chemical structure also in atmospheres and magnetospheres of magnetic O-type stars.

There exist some pieces of evidence that pulsations play an important role in the structure of the emitting plasma close to the photosphere in a massive star. A couple of years ago, Oskinova et al. (2014) reported that at least one β Cephei-variable, the extremely slowly rotating magnetic B0.7 IV star ξ¹ CMa, shows periodic variability in X-rays in phase with the optical pulsational light curve. The mechanism by which the X-rays are affected by the stellar pulsation remains enigmatic. According to Shenar et al. (2017), the X-ray flux of HD 54879 recorded with the XMM-Newton satellite indicates a higher X-ray luminosity compared to other stars with similar spectral types. However, the data set that was considered in this work did not cover significantly long time intervals to search for short-term variability of the X-ray light curve. Similar to HD 54879, ξ¹ CMa hosts a dynamical magnetosphere. Shultz et al. (2017) showed that Hα emission in this star is modulated by both pulsation and rotation. Although short- and long-term variability is detectable in the Hα line in the acquired spectra of HD 54879, our data are not sufficient to estimate short-term periodicity. Clearly, long-cadence spectroscopic and photometric observations are necessary to get more insight into the pulsational variability of HD 54879.

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DATA AVAILABILITY

The data obtained with ESO facilities will be available in the ESO Archive at http://archive.eso.org/ and can be found with the instrument and object name. The ESPaDOnS data underlying this article are available in the CFHT Science Archive at https://www.cadc-cdla.hia-iha.uro-nrc-cncr.gc.ca/en/cfht/ and can be accessed with the instrument and object name. The PEPSI data underlying this article will be shared on a reasonable request to the corresponding author.

APPENDIX A: PROFILES FOR LONGITUDINAL MAGNETIC FIELD MEASUREMENTS

LSD Stokes I, V, and null profiles are presented in Fig. A1 for the line list having both metal and helium lines, in Fig. A2 for the line list having only metal lines, in Fig. A3 for the line list having only twice ionized silicon lines, in Fig. A4 for the line list having only once ionized oxygen lines, and in Fig. A5 for the line list having only neutral hydrogen lines. The plots are sorted by observing epoch. Shaded regions in Stokes V and null panels indicate the mean uncertainty.

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Figure A1. LSD Stokes $I$, $V$, and null profiles for the line list having all lines. The plots are sorted by observing date and the instrument used is indicated after the date as follows: H=HARPS, E=ESPaDOnS, and P=PEPSI.

Figure A2. As Fig. A1, but using only metal lines.
Figure A3. As Fig. A1, but using only silicon lines.

Figure A4. As Fig. A1, but using only oxygen lines.
Figure A5. As Fig. A1, but using only neutral helium lines.

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