Zeeman Doppler imaging of $\xi$ Boo A and B*

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ABSTRACT

Aims. We present a magnetic-field surface map for both stellar components of the young visual binary $\xi$ Boo AB (A: G8V, B: K5V).

Methods. We employed high-resolution Stokes-V spectra obtained with the Potsdam Echelle Polarimetric and Spectroscopic Instrument (PEPSI) at the Large Binocular Telescope (LBT). We inverted Stokes V line profiles with our iMAP software and compared them with previous inversions. We employed an iterative regularization scheme without the need for a penalty function and incorporated a three-component description of the surface magnetic-field vector. The spectral resolution of our data is 130,000 (0.040–0.055 A) and we obtain a signal-to-noise ratio (S/N) of up to 3000 per pixel depending on wavelength. We used a singular-value decomposition (SVD) of a total of 1811 spectral lines to average Stokes-V profiles. Our mapping is accompanied by a residual bootstrap error analysis.

Results. We constructed magnetic flux densities on both stars (plus or –15–30 G), about a factor two weaker than what was seen previously for $\xi$ Boo A and B, respectively. We find only weak azimuthal and meridional field densities on both stars (plus or ~15–30 G), about a factor two weaker than what was seen previously for $\xi$ Boo A. The phase averaged longitudinal field component and dispersion is $+4.5\pm1.5$ G for $\xi$ Boo A and $-5.0\pm3.0$ G for $\xi$ Boo B.

Key words. stars: imaging – stars: activity – stars: magnetic field – starspots – stars: individual: $\xi$ Boo

1. Introduction

The technique of Zeeman–Doppler imaging (ZDI) was introduced three decades ago by Semel (1989) and has become an indispensable technique for cool-star magnetic field studies (see reviews by Kochukhov 2021; Reiners 2012; Strassmeier 2009; and Donati & Landstreet 2009). Until now, ZDI studies have almost exclusively employed circular polarization (CP) Stokes V spectra and have only rarely used Stokes IV, that is, intensity and CP line profiles together. This is due to the fact that Stokes I inversion is not feasible for stars with low rotational line broadening because the Doppler effect of the surface rotation is too small. The targets $\xi$ Boo A+B are among those cool stars with very small rotational line broadening but still with an active atmosphere. Therefore, only CP ZDI of the $\xi$ Boo AB binary system is possible.

The optical light variability of $\xi$ Boo was discovered by Chugainov (1983). He obtained a photometric period of $\approx10$ days with an average amplitude of just 5.5 mmag from 45 nights of $UBV$ data in 1980. This variability was assigned to $\xi$ Boo A due to the fact that only the combined light with $\xi$ Boo B could be measured. On two nights, Chugainov (1983) noted flare-like events on this star with $\Delta U$ of up to 0.71. Other determinations of the rotational period followed. For $\xi$ Boo A, Plachinda & Tarasova (2000) obtained 6.1455±0.0003 days using longitudinal magnetic field measurements. Activity indices based on the Ca II H&K lines were used by Noyes et al. (1984) to obtain 6.2±0.1 days, by Donahue et al. (1996) to obtain 6.31 days, and by Hempelmann et al. (2016) to obtain 6.299±0.037 days. Toner & Gray (1988) employed spectral line bisectors and line ratios, obtaining 6.43±0.01 days. As suggested by Morgenthaler et al. (2012), the differences between these values may be related to their probing of different stellar layers and latitudes and the star’s differential rotation. For $\xi$ Boo B, a mean period of 11.94 days was obtained by Donahue et al. (1996) from the Mt. Wilson Ca II data. Its period range – with a minimum value of 10.92 days and a maximum of 13.19 days – was also attributed to differential surface rotation. Vidotto et al. (2014) listed 10.3 days for $\xi$ Boo B in their sample table and referred to a paper by Petit et al. (in prep.); the origin of this period is therefore unclear.

A new determination of the lithium abundance of both $\xi$ Boo stars was recently presented by Strassmeier & Steffen (2022), who also reviewed the relevant global stellar parameters of both components together with the K5 reference dwarf star 61 Cyg A. We adopt their astrophysical parameters for our ZDI input in the present paper but also refer to Takeda et al. (2020) for an independent determination of the stellar parameters of the $\xi$ Boo A component. The $^7$Li abundance for $\xi$ Boo A is 23 times higher than that of the Sun, but that of $\xi$ Boo B is three times lower than solar, while both fit the trend of single stars in the similar-aged M35 open cluster. Both stars have an apparent age of $\approx200$ Myr.

Magnetic-field measurements have mostly concentrated on the brighter A component. Boesgaard (1974) presented an initial marginal detection based on a conventional Zeeman analyzer, while Boesgaard et al. (1975) followed up and concluded that the field was too weak for their kind of technique. The surface...
magnetic field of A component was firstly and conclusively detected from line broadening by Robinson et al. (1980) and was found to have an appreciable strength of up to 2.9 kG. This was followed up with a surprising null detection by Marcy (1981). Later, Marcy (1984) confirmed the field, albeit less strong, from further Zeeman broadening data and even found a 670 G field and a filling factor of 73% on the B component. Infrared measurements of Zeeman-sensitive Ti lines allowed Saar et al. (1994) to measure 2.3 kG and a filling factor of 20% for the B component. With the same technique, but based on four infrared Fe lines, Gondoin et al. (1985) reported another nondetection for ξ Boo A. It was suggested that the discrepant field strengths and sometimes even null detections for the brighter A component were due to intrinsic variability. The rotational modulation of the large-scale field was then first investigated by Plachinda & Tarasova (2000) from a collection of longitudinal field measurements collected over two decades. Using observations mostly from 1998, along with archival polarization measurements from Borra et al. (1984) and Hubrig et al. (1994), Plachinda & Tarasova (2000) even reported a sign reversal of the longitudinal field. From higher resolution observations, Petit et al. (2005) found ξ Boo A to have a magnetic field made up of two morphological components: a 40 G dipole inclined at 35° to the rotation axis, and a large-scale 120 G toroidal field. The BCool snapshot survey (Marsden 2014), also based on Stokes V spectra, claimed longitudinal fields of between 18.4±0.3 G and 0.5±1.0 G for the A component and an equally strong but negative field of −18.9±0.5 G for the B component. The first ZDI maps of ξ Boo Afor seven epochs came from Morgenthaler et al. (2012). These authors followed up the morphology suggestion from Petit et al. (2005) and found that the toroidal component persists with a constant polarity containing a significant fraction of the magnetic energy of the large-scale surface field throughout all observing epochs. The evolution of the field geometry was modeled with an increase in field strength and dipole inclination. The discrepancy of magnetic field strengths from Stokes-V spectropolarimetry and line-broadening studies was addressed again by Kochukhov et al. (2020). These authors determined a field strength and filling factor for ξ Boo A of 1.2±0.1 kG and 69±28%, respectively, from the broadening of specific lines, as compared to 36±26 G from ZDI, both based on the data from Morgenthaler et al. (2012).

Cotton et al. (2019) observed ξ Boo A with high precision broad-band linear polarimetry contemporaneously with circular spectropolarimetry and confirmed a modulation with a period of 36±26 G from ZDI, both based on the data from Morgenthaler et al. (2012).

2. Observations and ZDI data input

2.1. Spectroscopic data

High-resolution spectra were obtained with PEPSI at the effective 11.8 m LBT in southern Arizona. We employed both polarimeters in the two symmetric straight-through Gregorian foci at the LBT. Two pairs of octagonal 200 μm fibers per polarimeter feed the ordinary and extraordinary polarized beams into the spectrograph via a five-slice image slicer per fiber. PEPSI produces four spectra per échelle order recorded in a single exposure with a spectral resolution of ∆/∆λ=130,000 sampled by 4.2 pixels on the CCDs. Each fiber diaphragm appears on the sky as a circular projection with a diameter of 1.5″ and can therefore easily isolate the 7″ separated ξ Boo binary components. The two polarimeters are identical in design and construction but are separately calibrated. Both are of a classical dual-beam design with a modified Foster prism as linear polarizer with two orthogonally polarized beams exiting in parallel. The achromatic quarter-wave retarder is located in front of the Foster prism on a rotary stage. The Foster prism, the atmospheric dispersion correctors, two fiber heads, and two fiber viewing cameras are rotating as a single unit with respect to the parallactic axis on sky. This design avoids cross-talk between circular and linear polarization (Ilyin 2012). The spectograph and the polarimeters were described in detail in Strassmeier et al. (2015, 2018b).

Observations of both ξ Boo stars commenced over ten consecutive nights from May 6 to 16, 2019. Eight and six IQUV spectra for ξ Boo A and ξ Boo B, respectively, were obtained with cross disperser (CD) III covering 4800–5441 Å and with CD V covering 6278–7419 Å. Retarder angles of 45° and 135° were set for Stokes V (with the Foster prism position angle set to 0°). The zero level of the position angle of the Foster prism is aligned towards the North Pole. Its alignment accuracy is ±1° or better. Exposure time per integration was 5 min for ξ Boo A and 10 min for ξ Boo B. For Stokes V, this resulted in a (quantile 95%) S/N per pixel of up to 2100 in CD V and 1700 in CD III for ξ Boo A, and 1350 and 950 for ξ Boo B, respectively. The S/N of CP spectra in the present case is ≈60% of Stokes I because a Stokes-I spectrum combines the six QU&V subexposures while V combines only two subexposures. At this S/N, the polarization line signatures are even recognized by eye, as shown in Fig. 1 for a wavelength region around 5250 Å. The example spectra in this figure show three line pairs with strong Zeeman modulation; for a wavelength region around 5250 Å, Fe I 5254.9 Å, Fe I 5250.7 Å, and Fe I 5253.5 Å, and Fe I 5254.9 Å. The log of all observations is given in Table A.1.

Data reduction was performed with the software package SDS4PEPSI ("Spectroscopic Data Systems for PEPSI") based on Ilyin (2000), and described in some detail in Strassmeier et al. (2018a, 2015). The specific steps of image processing include bias subtraction and variance estimation of the source images, super-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 slicers and cosmic-spike elimination, normalization 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.

1 Analysis of the Stokes QU data is not part of the present paper.
2.2. Characteristics of the inversion code \textit{iMAP}

All image reconstructions in this paper are done with the \textit{iMAP} code (Carroll et al. 2007, 2012). \textit{iMAP} employs a three-component magnetic-field vector (radial, meridional, azimuthal) per surface pixel instead of the widely used spherical harmonics expansion for its description. We also use an iterative regularization technique where the step size and an appropriate stopping rule provide the regularization of the inverse problem. Our present inversion technique is therefore penalty free and is based on the Landweber iteration to minimize the sum of the squared errors (for more details, see Carroll et al. 2012 and references therein). The code can either perform multi-line inversions for a large number of photospheric line profiles simultaneously or use a single average SVD-extracted line profile. For the application in this paper, we use the latter for Stokes \textit{V}. Its eigenvalue decomposition of the signal covariance matrix, that is a SVD of the observation matrix, emphasizes the similarity of the individual Stokes profiles and allows one to identify the most coherent and systematic features. Incoherent features, such as noise and line blends, will be dispersed along many dimensions in the transformed eigenspace.

The stellar surface is partitioned into $5^\circ \times 5^\circ$ segments, resulting in 2592 surface pixels for the entire sphere. The local line-profile computation in \textit{iMAP} is based on a radiative transfer solution with the help of an artificial neural network (Carroll et al. 2008). The atomic parameters for the line synthesis are taken from the Vienna Atomic Line Database VALD3 (e.g., Ryabchikova et al. 2015). These are used with a grid of Kurucz ATLAS-9 model atmospheres (Castelli & Kurucz 2003) for local line profiles in 1D and in local thermodynamic equilibrium (LTE). The grid covers temperatures between 3500 K and 8000 K in steps of 250 K interpolated to the gravity and microturbulence values from Table 1. Table 1 is a quick-look version of the ZDI relevant astrophysical parameters of both stars and their adopted values.

2.3. ZDI input

We created SVD-averaged Stokes-\textit{V} line profiles from 1811 individual spectral lines. Each of the 1811 lines were modeled and synthesized to produce a single synthetic SVD profile that can then be compared to the observed SVD profile. Instead of building a large database of SVD profiles for all possible field configurations and viewing angles, our approach uses an artificial neural network to allow an almost on-the-fly calculation during the course of the inversion. A detailed description and error analysis of this method are given in Carroll et al. (2008).

![Fig. 1. Stokes IV example spectra for a wavelength range of 10 Å near 5250 Å. The vertical axis is relative intensity, and the horizontal axis is wavelength in Angstroms. Top: Stokes-I spectra of $\xi$ Boo A (blue) and $\xi$ Boo B (red). Bottom: Stokes-V spectra of $\xi$ Boo A (blue) and $\xi$ Boo B (red), the latter offset by –0.2 in intensity for better visualization, and both enhanced in scale by a factor 20 compared to Stokes I.](image-url)
are considerably lower than for typical targets employed for Doppler imaging. At a resolving power of 130 000 (2.3 km s\(^{-1}\) at 6000 Å), and an average full width of the lines at continuum level of 2 (\(\lambda/c\) \(v \sin i \approx 0.12\) Å for ξ Boo A, we have only 2.5 resolution elements across the rotating stellar disk. According to the Stokes-\(I\) simulations of Piskunov & Wohlfalu (1990), five resolution elements is the minimum for successful Doppler imaging because the test inversions performed by these authors with artificial data resulted in reasonable recovery of the input image when at least five resolution elements were available but not with fewer. We note that even our 2.5 resolution elements are twice as many as compared to previous ZDI maps of ξ Boo A based on the \(R \approx 65\,000\) NARVAL spectropolarimeter at the Telescope Bernard Lyot.

3. Analysis

3.1. Stokes \(V\) line-profile amplitudes

While for cool stars the strength of the signal in CP spectral lines rarely exceeds 1% of the continuum intensity and requires truly high S/N to be recognized by eye, the approximately ten-times-weaker LP signal (at least for the Sun) is expected to always remain below the noise level. For example, Kochukhov et al. (2013) find a Stokes \(V\) signature at the 2–3σ confidence level in only a few of the strongest spectral lines of the super-active star Π Peg in SOFIN data from the 2.4m NOT as well as in ESPaDOnS data from the 3.6m CFHT. Our PEPSI data from the 11.8m LBT reveal a Stokes \(V\) as in ESPaDOnS data from the 3.6m CFHT. Our PEPSI data for ξ Boo A show full amplitudes of up to \(\approx 0.001\) in Stokes \(V\), which is, as expected, significantly smaller (three times smaller) than for the super-active star Π Peg, despite a \(v \sin i\) difference between the two stars of a factor of seven.

We calculate the mean longitudinal magnetic field, \(\langle B_z \rangle\) in Gauss, from the first moment of Stokes \(V\), as formulated in Kochukhov et al. (2010):

\[
\langle B_z \rangle = -2.14 \times 10^{11} \int v V(v) \, dv / \lambda_0 \, g_0 \, c \int [I(v) - I(v)] \, dv,
\]

where \(v\) is the velocity shift in km s\(^{-1}\), \(V(v)\) the Stokes \(V\) profile, \(I(v)\) the Stokes \(I\) profile, \(c\) is the speed of light, and \(\lambda_0\) and \(g_0\) the respective average wavelength and Landé factor defined earlier.

3.2. V-only ZDI solution

Our ZDI typically proceeds with an alternating minimization between surface temperature and magnetic-field density. That is, we usually start the magnetic inversion with an already pre-iterated temperature image and then alternate all further iterations between temperature and magnetic inversions. However, this is not useful for stars with rotational line broadening below a Doppler resolution threshold of typically the aforementioned five resolution elements across the disk in velocity space. Both our target stars in this paper rotate far too slowly to reach this Doppler threshold. In a previous ZDI application – also based on ZDI, Strassmeier et al. (2019) found that the dependence of the temperature inversion on the magnetic inversion is not strong, while the dependence of the magnetic inversion on the temperature inversion is strong and leads to a nontrivial scaling of the

Figures 2a,b show the reconstructed sets of Stokes-\(V\) profiles for stars A and B, respectively, compared with the SVD-averaged data for all rotational phases. The final solution is only based on Stokes \(V\). ZMAP performed a total of about 3000 iterations for the final solution for each star. For each velocity bin, a mean standard error averaged over the velocity domain of 2.85 \(\times\) 10\(^{-5}\) and 4.53 \(\times\) 10\(^{-5}\) is achieved for ξ Boo A and ξ Boo B, respectively. These values are almost identical to the respective inverse S/N per pixel because of ZMAP’s inversion-stopping rule.
Our ZDI Stokes-V maps are shown in orthographic projection in Fig. 3a for ξ Boo A and in Fig. 3b for ξ Boo B. The reconstructed total flux density (loosely referred to as field strength) is plotted with a color code also indicating the polarity (red positive and blue negative). Magnetic field strengths are computed as the squared sum of the three vector components. Figures 4a, b show the same magnetic maps but in Mercator-style projection and split into the three vector components.

Figures 5a, b is the root-mean-square (rms) error maps for the three magnetic components for both stars. These maps are from inversions with different initializations for the three field parameters for all surface segments (radial, azimuthal, and meridional flux density) and are run 100 times on each of the original data sets. A random generator on the basis of a normal distribution provides the values for each parameter and surface segment. The inversions are run to the same accuracy given by the noise of the data. We note that we set the surface segment values below a Stellar latitude of $-20^\circ$ to zero because its derivatives become too weak to provide any substantial changes during the inversion.

The error map of the radial magnetic field for ξ Boo A shows a peak value of 5 G; the surface average rms error is less than half of this. The rms error for the meridional and azimuthal fields have peak values of around 1 G and both components have a mean rms error in the sub-Gauss regime. The error map of the radial field for ξ Boo B has a peak value of 3 G, and also sub-Gauss values for the other two field components. The fact that the obtained errors are nevertheless comparably small indicates that the inversion always settled in or near the same (local) $\chi^2$ minimum and that the final solution is very robust against errors on the initial conditions.

Our data show a significant phase gap of 0.42 due to a snow-storm event at LBT. While we cannot do anything against that, we may recall some of the Doppler-imaging tests with artificial data in the literature. For example, Rice & Strassmeier (2000) conducted extensive tests including recoveries with a phase gap of 100$^\circ$ (0.28) at various phase locations, with both moderate and high S/N data, different inclinations of the stellar rotation axis, and so on, and were always capable of correctly recovering the original spot locations as well as the individual spot contrasts/temperatures, and even within the phase gap. These tests also showed that the equatorial regions are more affected than the polar regions for low-inclination cases, as in ξ Boo. Also, the authors found that the higher the S/N, the less numerous the artifacts. The present phase gap is unfortunately larger but so is the S/N of our data. While we do not claim that such a big phase gap has no impact, we are confident that it does not corrupt the image. However, our ZDI images must be considered an approximation.

### 3.4. Magnetic surface morphology

Surface spots are reconstructed with a radial-field density of up to plus or $-115$ G, a meridional field density of up to plus or $-30$ G, and an azimuthal field density of up to plus or $-20$ G for ξ Boo A. Standard errors are up to $\pm 5$ G. For ξ Boo B, the values are significantly smaller with a radial-field density of up to plus or $-55$ G, a meridional field density of up to plus or $-15$ G, and an azimuthal field density of up to plus or $-15$ G. Its standard errors are up to $\pm 3$ G. Both maps almost satisfy the divergence-free condition already after the nonconstrained ZDI inversion. By adding only a small monopole contribution to the maps (1.2 G for ξ Boo A and $-0.9$ G for ξ Boo B), we obtain a zero integral of $B_r$ over the stellar surface.

Table 2 quantifies the reconstructed spots. The magnetic morphology of ξ Boo A is characterized by a very high latitude or even polar spot (dubbed P in Table 2) of negative polarity in combination with three confined low-to-mid-latitude
spots (dubbed ABC) of positive polarity. A weak meridional component of positive polarity is still reconstructed opposite the (radial) negative-polarity near-polar feature. An equally weak azimuthal component of negative polarity is only detected ≈180° away from the meridional feature and at medium latitude. However, neither feature from the meridional or azimuthal components is well constrained, and all are comparably weak, with +20±5 G and −22±5 G, respectively, and therefore relatively uncertain. The magnetic morphology of ξ Boo B, on the other hand, is dominated by four low-to-mid-latitude spots (dubbed ACDE) of mixed polarity, that is two spots with positive and two spots with negative polarity, where the negative-polarity spots fall within a different stellar hemisphere from the positive-polarity spots. A fifth feature (dubbed B) of
negative polarity is also reconstructed but appears comparably small and weak with just –15 G and therefore remains slightly doubtful. No polar magnetic feature is reconstructed on \( \xi \) Boo B; its meridional and azimuthal components appear morphologically comparable to those of \( \xi \) Boo A but weaker in strength by a factor two.

Figure 6 shows the disk-averaged longitudinal field versus rotational phase. The low phase-averaged values of +4.5 G for \( \xi \) Boo A and –5.0 G for \( \xi \) Boo B indicate an almost even distribution of polarities. Overall, the disk of \( \xi \) Boo A maintains an apparent net positive field while that of \( \xi \) Boo B maintains a net negative field, although both are very weak. The respective field dispersions are ±1.5 G and ±3 G. Our value for \( \xi \) Boo A in 2019 is at the lower end of the 4.1–11.2 G range measured by Morgenthaler et al. (2012) for the years 2007–2011, but is apparently in good agreement with the years 2008 and 2010 for which longitudinal fields of +4.6±3.1 G and +4.1±5.3 G were given, respectively. Plachinda & Tarasova (2000) obtained values in the range –10 to +30 G, mainly from 1998, and Hubrig et al. (1994) found values in the range –15 to +50 G using the same Crimean Observatory Stokesmeter at \( R \approx 30\,000 \) but in 1990. These two sets are therefore of much lower spectral resolution. Our mean value for \( \xi \) Boo B in 2019 is more than three times smaller than the snapshot value found by Marsden (2014) of –18.9±0.5 G in 2012, but is of the same (negative) sign. The maps of both stars are dominated by the radial field component.

Neither shows a strong azimuthal component as reconstructed by Petit et al. (2005) and Morgenthaler et al. (2012) for most of their maps for \( \xi \) Boo A, in particular for the epochs in 2007, 2009, 2010, and 2011 (four out of seven maps). For \( \xi \) Boo B, no other maps exist and therefore no comparison is possible. Regarding field strengths, our reconstructed map for \( \xi \) Boo A has a spot-averaged field strength of \( \pm 100 \) G compared to the range of 30–70 G for the five maps in Morgenthaler et al. (2012). However, we recall that the Morgenthaler et al. maps were for epochs between 2007 and 2011, while our map is from 2019. Any direct comparison of field strengths is therefore difficult, mostly because the surface spots likely changed during that time. Nevertheless, our values for radial-flux density are up to a factor of two higher than the previously published values by Petit et al. (2005) and Morgenthaler et al. (2012).

The total magnetic energy is 86% for \( \xi \) Boo A and 89% for \( \xi \) Boo B, almost exclusively in the radial component, while the meridional (13% for \( \xi \) Boo A and 10% for \( \xi \) Boo B) and azimuthal (\( \approx 1\% \) for \( \xi \) Boo A and \( \xi \) Boo B) components are comparably weak. The (radial) field distribution is 69% axisymmetric and 31% nonaxisymmetric for \( \xi \) Boo A, and 57% axisymmetric and 43% nonaxisymmetric for \( \xi \) Boo B. We used a scalar spherical harmonic decomposition of each resulting individual map (radial, meridional, and azimuthal) independently. This orthonormal decomposition is used exclusively to determine the symmetry properties of the individual components and the energy per spherical harmonic degree.

### 4. Summary and outlook

In this paper, we present new CP spectra for both components of the visual binary \( \xi \) Boo AB (G8V+K5V) and use them to perform a detailed analysis of their magnetic surfaces. Our new spectra are of the currently highest possible quality, with a spectral resolution of 130 000 and \( S/N \) per pixel of up to 2100 for \( \xi \) Boo A and 1350 for \( \xi \) Boo B. Our spectra therefore enable a line-by-line detection of the Zeeman pattern even without line
averaging. Together with the full radiative-transfer treatment of the local line profile in our ZDI inversion, we arrive at CP line-profile fits with spatially resolved magnetic-field densities with errors of only a few per cent.

Both stars still hold surprises. The magnetic-field polarities on the warmer G8V star ξ Boo A appear systematically separated in latitude (negative polarity around the visible polar region, positive polarity around the equator), while on the cooler K5V star the field appears separated in longitude (positive polarity dominantly in the leading hemisphere, negative polarity in the trailing hemisphere). No polar magnetic fields are reconstructed on ξ Boo B. Its morphology on both stars is dominated by the radial component of the field vector with magnetic energies at the 86% level for ξ Boo A and 89% for ξ Boo B. Its reconstructed peak densities are plus or −115±5 G for ξ Boo A and plus or −55±3 G for ξ Boo B. The value for ξ Boo A is approximately twice as large as those from the previous ZDI reconstructions by Petit et al. (2005) and Morgensthaler et al. (2012), while the peak meridional and azimuthal densities of (±20–30 G) are a factor of two smaller than the previous reconstructions. Rosén et al. (2015) argued that cross-talk between the radial and meridional field components can occur when only circular polarization is used in the magnetic inversion. This may be because Stokes V is formally only sensitive to the line-of-sight component of the magnetic field. In Stokes IV maps, the radial component appeared always to be the strongest of the three, while this component is the weakest in the IQUV inversion of Rosén et al. (2015). We cannot decide whether this discrepancy is due to the unaccounted Stokes I and/or linear polarization (LP) or is, for example, related to the $I^2$ penalty function applied in the inversion by Rosén et al. (2015). In any case, a physical effect is still needed to explain why the field density of a field parallel to the surface (meridional or azimuthal) is repeatedly higher than the radial field. Explanations for such a dominant horizontal field were proposed in ZDI studies and in numerical 3D magneto-hydrodynamic simulations. For example, in the simulations presented by Brown et al. (2010), the authors found striking wreaths of magnetism in the midst of the convection zone, with a toroidal magnetic field maintained by the differential rotation, and with a poloidal field from turbulent correlations between the convective flows and magnetic fields. Such magnetic-field structure may eventually, at least partly, propagate up to the surface and could then be seen.

Among the next steps will be adding LP to the line-profile inversion of ξ Boo. Unfortunately, LP in spectral lines of the Sun is not only typically up to ten times weaker than CP (e.g., Stenflo 1989) but is also much more complex and divergent in its line formation (Landi Degl’Innocenti & Landolfi 2004; Sampoorna et al. 2019), and is thus much more uncertain. The LP data of ξ Boo will eventually help in this respect in the future.

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### Appendix A: Observing log

Table A.1. Observing log.

<table>
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<th>$\phi$ (Eqs. 1)</th>
<th>$t_{\text{exp}}$ (min)</th>
<th>$\Delta \lambda$ (blue; red)</th>
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<th>S/N$_I$ blue</th>
<th>S/N$_V$ red</th>
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**Notes.** The first column gives the Barycentric coordinate time (TCB) for the time of mid exposure for Stokes $I$. The second column is the rotational phase based on the respective ephemeris in Eq. (1) for Stokes $I$. S/N is per pixel and is the 95% quantile within the respective wavelength region $\Delta \lambda$. **$a$.** Bad weather. **$b$.** Exposure time was accidentally set to 4 min in the blue, and to 5 min in the red.