Large Interstellar Polarisation Survey (LIPS)

I. FORS2 spectropolarimetry in the Southern Hemisphere^{*}

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ABSTRACT

Polarimetric studies of light transmitted through interstellar clouds may give constraints on the properties of the interstellar dust grains. Traditionally, broadband linear polarisation (BBLP) measurements have been considered an important diagnostic tool for the study of the interstellar dust, while comparatively less attention has been paid to spectropolarimetric measurements. However, spectropolarimetry may offer stronger constraints than BBLP, for example by revealing narrowband features, and by allowing us to distinguish the contribution of dust from the contribution of interstellar gas. Therefore, we have decided to carry out a Large Interstellar Polarisation Survey (LIPS) using spectropolarimetric facilities in both hemispheres. Here we present the results obtained in the Southern Hemisphere with the FORS2 instrument of the ESO Very Large Telescope. Our spectra cover the wavelength range 380–950 nm at a spectral resolving power of about 880. We have produced a publicly available catalogue of 127 linear polarisation spectra of 101 targets. We also provide the Serkowski-curve parameters, as well as the wavelength gradient of the polarisation position angle for the interstellar polarisation along 76 different lines of sight. In agreement with previous literature, we found that the best-fit parameters of the Serkowski-curve are not independent of each other. However, the relationships that we obtained are not always consistent with what has been found in previous studies.

Key words. polarization – dust, extinction

1. Introduction

A full characterisation of the interstellar medium (ISM) is of crucial importance to understand the chemical history of the Universe and various fundamental astrophysical processes, such as the formation and evolution of the stars and their planetary systems. Most of the heavy elements are present in the ISM in the form of dust grains. Non-spherical dust grains, aligned along a preferred direction, linearly polarise the stellar background radiation at wavelengths close to the grain size. Therefore, linear polarimetric measurements of stars that are not intrinsically polarised may set constraints on the chemical composition, shape, and size distribution of the interstellar dust, as well as on the mechanisms responsible for dust grain alignment.

Polarimetry of the ISM started with the discovery work by Hiltner (1949), Hall (1949), and Dombrowskii (1949), culminating later into major surveys such as those by Serkowski et al. (1975), who performed broadband linear polarimetry (BBLP)

in the optical filters *UBVR*, and by Whittet et al. (1992), who extended BBLP measurements to the full optical and near-IR *UBVRIJHK* filter set (the results of many BBLP surveys have been collected in a catalogue by Heiles 2000). BBLP surveys have also been carried out in just one filter (e.g. Leroy 1993; Santos et al. 2011), and have been used to explore the boundaries of the Local Cavity (Leroy 1999; Santos et al. 2011) and its possible interaction with a nearby superbubble seen in the direction of the Galactic Centre (Santos et al. 2011). However, since the fraction of interstellar polarisation depends on wavelength, multi-filter measurements are crucial for the physical interpretation of the observations. The amount of linear polarisation is linked to the column density (in very simple terms: the higher the amount of aligned dust along the line of sight, the higher the polarisation) and to the optical properties of the dust, while the wavelength at which the polarisation reaches its maximum depends on the grain size (or size distribution; Carrasco et al. 1973). The polarisation position angle, if due to a single interstellar cloud with a homogeneous magnetic field, does not change with wavelength, and is determined by the direction of the interstellar magnetic field in the plane of the sky.

^{*} Table 2 and reduced data are available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/608/A146>

While BBLP surveys – historically more common than spectropolarimetric surveys – give substantial insight into the behaviour of interstellar polarisation, better constraints may be obtained with a more refined sampling of the polarisation as a function of wavelength. Compared to multicolour BBLP measurements, spectropolarimetry may allow us to better test if the well-known Serkowski curve provides good fits to the interstellar polarisation, or if polarisation spectra present narrowband features that deviate from it, maybe systematically. Another advantage of spectropolarimetry versus multicolour BBLP is that the former technique allows us to distinguish the contribution of dust from that of gas. Finally, we note that although much effort has been dedicated to the observations of the ISM, many lines of sight have never been observed in polarimetric mode.

Spectropolarimetry is therefore the obvious choice for modern polarimetric surveys, when this mode is available at the telescope. Some initial low-resolution polarisation spectra were presented first by Wolstencroft & Nandy (1971) and later by Wolstencroft & Smith (1984). Anderson et al. (1996) presented spectropolarimetric data in the UV and optical range for 38 objects at a spectral resolution of ~ 20 nm. In the past 25 yr, optical spectropolarimetry of the ISM was obtained with the observations of more than 200 stars at the Pine Bluff Observatory near Madison, Wisconsin, USA, using the HPOL spectropolarimeter. The observed spectral range was 320–775 nm, then extended to 1050 nm, with a spectral resolution of 2.5 nm (resolving power $R \sim 300$), then refined to 1 nm ($R \sim 775$). The database of processed data is publicly available¹, and details of the project are given in Weitenbeck (1999) and Meade et al. (2012). More in-depth insight into the shape, size distribution, and composition of interstellar grains can come from detailed physical models that treat the interaction of dust with photons. For example, Siebenmorgen et al. (2014) presented state-of-the-art models that simultaneously reproduce the observed linear polarisation curve and the UV/visual extinction curve. These recent studies show that models are more advanced than most ISM polarisation data and make clear that medium-resolution linear spectropolarimetry with a high signal-to-noise ratio (S/N) brings a new perspective to the issue of the dust size distribution and composition in the Galactic ISM. Hence a spectropolarimetry survey is required to develop a comprehensive picture of the exact details of the cosmic dust – initially limited to Galactic environments – and to exhaustively test the new models in their applicability to a statistically representative sample (rather than concentrating on a handful of targets).

These considerations have prompted us to initiate a new spectropolarimetric survey, the Large Interstellar Polarisation Survey (LIPS) in both hemispheres with the Focal Reducer/low-dispersion Spectrograph (FORS2) instrument of the Very Large Telescope (VLT) of the European Southern Observatory (ESO) and the Intermediate-dispersion Spectrograph and Imaging System (ISIS) instrument of the William Herschel Telescope (WHT). LIPS fills a gap in our knowledge of dust properties in diffuse lines of sight, the gaseous content of which is being studied with the ESO Diffuse Interstellar Band Large Exploration Survey (EDIBLES, Cox et al. 2017). The main goal of EDIBLES is to create a detailed inventory of interstellar gas in diffuse clouds and to derive accurate physical conditions in order to determine molecular properties of the unidentified diffuse interstellar bands (Sarre 2006; Cami & Cox 2014). Together with existing UV spectroscopy, LIPS and EDIBLES constitute

Fig. 1. Location of our targets in the Galaxy (red circles) compared to those of other major surveys: HPOL (blue circles) and Whittet et al. (1992; black triangles).

an extensive dataset for interstellar extinction and polarisation, which provides a comprehensive simultaneous view of the properties of the interstellar gas and dust in diffuse interstellar lines of sight.

This paper presents the FORS2 survey in the Southern Hemisphere.

2. Observations

2.1. Target list

The targets of the FORS2 survey are a set of O- and B-type stars selected from the EDIBLES target list, excluding the brightest stars ($V \leq 5$ mag) and those accessible with ISIS at the WHT (La Palma), although a few northern targets ($V \sim 8$ mag) were included for cross-calibration and characterising instrumental effects. The initial set of selected targets covers a wide range of interstellar properties in terms of dust extinction ($E(B - V) = 0$ to 2 mag, $R_V = 1.5$ to 6), molecular abundances ($f(\text{H}_2) = 0.0$ to 0.8), radiation fields, gas, and dust temperatures (Cox et al. 2017). To expand the parameter space of dust and environments, additional sightlines in the Magellanic Clouds were added, as well as a few faint ($V \geq 9$) highly reddened Galactic targets that are too faint for the EDIBLES survey. The full target list/observing log is given in Table A.1, and their position in Galactic coordinates is shown with red symbols in Fig. 1, which also shows the position of the targets of two other major surveys.

2.2. Instrument and instrument settings

FORS2 is a multi-purpose instrument capable of imaging and low-resolution spectroscopy in the optical; it is equipped with polarimetric optics. It is attached at the Cassegrain focus of Unit 1, Antu, of the ESO VLT of the Paranal Observatory. The instrument is described in Appenzeller & Rupprecht (1992) and Appenzeller et al. (1998).

The polarimetric optics are arranged according to the optical design described by Appenzeller (1967). The polarimetric module consists of a retarder waveplate ($\lambda/2$ for observations of linear polarisation, and $\lambda/4$ for observations of circular polarisation) followed by a Wollaston prism. The Wollaston prism splits the beam into two components, one linearly polarised along the principal plane of the Wollaston (the parallel beam $f^{\parallel}$), and one linearly polarised perpendicularly to that plane (the perpendicular beam $f^{\perp}$). Following the scheme by Scarrott et al. (1983),

¹ See <http://www.sal.wisc.edu/HPOL/> and CDS catalogue J/A&A/49/59

a $6.8' \times 22''$ Wollaston mask prevents the superposition of the two beams.

2.2.1. Grism

Grism 300 V was employed for our observations. With a $0.5''$ slit width, it provides a spectral resolving power of about 880. The order-separating filter GG435 may be used to cut off the incoming radiation at $\lambda \lesssim 435$ nm to avoid second-order contamination from the blue part of the spectrum into the red part (at $\lambda \gtrsim 650$ nm). However, since our targets are mostly highly reddened, when planning the observations, we assumed that it would probably be safe to observe without order-separating filter, and cover the wavelength range down to ~ 360 nm, which is the blue limit of the spectral range covered by the instrument (for further considerations on the effects of second-order contamination on spectropolarimetric measurements, see Patat et al. 2010). For each star, we therefore decided to obtain an observing series with order-separating filter GG435, and one observing series without it. Observing both with and without order-separating filter allowed us to verify this hypothesis (see Sect. 4), and to have some redundancy in the range 435–650 nm that would serve as a quality check. Our expectation was that the polarised spectra obtained with and without order-separating filter in the wavelength range 435–650 nm would be identical within photon-noise uncertainties, while at $\lambda \gtrsim 650$ nm, a possible difference between the two would be ascribed to contamination from the second order in the spectra obtained without filter. In fact, since CCD sensitivity drops dramatically at $\lambda \lesssim 380$ nm, the useful spectral range covered by our observations was finally 380–930 nm with no filter, and 435–930 nm with the filter GG435 inserted.

2.2.2. CCD and CCD readout

In service mode, the detector installed in FORS2 is a mosaic composed of two $2k \times 4k$ E2V CCDs (pixel size of $15 \times 15 \mu\text{m}^2$, pixel scale of $0.125''$), optimised for the red. Most of our observations were obtained without rebinning, in order to maximise the S/N and avoid saturation towards the bright targets, while for certain fainter targets, we used the 2×2 rebinning mode.

2.3. Observing strategy and data reduction

Our observations were obtained setting the retarder waveplate at four position angles: 0° , 22.5° , 45° , and 67.5° . This implementation of the so-called “beam-swapping technique” allowed us to minimise instrumental effects, as explicitly suggested in the FORS1/2 manual and thoroughly discussed by Bagnulo et al. (2009), for instance.

Stokes Q and U parameters are defined as in Shurcliff (1962). In the following, we consider the ratios Q/I and U/I , adopting the notation

$$P'_Q = \frac{Q}{I} \quad \text{and} \quad P'_U = \frac{U}{I}. \quad (1)$$

The reduced Stokes parameters P'_Q and P'_U were measured by combining the photon counts of the parallel and perpendicular beams ($f^\parallel$ and $f^\perp$, respectively) observed at retarder waveplate positions $\alpha = 0^\circ, 22.5^\circ, 45^\circ$, and 67.5° , as given by the following formula:

$$P'_X = \frac{1}{2} \left\{ \left(\frac{f^\parallel - f^\perp}{f^\parallel + f^\perp} \right)_{\alpha=\phi_0} - \left(\frac{f^\parallel - f^\perp}{f^\parallel + f^\perp} \right)_{\alpha=\phi_0+45^\circ} \right\}, \quad (2)$$

where $\phi_0 = 0$ if $X = Q$ and $\phi_0 = 22.5^\circ$ if $X = U$. The uncertainty due to photon-noise on P'_X is

$$\sigma_{P'_X}^2 = \left(\left(\frac{f^\perp}{(f^\parallel + f^\perp)^2} \right)^2 \sigma_{f^\parallel}^2 + \left(\frac{f^\parallel}{(f^\parallel + f^\perp)^2} \right)^2 \sigma_{f^\perp}^2 \right)_{\alpha=\phi_0} + \left(\left(\frac{f^\perp}{(f^\parallel + f^\perp)^2} \right)^2 \sigma_{f^\parallel}^2 + \left(\frac{f^\parallel}{(f^\parallel + f^\perp)^2} \right)^2 \sigma_{f^\perp}^2 \right)_{\alpha=\phi_0+45^\circ}. \quad (3)$$

Assuming that the fluxes in both beams and for all retarder waveplate positions are similar, we obtain

$$\sigma_{P'_X} = \frac{1}{S/N}, \quad (4)$$

where S/N is the signal-to-noise ratio accumulated in all beams used to calculate P'_X .

2.4. Correction for the chromatism (wavelength dependence) of the retarder waveplate and for instrumental polarisation

The position angle of the retarder waveplate identifies the direction along which the electric field propagates with no phase shift (this is the fast axis of the retarder waveplate). This direction is slightly wavelength dependent, and this deviation introduces a rotation of the measured position angle of the polarisation that may be corrected as explained, for example in Sect. 4.2 of Bagnulo et al. (2009; see also Patat & Taubenberger 2011), that is,

$$\begin{aligned} P_Q &= P'_Q \cos 2\epsilon + P'_U \sin 2\epsilon \\ P_U &= -P'_Q \sin 2\epsilon + P'_U \cos 2\epsilon, \end{aligned} \quad (5)$$

where ϵ is the deviation angle tabulated in the instrument web-pages. The fraction of linear polarisation

$$P = \sqrt{P_Q^2 + P_U^2} \quad (6)$$

is not affected by the problem of the chromatism of the retarder waveplate (i.e. $P = P'$), while the measured position angle θ' and the “true” position angle θ are simply related by

$$\theta = \theta' - \epsilon. \quad (7)$$

Fossati et al. (2007) and Siebenmorgen et al. (2014) noted that FORS2 spectropolarimetric observations are affected by a small amount of wavelength-dependent instrumental polarisation (mainly in Q), which has been further analysed and analytically quantified by Cikota et al. (2017) for grism 300V as

$$\begin{aligned} P_Q^{\text{instr.}} &= 9.66 \times 10^{-8} \lambda + 3.29 \times 10^{-5} \\ P_U^{\text{instr.}} &= 7.28 \times 10^{-8} \lambda - 4.54 \times 10^{-4}, \end{aligned} \quad (8)$$

where λ must be expressed in $\text{\AA}$. Cikota et al. (2017) derived Eqs. (8) from observations taken with the instrument position angle χ set to zero (i.e. with the parallel beam of the Wollaston prism parallel to the north celestial meridian). Various experiments presented by Siebenmorgen et al. (2014) show that FORS2 instrumental polarisation tends to be constant in the instrument reference system; when we wish to express the Stokes parameters in a reference system other than the instrumental one, instrumental polarisation therefore has to be corrected before rotating the Stokes parameters. We assume that Stokes parameters

P_Q and P_U were measured with the instrument position angle on sky set to a value PA, counted counterclockwise from the north celestial meridian (for instance, PA could correspond to the parallactic angle), and already corrected for the chromatism of the retarder waveplate. To transform the Stokes parameters P'_Q, P'_U into a new reference system with its reference direction parallel to the north celestial meridian, we have to apply

$$\begin{aligned} P_Q^E &= (P_Q - P_Q^{\text{instr.}}) \cos 2\chi + (P_U - P_U^{\text{instr.}}) \sin 2\chi \\ P_U^E &= -(P_Q - P_Q^{\text{instr.}}) \sin 2\chi + (P_U - P_U^{\text{instr.}}) \cos 2\chi, \end{aligned} \quad (9)$$

where P_X are given by Eqs. (5), $P_X^{\text{instr.}}$ are given by Eqs. (8), and χ is the angle, counted counterclockwise and looking at the source by which the old (instrument) reference system has to be rotated to coincide with the new (equatorial) reference system (e.g. Landi Degl'Innocenti et al. 2007), that is, $\chi = -\text{PA}^2$, while the fraction of linear polarisation and its position angle are given by

$$\begin{aligned} P &= \sqrt{(P_Q - P_Q^{\text{instr.}})^2 + (P_U - P_U^{\text{instr.}})^2} \\ \theta^E &= \theta + \chi, \end{aligned} \quad (10)$$

where θ is given by Eq. (7).

Our final results can be given either using the reduced Stokes parameters P_Q and P_U or the fraction of linear polarisation P and its position angle θ . The latter representation is more convenient when the interest is in a map of the polarisation and its direction, for example, as function of the Galactic coordinates, as is our interest here. In our case, it is also convenient to refer the position angle of the polarisation to the direction of the galactic pole. This angle θ^G may be obtained for the equatorial position angle θ^E as

$$\theta^G = \theta^E + \eta, \quad (11)$$

where

$$\cos \eta = \frac{\cos(\delta) \sin(\delta_G) - \sin(\delta) \cos(\delta_G) \cos(\alpha - \alpha_G)}{\cos(b)}, \quad (12)$$

where b , α , and δ are the galactic latitude, right ascension, and declination of the star, respectively, and (α_G, δ_G) are the right ascension and declination of the North Galactic Pole.

3. Analysis

Our dataset has low photon-noise. Figure 2 shows the histogram of the error bars of the fraction of polarisation P per nm, obtained after averaging out the spectra obtained with and without order-separating filter. If we were to integrate a broadband filter, these error bars would decrease to the order of a few units in 10^{-4} . As discussed below, these uncertainties are hardly representative of the actual accuracy of our measurements. In this section we describe how we discovered various non-photon-noise errors, and the way we have tried to minimise them.

Fig. 2. Histogram of the photon-noise error bars of the linear polarisation P per nm, in the wavelength range where the S/N is highest (typically around 500 nm).

3.1. Uncertainties due to data reduction

Bagnulo et al. (2012) have discussed the noise due to data reduction, meaning that different but still reasonable choices in the way data are treated lead to (slightly) different results. In case of measurements with a very high S/N, these differences may sometimes be comparable to photon noise, especially in the presence of sharp spectral features (such as emission lines of the telluric O_2 bands). As a first check, we decided to verify whether the differences between the products of independent data reduction were random and well within the photon noise. A dozen observations were reduced independently by two of us (SB and AC), and results were compared. The reduction methods differed mainly in the way background and flux extraction were treated: in one case, no background was subtracted (since the exposure time was very short) and wavelength calibration was carried out on the extracted spectra; in another case, the background was removed and wavelength calibration performed on the 2D spectra. The final products were found perfectly consistent in the continuum; an example is shown in Fig. 3. The two different reductions led to discrepant results around the sharp features discussed in Sect. 3.3, and they are due to a different spectral sampling/rebinning.

3.2. Inconsistencies between consecutive observations

All our stars were observed consecutively with and without order-separating filter. In some cases, the polarisation spectra measured in the wavelength range common to the two instrument setups were found inconsistent among themselves, in that the polarisation spectra obtained with and without filter would appear systematically shifted by a quantity much larger than the photon-noise error bars. The most dramatic example in our database is represented by the observations of HD 149404 obtained on 2015 May 5, shown in Fig. 4, where the red empty circles refer to the polarisation measured with the order-separating

² The instrument position angle counted counterclockwise on sky from the north celestial meridian, $\chi_{\text{instr.}}$ is given by the FORS2 fits-header keyword ADA.POSANG taken with the opposite sign ($\chi_{\text{instr.}} = -\text{ADA.POSANG}$), hence in Eqs. (9), $\chi = \text{ADA.POSANG}$ should be used.

Fig. 3. Residuals of independently reduced data, plotted with photon-noise error bars.

filter, the blue solid circles to the polarisation measured without filter, and the solid black line to their average calculated as explained later in this section. In this example, the polarisation measured with the order-separating filter appears systematically higher ($\Delta P \approx 0.1\%$) than that observed without filter.

HD 149404 is a detached massive O-star binary (O7.5 If + ON9.7 I), with a period of 9.81 d (Massey & Conti 1979). Previous literature data show that HD 149404 exhibits polarimetric variability, but on a much longer timescale than the interval of time between our two observations: Luna (1988) obtained BBLP in the *B* filter, finding that the fraction of linear polarisation is nearly constant with time, but the position angle changes periodically, so that the polarisation variation in the P_Q - P_U plane shows a nearly circular pattern. However, it is unlikely that the differences observed in two observing series obtained within a few minutes from each other have an origin intrinsic to the source. We also note that the pairs of observations of the same star obtained on 2016 January 30 are fully consistent among themselves, therefore we conclude that the variability observed on 2015 May 5 has an instrumental origin.

Numerical simulations performed by Cikota et al. (2017, presentation at the ESO Calibration Workshop) suggested that this short-timescale variability could be linked to an inaccurate setting of the retarder waveplate.

The idea of Cikota et al. (2017) may be tested analytically starting from Eqs. (34) and (36) of Bagnulo et al. (2009), assuming that the chromatism of the retarder waveplate and of the Wollaston prism are perfectly corrected, that is, by setting $\delta\alpha = \delta\beta = 0$ in the expressions of $\hat{G}_X$ of Eqs. (34), assuming a perfect flat-field ($\delta h = 0$) and assuming that the phase shift introduced by the retarder waveplate is exactly 180° ($\delta\gamma = 0$), but associating with each position α of the retarder waveplate an

indetermination δ_α . Using Eqs. (34) and (36) of Bagnulo et al. (2009), setting $N = 1$, and considering the retarder waveplate at the angles $0^\circ + \delta_0$, $22.5^\circ + \delta_{22.5}$, $45^\circ + \delta_{45}$, $67.5^\circ + \delta_{67.5}$, we find that the measured parameters $\hat{P}_Q$, $\hat{P}_U$ are connected to the “true” parameters P_Q and P_U via

$$\begin{aligned}\hat{P}_Q &= P_Q + 4P_U \frac{1}{2} (\delta_0 + \delta_{45}) \\ \hat{P}_U &= P_U - 4P_Q \frac{1}{2} (\delta_{22.5} + \delta_{67.5}).\end{aligned}\quad (13)$$

Equations (13) show that the inaccuracy of the setting of the retarder waveplate is responsible for a cross-talk from P_Q to P_U and vice versa. According to the signs of the actual reduced Stokes parameters and of the difference between actual and nominal position of the retarder waveplate, the measurement may be either an over-estimate or an under-estimate of the “true” polarisation. In particular, we can write

$$\begin{aligned}\text{rms}^2(\hat{P}_Q - P_Q) &= 4P_U^2 (\text{rms}^2(\delta_0) + \text{rms}^2(\delta_{45})) \\ \text{rms}^2(\hat{P}_U - P_U) &= 4P_Q^2 (\text{rms}^2(\delta_{22.5}) + \text{rms}^2(\delta_{67.5})),\end{aligned}\quad (14)$$

and assuming a constant rms δ for all waveplate positions, we obtain

$$\begin{aligned}\text{rms}(\hat{P}_Q) &= 2\sqrt{2}|P_U|\text{rms}(\delta) \\ \text{rms}(\hat{P}_U) &= 2\sqrt{2}|P_Q|\text{rms}(\delta).\end{aligned}\quad (15)$$

The FORS2 User Manual states that the accuracy of the setting of the retarder waveplate is $\sim 0.1^\circ$. This means, for instance, that the expected absolute uncertainty in the P_Q measurement of a source with $P_U = 1\%$ is 0.005%. We note that by using Eqs. (34) and (36) of Bagnulo et al. (2009), we have considered the case in which the reduced Stokes parameters are calculated with the difference method. Similar results would apply by adopting the ratio method, as can be verified by using Eqs. (40) and (41) of Bagnulo et al. (2009). In the following, we test whether these uncertainties may be responsible for the observed discrepancies.

In case of two consecutive measurements (1) and (2), we have

$$\begin{aligned}\text{rms}\left(\frac{\hat{P}_Q^{(2)} - \hat{P}_Q^{(1)}}{8P_U}\right) &= \text{rms}(\delta) \\ \text{rms}\left(\frac{\hat{P}_U^{(2)} - \hat{P}_U^{(1)}}{8P_Q}\right) &= \text{rms}(\delta).\end{aligned}\quad (16)$$

From our dataset we calculated the BBLP value in the *V* filter (see Sect. 3.4.3) and measured the distributions of the quantities

$$\frac{180}{\pi} \frac{\hat{P}_Q^{(2)} - \hat{P}_Q^{(1)}}{8P_U} \quad \text{and} \quad \frac{180}{\pi} \frac{\hat{P}_U^{(2)} - \hat{P}_U^{(1)}}{8P_Q},$$

where the “true” parameters P_X ($X = Q, U$) were approximated by $(\hat{P}_X^{(1)} + \hat{P}_X^{(2)})/2$. We report these distributions in form of histograms in Fig. 5. These distributions were found approximately centred about zero (as expected), but could not be represented by Gaussian distributions with $\sigma = 0.1^\circ$. We then decided to remove the points for which the denominator was $\leq 0.5\%$, finding the Gaussian best fits with $\sigma = 0.28^\circ$ and 0.35° , respectively. Although these values are still about three times higher than the uncertainty declared in the FORS User Manual, our considerations analytically support the conclusion by Cikota et al. (2017) that an inaccuracy of the setting of the retarder waveplate is responsible for the discrepancies that we found in our dataset.

Fig. 4. Observations of star HD 149404 obtained on 2015-05-12. The *top left panel* shows P_Q^E , the *top right panel* shows P_U^E , the *bottom left panel* shows P_L , and the *bottom right panel* shows θ_E . In each panel, red empty circles refer to the observations obtained with order-separating filter, and blue solid circles refer to the observations obtained without order separating filter, with a 41.4 nm wavelength bin size. The black solid line is their average obtained from Eqs. (17). The green solid line (in arbitrary units and identical in all panels) shows the stellar flux not corrected for instrument+telescope transmission function, and with a 0.7 nm bin size. Error bars due to photon noise are smaller than or comparable to the symbol size, but the shape of the SED may help to visualise how the photon-noise error bars, which are proportional to the inverse of the S/N, change with wavelength.

3.3. Spikes in the polarisation spectra

Our polarisation spectra exhibit some departures from a smooth behaviour, some of which are due to cosmic rays. Cosmic rays are generally not well removed during flux extraction because models of the line spread function (LSF) may not be accurate enough compared to the small polarimetric signals that we intend to measure, leaving some spurious spikes randomly distributed in wavelength.

Spikes appear more frequently in proximity of sharp spectral lines (e.g. strong H emission lines), or telluric bands (e.g. O₂-A band at 760 nm), in the form of a sharp increase or decrease of the polarisation, and/or a sudden change in position angle. In several cases, polarimetric spikes appear in the observations obtained with the order-separating filter, but not in those obtained without filter, or vice versa. Only rarely are they present in both datasets, and their shape and amplitude largely depends on spectral sampling and rebinning. Most of these features are probably spurious and are caused by a tiny offset that is introduced either by imperfect wavelength calibration or by instrument flexures, which creates a difference in the fluxes measured in the spectral bins of different beams when the flux changes rapidly with wavelength. Similar problems were found in FORS circular polarisation measurements and were discussed by [Bagnulo et al. \(2013\)](#). However, there might be situations in which the spikes that we

have detected are real. For instance, in stars with emission lines (e.g. Be stars), the observed linear polarisation is probably due to a combination of the contribution from interstellar and disc scattering. Strong emission lines may dilute the radiation polarised in the circumstellar disc, causing a change in polarisation. To determine which of these spikes (if any) are real or if real features are hidden behind spurious spikes requires observations with much higher spectral resolution obtained with a very stable instrument, such as ESPaDOnS at the CHFT or HARPSpol of the La Silla Observatory.

3.4. Presenting the results

3.4.1. Averaging the observations

The uncertainties introduced by random misalignments of the retarder waveplate discussed in Sect. 3.2 may be reduced by increasing the number of waveplate positions at which the retarder waveplate is set during the observing sequence, for example, by considering a sequence 0°, 22.5°, ..., 157.5° instead of 0°, 22.5°, 45°, and 67.5°. Unfortunately, our observing strategy was decided before we discovered the accuracy problem of the retarder waveplate setting, therefore our observations were carried out using only four positions of the retarder waveplate. However, the accuracy of our polarisation spectra may still be improved

Fig. 5. Histograms of two distributions used to estimate the uncertainty due to an imperfect setting of the retarder waveplate (see text) and their best fits with Gaussian distributions. Blue lines correspond to the data obtained without order-separating filter, and red lines to the data obtained with GG435 filter. Best fits were obtained using data with $|P_Q| \geq 0.5\%$ and $|P_U| \geq 0.5\%$, respectively, as explained in the text.

by adopting the average of the measurements obtained with and without order-separating filter. The spectral range 380–435 nm is covered only by the observations without order-separating filter. In this interval range, we therefore adopted the sum of the reduced Stokes parameters measured without filter and the average of the half-difference between the P_Q and P_U values measured with and without filter in the common wavelength range ($\lambda \geq 435$ nm). In other words, we have adopted

$$P_X = \frac{1}{2} (P_X^{(2)} + P_X^{(1)}) \quad \text{if } \lambda \geq 435 \text{ nm}$$

$$P_X = P_X^{(2)} + \frac{1}{2N} \sum_{i=1}^N (P_X^{(1)}(\lambda_i) - P_X^{(2)}(\lambda_i)) \quad \text{if } \lambda < 435 \text{ nm},$$
(17)

where the index (1) refers to the observations obtained with order-separating filter, and the index (2) refers to those obtained without filter.

3.4.2. Rebinning

Most of our targets are very bright, and it is in principle possible to reach extremely high S/N with a very short exposure time. The ADU converter sets an upper limit to the S/N that may be reached per pixel bin, which in general depends on CCD gain, on the full-well capacity, on the seeing conditions (when seeing is worse, the flux may be spread over more pixels, and this increases the flux that may be measured before saturation is reached, simply by increasing the exposure time), and on the number of frames that are obtained per target. For each frame with $1''$ seeing conditions and with a converting factor $1.25 \text{ e}^- \text{ ADU}^{-1}$, the maximum S/N that can be reached in the wavelength bin that corresponds to the dispersion bin is ~ 800 . Adding the flux accumulated in

Fig. 6. Observations of the low-polarisation star HD 101065. The empty blue circle shows the linear polarisation with the original bin size of 0.16 nm. Red solid circles show the polarisation values obtained after rebinning $f^{\parallel}$ and $f^{\perp}$ into ~ 20 nm size bins.

two beams and in two frames, this corresponds to an error bar $\sigma_X \sim 0.06\%$. Typically, our frames were exposed at 20–30% of the maximum, and each observing series consisted of two frames per Stokes parameter. Therefore, our typical error bar per spectral bin in each Stokes parameter was 0.12–0.15%. Our spectral resolution of 880 is preserved up to a rebinning of two 0.161 nm pixels, but when no narrow spectral features are present in our spectra, it makes sense to consider heavier rebinning. We experimented by combining the signals of 2, 4, 8, 16, 32, 64, 128, and 256 spectral bins, and for our figures we decided to adopt a 20.6 nm bin for a formal uncertainty due to photon noise of 0.01–0.02%.

We should note that rebinning must be performed on the fluxes $f^{\parallel}$ and $f^{\perp}$ before combining the flux to obtain the P_Q and P_U spectra since

$$\frac{\sum_{i=1}^N (f^{\parallel}(\lambda_i) - f^{\perp}(\lambda_i))}{\sum_{i=1}^N (f^{\parallel}(\lambda_i) + f^{\perp}(\lambda_i))} \neq \sum_{i=1}^N \frac{f^{\parallel}(\lambda_i) - f^{\perp}(\lambda_i)}{f^{\parallel}(\lambda_i) + f^{\perp}(\lambda_i)}.$$

We note also that in case of low polarisation signals, the fraction of linear polarisation pertaining to a larger bin size may appear to be lower than the average of the polarisation signal plotted with a smaller bin size. An example of this situation is given in Fig. 6, which shows a polarisation spectrum with a wavelength bin size of 0.16 nm (corresponding to one CCD pixel) and the polarisation spectrum of the same star rebinned to a 20.6 nm bin size. The reason for this apparent inconsistency is that the P distribution may be approximated with a Gaussian distribution only for $P \gg \sigma_P$, a condition that may not be satisfied by the signal accumulated in a small wavelength bin. For the same reason, the best fit to P with a Serkowski curve with a least-squares technique must be performed on spectra that have been rebinned so that for each spectral bin $P \gg \sigma_P$. In previous literature, for example, Whittet et al. (1992), this problem was mitigated by

adopting the correction formula derived by [Wardle & Kronberg \(1974\)](#) and by [Clarke & Stewart \(1986\)](#), namely

$$P^{(c)} = P \left[1 - \left(\frac{\sigma_P}{P} \right)^2 \right]^{\frac{1}{2}}, \quad (18)$$

but in our case, after rebinning at 20.6 nm, we found $\sigma_P/P \ll 1$ was always valid, in particular, that $\sigma_P/P \leq 10$ in all spectral bins of all our targets, even in the bluest spectral regions where the S/N is lowest.

3.4.3. Synthetic broadband linear polarisation

For comparison with previous and future BBLP measurements, we calculated for each filter F of *BVRI*

$$P_Q(F) = \frac{\int_0^\infty d\lambda P_Q(\lambda) I_Q(\lambda) T_F(\lambda)}{\int_0^\infty d\lambda I_Q(\lambda) T_F(\lambda)}$$

$$P_U(F) = \frac{\int_0^\infty d\lambda P_U(\lambda) I_U(\lambda) T_F(\lambda)}{\int_0^\infty d\lambda I_U(\lambda) T_F(\lambda)}, \quad (19)$$

where T_F is the transmission function of the F filter³, and

$$I_Q = (f^\parallel + f^\perp)|_{\alpha=0^\circ} + (f^\parallel - f^\perp)|_{\alpha=45^\circ}$$

$$I_U = (f^\parallel + f^\perp)|_{\alpha=22.5^\circ} + (f^\parallel - f^\perp)|_{\alpha=67.5^\circ}. \quad (20)$$

3.5. Fitting the polarisation spectra with the Serkowski curve

The wavelength dependence of linear polarisation due to interstellar dust is usually well fit by the Serkowski curve introduced by [Serkowski \(1973\)](#)

$$\frac{P(\lambda)}{P_{\max}} = \exp \left[-K \ln^2 \left(\frac{\lambda_{\max}}{\lambda} \right) \right], \quad (21)$$

where $\lambda_{\max}$ is the wavelength where the polarisation reaches its maximum $P_{\max}$, and K is a constant that controls the half-width of the curve. The values of $P_{\max}$ (generally of a few units per cent at most) and $\lambda_{\max}$ (typically between 400 and 800 nm) depend on the position of the star (distance and galactic coordinates).

Although alternative functional forms have been proposed to describe the interstellar polarisation curve (see for example [Wolstencroft & Smith 1984](#); and [Efimov 2009](#)), only the Serkowski-curve parameters are presented here for comparison to the literature. Linear polarisation spectra are publicly available⁴ to facilitate future comparisons, dust modelling, and analysis.

We have applied a least-squares technique by minimising the expression

$$\chi^2 = \sum_i^N \frac{(y_i - A - B x_i - C x_i^2)^2}{\sigma_i^2}, \quad (22)$$

where

$$x_i = \ln(\lambda_i)$$

$$y_i = \ln(P(\lambda_i))$$

$$\sigma_i = \sigma_P/P(\lambda_i)$$

$$A = \ln P_{\max} - K \ln^2 \lambda_{\max}$$

$$B = 2K \ln \lambda_{\max}$$

$$C = -K,$$

hence

$$K = -C,$$

$$\lambda_{\max} = \exp \left(-\frac{B}{2C} \right),$$

$$P_{\max} = \exp \left(A - \frac{B^2}{4C} \right),$$

and the parameter errors are

$$\sigma_K^2 = \sigma_{CC}^2$$

$$\sigma_\lambda^2 = \frac{1}{4C^2} \exp \left(-\frac{B}{C} \right) (C^2 \sigma_{BB}^2 + B^2 \sigma_{CC}^2 - 2BC \sigma_{BC})$$

$$\sigma_P^2 = \frac{1}{16C^4} \exp \left(2A - \frac{B^2}{2C} \right) (16C^4 \sigma_{AA}^2 + 4B^2 C^2 \sigma_{BB}^2 + B^4 \sigma_{CC}^2 + -16BC^3 \sigma_{AB}^2 + 8B^2 C^2 \sigma_{AC}^2 - 4B^3 C \sigma_{BC}^2),$$

where σ_{XY} ($X, Y = A, B, C$) are the elements of the inverse of the χ^2 matrix. Since photon noise alone underestimates the actual error bars, the best-fit parameter uncertainties were finally multiplied by $(\chi^2/\nu)^{1/2}$, where χ^2 is given by Eq. (22) and ν is the number of degrees of freedom, as discussed by [\(Bagnulo et al. 2012\)](#).

3.6. Fitting the polarisation position angle

In many cases, the polarisation position angle was found to be slightly wavelength dependent. In order to quantify the deviations from a constant value, we decided to fit the position angle $\theta^E(\lambda)$ with a straight line and to consider the slope of this line in addition to the Serkowski parameters.

4. Results

Table A.2 shows the values obtained by calculating from our polarisation spectra synthetic BBLP values in the *BVRI* filters, as well as the best-fit parameters K , $\lambda_{\max}$, $P_{\max}$, and $d\theta^E/d\lambda$. Photon-noise error bars in the broadband values are virtually negligible ($\sim 10^{-4}$), and the accuracy of our measurements is limited by non-photon noise, as discussed in Sect. 3.2. All our polarisation spectra are shown in the figures of the Appendix in the form of P and θ^E plots. We set the same P -axis range (1.5%) and θ^E range (40°) to facilitate visual comparison. In some cases, the P range was expanded to 3.0% or 3.5%, and the θ^E range to 80° or 120° . To facilitate the comparison between plots with different y -scales, we adopted identical tick sizes throughout (0.1/0.5%). We note also that the figures are sorted by RA, but with some exceptions, in order to display in the same row the observations

³ <http://www.eso.org/sci/facilities/paranal/instruments/fors/inst/Filters/curves.html>

⁴ See footnote to the title.

Fig. 7. Comparison of the best-fit parameters of the Serkowski curve and the position-angle gradient from pairs of observations of the same stars obtained with FORS2 at different epochs. The red empty squares correspond to three stars that are likely polarimetric variables, namely HD 149404, HD 153919, and HD 116852 (see Sect. 6.4.2).

of the same star obtained in different epochs. Stellar fluxes (not corrected for atmosphere and instrument+telescope transmission function) are also plotted in arbitrary units both in the P and in the θ^E panels.

Around the telluric O_2 A-band (759–770 nm) in some polarisation spectra, we note a depolarisation of the continuum. In other cases, the polarisation across a sharp spectral emission line increases and changes direction. In these cases, the best-fit parameters of the Serkowski curve were calculated after interpolating the continuum. These spectral regions were not used to calculate the BBLP measurements given in Table A.2 or for the best fit with the Serkowski curve.

We did not fit any of the stars with $P_{\max} \leq 0.70\%$ with the Serkowski curve. We finally note that the following stars have very low (but non-zero) polarisation values: HD 50820 (0.1–0.2%), HD 101065 (0.1–0.2%), HD 105416 (0.2%), HD 115842 (0.4%), HD 134591 (0.3–0.4%), and HD 152424 (0.0–0.4%).

5. Quality checks

5.1. Consistency of the observations of stars observed at more than one epoch

Some of our targets have been observed at more than one epoch: 25 stars were observed twice and one target was observed three times. The consistency between these observations can be checked in Table A.2 and by visual inspection of the figures in Appendix A direct comparison of the Serkowski curve parameters and of the position-angle gradient is shown in Fig. 7. Three of the targets are probably polarimetrically variable (see Sect. 6.4.2) and are highlighted with special symbols in the figure. Except for these three cases, the consistency of the $\lambda_{\max}$ and $P_{\max}$ parameters recovered from different datasets is generally very good, while the consistency of the K parameter

and of the gradient of the polarisation angle appears less satisfactory.

5.2. Consistency with previous work

Only a few stars in our sample have previously been observed in polarimetric mode. Six stars have been observed with HPOL, and Fig. 8 shows the comparison between our observations and HPOL observations for two of them, HD 147888 and HD 161056. HD 37903 was also observed in spectropolarimetric mode with FORS2 by [Siebenmorgen et al. \(2014\)](#). For another five stars, BBLP measurements were available in the literature. A good but not perfect agreement was found, as demonstrated in Table A.3, which shows a comparison between the Serkowski best-fit parameters obtained from this work and those from previous works.

6. Discussion

In this section we present an initial qualitative discussion of our results, in particular in comparison with previous works.

6.1. Galactic polarisation map

The most immediate way to globally visualise our data is to plot a polarisation map as a function of galactic coordinates. This is done in Fig. 9 for our new FORS2 data (top panel), the data from HPOL (middle panel), and those from [Whittet et al. \(1992\)](#) (bottom panel). Pending accurate *Gaia* distances for the targets in this survey ([Gaia Collaboration 2016](#)), we do not show distance-longitude distribution plots.

6.2. Relationships between the best-fit parameters K and $\lambda_{\max}$ of the Serkowski curve

In this section we discuss the relationship between the free-parameters K and $\lambda_{\max}$ of Eq. (21) obtained as explained in Sect. 3.5 from our dataset, and we compare our results with those previously obtained in the literature.

In some earlier works, the value of $K = 1.15$ originally introduced by [Serkowski \(1973\)](#) was assumed as a standard. Eventually, it was found that infrared polarimetric data could not be fitted by adopting this fixed value for K ([Dyck & Jones 1978](#); [Wilking et al. 1980](#)), and K was considered as a free parameter. [Wilking et al. \(1980\)](#) found a correlation between $\lambda_{\max}$ and K : the normalised polarisation curve would be narrowing as $\lambda_{\max}$ increases. [Wilking et al. \(1980\)](#) suggested to adopt

$$K = 1.7 \lambda_{\max},$$

and later, [Whittet et al. \(1992\)](#) suggested the relationship

$$K = (0.01 \pm 0.05) + (1.66 \pm 0.09) \lambda_{\max}, \quad (23)$$

where in both equations $\lambda_{\max}$ is expressed in μm . Figure 10 shows the relationship between best-fit values of K and $\lambda_{\max}$ from our survey and those obtained from the dataset by [Whittet et al. \(1992\)](#) and HPOL. It clearly appears that our data (red circles) and those from HPOL (blue circles) are located in the same region of the $\lambda_{\max} - K$ plane, but none of these two datasets follows the linear trend seen in [Whittet et al. \(1992\)](#) data (black symbols).

Fig. 8. Comparison between FORS2 (blue and red symbols) and HPOL (black symbols) data. Black solid lines are best fits with the Serkowski curve to the HPOL data. *Left panel:* HD 147888. *Right panel:* HD 161056.

The question now is whether this discrepancy is due to different features of the ISM in the regions probed by the different surveys, or whether it is an artefact due to either photon noise or systematic error. We should keep in mind that the results of Sect. 4 suggest that while the $P_{\max}$ and $\lambda_{\max}$ values retrieved from different datasets are generally consistent among themselves, the recovery of the K parameter, representing the width of the polarisation spectrum, seems less robust. We note that these inconsistencies cannot be due to the issues with the positioning of the retarder waveplate discussed in Sect. 3.2, as they would not affect the ratio $P(\lambda)/P_{\max}$ of Eq. (21).

To answer to this question, we first studied whether the observed discrepancy may be an artefact caused by the shorter wavelength range of our observations compared to those of Whittet et al. (1992), which extends into the U filter and into the near-IR. Clarke & Al-Roubaie (1983) indeed suggested that the estimated $\lambda_{\max} - K$ correlation depends on the wavelength range in which the observations are carried out. For instance, by adopting the $UBVR$ polarimetric data from Serkowski et al. (1975), Clarke & Al-Roubaie (1983) found that K and $\lambda_{\max}$ are anti-correlated. By considering another $UBVR$ literature dataset, they again obtained a linear relationship with a negative slope, which is opposite to what has been found by Wilking et al. (1980). However, using all available data within the wavelength range from 330 to 950 nm, Clarke & Al-Roubaie (1983) found a positive correlation between K and $\lambda_{\max}$. Inspired by these earlier tests, we performed a similar experiment. We fitted the Whittet et al. (1992) dataset discarding data obtained with the U and JHK filters, and considering only those obtained with

the $BVRI$ filters. With this subset, we were still able to recover a loosely linear relationship between K and $\lambda_{\max}$ but opposite to that given by Eq. (23) and closer to the relationship found with our survey (see Fig. 11 and compare it with Fig. 10). This result is in agreement with the previous studies of Clarke & Al-Roubaie (1983), and suggests that the lack of consistency between our results and those from Whittet et al. (1992) may indeed be an artefact that is due to the different wavelength coverage of the datasets.

To further investigate this issue, we performed Monte Carlo simulations in order to test which types of observational constraints are needed to retrieve a linear relationship between K and $\lambda_{\max}$. We generated a number of initial Serkowski-curve parameter values $\lambda_{\max}$, $P_{\max}$, and K randomly selected within these limits: $470 \text{ nm} \leq \lambda_{\max} \leq 730 \text{ nm}$, and $1.4 \leq P_{\max} \leq 5.8$. The parameter K was then calculated via Eq. (23). We then generated artificial polarisation spectra with 100 nm wavelength bins in the spectral range 400 to 900 nm using the Serkowski curve, and we scattered all data points according to a Gaussian distribution with $\sigma = 0.1\%$. Then we fitted our artificially generated polarisation spectra with a Serkowski curve, adopting $\lambda_{\max}$, $P_{\max}$ and K as free parameters, and we used our best-fit parameters to create a new $\lambda_{\max} - K$ plot. The results are shown in the left panel of Fig. 12, where the black solid line represents the relationship given by Whittet et al. (1992), the black dots correspond to the K and $\lambda_{\max}$ parameters scattered around this relationship, the red dots show their values as recovered after our numerical simulation of photon noise, and the red solid line represents the best fit to the recovered K and $\lambda_{\max}$ parameters. These results

Fig. 9. Polarisation map of our Galaxy from our data (*top panel*), from HPOL data (*middle panel*), and from Whittet et al. (1992; *bottom panel*). The length of the segments is directly proportional to the fraction of linear polarisation.

are consistent with our previous finding that measuring BBLP in only four filters does not allow us to recover the linear relationship between K and $\lambda_{\max}$, while when adding three additional data points in the near-IR, we were able to recover it.

Next we performed a numerical simulation to investigate the LIPS database. We repeated the same experiment as before, but using a 20 nm step size instead of 100 nm, still associating a 0.1% error bar per spectral bin. For comparison with our real dataset, we note that the typical residual of the best-fit Serkowski curve to the LIPS data is $\lesssim 0.05\%$. The result of this test is shown in the right panel of Fig. 12. Although the red straight line in the right panel of Fig. 12 slightly deviates from the original distribution of black dots, the results of our second test suggest that if the polarisation that we have measured with FORS2 followed the linear relationship by Whittet et al. (1992), then we would still have been able to recover a similar (although not identical) linear relationship. Therefore the results of this final experiment seem to contradict the idea that the discrepancies between our results and those found by Whittet et al. (1992) are due to the limited wavelength range of the spectropolarimetric observations compared to the sample by Whittet et al. (1992).

Fig. 10. K vs. $\lambda_{\max}$ from the best fit obtained with the Serkowski curve using the targets of this survey (red symbols), HPOL data (blue symbols), and data from Whittet et al. (1992; black symbols).

Fig. 11. Relationship between K and $\lambda_{\max}$ using all UBVRJHK filters of Whittet et al. (1992; black symbols, as in Fig. 10), and using only their BVRI photometry (red symbols).

In conclusion, if the results by Whittet et al. (1992) are correct, it means that the shape of our polarisation spectra is affected by errors that are substantially larger than photon noise, probably $\lesssim 0.1\%$ in the BBLP filters, and we suggest that in order to retrieve meaningful K values of the Serkowski-curve parameters, it is desirable to obtain a stronger constraint in the blue and red spectral regions than is possible with FORS optical spectropolarimetry. However, the observed discrepancies between our sample and that of Whittet et al. (1992) may also be due to the fact that different surveys probe regions of the ISM with different dust grain features (e.g. Voshchinnikov 2012). The differences between the surveys are also evident in the $P_{\max}$ histogram of Fig. 13.

6.3. Relationships between $\lambda_{\max}$, $P_{\max}$ and the extinction

The $\lambda_{\max}$ and $P_{\max}$ parameters retrieved from the best fit seem accurate enough to allow us a meaningful discussion of their relationships with other features of the ISM, like for instance the visual extinction.

Fig. 12. Simulation of the recovery of the free parameters of the Serkowski curve from a numerical dataset simulating noisy data. *Left panel:* using a 100 nm step size. *Right panel:* using a 20 nm step size. The figure is explained in the text.

Fig. 13. Distribution of $P_{\max}$ for our sample and for that of Whittet et al. (1992). The red dashed line at 0.70% shows the $P_{\max}$ limit below which we did not calculate the best-fit parameters of the Serkowski curve.

6.3.1. Polarising efficiency $P_{\max}/A_V$ vs. visual extinction A_V

Figure 14 shows the parameter $P_{\max}/A_V$, the historically defined polarising efficiency (Tamura et al. 1987; Whittet et al. 1994; Greenberg et al. 1995), plotted versus the total visual extinction A_V . The polarisation efficiency decreases as visual extinction increases, in agreement with what was found by Whittet et al. (1994, see their Fig. 7), by Gerakines et al. (1995), who proposed the relationship $p_{\max}/A_V = 1.38 A_V^{-0.56}$ (see their Fig. 1), and Whittet et al. (2001), who proposed the relationship $p_{\max}/A_V = 2.5 A_V^{-0.71}$ (see their Fig. 10).

6.3.2. Relationships between $\lambda_{\max}$, $P_{\max}$ and the extinction

Another quantity representing the polarising efficiency is the ratio $P_{\max}/E(B-V)$, where $E(B-V) = A_B - A_V$ is the selective extinction. Serkowski et al. (1975) found that this parameter is always $\lesssim 9\% \text{ mag}^{-1}$. The relationship between $P_{\max}/E(B-V)$ and $E(B-V)$ depends on the dust grain size and has been discussed by Yoshchinnikov et al. (2016). Figure 15 shows this relationship for our dataset.

Fig. 14. Relationship between polarisation efficiency and visual extinction. The red symbols (“LIPS low”) refer to data with $P \leq 0.7\%$.

6.3.3. Total-to-selective extinction ratio R_V vs. $\lambda_{\max}$

Whittet & van Breda (1978) derived the linear relationship

$$R_V = (5.6 \pm 0.3) \lambda_{\max}, \quad (24)$$

where $R_V = A_V/E(B-V)$ is the ratio between total and selective extinction, and $\lambda_{\max}$ is expressed in μm , while Clayton & Mathis (1988) suggested

$$R_V = -0.29 \pm 0.74 + (6.67 \pm 1.17) \lambda_{\max}. \quad (25)$$

The validity of this relationship was not confirmed in later studies (e.g. Whittet et al. 2001), and our data do not follow any of these relationships either (see Fig. 16).

6.4. Comments on special cases

6.4.1. Position angle varying with wavelength

If polarisation is due to dichroic extinction from interstellar dust, we would expect a fairly smooth function $P(\lambda)$ that is reasonably well reproduced by the Serkowski curve, with the position angle independent of λ .

Of special interest are stars for which the position angle of the polarisation is not constant with wavelength. These cases may be identified from inspection of the last column of

Fig. 15. Relationship between maximum polarisation and $E(B - V)$. “LIPS (low)” refer to stars for which $P \leq 0.7\%$.

Fig. 16. Relationship between R_V and $\lambda_{\max}$. Symbols refer to the data from our survey, and the solid lines are the relationships of Eqs. (24) and (25).

Table A.2, which provides the wavelength gradients of the polarisation position angle. This may be due to the presence of more than one dust cloud along the line of sight, with different characteristics, but we should note that the steepest gradients are usually associated with stars with low polarisation (e.g. the blue supergiant HD 154368 and the main-sequence O star HD 93222). Particularly puzzling is the case of the Be stars HD 155851 and HD 172694, which show a sharp change in slope in both the polarisation and the position angle at wavelengths longer than 820 nm. The observed polarisation is probably given by the superposition of the contribution from the circumstellar disc and the ISM dust, and the change in polarisation, which corresponds to the Paschen edge, almost certainly originates in the disc. The polarimetric properties (including variability) of Be stars have been studied in the past (e.g. Bjorkman 1994), but to our best knowledge, the observed sharp change in polarisation at longer wavelength has not previously been reported.

6.4.2. Time variability

Twenty-two stars of our sample were observed twice and one was observed three times. These stars can be checked for variability.

From our observations, it appears that the high-mass X-binary HD 153919 shows variability in the fraction of linear polarisation, consistent with the observations by van Paradijs (1980), Oestreicher & Schulte-Ladbeck (1982), and Dolan & Tapia (1984), who found the star to be periodically variable with an amplitude of $\sim 0.3\%$.

The blue supergiant HD 149404 (observed twice by us) shows variability both in P and θ^E (the θ^E variability was already detected in a previous work, see the discussion in Sect. 3.2).

Star HD 116852 shows a discrepancy of 0.2% between the polarisation measured in two different observing epochs, which may also be due to intrinsic variability.

7. Conclusions

Using the FORS2 instrument of the ESO VLT, we have obtained moderate-resolution ($R \sim 880$) polarisation spectra with high S/N for 101 diffuse interstellar lines of sight, and made them publicly available (at different rebinning steps) at CDS. We used the polarisation spectra to estimate broadband linear polarisation values in the $BVRI$ filters and for an analysis with the Serkowski curve. In particular, we fitted the polarisation spectra of all stars with $P_{\max} \geq 0.7\%$ (76 targets) with the Serkowski curve, and, in addition, we fitted the wavelength-dependent position angle with a first-order polynomial, estimating for each star the newly introduced parameter $d\theta/d\lambda$ (measured in $^\circ/100$ nm). As expected, we often found this parameter to be consistent with zero, but with exceptions, especially for stars with low polarisation. Remarkable exceptions are represented by the Be stars HD 155851 and HD 172694, which exhibit a sharp change in slope in the polarisation and its position angle at wavelengths ≥ 820 nm, in proximity of the Paschen edge.

Uncertainties due to photon noise are very small (typically $\leq 0.1\%$ per nm, reduced to a few units in 10^{-4} when integrating in a broadband filter). However, while processing the data, we discovered some small discrepancies larger than photon noise between datasets obtained within a very short interval of time. We have ascribed these discrepancies to an imperfectly accurate setting of the retarder waveplate. This issue was mitigated by combining data obtained with and without order-separating filter. Spectra are also affected by cosmic rays, and, corresponding to sharp features in intensity (such as emission lines or the O_2 -A band), exhibit polarisation spikes that we believe to be spurious (at least most of them). In spite of these caveats, our Large Interstellar Polarisation Survey (LIPS) of the Southern Hemisphere significantly extends the current dataset of moderate-resolution spectropolarimetry of the diffuse ISM, particularly for sightlines with relatively low interstellar reddening. Owing to systematic errors, we estimate that the accuracy of our BBLP measurements is of the order of 0.1%.

In previous works, it was found that the parameters of the Serkowski curve are not independent of each other; for example, Whittet et al. (1992) found a linear relationship between the wavelength $\lambda_{\max}$ at which the polarisation reaches maximum and the width K of the polarisation spectrum. Our results deviate significantly from the trends found by Whittet et al. (1992). We have investigated this issue by means of numerical simulations, without reaching a clear conclusion. On the one hand, the K parameter of the Serkowski curve (which is related to the width

of the polarisation spectrum) may not be sufficiently well constrained by our observations. However, the observed deviations may also be attributed to real physical differences – either in dust grains or interstellar conditions – between the different regions probed with LIPS and the sample by Whittet et al. (1992).

We have also performed a preliminary investigation of the relationship between polarisation and interstellar extinction, improving a previously found relationship between polarisation efficiency and visual (or selective) extinction. In agreement with previous works, we were unable to confirm the existence of a linear relationship between the ratio of total-to-selective extinction and the wavelength at which the polarisation reached maximum.

Moderate-resolution spectropolarimetry adds new information that can help us to better understand the properties of dust and/or ISM conditions. Our Southern Hemisphere FORS2 data will be combined with the Northern Hemisphere ISIS data, which will be described in a separate publication. This combined LIPS dataset will then enable a number of detailed studies of polarisation properties and modelling of dust grains.

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Appendix A: Additional tables and figures

Table A.1. Target list with essential parameters and observing log.

Star	RA	Dec	V	Spectral type	$E(B - V)$	R_V	A_V	REF	DATE	UT	Exp (s)
AzV18	00:47:12.0	-73:06:33.2	12.48	B2.5Ia	0.17 ± 0.03	2.90 ± 0.42	0.49 ± 0.11	C	2015-10-14	04:19	720
AzV456	01:10:55.0	-72:42:56.3	12.89	O9.7Ib	0.26 ± 0.03	2.19 ± 0.23	0.57 ± 0.08	C	2015-10-14	03:33	720
HD 36982	05:35:09.8	-05:27:53.3	8.46	B1.5Vp	0.36 ± 0.06	4.84 ± 0.52	1.74 ± 0.34	V	2015-10-17	05:14	32
HD 37021	05:35:16.1	-05:23:06.9	7.96	B0 V	0.48 ± 0.02	5.84 ± 0.26	2.80 ± 0.17	V	2015-10-17	05:27	24
HD 37061	05:35:31.4	-5:16:02.6	6.83	B0.5 V	0.56 ± 0.04	4.29 ± 0.21	2.40 ± 0.21	V	2015-10-14	05:27	24
HD 38029	05:36:55.2	-69:11:37.7	11.56	WC+O6/6.5III	0.27 ± 0.03	3.80 ± 0.20	1.00 ± 0.12	C06	2015-10-14	04:45	480
HD 37367	05:39:18.3	29:12:54.8	5.99	B2IV-V	0.42 ± 0.04	3.55 ± 0.44	1.49 ± 0.24	V	2015-10-16	08:54	8
HD 37903	05:41:38.4	-02:15:32.5	7.83	B1.5 V	0.35 ± 0.04	3.74 ± 0.31	1.31 ± 0.18	V	2015-10-17	05:40	16
HD 38087	05:43:00.6	-02:18:45.4	8.29	B5 V	0.30 ± 0.04	4.93 ± 0.44	1.48 ± 0.24	V	2015-10-17	07:21	24
HD 39680	05:54:44.7	13:51:17.1	7.99	O6V:[n]pevar	0.32	4.73 ± 0.72	1.52 ± 0.72	P	2015-10-14	08:50	24
									2015-12-01	04:18	48
HD 251204	06:05:05.7	23:23:38.5	10.20	B0	0.78 ± 0.04	2.97 ± 0.12	2.32 ± 0.15	V	2015-10-14	08:17	160
HD 252325	06:09:00.3	20:38:25.9	10.80	B1:V:	0.87	3.55 ± 0.13	3.09 ± 0.18	V	2015-10-14	08:33	240
HD 43384	06:16:58.7	23:44:27.3	6.25	B3Iab	0.58	3.29 ± 0.08	1.90 ± 0.08	W	2015-10-14	09:05	12
HD 45314	06:27:15.8	14:53:21.2	6.64	O9:npe	0.43 ± 0.04	4.42 ± 0.30	1.90 ± 0.22	V	2015-10-17	07:36	16
Walker 67	06:40:37.2	09:47:29.7	10.79	B1 V	0.87 ± 0.09	5.06 ± 0.32	4.40 ± 0.53	V	2015-10-17	07:52	240
HD 49787	06:49:55.5	-05:30:47.5	7.54	B1 V:pe	0.18	2.39 ± 0.20	0.43	W	2015-10-17	06:11	12
HD 50820	06:54:42.0	-01:45:23.4	6.21	B3IVe+K2II	0.77	4.39 ± 0.08	3.38 ± 0.08	W	2015-10-17	06:24	12
HD 54662	07:09:20.2	-10:20:47.6	6.21	O7Vzvar?	0.26	3.12 ± 0.22	0.81 ± 0.22	W	2015-10-17	06:41	12
HD 61827	07:39:49.3	-32:34:42.1	8.20	B3 Iab	0.81	3.22 ± 0.06	2.61 ± 0.06	W	2015-05-22	23:00	32
CD-28 5205	07:58:42.9	-28:26:19.8	11.16	B3/4	0.57 ± 0.11	3.09 ± 0.39	1.76 ± 0.40	V	2015-05-12	00:43	400
HD 66194	07:58:50.6	-60:49:28.1	5.81	B2 Vne	0.18	2.25 ± 0.32	0.41 ± 0.32	V	2015-05-22	23:17	4
LS 908	07:59:12.0	-28:34:04.3	11.59	O9	0.64 ± 0.07	2.85 ± 0.23	1.82 ± 0.25	V	2015-05-12	01:07	480
HD 73882	08:39:09.5	-40:25:09.3	7.19	O8.5IV	0.69 ± 0.04	3.56 ± 0.13	2.46 ± 0.17	V	2015-05-22	23:35	12
HD 75309	08:47:28.0	-46:27:04.0	7.84	B2Ib/II	0.29 ± 0.04	3.53 ± 0.40	1.02 ± 0.18	V	2015-05-23	00:44	20
HD 75860	08:50:53.2	-43:45:05.4	7.58	B2C Iab	0.90	3.44 ± 0.06	3.10 ± 0.06	W	2015-05-22	23:54	20
HD 76868	08:58:59.3	03:39:22.0	8.04	B5/7e	0.39	5.70 ± 0.15	2.22 ± 0.15	W	2015-05-29	23:36	32
HD 79186	09:11:04.4	-44:52:04.4	5.00	B5Ia	0.40 ± 0.04	3.21 ± 0.56	1.28 ± 0.26	V	2015-05-23	00:11	2
HD 80558	09:18:42.4	-51:33:38.3	5.93	B6Ia	0.60	3.35 ± 0.08	2.01 ± 0.08	W	2015-05-23	00:27	4
HD 89137	10:15:40.1	-51:15:24.1	7.97	ON9.7II(n)	0.27 ± 0.04	2.68 ± 0.28	0.72 ± 0.13	V	2015-05-23	01:02	32
HD 91824	10:34:46.6	-58:09:22.0	8.15	O7V((f))z	0.24 ± 0.07	3.35 ± 0.62	0.80 ± 0.28	V	2015-05-24	01:55	32
HD 91983	10:35:54.2	-58:15:27.4	8.58	O9.5/B0I/II	0.29 ± 0.04	2.89 ± 0.34	0.84 ± 0.15	V	2016-01-30	05:37	32
HD 93160	10:44:07.3	-59:34:30.6	7.60	O7III((f))	0.39 ± 0.05	4.87 ± 0.38	1.90 ± 0.28	V	2015-05-24	02:12	20
HD 93205	10:44:33.7	-59:44:15.5	7.75	O3.5V((f))+O8V	0.38 ± 0.04	3.25 ± 0.24	1.23 ± 0.16	V	2015-05-24	01:06	24
HD 93222	10:44:36.2	-60:05:29.0	8.10	O7V((f))z	0.36 ± 0.06	4.76 ± 0.48	1.71 ± 0.33	V	2015-05-24	01:22	32
HD 303308	10:45:05.8	-59:40:06.4	8.17	O4.5V((fc))	0.45 ± 0.05	3.02 ± 0.21	1.36 ± 0.17	V	2015-05-24	01:39	32
									2016-01-30	04:47	24
HD 93632	10:47:12.5	-60:05:49.8	9.10	O5Ifvar	0.56 ± 0.05	4.17 ± 0.24	2.33 ± 0.25	V	2015-05-12	01:29	80
									2015-12-29	08:01	48
HD 93843	10:48:37.8	-60:13:25.5	7.33	O5III(fc)	0.27 ± 0.05	3.89 ± 0.41	1.05 ± 0.20	V	2015-05-12	01:45	12
									2015-12-29	07:03	8
HD 94493	10:53:15.1	-60:48:53.2	7.27	B0.5 Ib	0.23 ± 0.04	3.57 ± 0.45	0.82 ± 0.18	V	2015-05-12	02:02	12
									2016-01-26	05:19	12
HD 96715	11:07:32.8	-59:57:48.7	8.30	O4V((f))z	0.43 ± 0.04	2.62 ± 0.18	1.13 ± 0.13	V	2015-05-20	04:42	32
HD 97484	11:12:04.5	-61:05:42.9	8.52	O8V	0.60 ± 0.05	2.57 ± 0.15	1.54 ± 0.16	V	2015-05-17	02:13	40
									2016-02-14	03:26	32
HD 99953	11:29:15.1	-63:33:14.2	6.57	B1 Ia	0.48 ± 0.06	3.69 ± 0.30	1.77 ± 0.27	V	2015-05-25	01:33	8
HD 101065	11:37:37.0	-46:42:34.9	8.03	F8/G0p	0.91	2.30 ± 0.05	2.09 ± 0.05	W	2015-05-25	01:49	32
HD 103779	11:56:57.5	-63:14:56.7	7.22	B0.5 Iab	0.21 ± 0.04	3.29 ± 0.43	0.69 ± 0.15	V	2015-05-23	01:21	12
HD 104705	12:03:23.9	-62:41:45.1	7.83	B0.5 III	0.23 ± 0.07	2.81 ± 0.57	0.65 ± 0.24	V	2015-05-23	01:39	20
HD 105416	12:08:14.7	-48:41:32.9	5.34	B9.5/A0V	0.05	4.62 ± 0.75	0.23 ± 0.04	W	2015-05-12	03:58	2
									2016-02-07	04:24	4
HD 108639	12:29:09.5	-60:48:17.5	7.81	B1III	0.35			X	2016-01-23	04:51	16
HD 109399	12:35:16.5	-72:43:00.8	7.67	B0.5 Ib	0.21	3.26 ± 0.18	0.68 ± 0.04	W	2015-05-23	01:56	20
HD 111934	12:53:37.6	-60:21:25.4	6.92	B1.5 Ib	0.51 ± 0.06	2.45 ± 0.20	1.25 ± 0.18	V	2015-04-07	08:54	12
HD 112272	12:56:33.7	-64:21:39.2	7.39	B0.5 Ia	1.00 ± 0.04	3.09 ± 0.09	3.09 ± 0.15	V	2015-04-07	09:11	16
									2015-12-29	07:37	12
CPD-63 2495	13:02:47.7	-63:50:08.7	10.08	O9.5Ve	1.02 ± 0.06	3.75 ± 0.15	3.83 ± 0.27	V	2015-04-07	07:50	160
HD 113904	13:08:07.2	-65:18:21.7	5.53	O9 III	0.21	3.63 ± 0.17	0.76 ± 0.04	W	2015-04-07	09:27	3
									2015-12-29	07:20	6
HD 114886	13:14:44.4	-63:34:51.8	6.89	O9 III+O9.5 III	0.29	2.90 ± 0.16	0.84 ± 0.05	W	2015-05-12	02:23	12
									2016-01-30	05:06	24
HD 115071	13:16:04.8	-62:35:01.5	7.97	O9.5III+B0Ib	0.44			X	2016-01-26	05:42	24
HD 115842	13:20:48.3	-55:48:02.5	6.09	B0.5Ia/ab	0.51	3.18 ± 0.10	1.62 ± 0.05	W	2015-05-12	03:39	4
									2016-01-30	05:22	8
HD 116852	13:30:23.5	-78:51:20.5	8.47	O8.5II-III((f))	0.21 ± 0.04	2.42 ± 0.37	0.51 ± 0.12	V	2015-05-12	05:03	40
									2016-02-22	05:02	32

Notes. Coefficients in Cols. 6 to 8 are taken from the references of Col. 9. The exposure time corresponds to the sum of all exposures obtained with and without order-separating filter (typically evenly split between the two settings). Key to references: V = Valencic et al. (2004); W = Wegner (2003); C = Cartledge et al. (2005); C06 = Cox et al. (2006); P = Patriarchi et al. (2003); G = Gordon et al. (2003); X = No R(V) data.

Table A.1. continued.

Star	RA	Dec	V	Spectral type	$E(B - V)$	R_V	A_V	REF	DATE	UT	Exp (s)
HD 119159	13:42:56.1	-56:46:04.7	6.00	B1/2II	0.09	2.59 ± 0.60	0.23 ± 0.05	W	2015-05-12	03:23	4
HD 122879	14:06:25.2	-59:42:57.2	6.50	B0Ia	0.36 ± 0.05	3.15 ± 0.30	1.13 ± 0.20	V	2016-01-28	07:56	8
HD 124314	14:15:01.6	-61:42:24.4	6.64	O6 IV(n)((f))	0.50	2.97 ± 0.12	1.49 ± 0.06	W	2015-05-12	04:13	8
									2016-02-22	05:33	16
HD 129557	14:45:11.0	-55:36:05.9	6.09	B2III	0.23 ± 0.07	2.29 ± 0.56	0.53 ± 0.23	V	2015-05-11	08:48	4
									2016-02-22	04:46	8
HD 133518	15:06:56.0	-52:01:47.2	6.39	B2 Vp	0.15	1.79 ± 0.37	0.27 ± 0.06	W	2015-05-11	09:06	4
									2016-02-12	07:10	8
HD 134591	15:11:51.0	-34:45:47.4	8.37	B5III	0.24 ± 0.05	2.51 ± 0.40	0.60 ± 0.16	V	2015-05-12	02:47	40
									2016-02-22	05:18	32
HD 135591	15:18:49.1	-60:29:46.8	5.46	O8IV((f))	0.22	3.57 ± 0.18	0.79 ± 0.04	W	2015-05-12	04:46	3
									2016-01-29	08:42	6
HD 147683	16:24:43.7	-34:53:37.5	7.05	B3: Vn	0.28			X	2016-02-12	08:08	8
HD 147888	16:25:24.3	-23:27:36.8	6.74	B3 V:	0.51 ± 0.04	3.89 ± 0.20	1.99 ± 0.18	V	2015-05-12	08:40	24
HD 147889	16:25:24.3	-24:27:56.6	7.90	B2 V	1.10 ± 0.04	3.95 ± 0.13	4.35 ± 0.21	V	2015-05-13	09:53	32
									2015-05-24	03:21	32
									2016-01-28	08:58	24
HD 148379	16:29:42.3	-46:14:35.6	5.37	B2Iab	0.73 ± 0.07	3.28 ± 0.36	2.40 ± 0.35	V	2015-05-11	09:26	2
HD 148688	16:31:41.8	-41:49:01.7	5.39	B1Iaeqp	0.58	3.33 ± 0.06	1.93 ± 0.03	W	2015-05-11	09:42	2
HD 148937	16:33:52.4	-48:06:40.5	6.71	O6f?p	0.67	3.28 ± 0.06	2.20 ± 0.04	W	2015-05-12	05:20	8
									2016-02-12	07:52	16
HD 149404	16:36:22.6	-42:51:31.9	5.47	O8.5Iab(f)p	0.62 ± 0.06	3.53 ± 0.38	2.19 ± 0.31	V	2015-05-12	05:38	3
									2016-01-30	08:57	6
HD 150136	16:41:20.4	-48:45:46.7	5.65	O3.5-4 III(f*)+O	0.50	3.27 ± 0.13	1.64 ± 0.07	W	2015-05-20	05:00	3
HD 151804	16:51:33.7	-41:13:49.9	5.22	O8Iaf	0.30 ± 0.03	4.33 ± 0.30	1.30 ± 0.16	V	2015-05-24	03:39	3
HD 151805	16:51:35.7	-41:46:35.5	9.01	B1Ib	0.43 ± 0.05	3.29 ± 0.30	1.42 ± 0.21	V	2016-02-22	08:24	48
HD 152235	16:53:58.9	-41:59:39.6	6.38	B0.5Ia	0.71 ± 0.06	3.13 ± 0.25	2.22 ± 0.26	V	2015-05-24	03:58	4
HD 152248	16:54:10.1	-41:49:30.1	6.05	O7Iabf+O7Ib(f)	0.41 ± 0.04	3.68 ± 0.26	1.51 ± 0.18	V	2015-05-24	04:15	4
HD 152249	16:54:11.6	-41:50:57.2	6.45	OC9Iab	0.46 ± 0.10	3.54 ± 0.45	1.63 ± 0.40	V	2015-05-24	04:31	8
HD 152408	16:54:58.5	-41:09:03.1	5.77	O8Iape	0.42 ± 0.05	4.17 ± 0.33	1.75 ± 0.25	V	2015-05-24	04:47	3
HD 152424	16:55:03.3	-42:05:27.0	6.27	OC9.2Ia	0.68 ± 0.04	3.28 ± 0.15	2.23 ± 0.17	V	2015-05-24	05:04	4
									2016-02-12	07:34	12
HD 153919	17:03:56.8	-37:50:38.9	6.51	O6Iafcp	0.51 ± 0.04	3.87 ± 0.22	1.97 ± 0.19	V	2015-04-12	08:58	8
									2016-02-22	07:26	16
HD 154043	17:05:18.9	-47:04:08.5	7.10	B2Iab	0.78	3.30 ± 0.06	2.57 ± 0.05	W	2015-04-12	08:39	12
									2016-02-02	09:08	8
HD 154368	17:06:28.4	-35:27:03.8	6.13	O9.2Iab	0.76 ± 0.05	3.33 ± 0.15	2.53 ± 0.20	V	2015-04-12	09:19	4
									2016-02-22	08:44	8
HD 155806	17:15:19.2	-33:32:54.3	5.53	O7.5V((f))z(e)	0.28	2.48 ± 1.92	0.70 ± 0.49	P	2015-05-24	05:36	3
HD 155851	17:15:33.8	-32:41:23.1	8.13	B0Vne	0.32	5.25 ± 0.30	1.68 ± 0.10	W	2015-05-24	05:19	32
HD 156201	17:17:45.5	-35:13:27.0	8.01	B0.5 Ia	0.86	3.23 ± 0.05	2.78 ± 0.04	W	2015-05-25	02:06	32
HD 157038	17:22:39.2	-37:48:16.7	6.44	B3Iap	0.81	3.70 ± 0.05	3.00 ± 0.04	W	2015-05-25	02:32	8
HD 157978	17:26:19.0	07:35:44.3	6.04	G0/K0 II:+A1	0.65	3.72 ± 0.06	2.42 ± 0.04	W	2016-03-14	09:27	8
HD 161056	17:43:47.0	-07:04:46.6	6.32	B1.5 V	0.59	3.13 ± 0.08	1.85 ± 0.05	W	2016-02-17	08:57	12
HD 163181	17:56:16.1	-32:28:30.0	6.61	O9.5Ia/ab	0.74 ± 0.06	3.24 ± 0.32	2.40 ± 0.32	V	2015-05-25	02:57	8
HD 164073	18:02:00.6	-48:48:37.7	8.03	B3III/IV	0.21 ± 0.04	2.96 ± 0.42	0.62 ± 0.15	V	2015-05-25	03:19	32
HD 164740	18:03:38.3	-24:22:35.0	9.10	O7: V + sec	0.89 ± 0.03	5.03 ± 0.11	4.48 ± 0.18	V	2015-04-07	07:29	160
HD 315023	18:04:20.6	-24:13:54.9	10.03	OB	0.40 ± 0.06	4.12 ± 0.40	1.65 ± 0.29	V	2015-04-07	08:11	160
HD 165319	18:05:58.8	-14:11:53.0	8.04	O9.7Ib C	0.83	3.25 ± 0.05	2.70 ± 0.04	W	2015-10-16	01:15	24
HD 167838	18:17:37.7	-15:25:50.6	6.73	B5 Ia	0.63 ± 0.04	3.39 ± 0.14	2.13 ± 0.17	V	2016-03-13	09:06	16
BD-13 4920	18:18:26.2	-13:50:05.2	10.06	B1V	0.73 ± 0.04	3.22 ± 0.19	2.35 ± 0.26	V	2015-04-07	08:30	160
HD 168076	18:18:36.4	-13:48:02.0	8.25	O4III(f)	0.76 ± 0.04	3.47 ± 0.12	2.64 ± 0.17	V	2015-05-30	09:49	32
HD 169454	18:25:15.2	-13:58:42.3	6.71	B1Ia	1.08 ± 0.04	3.37 ± 0.09	3.64 ± 0.17	V	2016-03-13	09:22	16
HD 170740	18:31:25.7	-10:47:45.0	5.72	B2 V	0.50 ± 0.13	3.01 ± 0.49	1.51 ± 0.46	V	2016-03-15	09:06	12
HD 170938	18:32:37.8	-15:42:05.9	7.99	B1 Ia	1.04	3.34 ± 0.04	3.47 ± 0.04	W	2015-11-08	00:08	16
HD 171957	18:38:04.5	-14:00:17.2	6.47	B9 IV	0.27			X	2015-11-08	00:41	12
HD 172694	18:42:16.6	-15:51:20.8	8.12	B1: Vne	0.37	5.04 ± 0.16	1.86 ± 0.06	W	2015-06-02	04:27	160
HD 203532	21:33:54.6	-82:40:59.1	6.38	B3 IV	0.28 ± 0.03	3.37 ± 0.24	0.94 ± 0.11	V	2015-06-02	06:22	8
HD 210121	22:08:11.9	-03:31:52.8	7.68	B7II	0.31 ± 0.05	2.42 ± 0.29	0.75 ± 0.15	V	2015-10-02	03:02	24

Table A.2. BBLP values in the BVRI filters, parameters of the Serkowski curves, and wavelength gradients for the stars observed in this LIPS survey.

Star	Date	<i>B</i>		<i>V</i>		<i>R</i>		<i>I</i>		<i>K</i>	$\lambda_{\max}$ (nm)	$P_{\max}$ (%)	$d\theta/d\lambda$ (°/100 nm)	<i>C</i>
		<i>P</i> (%)	θ^E (°)	<i>P</i> (%)	θ^E (°)	<i>P</i> (%)	θ^E (°)	<i>P</i> (%)	θ^E (°)					
AzV 18	2015-10-14	0.41	105.7	0.40	105.4	0.36	105.1	0.30	105.9				-0.37 ± 0.52	
AzV 456	2015-10-14	1.24	162.3	1.32	161.1	1.33	161.6	1.30	161.1	0.27 ± 0.16	626 ± 32	1.33 ± 0.02	-0.30 ± 0.23	
HD 36982	2015-10-17	0.57	62.2	0.68	59.9	0.65	57.5	0.58	52.8				-2.56 ± 0.26	
HD 37021	2015-10-17	0.26	95.2	0.34	101.7	0.38	105.7	0.45	110.2				3.82 ± 0.34	
HD 37061	2015-10-14	1.25	64.6	1.54	61.6	1.64	59.5	1.64	57.5	1.41 ± 0.11	697 ± 12	1.68 ± 0.00	-1.85 ± 0.07	
HD 38029	2015-10-14	1.82	105.2	1.87	104.9	1.77	105.1	1.62	105.3	0.85 ± 0.17	514 ± 23	1.88 ± 0.01	0.23 ± 0.07	
HD 37367	2015-10-16	0.88	14.2	1.02	15.2	1.03	15.5	0.97	15.6	1.18 ± 0.08	624 ± 7	1.04 ± 0.02	0.27 ± 0.10	
HD 37903	2015-10-17	1.45	119.9	1.74	121.0	1.80	121.6	1.72	122.4	1.51 ± 0.23	646 ± 8	1.82 ± 0.01	0.69 ± 0.06	
HD 38087	2015-10-17	2.37	118.4	2.57	118.1	2.51	118.6	2.30	119.3	1.18 ± 0.04	572 ± 5	2.59 ± 0.01	0.30 ± 0.07	
HD 39680	2015-10-14	0.44	163.6	0.60	163.0	0.68	162.6	0.70	162.9				0.27 ± 0.21	1
	2015-12-01	0.39	166.1	0.56	163.9	0.63	163.0	0.65	163.4				-1.09 ± 0.17	1
HD 251204	2015-10-14	4.64	153.8	4.97	154.3	4.88	154.6	4.51	155.0	1.00 ± 0.02	575 ± 2	5.00 ± 0.01	0.33 ± 0.03	
HD 252325	2015-10-14	4.69	162.5	5.13	162.6	5.08	162.8	4.73	163.1	1.07 ± 0.04	595 ± 3	5.18 ± 0.01	0.19 ± 0.02	
HD 43384	2015-10-14	2.88	170.5	3.05	171.1	2.98	171.4	2.75	171.7	0.92 ± 0.03	566 ± 2	3.06 ± 0.01	0.27 ± 0.02	
HD 45314	2015-10-17	0.91	162.8	1.15	160.1	1.21	159.2	1.17	158.8	1.58 ± 0.06	665 ± 9	1.23 ± 0.00	-0.79 ± 0.13	
Walker 67	2015-10-17	3.01	18.7	4.16	17.2	4.81	16.4	5.16	16.0	1.40 ± 0.05	826 ± 3	5.20 ± 0.04	-0.58 ± 0.06	
HD 49787	2015-10-17	0.23	10.7	0.26	4.2	0.26	4.5	0.28	8.6				0.07 ± 0.82	
HD 50820	2015-10-17	0.15	112.7	0.15	117.9	0.13	126.3	0.13	138.2				7.05 ± 0.62	
HD 54662	2015-10-17	0.79	145.0	0.86	145.1	0.84	146.3	0.79	148.6	0.95 ± 0.24	571 ± 8	0.86 ± 0.01	1.10 ± 0.13	
HD 61827	2015-05-22	1.59	4.0	1.78	3.5	1.80	3.5	1.71	3.6	1.09 ± 0.04	624 ± 7	1.82 ± 0.00	-0.11 ± 0.06	
CD-28 5205	2015-05-12	1.01	100.7	1.18	100.6	1.17	100.5	1.09	100.7	1.55 ± 0.10	610 ± 7	1.21 ± 0.01	-0.06 ± 0.10	
HD 66194	2015-05-22	0.42	144.0	0.43	144.0	0.42	149.4	0.39	156.5				4.05 ± 0.34	
LS 908	2015-05-12	1.74	110.0	1.90	110.0	1.85	109.7	1.67	109.7	1.19 ± 0.16	567 ± 11	1.91 ± 0.01	0.02 ± 0.12	
HD 73882	2015-05-22	1.58	164.6	1.95	164.1	2.07	164.0	2.02	164.1	1.42 ± 0.12	684 ± 8	2.10 ± 0.02	-0.09 ± 0.08	
HD 75309	2015-05-23	0.61	52.1	0.62	54.3	0.58	53.0	0.51	50.1				-0.43 ± 0.33	
HD 75860	2015-05-22	1.57	142.0	1.66	142.3	1.57	142.3	1.38	142.3	1.41 ± 0.06	541 ± 5	1.68 ± 0.01	0.06 ± 0.04	
HD 76868	2015-05-29	0.20	27.6	0.19	23.0	0.21	18.2	0.22	14.2				-3.51 ± 0.37	
HD 79186	2015-05-23	2.52	46.8	2.60	46.9	2.46	46.5	2.17	46.2	1.07 ± 0.02	520 ± 10	2.62 ± 0.00	-0.22 ± 0.05	
HD 80558	2015-05-23	2.88	164.0	3.30	163.3	3.27	163.3	3.00	163.7	1.33 ± 0.03	597 ± 10	3.34 ± 0.06	0.14 ± 0.04	2
HD 89137	2015-05-23	0.37	32.6	0.44	31.0	0.47	28.7	0.46	27.6				-1.52 ± 0.22	
HD 91824	2015-05-24	1.27	96.9	1.33	96.2	1.23	96.0	1.04	95.7	1.49 ± 0.06	517 ± 5	1.35 ± 0.01	-0.23 ± 0.06	
HD 91983	2016-01-30	1.05	130.0	1.09	132.2	1.05	134.8	0.97	137.2	1.00 ± 0.21	542 ± 6	1.10 ± 0.01	2.16 ± 0.10	
HD 93160	2015-05-24	2.22	114.5	2.29	114.7	2.18	115.0	1.92	115.9	1.12 ± 0.13	530 ± 4	2.31 ± 0.01	0.42 ± 0.03	
HD 93205	2015-05-24	1.96	100.5	2.09	99.5	2.01	99.2	1.79	98.4	1.27 ± 0.05	552 ± 3	2.10 ± 0.01	-0.47 ± 0.05	
HD 93222	2015-05-24	0.79	127.1	0.68	134.7	0.57	146.5	0.53	162.2				9.34 ± 0.38	3
HD 303308	2015-05-24	2.69	99.0	2.88	99.0	2.76	98.9	2.42	98.9	1.35 ± 0.04	550 ± 3	2.90 ± 0.01	-0.01 ± 0.05	
	2016-01-30	2.73	100.1	2.93	99.9	2.81	100.0	2.49	100.0	1.35 ± 0.04	551 ± 3	2.95 ± 0.01	0.04 ± 0.04	
HD 93632	2015-05-12	0.75	54.9	1.15	52.0	1.35	49.3	1.47	47.6	1.57 ± 0.10	828 ± 17	1.49 ± 0.01	-1.96 ± 0.12	
	2015-12-29	0.93	60.5	1.17	54.6	1.33	51.5	1.40	48.2	1.41 ± 0.19	781 ± 24	1.40 ± 0.05	-2.76 ± 0.12	
HD 93843	2015-05-12	0.64	101.5	0.61	100.0	0.53	98.2	0.44	94.7				-2.15 ± 0.15	
	2015-12-29	0.66	101.5	0.64	100.8	0.55	100.1	0.43	99.7				-0.44 ± 0.29	
HD 94493	2015-05-12	0.61	107.9	0.62	106.0	0.55	106.7	0.44	108.4				-0.04 ± 0.29	
	2016-01-26	0.66	107.8	0.63	107.2	0.55	109.2	0.42	111.9				1.13 ± 0.30	
HD 96715	2015-05-20	1.85	3.4	2.03	2.5	2.00	2.2	1.88	2.4	0.90 ± 0.07	591 ± 5	2.03 ± 0.01	-0.19 ± 0.08	
HD 97484	2015-05-17	0.97	55.0	1.02	57.1	0.95	57.9	0.86	57.8	1.23 ± 0.19	537 ± 17	1.03 ± 0.01	0.51 ± 0.15	
	2016-02-14	0.93	58.7	0.98	59.8	0.92	61.3	0.82	62.8	1.15 ± 0.11	529 ± 9	0.98 ± 0.03	1.31 ± 0.17	
HD 99953	2015-05-25	1.88	107.6	1.93	107.2	1.80	107.8	1.55	108.4	1.24 ± 0.07	516 ± 8	1.95 ± 0.00	0.47 ± 0.05	
HD 101065	2015-05-25	0.02	6.7	0.10	13.5	0.12	8.7	0.16	4.2				-2.87 ± 0.40	
HD 103779	2015-05-23	0.59	77.2	0.61	75.1	0.54	72.0	0.45	69.9				-2.89 ± 0.17	
HD 104705	2015-05-23	0.69	89.4	0.76	88.3	0.79	88.6	0.71	86.8	0.34 ± 0.39	647 ± 99	0.77 ± 0.07	-1.66 ± 0.45	
HD 105416	2015-05-12	0.18	91.2	0.21	79.6	0.16	76.9	0.12	66.2				-4.78 ± 0.83	
	2016-02-07	0.31	86.1	0.25	89.1	0.23	88.5	0.18	88.2				0.85 ± 0.41	
HD 108639	2016-01-23	1.72	90.7	1.92	90.7	1.83	90.9	1.64	91.3	1.29 ± 0.23	550 ± 5	1.92 ± 0.04	0.21 ± 0.08	

Notes. Best-fit parameters are omitted for stars with $P \leq 0.7\%$. The last column refers to some comments listed at the end of the table. 1. HD 39680 on 2015-10-04 and 2015-12-01: depolarisation and change of position angle in the Paschen line spectral region. 2. HD 80558 on 2015-05-23: polarisation spectra obtained with and without order-separating filter show a remarkable difference ($\Delta P \sim 0.1\%$). 3. HD 93222 on 2015-05-24 shows an increase of polarisation at $\lambda \gtrsim 820$ nm, and the position angle has a strong wavelength gradient. 4. HD 113904 is a triple system and on 2015-04-07 and on 2015-12-29 shows differences in the intensity and polarisation spectra. 5. HD 133518 on 2015-05-11: inconsistencies in the polarisation measured with and without order separating filter at longer wavelengths. 6. HD 133518 on 2016-02-12: observations without filter show an artifact in one of the beams of the frame obtained at PA = 67.5°, in the wavelength range 796.7 to 820.6 nm. We have arbitrarily fixed this problem by replacing the fluxes of both beams in this wavelength range with those obtained at the same retarder PA measured in the series obtained with the order-separating filter in. 7. HD 134591 on 2015-05-12 was observed only with order-separating filter. 8. HD 148379 on 2015-05-11: polarisation spectra measured with and without order-separating filter show large inconsistencies ($\Delta P \gtrsim 0.1\%$). 9. HD 149404 shows variability in polarisation (both in value and in position angle). 10. HD 152424 variability in the intensity spectrum. Position angles measured on 2015-05-24 has larger errors. 11. HD 153919 shows some variability in the fraction of linear polarisation (but not in the position angle). 12. HD 154368 shows a strong variation of the position angle with wavelength in both observing dates. 13. HD 155851 on 2015-05-24: at $\lambda \gtrsim 820$ nm the polarisation decreases, and the gradient of its position angle changes its sign. 14. HD 172694 on 2015-06-02 shows a sudden increase of polarisation at $\lambda \gtrsim 820$ nm. In the same wavelength region, the gradient of the polarisation position angle changes its sign, however the intensity spectrum does not show anything remarkable in that interval.

Table A.2. continued.

Star	Date	<i>P</i> (%)	<i>B</i> θ^E (°)	<i>P</i> (%)	<i>V</i> θ^E (°)	<i>P</i> (%)	<i>R</i> θ^E (°)	<i>P</i> (%)	<i>I</i> θ^E (°)	<i>K</i>	$\lambda_{\max}$ (nm)	<i>P</i> _{max} (%)	d <i>θ</i> /d <i>λ</i> (°/100 nm)	C
HD 109399	2015-05-23	2.08	114.5	2.19	114.5	2.09	114.7	1.81	115.5	1.30 ± 0.06	538 ± 8	2.20 ± 0.01	0.29 ± 0.06	
HD 111934	2015-04-07	2.61	74.9	2.82	74.2	2.71	73.8	2.40	73.7	1.35 ± 0.09	556 ± 10	2.83 ± 0.02	-0.22 ± 0.05	
HD 112272	2015-04-07	0.73	56.7	0.84	56.3	0.81	55.0	0.71	53.8	1.93 ± 0.13	584 ± 23	0.85 ± 0.02	-1.12 ± 0.13	
	2015-12-29	0.68	48.2	0.72	51.8	0.71	50.3	0.64	46.6	1.56 ± 0.19	591 ± 24	0.73 ± 0.02	-2.01 ± 0.19	
CPD-63 2495	2015-04-07	2.49	76.2	2.75	72.3	2.63	70.6	2.36	69.4	1.31 ± 0.08	569 ± 9	2.75 ± 0.04	-1.56 ± 0.12	
HD 113904	2015-04-07	1.33	83.1	1.38	82.4	1.35	81.8	1.27	81.2	0.79 ± 0.39	540 ± 8	1.40 ± 0.05	-0.01 ± 0.15	4
	2015-12-29	1.19	81.9	1.38	83.8	1.30	84.0	1.12	84.3	1.99 ± 0.34	562 ± 42	1.39 ± 0.02	0.72 ± 0.13	4
HD 114886	2015-05-12	1.76	74.1	1.89	73.9	1.80	73.3	1.58	72.4	1.31 ± 0.07	537 ± 5	1.90 ± 0.02	-0.54 ± 0.06	
	2016-01-30	1.78	74.9	1.93	74.8	1.83	74.5	1.62	74.3	1.34 ± 0.04	547 ± 4	1.93 ± 0.02	-0.14 ± 0.04	
HD 115071	2016-01-26	1.87	78.4	2.03	79.3	1.94	79.1	1.69	79.3	1.35 ± 0.05	546 ± 4	2.04 ± 0.02	-0.01 ± 0.04	
HD 115842	2015-05-12	0.31	137.4	0.28	142.6	0.27	153.0	0.34	158.0				6.73 ± 0.86	
	2016-01-30	0.29	117.9	0.29	125.9	0.29	135.5	0.29	141.6				7.18 ± 0.41	
HD 116852	2015-05-12	1.14	115.4	1.23	115.4	1.15	116.3	0.99	116.9	1.20 ± 0.09	517 ± 4	1.23 ± 0.01	0.23 ± 0.13	
	2016-02-22	0.84	111.9	1.03	114.8	1.02	116.6	0.92	117.7	1.56 ± 0.11	603 ± 21	1.04 ± 0.06	1.57 ± 0.17	
HD 119159	2015-05-12	1.16	71.0	1.24	68.8	1.17	67.8	0.99	67.2	1.56 ± 0.07	533 ± 8	1.25 ± 0.01	-0.65 ± 0.09	
	2016-01-28	1.16	69.8	1.24	69.0	1.17	68.2	1.00	67.1	1.19 ± 0.20	511 ± 9	1.25 ± 0.02	-0.30 ± 0.13	
HD 122879	2015-05-12	1.66	70.0	1.79	69.6	1.71	69.0	1.48	68.7	1.68 ± 0.04	560 ± 12	1.81 ± 0.01	-0.57 ± 0.07	
HD 124314	2015-05-12	2.12	70.0	2.22	70.0	2.14	70.2	1.92	70.1	1.19 ± 0.18	544 ± 8	2.24 ± 0.01	0.10 ± 0.07	
	2016-02-22	2.15	69.7	2.25	70.5	2.11	70.6	1.85	71.0	1.30 ± 0.06	530 ± 10	2.27 ± 0.01	0.40 ± 0.06	
HD 129557	2015-05-11	1.21	80.4	1.49	80.6	1.47	79.7	1.38	79.1	1.44 ± 0.26	607 ± 9	1.51 ± 0.07	-0.77 ± 0.13	
	2016-02-22	1.20	80.1	1.34	80.3	1.27	80.3	1.11	80.8	1.51 ± 0.20	557 ± 18	1.34 ± 0.01	0.08 ± 0.07	
HD 133518	2015-05-11	0.69	58.4	0.78	58.2	0.73	58.3	0.60	58.9	1.61 ± 1.27	525 ± 99	0.79 ± 0.05	0.81 ± 0.26	5
	2016-02-12	0.80	57.0	0.80	58.9	0.74	58.6	0.66	57.3	1.25 ± 0.14	524 ± 26	0.80 ± 0.04	0.28 ± 0.18	6
HD 134591	2015-05-12			0.28	105.0	0.25	102.6	0.26	97.2				-1.94 ± 1.15	7
	2016-02-22	0.30	111.7	0.29	112.6	0.25	116.5	0.22	122.4				2.54 ± 1.02	
HD 135591	2015-05-12	1.28	62.7	1.42	63.0	1.36	62.5	1.20	62.6	1.53 ± 0.08	564 ± 6	1.42 ± 0.01	-0.21 ± 0.06	
	2016-01-29	1.32	64.4	1.45	64.3	1.39	64.6	1.24	65.3	1.37 ± 0.27	557 ± 7	1.45 ± 0.02	0.16 ± 0.08	
HD 147683	2016-02-12	1.58	28.1	1.71	27.6	1.66	27.1	1.50	27.4	1.13 ± 0.08	569 ± 8	1.71 ± 0.03	-0.16 ± 0.12	
HD 147888	2016-01-30	2.73	54.4	3.31	53.9	3.45	53.5	3.33	53.0	1.43 ± 0.02	662 ± 4	3.49 ± 0.01	-0.38 ± 0.02	
HD 147889	2015-05-13	2.60	177.5	3.48	176.4	3.97	175.5	4.21	174.6	1.32 ± 0.02	809 ± 4	4.22 ± 0.00	-0.72 ± 0.03	
	2015-05-24	2.59	178.7	3.47	176.8	3.96	175.9	4.16	175.0	1.37 ± 0.04	798 ± 7	4.18 ± 0.01	-0.78 ± 0.04	
	2016-01-28	2.70	178.9	3.49	177.2	3.95	176.1	4.16	175.1	1.18 ± 0.09	813 ± 13	4.18 ± 0.01	-0.83 ± 0.04	
HD 148379	2015-05-11	1.82	29.5	1.85	28.4	1.82	27.8	1.69	27.2	0.95 ± 0.06	582 ± 4	1.86 ± 0.09	-0.37 ± 0.07	8
HD 148688	2015-05-11	1.32	17.7	1.38	20.1	1.34	20.3	1.22	20.5	0.76 ± 0.06	527 ± 5	1.39 ± 0.01	0.86 ± 0.17	
HD 148937	2015-05-12	1.54	48.5	1.70	47.9	1.66	47.2	1.50	46.8	1.31 ± 0.11	576 ± 6	1.71 ± 0.01	-0.47 ± 0.06	
	2016-02-12	1.56	48.0	1.74	48.1	1.72	47.6	1.58	47.4	1.36 ± 0.15	597 ± 5	1.76 ± 0.01	-0.30 ± 0.05	
HD 149404	2015-05-12	2.70	177.7	2.98	178.9	2.93	179.7	2.67	0.5	1.02 ± 0.08	569 ± 4	3.00 ± 0.04	0.86 ± 0.05	9
	2016-01-30	2.44	3.9	2.71	3.4	2.71	3.1	2.50	2.5	1.24 ± 0.03	600 ± 9	2.76 ± 0.01	-0.32 ± 0.03	9
HD 150136	2015-05-20	1.04	56.6	1.15	58.6	1.09	59.1	0.98	58.5	1.19 ± 0.12	537 ± 8	1.15 ± 0.04	0.44 ± 0.16	
HD 151804	2015-05-24	1.04	43.2	1.10	43.2	1.09	42.1	0.98	41.3	1.17 ± 0.12	572 ± 8	1.11 ± 0.01	-0.65 ± 0.08	
HD 151805	2016-02-22	0.63	29.4	0.64	34.3	0.60	36.5	0.52	37.8				2.39 ± 0.39	
HD 152235	2015-05-24	0.77	117.3	0.75	114.7	0.66	113.5	0.53	112.9	1.77 ± 0.13	490 ± 12	0.78 ± 0.01	-0.80 ± 0.21	
HD 152248	2015-05-24	0.50	118.6	0.50	116.2	0.45	115.4	0.35	115.2				-1.38 ± 0.27	
HD 152249	2015-05-24	0.20	66.8	0.28	64.2	0.30	59.7	0.29	57.7				-3.09 ± 0.38	
HD 152408	2015-05-24	0.55	35.3	0.69	35.7	0.71	35.2	0.63	33.7	1.72 ± 0.12	618 ± 10	0.71 ± 0.03	-0.81 ± 0.15	
HD 152424	2015-05-24	0.31	109.9	0.24	107.3	0.14	108.9	0.05	141.8				3.61 ± 1.95	10
	2016-02-12	0.38	89.6	0.31	87.6	0.27	82.9	0.21	76.3				-4.73 ± 0.29	10
HD 153919	2015-04-12	2.40	8.1	2.60	9.9	2.55	10.7	2.32	11.4	1.09 ± 0.12	569 ± 4	2.62 ± 0.01	0.78 ± 0.06	11
	2016-02-22	2.65	8.5	2.75	10.2	2.67	10.7	2.41	11.5	0.99 ± 0.04	546 ± 2	2.77 ± 0.02	0.60 ± 0.05	11
HD 154043	2015-04-12	3.12	34.8	3.51	34.1	3.45	33.4	3.17	32.1	1.30 ± 0.03	596 ± 4	3.54 ± 0.01	-0.79 ± 0.03	
	2016-02-02	3.21	36.8	3.51	36.2	3.43	35.4	3.13	34.7	1.26 ± 0.03	579 ± 8	3.54 ± 0.02	-0.65 ± 0.04	
HD 154368	2015-04-12	0.39	166.1	0.30	158.8	0.27	148.8	0.25	138.0				-7.96 ± 0.32	12
	2016-02-22	0.37	166.0	0.28	152.0	0.27	142.9	0.28	133.5				-8.29 ± 0.41	12
HD 155806	2015-05-24	0.77	153.3	0.90	154.6	0.90	156.0	0.82	156.8	1.05 ± 0.29	590 ± 18	0.90 ± 0.02	1.35 ± 0.14	
HD 155851	2015-05-24	2.48	147.5	2.44	146.5	2.31	145.9	2.12	145.8	0.78 ± 0.05	496 ± 4	2.47 ± 0.01	-0.78 ± 0.08	13
HD 156201	2015-05-25	0.87	133.8	0.98	129.0	0.98	127.9	0.91	127.8	1.12 ± 0.11	607 ± 9	1.00 ± 0.03	-0.54 ± 0.22	
HD 157038	2015-05-25	2.50	170.5	2.54	168.4	2.36	166.7	2.08	165.4	1.14 ± 0.05	513 ± 6	2.57 ± 0.02	-1.47 ± 0.10	
HD 157978	2016-03-14	0.62	83.1	0.67	81.5	0.61	81.0	0.53	80.0				-0.61 ± 0.09	
HD 161056	2016-02-17	3.59	67.4	3.98	67.6	3.87	67.4	3.47	67.1	1.43 ± 0.05	572 ± 2	4.02 ± 0.04	-0.15 ± 0.03	
HD 163181	2015-05-25	1.43	173.0	1.43	175.1	1.38	176.8	1.29	178.6	0.50 ± 0.13	485 ± 18	1.45 ± 0.01	1.69 ± 0.09	
HD 164073	2015-05-25	0.91	1.4	1.08	1.3	1.08	1.0	1.02	0.4	1.05 ± 0.10	630 ± 9	1.09 ± 0.02	-0.26 ± 0.10	
HD 164740	2015-04-07	5.48	93.8	6.78	94.6	7.09	94.9	6.74	95.2	1.72 ± 0.02	657 ± 2	7.20 ± 0.02	0.33 ± 0.02	
HD 315023	2015-04-07	1.07	151.9	1.29	151.0	1.38	151.1	1.35	151.7	1.33 ± 0.52	682 ± 25	1.39 ± 0.02	0.21 ± 0.06	
HD 165319	2015-10-16	1.14	58.4	1.16	60.8	1.07	61.7	0.87	63.2	1.58 ± 0.12	511 ± 10	1.18 ± 0.01	1.25 ± 0.13	
HD 167838	2016-03-13	0.29	91.6	0.32	97.2	0.30	101.7	0.27	108.5				4.76 ± 0.21	
BD-13 4920	2015-04-07	2.92	71.2	3.28	71.4	3.22	71.5	2.91	71.5	1.41 ± 0.03	587 ± 2	3.31 ± 0.00	0.07 ± 0.03	
HD 168076	2015-05-30	3.07	67.1	3.38	66.4	3.30	65.8	2.99	65.3	1.31 ± 0.02	576 ± 1	3.41 ± 0.01	-0.52 ± 0.03	
HD 169454	2016-03-13	1.91	16.7	2.12	14.9	2.07	13.6	1.92	12.5	1.12 ± 0.08	585 ± 8	2.13 ± 0.01	-1.03 ± 0.05	
HD 170740	2016-03-15	1.84	78.2	1.97	77.4	1.90	76.8	1.71	76.2	1.35 ± 0.06	561 ± 4	1.99 ± 0.01	-0.58 ± 0.04	
HD 170938	2015-11-08	3.62	117.6	3.90	118.4	3.68	119.2	3.17	120.0	1.60 ± 0.04	552 ± 3	3.93 ± 0.02	0.63 ± 0.04	
HD 171957	2015-11-08	1.49	76.6	1.55	77.1	1.45	76.8	1.23	75.9	1.20 ± 0.06	501 ± 21	1.58 ± 0.01	-0.36 ± 0.08	
HD 172694	2015-06-02	1.01	141.8	1.02	146.3	0.98	147.9	0.89	148.0	0.67 ± 0.28	497 ± 32	1.03 ± 0.04	2.58 ± 0.23	14
HD 203532	2015-06-02	1.29	127.9	1.38	127.8	1.35	128.1	1.23	128.8	1.23 ± 0.05	574 ± 7	1.39 ± 0.03	0.24 ± 0.09	
HD 210121	2015-10-02	1.33	154.9	1.34	155.9	1.26	157.0	1.12	157.7	0.55 ± 0.12	434 ± 21	1.38 ± 0.02	0.86 ± 0.07	

Table A.3. Previously published Serkowski parameters for sightlines in common with LIPS.

STAR	Reference	Instrument	Best-fit parameters		
			K	$\lambda_{\max}$ (nm)	$P_{\max}$ (%)
HD 37903	(This work)	HPOL	0.73 ± 0.11	657 ± 10	1.95 ± 0.01
	Efimov (2009)		1.35	680	2.00
	This work	FORS2	1.51 ± 0.23	646 ± 8	1.82 ± 0.01
HD 38087	(This work)	HPOL	1.25 ± 0.21	585 ± 12	2.79 ± 0.02
	This work	FORS2	1.18 ± 0.04	572 ± 5	2.59 ± 0.01
HD 43384	Wilking et al. (1980)	FORS2	0.97 ± 0.04	560 ± 10	3.00 ± 0.04
	This work	FORS2	0.92 ± 0.03	566 ± 2	3.06 ± 0.01
Walker 67	Wilking et al. (1980)		1.39 ± 0.09	810 ± 2	5.31 ± 0.06
	This work	FORS2	1.40 ± 0.05	826 ± 3	5.20 ± 0.04
HD 108639	Heiles (2000)		0.87 ± 0.13	520 ± 10	1.91 ± 0.02
	This work	FORS2	1.29 ± 0.23	550 ± 5	1.92 ± 0.04
HD 147888	Wilking et al. (1982)		1.29 ± 0.05	720 ± 10	3.75 ± 0.07
	Martin et al. (1992)		1.28 ± 0.04	700 ± 10	3.63 ± 0.04
	(This work)	HPOL	1.51 ± 0.04	672 ± 20	3.53 ± 0.01
	This work	FORS2	1.43 ± 0.02	662 ± 4	3.49 ± 0.01
HD 147889	Wilking et al. (1980)		1.32 ± 0.05	800 ± 10	4.09 ± 0.07
	Martin et al. (1992)		1.25 ± 0.03	780 ± 10	4.02 ± 0.04
	This work	FORS2 (2015-05-13)	1.32 ± 0.02	809 ± 4	4.22 ± 0.01
	This work	FORS2 (2015-05-25)	1.37 ± 0.04	798 ± 7	4.18 ± 0.01
	This work	FORS2 (2016-01-28)	1.18 ± 0.09	815 ± 13	4.18 ± 0.01
HD 161056	Wilking et al. (1980)		0.96 ± 0.09	560 ± 2	3.8 ± 0.1
	(This work)	HPOL	1.3 ± 0.02	578 ± 1	4.08 ± 0.01
	This work	FORS2	1.43 ± 0.05	572 ± 2	4.02 ± 0.04
HD 164740	Wilking et al. (1982)		1.24 ± 0.12	670 ± 20	7.75 ± 0.15
	Martin et al. (1992)		1.24 ± 0.07	670 ± 10	7.45 ± 0.14
	This work	FORS2	1.72 ± 0.02	657 ± 2	7.20 ± 0.02
HD 210121	Larson (1999)		0.66 ± 0.09	380 ± 30	1.32 ± 0.04
	(This work)	HPOL	0.65 ± 0.15	402 ± 50	1.37 ± 0.06
	This work	FORS2	0.55 ± 0.12	434 ± 21	1.38 ± 0.02
HD 251204	(This work)	HPOL	1.25 ± 0.11	584 ± 7	4.95 ± 0.03
	This work	FORS2	1.00 ± 0.02	575 ± 2	5.00 ± 0.01

Notes. [Wilking et al. \(1980\)](#) and [Martin et al. \(1992\)](#) report updated Serkowski parameters from compilations of broad-band polarimetric data. The best-fit parameters from HPOL were obtained in this work using data made available at the Mikulski Archive for Space Telescopes (MAST).

Fig. A.1. Polarisation, position angle and flux (in arbitrary units) for the some of our targets as shown by the labels. Red symbols refer to data obtained with the order-separating filter GG435, blue symbols to the data obtained with no filter. In the plots showing the polarisation, the black solid line is the best-fit obtained with the Serkowski curve on the average data, while in the plots showing the position angle the black solid line shows the best-fit obtained with a first order polynomial. Green solid lines represent flux non corrected for the instrument and telescope transmission functions.

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