Dual-Beam Optical Linear Polarimetry from Southern Skies.
Characterisation of CasPol for high precision polarimetry

M. S. Sosa\textsuperscript{a,b,*}, C. von Essen\textsuperscript{c}, I. Andruchow\textsuperscript{a,b,e}, S. A. Cellone\textsuperscript{a,d,e}, and L. A. Mammana\textsuperscript{d}

\textsuperscript{a}Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque, B1900FWA, La Plata, Argentina
\textsuperscript{b}Instituto de Astrofísica de La Plata (CCT-La Plata, CONICET-UNLP), Paseo del Bosque, B1900FWA, La Plata, Argentina
\textsuperscript{c}Stellar Astrophysics Centre, Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark
\textsuperscript{d}Complejo Astronómico El Leoncito (CONICET-UNLP-UNC-UNSJ), Av. España 1512 Sur, San Juan, Argentina
\textsuperscript{e}Consejo Nacional de Investigaciones Científicas y Técnicas, Godoy Cruz 2290, C1425FQB, Ciudad Autónoma de Buenos Aires, Argentina

**ABSTRACT**

We present a characterization of CasPol, a dual-beam polarimeter mounted at the 2.15 meter Jorge Sahade Telescope, located at the Complejo Astronómico El Leoncito, Argentina. The telescope is one of the few available meter-sized optical telescopes located in the Southern
Hemisphere hosting a polarimeter. To carry out this work we collected photo-polarimetric data along five observing campaigns, the first one during January, 2014, and the remaining ones spread between August, 2017 and March, 2018. The data were taken through the Johnson-Cousins V, R and I filters. Along the campaigns, we observed eight unpolarized and four polarized standard stars. Our analysis begun characterizing the impact of seeing and aperture into the polarimetric measurements, defining an optimum aperture extraction and setting a clear limit for seeing conditions. Then, we used the unpolarized standard stars to characterize the level of instrumental polarization, and to assess the presence of polarization dependent on the position across the charge coupled-device. Polarized standard stars were investigated to quantify the stability of the instrument with wavelength. Specifically, we find that the overall instrumental polarization of CasPol is $\sim 0.2\%$ in the $V$, $R$ and $I$ bands, with a negligible polarization dependence on the position of the stars on the detector. The stability of the half-wave plate retarder is about 0.35 degrees, making CasPol comparable to already existing instruments. We also provide new measurements in the three photometric bands for both the unpolarized and polarized standard stars. Finally, we show scientific results, illustrating the capabilities of CasPol for precision polarimetry of relatively faint objects.

**Keywords:** Polarization - instrumentation: polarimeters - methods: observational - methods: data analysis - techniques: polarimetric - (galaxies:) BL Lacertae objects: individual: 1ES 1101-232

1. INTRODUCTION

The first modern polarimetric observations were scheduled to study the reflective properties of the Moon.$^{1,2}$ A century later,$^3$ predicted the optical radiation emitted by early-type stars to be polarized. This was the early beginning of a new branch of observational astronomy, setting the path to discoveries such as the Serkowski’s law.$^4$ BL Lac objects, a type of active galactic nuclei, have shown high and variable optical linear polarization owing to synchrotron radiation.$^5$ In
these cases, the power of polarimetric measurements relies on the information that they provide on the geometry and orientation of the magnetic field of these sources,\textsuperscript{6–8} which is not possible to obtain from photometric data alone.

The Southern Hemisphere hosts a variety of optical telescopes that can be used to study polarized light of astronomical sources. Examples are the $4 \times 8.2$ meter \textit{Very Large Telescopes}, located in Chile. Each one of these telescopes independently hosts several instruments for polarimetric studies, such as NACO\textsuperscript{9,10} and SPHERE,\textsuperscript{11} both focused in the near infrared wavelengths. Another example is the \textit{Gemini Planet Imager} (GPI) at the 8 m Gemini South telescope, capable of polarimetric imaging at diffraction-limited spatial resolution in the near infrared.\textsuperscript{12} These extremely powerful tools permit researchers to study in detail light from a large variety of sources. However, due to their frontier technology they are highly oversubscribed, making polarimetric follow-up campaigns of single objects and/or surveys involving large samples unlikely to be scheduled. These observations would then rely on meter-sized telescopes with high precision instruments. Examples of such instruments, located in the Southern Hemisphere, are the 84 cm \textit{Robotic Telescope} at Cerro Tololo, Chile.\textsuperscript{13} Although this instrument can collect high quality polarimetric data in the optical, it is not so suitable to follow-up intrinsically faint objects that are expected to show photo-polarimetric variability, such as blazars, with apparent magnitudes usually fainter than $R \sim 17$.\textsuperscript{14}

The Complejo Astronómico El Leoncito (CASLEO), located next to the Andes mountains in Argentina, hosts a dual-beam polarimeter, CasPol. This instrument provides one of the few available means to carry out optical photo-polarimetric measurements of relatively faint targets from the South, with a telescope that is not heavily over-subscribed. CasPol has been already used to study asteroids,\textsuperscript{15,16} and is currently used to study the photo-polarimetric microvariability of blazars (Sosa et al., in prep.). These celestial objects, of our particular interest, are expected to show photo-polarimetric variability of the order of few hours to days, making follow-up campaigns relevant for their study.\textsuperscript{17–19} In this work we present an in-detailed charac-
terization of the instrumental polarization of CasPol, along with a thoughtful description of the impact of seeing and aperture into our derived polarimetric measurements. From this analysis, we set clear limits to the observing conditions under which precision measurements should be done. In Section 3 we present our collected data, our reduction techniques and a brief description of the construction of the polarimetric data points. In Section 4 we describe the impact of seeing and aperture onto the derived polarimetric measurements, we study the instrumental polarization along and across the CCD, and we investigate the dependency of polarization angle with wavelength. Furthermore, we characterize the potential impact that flat-fielding the science frames has on the derived polarization values. We then give an illustrative example with results on the blazar 1ES 1101–232, closing in Section 5 with discussion and conclusive remarks.

2. GENERALITIES ABOUT CASPOL

The dual-beam polarimeter CasPol follows a similar design to the IAGPOL and the DBIP polarimeters. CasPol is mounted at the Cassegrain focus of the 2.15 meter Jorge Sahade telescope. The associated charge-coupled device is a 16 bits CCD TEK of $1024 \times 1024$ pixels, with a plate scale of 0.27 arcsec/pixel. The optical setup provides an unvignetted, circular field of view with a diameter of $\sim 4$ arcmin. CasPol consists basically of a unit with a mechanical shutter, a filter wheel with $UBVRI$ Johnson filters (the unfiltered option is also available), a neutral filter strip, a half-wave plate retarder (HWP) and a Savart plate. These two last optical elements have antireflectant coatings between 400 and 800 nm. The HWP can rotate in steps of 22.5 degrees, determined by software. Nonetheless, the angle can be changed upon request. The Savart plate produces two orthogonal images of the objects in the field, the so-called ordinary ($O$) and the extraordinary ($E$) beams. These are separated 0.9 mm, which is equivalent to 10.2 arcsec on the sky. This relatively small separation will constrain the seeing at which polarimetric data should be collected (see Section 4.1). Fig. 1, left, shows CasPol’s field of view around the blazar 1ES 1101–232. The original frame has been masked to minimize visual contamination produced by the vignetted region. The corresponding seeing (full width at half maximum, FWHM)
Fig 1: Typical field of view of CasPol. (a) The blazar 1ES 1101-232\textsuperscript{22} is placed at the centre of the field. The image has been masked to avoid visual contamination by the vignetted area. The double image is caused by the superposition of the $O/E$ beams. The white circle labelled with a number 4 indicates the star used to create Fig. 2. (b) A comparison of the field taken from Aladin. The black circle indicates the approximate coinciding area. As shown in the image, North is up and East is right. 

is 2 arcsec, and has been estimated from the stars in the field. The figure on the right panel shows an image taken from Aladin Sky Atlas and is placed there as comparison. The black circle indicates approximately coinciding fields.

Fig. 2 shows the angular separation between the ordinary and extraordinary beams for the star directly North of the blazar (indicated with #4 in Fig. 1, left), plotted in arcseconds and in $2 \times 2$ binned pixels, as comparison. The figure was performed over-plotting several diagonal cuts of the science frame in the vicinity of the mentioned star, thus revealing the maximum count rate and its variation with increasing distance to the $O/E$ centroids.

3. OBSERVATIONS AND DATA HANDLING

The dual-beam imaging system is very convenient.\textsuperscript{21} Through the simultaneous observations of both beams (along with the sky background), photometric conditions can be relaxed, be-
cause polarization due to moonlight or dust in our atmosphere is exactly compensated. More importantly, the dual-beam imaging system compensates for photometric variability due to atmospheric turbulence, and cancels out unwanted noise caused by passing clouds, water vapor and aerosols, among others. This observational benefit comes very handy for measurements involving extremely low polarization values, as it is the case of polarization of reflected light by exoplanets.\textsuperscript{23,24} Here, the polarization levels tend to be of the order of $P \sim 10^{-3} - 10^{-4}$. In the particular case of CasPol, due to the small angular separation between the $O/E$ beams, the instrument is mostly suitable for the observation of point sources.

To carry out a thorough characterization of the instrumental polarization of CasPol, we have been granted telescope time along five observing campaigns (OCs) along dark nights exclusively, taking place during January, 2014 (OC-1), August, 2017 (OC-2), October, 2017 (OC-3), January, 2018 (OC-4) and March, 2018 (OC-5). During these campaigns we observed twelve polarized and unpolarized standard stars, along with one astronomical source of our particular interest. The standard stars were mostly taken from,\textsuperscript{25} which provides a list of standards in good agreement with the visibility during our campaigns. Further standard stars observed and presented in this
Table 1: From left to right we detail the name, right ascension ($\alpha$) and declination ($\delta$) in J2000.0, the visual apparent magnitude, $V$, the corresponding bibliographic reference number (R. #), the nature (T) of the targets, the observing time (Obs. Date), the number of nights in which these were observed (N), the filter and the collected number of polarimetric points along the five OCs (F # points). P and nP correspond to polarized and non-polarized standard stars, respectively. The standard stars were taken from\(^{25}\) (Ref. #1),\(^{26}\) (Ref. #2),\(^{27}\) (Ref. #3),\(^{28}\) (Ref. #4),\(^{29}\) (Ref. #5) and\(^{22}\) (Ref. #6).

| Name | $\alpha$ (J2000.0) | $\delta$ (J2000.0) | $V$ [mag] | R# | T | Obs. Date | N | F(# points) |
|------|-------------------|--------------------|-----------|----|----|-----------|---|-------------|
| HD 10038 | 01:37:18.59 | $-40:10:38.5$ | 8.14 | 1 | nP | 2017/10/17 | 1 | $V(16)$, $R(15)$ |
| HD 12021 | 01:57:56.14 | $-02:05:57.7$ | 8.8 | 5 | nP | 2017/08/27 | 1 | $R(2)$ |
| NGC 2024 | 05:41:37.85 | $-01:54:36.5$ | 12.2 | 2 | P | 2018/01/21 | 1 | $V(1)$, $R(1)$, $I(1)$ |
| HD 38393 | 05:44:27.79 | $-22:26:54.2$ | 3.60 | 4 | nP | 2014/01/28 | 1 | $V(2)$, $R(2)$ |
| HD 42078 | 06:06:41.04 | $-42:17:55.7$ | 6.16 | 1 | nP | 2018/03/14-17 | 6 | $V(10)$, $R(11)$, $I(5)$ |
| HD 64299 | 07:52:25.51 | $-23:17:46.8$ | 10.01 | 1 | nP | 2018/01/20-21 | 3 | $V(4)$, $R(4)$, $I(3)$ |
| Ve6 23 | 09:06:00.01 | $-47:18:58.2$ | 12.12 | 2 | P | 2018/01/28-31 | 10 | $V(10)$, $R(12)$, $I(6)$ |
| HD 298383 | 09:22:29.76 | $-52:28:57.4$ | 9.75 | 3 | P | 2014/01/29-31 | 3 | $V(4)$, $R(5)$, $I(3)$ |
| HD 94851 | 10:56:44.17 | $-20:39:51.6$ | 9.29 | 3 | nP | 2018/01/20-22 | 3 | $V(15)$, $R(16)$, $I(15)$ |
| HD 97689 | 11:13:50.75 | $-52:51:21.2$ | 6.82 | 1 | nP | 2018/03/14-17 | 4 | $V(3)$, $R(3)$, $I(3)$ |
| BD-125133 | 18:40:01.70 | $-12:24:06.9$ | 10.40 | 1 | P | 2017/08/28 | 1 | $V(2)$, $R(2)$ |
| HD 176425 | 19:02:08.52 | $-41:54:37.8$ | 6.21 | 1 | nP | 2017/08/28 | 1 | $V(2)$, $R(2)$ |
| 1ES 1101-232 | 11:03:37.61 | $-23:29:31.20$ | 16.55 | 6 | blazar | 2018/03/16 | 1 | $R(21)$ |

work can be found under,\(^{26},^{27}\) and.\(^{28}\) The stars observed during the five campaigns, along with the relevant information about the collected data, can be found in Table 1. The visual apparent magnitudes and the right ascension and declination were extracted from the literature, which is also detailed in the Table.

### 3.1 Data reduction

We performed the data reduction and extraction of the $O/E$ fluxes analyzing all the OCs in an homogeneous way. For this end we used usual photometric packages of IRAF (CCDPROC/CCDRED), along with IRAF’s scripts created by our research group. All science frames are bias-subtracted. Between campaigns, CasPol was mounted on and dismounted off the telescope. Thus, the position of the shadows of the defocused dust grains that are usually registered by flat-fields changed
between campaigns. As a consequence, only when flat-fields taken during a given campaign were available, we also flat-fielded the images. These were taken together with the science frames using the exact same optical setup regarding the used filter, the binning, and the angles of the half-wave plate at which the standard stars were observed. In this work, the science frames corresponding to OC-2 and OC-3 are not calibrated by flats, while the ones corresponding to OC-1, OC-4 and OC-5, are (see Section 4.5 for a detailed analysis). We computed photometric fluxes using our own IRAF task, \textsc{multifot}. The task runs phot interactively, and is suitable to automatically extract $O/E$ fluxes from the science frames. We integrated fluxes in several apertures to investigate the impact of its choice on the derived polarimetric values (see Section 4.1 for an analysis in more detail).

3.2 Construction of polarimetric points

To construct the Stokes $Q$ and $U$ parameters, we followed\textsuperscript{30} and computed the intermediate values,

\begin{align}
R_Q^2 &= \frac{I_O^0 / I_E^0}{I_O^{45} / I_E^{45}}, \\
R_U^2 &= \frac{I_O^{22.5} / I_E^{22.5}}{I_O^{67.5} / I_E^{67.5}},
\end{align}

(1)

taking into account that one polarimetric point was observed rotating the half-wave plate retarder to angles of 0, 22.5, 45 and 67.5 degrees. In general, $I_O^\beta$ and $I_E^\beta$ are the object ordinary and extraordinary integrated fluxes, respectively, and $\beta$ is the position angle of the half-wave plate.\textsuperscript{18,31} The Stokes parameters are then computed from these values as:

\begin{align}
Q &= \frac{R_Q - 1}{R_Q + 1}, \\
U &= \frac{R_U - 1}{R_U + 1}.
\end{align}

(2)

Based on these parameters, we calculated the degree of linear polarization and corresponding
polarization angle in the usual way:

\[ P = \sqrt{Q^2 + U^2}, \quad \Theta = \frac{1}{2} \arctan \left( \frac{U}{Q} \right). \]  

(3)

Error estimates for the Stokes \( Q \) and \( U \) parameters, the polarization degree and the polarization angle, are computed following standard error propagation techniques. These, in turn, depend on the uncertainties on the fluxes given by IRAF’s `phot`. Here, the error associated to a flux measurement is based on three terms. These are the photon noise within the aperture, the standard deviation of the pixels comprising the sky ring that are used to determine the background, and a term that accounts for the uncertainty in the background level.\(^{32}\) Our derived error estimates were verified with and compared to the ones available in.\(^{33}\) Our uncertainties for the polarization degree, \( \sigma_P \), and the polarization angle, \( \sigma_\Theta \), are:

\[ \sigma_P = \left( Q^2 \sigma_Q^2 + U^2 \sigma_U^2 \right)^{1/2} \frac{1}{P}, \quad \sigma_\Theta = \left( Q^2 \sigma_Q^2 + U^2 \sigma_U^2 \right)^{1/2} \frac{1}{2P^2}. \]  

(4)

As pointed out by,\(^{32}\) it is known that the photometric errors determined by IRAF are underestimated and, in consequence, individual errors on \( P \) and \( \Theta \) are underestimated as well. However, it is worth to mention that when computing polarimetric measurements from a set of points, we always computed errors in two ways. These are from error propagation, and computing the standard error of the mean for objects assumed to be non-variable. The latter uses the natural scatter of the data and, thus, reflects more realistically the precision of our measurements.

Since polarization is positive-definite, when calculating the polarization degree the noise in their involved quantities contribute in a positive way, producing biased results. This has been addressed by numerous authors,\(^{34–36}\) also detailed in.\(^{19}\) To correct for this bias, for all the unpolarized standard stars we computed the unbiased degree of linear polarization, \( P_{\text{unbiased}} \),
using the expression found in\textsuperscript{35}

\begin{equation}
P_{\text{unbiased}} = \sqrt{P^2 - a \times \sigma P^2}. \tag{5}\end{equation}

Here, $P_{\text{unbiased}}$ was computed using the maximum likelihood estimator that can be found in their work ($a = 1.41$) and $\sigma P = (\sigma Q + \sigma U)/2$. To determine when it is necessary to apply the bias correction, we followed the selection criteria adopted and described in\textsuperscript{36} The authors assume that a given celestial object is polarized if the lower confidence limit (95\%) of $P$ is $>0$. In this case, $P_{\text{unbiased}}$ is obtained computing Eq. 5. If $P$ is consistent with 0, then, an upper limit is assigned to $P$ considering the upper 95\% confidence limit. The corrected values of polarization, $P_{\text{unbiased}}$, are listed in Tables 2, 3, and shown in Fig. 7, 8 and 9.

4. RESULTS

4.1 Testing the impact of seeing and aperture on our polarimetric measurements

The data collected during the five observing campaigns comprise different observing conditions, mostly reflected as changes of airmass and seeing during observations. In order to compare the photo-polarimetric values derived from these data, it is fundamental to find an extraction aperture common to all the campaigns that both minimizes the scatter of the polarimetric measurements and maximizes the signal-to-noise ratio of the individual points. As shown in previous sections, the separation between ordinary and extraordinary beams is fixed to 10.2 arcsec (equivalently, $\sim 38$ unbinned pixels). To avoid the inclusion of a significant amount of flux from the extraordinary beam within the aperture centred on the ordinary image (and vice versa), one half of this separation should not be exceeded.

To sample the effects of aperture and seeing adequately, we measured $O/E$ fluxes for all the unpolarized standard stars with circular aperture radii ranging from $\sim 0.5$ to $\sim 7$ arcsec with steps of $\sim 0.5$ arcsec (equivalently, from 2 to 26 pixels, each 2 pixels). For all the derived
polarimetric measurements we observe a similar behaviour, but for a better and clear visualization we only shown the results of some representative targets in Fig. 3. For apertures lower than the mean full-width at half maximum (FWHM) of a given polarimetric point, the derived polarimetric values and their scatter are large and inconsistent with zero. Due to the rapid changes in seeing during observations, the shape of the point-spread functions (PSFs) suffer irregular deformations, which differ between the $O/E$ beams. These deformations are enhanced at the core of the PSFs. Thus, when integrating within small apertures (i.e., mostly the cores at typical values of seeing of 2-3 arcsec) these differences translate into the systematic increase of polarimetric scatter. For larger apertures, particularly larger than half the angular separation between $O/E$ beams, we observe again an increment in the polarimetric scatter, but not as large as for apertures smaller than the FWHM. This effect is caused because the wings of the extraordinary beam contribute significantly to the flux within the photometric aperture of the ordinary image (and vice versa), and it can be especially noted during observing nights with poor seeing. Taking these aspects into consideration, for nights when the seeing was low ($\sim 2$ arcsec or lower) aperture sizes can reliably range from 3.5 up to 5 arcsec. If seeing is large (typically 3-4 arcsec) or significantly variable during an observing run, it is convenient to take larger apertures but always smaller than half the separation between the $O/E$ centroids. To consider these aspects simultaneously, throughout this work fluxes are integrated using apertures of 5 arcseconds. This value was obtained by fitting a second-order polynomial —through a simple least-squares minimization technique— to the aperture-dependent polarimetric points (the minimum of the polynomial is exactly at 4.67 arcsec), and to their scatter (4.95 arcsec, respectively). The final value of 5 arcsec conservatively considers these two aspects. It is worth to mention that observations taken with seeing larger than $\sim 6$ arcsec should not be used for scientific purposes, because of the contamination between the $O/E$ beams. On the other hand, seeing values between $\sim 2$ and $\sim 5$ arcsec should not be necessarily thought as bad, especially if seeing is constant along the night. In sparse fields, the natural defocusing that these seeing
Fig 3: *Top:* values of polarization degree in percentage for three unpolarized standard stars as a function of photometric aperture size, in arcsec. Different minor horizontal offsets where applied for a better visualisation. *Bottom:* their respective means (dots) and standard deviations (bars), focused on polarization degrees smaller than 1%. These were obtained averaging all polarimetric measurements per aperture.

values produce can significantly improve the photometric precision of CCD data, because the noise associated to the intra-pixel response variability can be better averaged out when the PSFs are spread over many pixels. This is particularly relevant for telescopes without guiding system, and can boost the photo-polarimetric precision of astronomical data.

4.2 Instrumental polarization

All polarimeters have sources that can introduce instrumental polarization that need to be carefully removed to faithfully recover the true polarization. Specifically, design factors and optical setup. Possibly, in CasPol the main contribution arises within the telescope mirrors. To characterize the level of instrumental polarization introduced by CasPol, we focused our analysis on the in-depth study of three unpolarized standard stars that were observed during OC-2, OC-3 and OC-5, namely HD 42078, HD 97689 and HD 176425. Even though our sample of unpolarized standard stars is larger than these three, some of them present additional challenges that we consciously wanted to avoid when characterizing the level of instrumental polarization of
CasPol. For instance, HD 64299 has been initially catalogued as being an unpolarized standard star. However, in a subsequent work a 0.1% polarization level was detected. In addition, HD 94851 and HD 10038 were not included in this analysis because they were observed purposely in different positions across the CCD. These observations were used to characterize the instrumental polarization dependent on position. To minimize contamination introduced by instrumental artifacts, such as potential polarization dependent on position, the three unpolarized standard stars were placed at the exact same positions, coinciding with the centre of the CCD.

To compute the averaged Stokes $Q$ and $U$ parameters we used the data corresponding to the three unpolarized standard stars collected along the three observing campaigns. Before doing so, we visually inspected the Stokes $Q - U$ values to identify and discard outliers. To do so, we made use of the Generalized Extreme Studentized Deviate (ESD) test. The test can be used for a data set which follows approximately a normal distribution. In our case, a given point was identified as outlier if the distances to its right and left neighbours are abnormal as judged by the generalized ESD. As a conservative distance we used five times the standard deviation of the points. A posterior individual checkup of the outliers resulted in corresponding poor photometric signal. Then, for each one of the stars we computed the differences between the averaged $(Q, U)$ values and the ones tabulated in the literature, and averaged these differences among the three stars to arrive to the final instrumental polarization. The three unpolarized standard stars do not have published values for both $R$ and $I$. However, between 2010 and 2016 observed these stars in the mentioned filters. Rather than reporting final values for their polarization state, the authors provide the individual values along with an estimate of the signal-to-noise ratio (SNR) of their measurements. Thus, as reference we used the values that show the largest SNR. Errors were computed in two ways, from error propagation and computing the standard error of the mean, $\sigma/\sqrt{n}$. Here, $\sigma$ corresponds to the standard deviation of the Stokes parameters, and $n$ to the number of polarimetric points. To be as conservative as possible, we chose as final error the largest one of these two. For each photometric band we repeated the same procedure. Table 2
Table 2: Derived values for the instrumental polarization of CasPol as a function of the photometric band. Uncertainties are given at 1 σ level.

| Band | $Q$ (%) | $U$ (%) | $P$ (%) | $P_{\text{unbiased}}$ (%) |
|------|---------|---------|---------|---------------------------|
| $V$  | $-0.12 \pm 0.03$ | $0.10 \pm 0.05$ | $0.16 \pm 0.03$ | $0.15 \pm 0.03$ |
| $R$  | $-0.10 \pm 0.06$ | $0.03 \pm 0.06$ | $0.10 \pm 0.06$ | $< 0.22$ |
| $I$  | $-0.03 \pm 0.08$ | $0.09 \pm 0.04$ | $0.09 \pm 0.05$ | $< 0.19$ |

shows our derived values for the instrumental polarization of CasPol, for the $V$, $R$ and $I$ filters. We find the level of instrumental polarization of CasPol to be lower than $\sim 0.2\%$.

4.3 Polarized standard stars

To compare our derived polarimetric measurements with values from the literature, after correcting for instrumental polarization it is required to convert our measurements to the standard system. To do so, we observed four polarized standard stars during our observing campaigns. To determine the adequate rotation angle in order to rotate the data to the standard system we analyzed the polarimetric data of only three of them, namely NGC 2024, Ve6-23 and HD 298383. The procedure was similar to the one carried out to analyze the unpolarized standard stars. From the averaged Stokes $Q$ and $U$ values, we computed the observed polarization angle and the correction angle in the following way: $\Delta \theta = \theta_{\text{bib}} - \langle \theta_{\text{obs}} \rangle$. Here, $\theta_{\text{bib}}$ corresponds to the published polarization angle of the polarized standard stars, while $\langle \theta_{\text{obs}} \rangle$ corresponds to the observed polarimetric angle determined from our averaged $Q$ and $U$ values. We carried out this procedure for each polarized standard star and each photometric band. Afterwards, we computed a correction per filter, averaging the individual corrections determined from each one of the three stars. The derived values are $\Delta \theta_V = -4.2 \pm 0.2$ degrees, $\Delta \theta_R = -4.3 \pm 0.6$ degrees, and $\Delta \theta_I = -4.2 \pm 0.7$ degrees.

After characterizing the instrumental polarization of CasPol and determining the $\Delta \theta$ that allows us to report values in the standard system, we corrected all the remaining unpolarized
and polarized standard stars by both effects, always in the Stokes $Q - U$ plane. The resulting values are listed in Table 3 for the unpolarized stars, and Table 4 for the polarized stars. In most cases, we can assess the goodness of our procedure by comparing the polarization level between CasPol and the values reported in the literature. In the remaining cases, there were no reported values for polarization in all (or some) of our three observed bands. In consequence, for several unpolarized and polarized standard stars we also report, for the first time, their wavelength-dependent polarization degree and angle. This holds right for HB 12021, HD 38393, HD 64299 and HD 298383. In almost all cases, our derived quantities for the polarized stars in the $V$ band are in agreement at $1 \sigma$ level with published values. In the case of the unpolarized stars, this percentage is about 50%.

An usual way to test the stability of a polarimeter in the different wavelengths is by analyzing the behaviour of polarization as a function of colour. The polarization generated by interstellar dust is a component associated with the Galaxy, generated by the orientation of interstellar dust particles with respect to the magnetic field of the Milky Way. Since we are sampling different grain populations with different sizes, composition and shapes for a constant position angle, we expect to observe a constant change rate between wavelength and polarization. To test the stability of CasPol we observed the polarized standard stars in the Johnson-Cousins $V$, $R$ and $I$ filters. Fig. 4 shows the derived values for the polarization degree, the Stokes $Q$ and $U$ parameters, and the polarization angle for Ve6 23. The same polarized standard star was observed and analyzed by (Vela 1 95), allowing for a comparison between results. As a main difference, data present a continuous wavelength coverage between 4000 to 9500 Å, while our observations comprise only three broad-band photometric filters. Nonetheless, to compare our results with we fitted to our polarimetric values the Serkowski’s law:

$$p(\lambda)/p_{\text{max}} = \exp[-K \ln^2(\lambda_{\text{max}}/\lambda)],$$

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**Table 3:** Stokes $Q$ and $U$ values, and polarization degree for the unpolarized standard stars observed during OC-1 to OC-5, corrected by instrumental polarization and rotated to the standard system. Errors are at $1\sigma$ level. When available, the last column shows published values for the polarization degree.

| Name    | Filter | $Q_{\text{CasPol}}$ (%) | $U_{\text{CasPol}}$ (%) | $P_{\text{CasPol}}$ (%) | $P_{\text{unbiased}}$ (%) | $P_{\text{pub}}$ (%) |
|---------|--------|--------------------------|--------------------------|--------------------------|----------------------------|----------------------|
| HD 42078 | $V$    | 0.10 ± 0.03              | 0.04 ± 0.09              | 0.12 ± 0.06              | 0.09 ± 0.07                | 0.07 ± 0.01          |
|         | $R$    | 0.13 ± 0.1               | −0.08 ± 0.1              | 0.19 ± 0.1               | < 0.39                     | ...                  |
|         | $I$    | 0.08 ± 0.07              | 0.03 ± 0.1               | 0.09 ± 0.08              | < 0.25                     | ...                  |
| HD 97689 | $V$    | 0.05 ± 0.02              | −0.11 ± 0.02             | 0.12 ± 0.02              | 0.12 ± 0.02                | 0.14 ± 0.08          |
|         | $R$    | 0.00 ± 0.05              | −0.04 ± 0.08             | 0.04 ± 0.08              | < 0.2                      | ...                  |
|         | $I$    | −0.04 ± 0.2              | 0.02 ± 0.1               | 0.04 ± 0.2               | < 0.44                     | ...                  |
| HD 176425 | $V$   | 0.18 ± 0.04              | −0.09 ± 0.01             | 0.20 ± 0.04              | 0.19 ± 0.04                | 0.17 ± 0.03          |
|         | $R$    | 0.17 ± 0.02              | −0.04 ± 0.02             | 0.18 ± 0.02              | 0.18 ± 0.02                | ...                  |
|         | $I$    | ...                      | ...                      | ...                      | ...                        | ...                  |
| HD 94851 | $V$    | 0.15 ± 0.04              | −0.03 ± 0.02             | 0.15 ± 0.04              | 0.14 ± 0.04                | ...                  |
|         | $R$    | 0.02 ± 0.02              | 0.00 ± 0.01              | 0.02 ± 0.02              | < 0.06                     | ...                  |
|         | $I$    | −0.10 ± 0.04             | 0.02 ± 0.02              | 0.10 ± 0.04              | 0.09 ± 0.04                | ...                  |
| HD 10038 | $V$    | 0.12 ± 0.01              | −0.15 ± 0.02             | 0.19 ± 0.01              | 0.19 ± 0.01                | 0.11 ± 0.01          |
|         | $R$    | 0.01 ± 0.07              | −0.04 ± 0.08             | 0.05 ± 0.07              | < 0.19                     | ...                  |
|         | $I$    | ...                      | ...                      | ...                      | ...                        | ...                  |
| HD 12021 | $V$    | ...                      | ...                      | ...                      | ...                        | 0.078 ± 0.018        |
|         | $R$    | −0.00 ± 0.43             | −0.10 ± 0.2              | 0.10 ± 0.1               | < 0.3                      | ...                  |
|         | $I$    | ...                      | ...                      | ...                      | ...                        | ...                  |
| HD 38393 | $V$    | 0.12 ± 0.07              | −0.11 ± 0.07             | 0.16 ± 0.07              | 0.14 ± 0.08                | 0.0006 ± 0.0003      |
|         | $R$    | 0.09 ± 0.07              | −0.19 ± 0.09             | 0.21 ± 0.07              | 0.19 ± 0.08                | ...                  |
|         | $I$    | ...                      | ...                      | ...                      | ...                        | ...                  |
| HD 64299 | $V$    | 0.06 ± 0.02              | −0.06 ± 0.06             | 0.08 ± 0.05              | < 0.18                     | 0.06 ± 0.07          |
|         | $R$    | −0.02 ± 0.03             | −0.09 ± 0.03             | 0.09 ± 0.03              | 0.08 ± 0.03                | ...                  |
|         | $I$    | −0.13 ± 0.01             | −0.09 ± 0.00             | 0.16 ± 0.01              | 0.16 ± 0.01                | ...                  |
where the fitting parameters, $p_{\text{max}}$ and $K$, correspond to the peak polarization level and the width constant, respectively. Due to the discontinuous nature of our data, we used the value $\lambda_{\text{max}} = 5864$ Å reported by.\textsuperscript{26} To obtain the best fit values and their errors, we sampled from the posterior probability distributions using a Markov-chain Monte Carlo approach, all wrapped up in Python routines that make use of the PyAstronomy\textsuperscript{*} package. In this work, errors are given as 68.3\% highest probability density credibility intervals. Our derived values are $p_{\text{max}} = 8.17 \pm 0.05\%$, and $K = 0.96 \pm 0.10$, inconsistent to the ones reported by.\textsuperscript{26} We noted, however, that the authors also found an inconsistency with the values reported by.\textsuperscript{42} Changing $\lambda_{\text{max}}$ to 5606 Å,\textsuperscript{42} and re-fitting the polarization level and the width constant afterwards, results in $p_{\text{max}} = 8.08 \pm 0.03\%$, and $K = 1.28 \pm 0.03$. These values are in full agreement at 1\,\sigma level with.\textsuperscript{42} The reasons behind this incompatibility escape the scope of this paper; however, we believe they can be related to different transmission functions of the $I$-band filters, combined with different quantum efficiency drops of the CCDs, that strongly diverge around the $I$ wavelengths.

Fig. 5 shows our derived $Q$, $U$ values corrected for instrumental polarization for the three

\textsuperscript{*}http://www.hs.uni-hamburg.de/DE/Ins/Per/Czesla/PyA/PyA/index.html

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Fig 4: From top to bottom: values of the polarization degree and the Stokes $U$ and $Q$ parameters, in percentage, and the angle, in degrees, for the polarized standard star Ve6 23. The derived values are shown per photometric band. The widths of the lines correspond to the FWHM of the filter responses. The black line shows our best-fit Serkowski law. Black squares with error bars correspond to the values reported by.\textsuperscript{26}

To quantify the change in polarization with wavelength, we fitted to these data points a first order, wavelength-dependent polynomial, $f(\lambda) = a \lambda + b$, with parameters $a = -0.26 \pm 0.02$, and $b = -0.12 \pm 0.17$. The derived slope is consistent with the one observed by.\textsuperscript{26}
Fig 5: $Q/U$ diagram for Ve6 23 in percentage, as a function of wavelength. The black lines show the approximate range of $Q/U$ points.

The polarized standard stars also allow us to quantify the stability of the HWP retarder. Fig. 6 shows the residuals of the mean $\theta$ values for all our polarized standard stars that were in turn computed subtracting to each polarization angle the corresponding mean value of the polarization angle. The points are colour-coded in the usual way according to the photometric band, and different symbols correspond to different stars. The data points are plotted as a function of time in Julian dates, and have been arbitrarily shifted to allow for a better visual inspection of the individual campaigns. The four observing groups where polarized standard stars were observed can be clearly identified. We determined the stability of the HWP from the standard deviation of the residuals of the angles. We do not observe any systematic effect with wavelength. While the variability amplitudes are $Amp_V = 2.2$ deg, $Amp_R = 1.7$ deg, and $Amp_I = 1.4$ deg, the standard deviations are $\sigma_V = 0.55$, $\sigma_R = 0.39$, $\sigma_I = 0.45$ deg. Note, however, how the scatter of the residuals of the angles decreases towards the last two observing campaigns. During the first and second campaigns the seeing was high, almost reaching our imposed limit of 6 arcsec. Neglecting these campaigns and limiting our stability analysis to the last two, the averaged amplitude of variability is 1.8 deg, while the standard deviation of the residuals is $\Delta \theta = 0.35$ deg, averaged over all the bands.
Fig 6: Stability of the polarization angle of CasPol as a function of time in Julian dates (JD) along four observing campaigns. Our $V$, $R$ and $I$ measurements are colour-coded in the usual way. Different symbols correspond to different polarized standard stars.

4.4 Observed polarization with position on the CCD

To quantify the behaviour of instrumental polarization with position on the CCD, following\textsuperscript{33} we observed unpolarized standard stars in locations as homogeneously distributed as possible on the CCD. Here, we focus our analysis on the unpolarized standard stars HD 94851 and HD 10038. While the first one was observed in 12 different positions and in the three photometric bands, the second one was observed in 15 positions but only in the $V$ and $R$ bands. The measured polarimetric values for HD 94851, as a function of the $(X,Y)$ positions that correspond to the centroid of the O image, are shown in Fig. 7 exemplifying our results. The science frames were taken in the binning $2 \times 2$ configuration. In particular, the $(X,Y)$ positions are derived averaging the $(X,Y)$ coordinates of the centroids of the four images used to construct each polarimetric point, to account as much as possible for irregularities in the tracking of the telescope. The figures show a square contained within the unvignetted area of the CCD, where we placed the stars. The base of the arrows indicate the exact locations of the stars. The maps are a bi-linear interpolation of the sampled points.

To characterize the dependence of polarization with position of the star on the CCD, we
Fig 7: From top to bottom: map of polarization degree in percentage as a function of the X and Y positions of the O beams on the CCD for the V, R and I bands, respectively. Cyan arrows show the directions of their respective Stokes Q, U parameters corrected for instrumental polarization and rotated to the standard system; they have been equally enlarged to meet the scale of the figures.
computed the Pearson† and the Spearman‡ correlation coefficients between the polarization degree and the $X$ position, the $Y$ position, and the distance $d$ with respect to the centre of the CCD, following the pre-established tasks in the python-scipy library. To be conservative, the values listed in the second and fourth column of Table 5 always correspond to the largest value of the two correlation coefficients. The derived values do not show a strong correlation for the $V$ and $R$ bands, and only marginal for the $I$ band. Despite the magnitude of the derived values, it is important to evaluate the confidence interval of the correlation coefficients. For this end, we made use of the bootstrapping technique. Here, we kept the same polarization values fixed, but we randomly permuted their corresponding $X$, $Y$, and $d$ values $10^4$ times each. For each bootstrapped sample we computed the Pearson/Spearman correlation coefficient between the polarization degree and the permuted $X$, $Y$, and $d$ values. Then, we simply counted the number of times that the derived correlation was larger than the original one. After the total iterations were reached, we computed the percentage of exceeding the correlation coefficient as the number of times the correlations from the shuffled values were larger than the real one, divided by the total number of iterations. The strength of the correlation value is measured inversely to the derived percentage. Thus, a large percentage implies a weak correlation signal. In addition, from the $10^4$ correlation values computed for $X$, $Y$, and $d$ we determined their mean and standard deviations. In all cases, the mean values for the correlations were close to 0, while the standard deviations were of the order of 0.3. Thus, we interpret all correlation values between ±0.3 to be inconsequential.

To quantify stability in the polarimetric maps we computed two variability indices, namely the ratio of the standard deviation to the sample mean:

†https://docs.scipy.org/doc/scipy-0.14.0/reference/generated/scipy.stats.pearsonr.html?fbclid=IwAR0RfSg5ejqD0PpWkJrkgIveL1CG4smlxIXnZ-akF_rNX8KWAZoOuYDmFYc
‡https://docs.scipy.org/doc/scipy-0.15.1/reference/generated/scipy.stats.spearmanr.html?fbclid=IwAR1XLBuK1d1C-mJgfPbJdGJF9D130cZtTGHcwCnges-Dj2WbjPI--8yMko
Table 5: Correlation coefficients for $P$ vs. position on the CCD, corresponding to both unpolarized standard stars in $V$, $R$, $I$. Values for the original data points and the shuffled ones (sub-index S) are given (see text). $P$ corresponds to the polarization degree, $X$ and $Y$ to the CCD positions in pixels, and $d$ to the distance from the centre of the CCD.

|        | HD 94851 | HD 94851s (%) | HD 10038 | HD 10038s (%) |
|--------|----------|---------------|----------|---------------|
| $P/X$  | 0.06     | 90            | 0.22     | 50            |
| $P/Y$  | 0.07     | 80            | -0.20    | 49            |
| $P/d$  | 0.23     | 48            | -0.18    | 48            |
| $P/X$  | -0.35    | 26            | -0.03    | 87            |
| $P/Y$  | 0.24     | 43            | 0.35     | 22            |
| $P/d$  | -0.18    | 57            | -0.11    | 75            |
| $P/X$  | 0.35     | 21            | ...      | ...           |
| $P/Y$  | 0.46     | 10            | ...      | ...           |
| $P/d$  | 0.38     | 21            | ...      | ...           |

$$\sigma = \sqrt{\frac{\sum_{n=1}^{N}(x_n - \mu)^2/(N - 1)}{\sum_{n=1}^{N}x_n/N}}, \quad (7)$$

where $N$ is the total number of polarimetric points, and the ratio of the mean square successive difference to the variance of the polarimetric points:

$$\eta = \frac{\delta^2}{\sigma^2} = \frac{\sqrt{\sum_{n=1}^{N-1}(x_{n+1} - x_n)^2/(N - 1)}}{\sigma^2}. \quad (8)$$

For the ratio of the standard deviation to the sample mean, a large quotient ($\frac{\sigma}{\mu} > 2$) implies strong variability. In all photometric bands, the derived ratio is well below 0.5, thus no significant variability was detected in the polarization degree. In the second case, if serial correlation exists (i.e., the relationship between a given point and a lagged version of itself over various time intervals) the ratio is significantly high or small. Our derived values range between $\eta = 2.2$ and $\eta = 2.6$, thus showing no serial correlation between consecutive polarimetric points in neither of the photometric bands. This is illustrated in Fig. 7, where visual inspection does not reveal
any correlation pattern between polarization and position, as reported by for instance\textsuperscript{36} in the CAFOS polarimeter.

Besides the magnitude of the polarimetric points, the direction of the position-dependent polarization values could be suffering from instrumental artifacts. To check if the derived \((Q, U)\) values are randomly distributed on the Stokes \(Q - U\) plane or do show any systematic trend, we carried out the following exercise (for both unpolarized stars, in each photometric band). First, we shifted the \((Q, U)\) values around \((Q, U) = (0, 0)\) subtracting to each \((Q, U)\) pair their respective averages. Afterwards, we counted how many \((Q, U)\) pairs were placed in each quadrant, \(N_{\text{quad}}\), and kept these four numbers for future analyses. From here, the quadrants to which we refer are: \(+Q+U\), \(+Q-U\), \(-Q-U\) and \(-Q+U\). After this, we generated fake \((Q, U)\) values that were randomly distributed about the four quadrants. The length of this fake set of pairs equals the length of the real data. Once generated, we counted how many \((Q, U)\) pairs were placed in each quadrant, \(N_{\text{quad, fake}}\), and kept this number as reference.

Knowing that the nature of the fake \((Q, U)\) values is random, we wanted to quantify how many times randomly generated \((Q, U)\) values would fall in the four quadrants, equally, when compared to the observed Stokes parameters. To quantify this number, we iterated \(10^5\) times. At each iteration we computed a set of \((Q, U)\) values randomly distributed with the same size as the real sample, and counted how many times the number of elements per quadrant was the same as \(N_{\text{quad, fake}}\). This percentage, with typical values around 3\%, was used as reference. We repeated this exact same exercise but using the real \((Q, U)\) values. All this process was repeated \(10^4\) times. If \(N_{\text{quad}}\) is at least as large as \(N_{\text{quad, fake}}\), then we understand the nature of the \((Q, U)\) values to be as random as the fake data, i.e., random. Counting the number of times that \(N_{\text{quad}} > N_{\text{quad, fake}}\), divided by the total number of iterations, gives us an idea of the strength of the randomness of the \((Q, U)\) values. For the different photometric bands, the derived percentages are \(\text{Rand}_V = 75\%\), \(\text{Rand}_R = 57\%\), and \(\text{Rand}_I = 60\%\). As an internal checkup of this procedure, we consciously used the absolute value of the Stokes \(Q, U\) parameters.
instead the real values, shifting them in this way to the first quadrant exclusively. The derived percentages are, as expected, significantly lower. The corresponding values are $\text{Rand}_V = 14\%$, $\text{Rand}_R = 15\%$, and $\text{Rand}_I = 12\%$.

4.5 Flat-fielding

An important matter to define before analyzing polarimetric data taken with a dual-beam imaging polarimeter is what kind of flats are going to be used to calibrate the science frames. Ideally, the light collected by flat frames should suffer the same effects than stellar light. However, the sources of light used to acquire flats are not homogeneously illuminated (either sky or dome flats). To minimize this effect, a technique that can be used is to create a master flat averaging individual flats taken in all the angles at which the HWP was rotated.\textsuperscript{44} However, this procedure is not always effective because the intensity of the source of light used to acquire the flats is not really stable.\textsuperscript{33} An alternative, carried out in this work, and also chosen by some groups\textsuperscript{45,46} is to take a minimum of ten flats for each angle of the HWP, creating afterwards a master flat per rotation angle. Then, each science frame should be divided depending on the angle of the HWP at which it was taken. We also used un-flattened science frames, as a test. The derived $Q$ and $U$ parameters of the unpolarized standard stars were divided into two groups: those obtained from flat-fielded images (62 polarimetric points), and those corresponding to nights with no flat-fields available (42 points). After verifying that the $Q$, $U$ points are normally distributed, we compared the two samples by carrying out a $Z$-test.\textsuperscript{47} Here, the null hypothesis is that the two set of points are drawn from identical populations. The $Z$-statistic was computed in the following way:

$$Z = \frac{\mu_f - \mu_{nf}}{\sqrt{\sigma_f^2/n_f + \sigma_{nf}^2/n_{nf}}}.$$ \hspace{1cm} (9)

Here, $\mu_f$ and $\mu_{nf}$ correspond to the means of the Stokes $Q$, $U$ values and the polarization degree of the flat-fielded and unflat-fielded data, respectively, $\sigma_f$ and $\sigma_{nf}$ correspond to their
standard deviations, and $n_f$ and $n_{nf}$ to the number of data points in each sample. From our data, $Z_{Q,V} = 1.52$, $Z_{U,V} = -1.35$, $Z_{P,V} = 0.58$, $Z_{Q,R} = 0.54$, $Z_{U,R} = 0.75$, and $Z_{P,R} = 1.45$. Setting $\alpha = 5\%$, we can not reject the null hypothesis of the two samples being drawn from the same distribution with a 95\% confidence level. As a consistency check, we carried out the same exercise, but rather than comparing two samples of different stars we compared the derived polarimetric values of the same science frames, both applying and not applying the flat-field correction to them, thus allowing for a one-on-one comparison. As expected, a $Z$-test and a Kolmogorov-Smirnov test revealed no significant difference between the two samples. We thus conclude that, within the precision of our data, we do not observe any significant effect introduced by our flat-fielding procedure.

4.6 The case of 1ES 1101–232

As an illustrative example, we show results on the blazar 1ES 1101-232, which was observed as part of our photo-polarimetric monitoring of blazars. This BL Lac object shows a changing polarimetric behaviour with time. One of its first polarimetric measurements in the optical was given by, who reported a maximum polarization degree of 2.7\%, while observed the largest value in polarization degree ever reported so far ($\sim 14.7\%$) for this object. Besides that strong change in polarization degree, the blazar is of our particular interest because it is relatively nearby ($z = 0.186$). Hence, it shows a resolved galaxy that will allow us to test our method to correct the polarimetric data by the depolarizing effect introduced by the host galaxy and by the changes in seeing taking place during the observing runs. For an in-detailed description and motivation of these corrections, see. We observed the blazar 1ES 1101-232 during OC-5 (14th, 16th, and 17th of March, 2018) in the $R$ band. We collected a total of 16 polarimetric points with typical exposure times of 180 seconds. We corrected the data for instrumental polarization and foreground polarization following. In addition, we transformed the polarization angles to the standard system using data from highly polarized standard stars. Fig. 8 shows the time evolution of the polarimetric parameters of
1ES 1101-232 and field stars (FS-1, FS-2, FS-3 and FS-4), corresponding to the 16th of March. 1ES 1101-232 shows a marginal evidence of intra-night variability, manifested as a decrease and posterior increase of $\sim 1\%$ in the degree of linear polarization. Regardless this low-amplitude variability, the low averaged polarization degree ($P = 1.39 \pm 0.27\%$) could be indicative of a current low activity state. The angle is steady, with a mean value $\langle \theta \rangle = 196.2 \pm 4.8$ deg. Fig. 8 also shows the behaviour with time of the polarimetric parameters of four field stars indicated with triangles. The mean polarization of the brightest field stars is roughly consistent with the expected interstellar polarization, $P_{\text{IS}} \leq 0.5\%$. The faintest star (FS-3), in turn, shows a higher polarization degree, although in this case the S/N ratio is poorer. In the same way as in Section 4.4, we tested the stability of the polarimetric parameters for the field stars. We found no significant serial correlation in the polarization values. Furthermore, Fig. 9 shows the behaviour of the polarization as a function of the standard $R$ magnitude of the blazar and the field stars, collected on the 16th of March. We observe a moderate increase of the individual polarimetric errors and the scatter of the polarimetric points for weaker magnitudes. This is expected to occur, and directly linked to a detriment in the signal-to-noise ratio of the photometry of weaker stars for a fixed exposure time. In the case of 1ES 1101-232, the observed scatter it could be associated with the possibility that the polarization of the blazar varies intrinsically as shown in Fig. 8. Finally, we measured a mean standard magnitude in the $R$ band for 1ES 1101-232 of 16.1(3) mag. A complete study of this source will be shown in Sosa et al. 2019 (in preparation).

5. CONCLUSIONS

In this work we studied the behaviour of the instrumental polarization of CasPol, a dual-beam imaging polarimeter mounted at the Argentinean 2.15 meter Jorge Sahade Telescope. For this end we observed twelve polarized and unpolarized standard stars spread along five observing campaigns during dark nights. After making a detailed analysis of the aperture size for optimum polarimetric measurements, we characterize the instrumental polarization of CasPol to be of $\sim 0.2\%$ for the three bands. From the observation of unpolarized standard stars evenly
Fig 8: Time evolution of the polarimetric parameters for 1ES 1101-232 (red squares) and field stars (coloured empty triangles). The data points correspond to the R band and have been corrected by instrumental polarization. Top: the polarization degree in percentage. Bottom: the polarization angle in degrees.

Fig 9: Polarization degree in percentage as a function of the standard magnitudes of the blazar and the field stars, FS, for the R band. The symbols are equivalent to the ones in Fig. 8.
distributed on the CCD, we estimated a negligible dependence of instrumental polarization on position for the \( V \) and \( R \) bands, and only a marginal dependence for the \( I \) band. Our derived Stokes \( U \), \( Q \) parameters, (as well as their corresponding polarization degree and angle) for several polarized and unpolarized standard stars are compared to published values, when possible, showing consistency at a minimum of 2\( \sigma \) level. We made an in-depth comparison between our observed polarized standard star, Ve6 23, to the values reported by.\(^{26}\) In all cases we find consistent results, with the exception of the \( I \) band. We also report new values for the polarization state of our observed standard stars. Furthermore, we determine that flat-fielding does not introduce any significant (within the precision of our data) instrumental effect to the resulting polarimetric states by comparing a large sample of unpolarized standard stars that were (and were not) calibrated with flat-fields. We determine the stability with the polarization angle to be \( \sim 0.3 \) deg, and we do not find any significant dependency of this stability with wavelength.

Overall, CasPol is a well behaved optical dual-beam polarimeter, allowing researchers to carry out follow-up campaigns with reliable, stable measurements. With respect to the unpolarized standard star HD 64299, the values computed in this work in the \( V \)-band are consistent within 1\( \sigma \) uncertainties with\(^{25}\) and\(^{21}\) We believe it is necessary to re-observe this star to establish its polarization state. Finally, we tested the instrument through observations of the blazar 1ES 1101-232. We analyzed the behaviour of its linear polarization computing the parameters \( P \) and \( \theta \) corresponding to the 16\(^{\text{th}}\) of March. We measured \( P = 1.39 \pm 0.27 \% \) which would indicate that the blazar is currently in a low activity state, since values as high as \( P \sim 14.7\% \) were reported in the literature.

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REFERENCES

[1] D. F. J. Arago and F.-A. Barral, *Astronomie populaire, 1 - 2.* (1855).
[2] D. F. J. Arago, “Observations sur la Lumière de la Lune - Mémoires Scientifiques 1,” *Gide, Éditeur, Paris* 564, 6 (1858).
[3] S. Chandrasekhar, “On the Radiative Equilibrium of a Stellar Atmosphere. X.,” *ApJ* 103, 351 (1946).
[4] K. Serkowski, “Interstellar Polarization (review),” in *Interstellar Dust and Related Topics*, J. M. Greenberg and H. C. van de Hulst, Eds., *IAU Symposium* 52, 145 (1973).
[5] V. Beckmann and C. R. Shrader, *Active Galactic Nuclei* (2012).
[6] E. V. Kravchenko, Y. Y. Kovalev, and K. V. Sokolovsky, “Parsec-scale Faraday rotation and polarization of 20 active galactic nuclei jets,” *MNRAS* 467, 83–101 (2017).
[7] S. P. O’Sullivan and D. C. Gabuzda, “Parsec-Scale Investigation of the Magnetic Field Structure of Several AGN Jets,” *International Journal of Modern Physics D* 17, 1553–1560 (2008).
[8] A. P. Marscher, S. G. Jorstad, F. D. D’Arcangelo, *et al.*, “The inner jet of an active galactic nucleus as revealed by a radio-to-γ-ray outburst,” *Nature* 452, 966–969 (2008).
[9] R. Lenzen, M. Hartung, W. Brandner, *et al.*, “NAOS-CONICA first on sky results in a variety of observing modes,” in *Instrument Design and Performance for Optical/Infrared Ground-based Telescopes*, M. Iye and A. F. M. Moorwood, Eds., *Proc. SPIE* 4841, 944–952 (2003).
[10] G. Rousset, F. Lacombe, P. Puget, *et al.*, “NAOS, the first AO system of the VLT: on-sky performance,” in *Adaptive Optical System Technologies II*, P. L. Wizinowich and D. Bonaccini, Eds., *Proc. SPIE* 4839, 140–149 (2003).
[11] J.-L. Beuzit, M. Feldt, K. Dohlen, et al., “SPHERE: A ‘Planet Finder’ Instrument for the VLT,” *The Messenger* **125** (2006).

[12] B. Macintosh, J. R. Graham, P. Ingraham, et al., “First light of the Gemini Planet Imager,” *Proceedings of the National Academy of Science* **111**, 12661–12666 (2014).

[13] A. M. M. Magalhaes, E. Ramírez, N. Ribeiro, et al., “SOUTH POL: Revealing the Polarized Southern Sky,” in *American Astronomical Society Meeting Abstracts 231, American Astronomical Society Meeting Abstracts* **231**, 436.07 (2018).

[14] C. M. Urry, R. Scarpa, M. O’Dowd, et al., “The Hubble Space Telescope Survey of BL Lacertae Objects. II. Host Galaxies,” *ApJ* **532**, 816–829 (2000).

[15] R. Gil-Hutton, C. López-Sisterna, and M. F. Calandra, “Polarimetric survey of main-belt asteroids. V. The unusual polarimetric behavior of V-type asteroids,” *A&A* **599**, A114 (2017).

[16] R. Gil-Hutton and E. García-Migani, “Polarimetric survey of main-belt asteroids. VI. New results from the second epoch of the CASLEO survey,” *A&A* **607**, A103 (2017).

[17] S. A. Cellone, G. E. Romero, J. A. Combi, et al., “Extreme photopolarimetric behaviour of the blazar AO0235+164,” *MNRAS* **381**, L60–L64 (2007).

[18] I. Andruchow, J. A. Combi, A. J. Muñoz-Arjona, et al., “Polarization and photometric observations of the gamma-ray blazar PG 1553+113,” *A&A* **531**, A38 (2011).

[19] M. S. Sosa, C. von Essen, I. Andruchow, et al., “Impact of seeing and host galaxy into the analysis of photo-polarimetric microvariability in blazars. Case study of the nearby blazars 1ES 1959+650 and HB89 2201+044,” *A&A* **607**, A49 (2017).

[20] A. M. Magalhaes, C. V. Rodrigues, V. E. Margoniner, et al., “High Precision CCD Imaging Polarimetry,” in *Polarimetry of the Interstellar Medium*, W. G. Roberge and D. C. B. Whittet, Eds., *Astronomical Society of the Pacific Conference Series* **97**, 118 (1996).

[21] J. Masiero, K. Hodapp, D. Harrington, et al., “Commissioning of the Dual-Beam Imaging Polarimeter for the University of Hawaii 88 inch Telescope,” *PASP* **119**, 1126–1132 (2007).

[22] F. Aharonian, A. G. Akhperjian, A. R. Bazer-Bachi, et al., “Detection of VHE gamma-ray emission from the distant blazar 1ES 1101-232 with HESS and broadband characterisation,” *A&A* **470**, 475–489 (2007).
[23] S. V. Berdyugina, A. V. Berdyugin, D. M. Fluri, et al., “Polarized Reflected Light from the Exoplanet HD189733b: First Multicolor Observations and Confirmation of Detection,” *ApJ* **728**, L6 (2011).

[24] S. V. Berdyugina, A. V. Berdyugin, D. M. Fluri, et al., “First Detection of Polarized Scattered Light from an Exoplanetary Atmosphere,” *ApJ* **673**, L83 (2008).

[25] L. Fossati, S. Bagnulo, E. Mason, et al., “Standard Stars for Linear Polarization Observed with FORS1,” in *The Future of Photometric, Spectrophotometric and Polarimetric Standardization*, C. Sterken, Ed., *Astronomical Society of the Pacific Conference Series* **364**, 503 (2007).

[26] A. Cikota, F. Patat, S. Cikota, et al., “Linear spectropolarimetry of polarimetric standard stars with VLT/FORS2,” *MNRAS* **464**, 4146–4159 (2017).

[27] D. A. Turnshek, R. C. Bohlin, R. L. Williamson, II, et al., “An atlas of Hubble Space Telescope photometric, spectrophotometric, and polarimetric calibration objects,” *AJ* **99**, 1243–1261 (1990).

[28] K. Serkowski, “Correlation Between the Regional Variations in Wavelength Dependence of Interstellar Extinction and Polarization,” *ApJ* **154**, 115 (1968).

[29] G. D. Schmidt, R. Elston, and O. L. Lupie, “The Hubble Space Telescope Northern-Hemisphere grid of stellar polarimetric standards,” *AJ* **104**, 1563–1567 (1992).

[30] J. S. Miller, L. B. Robinson, and R. W. Goodrich, “A CCD Spectropolarimeter for the Lick Observatory 3- Meter Telescope,” in *Instrumentation for Ground-Based Optical Astronomy*, L. B. Robinson, Ed., 157 (1988).

[31] M. R. Zapatero Osorio, J. A. Caballero, and V. J. S. Béjar, “Optical Linear Polarization of Late M and L Type Dwarfs,” *ApJ* **621**, 445–460 (2005).

[32] S. Sonnett, K. Meech, R. Jedid, et al., “Testing Accuracy and Precision of Existing Photometry Algorithms on Moving Targets,” *PASP* **125**, 456 (2013).

[33] F. Patat and M. Romaniello, “Error Analysis for Dual-Beam Optical Linear Polarimetry,” *PASP* **118**, 146–161 (2006).

[34] J. F. C. Wardle and P. P. Kronberg, “The linear polarization of quasi-stellar radio sources at 3.71 and 11.1 centimeters,” *ApJ* **194**, 249–255 (1974).
[35] J. F. L. Simmons and B. G. Stewart, “Point and interval estimation of the true unbiased degree of linear polarization in the presence of low signal-to-noise ratios,” *A&A* 142, 100–106 (1985).

[36] J. Heidt and K. Nilsson, “Polarimetry of optically selected BL Lacertae candidates from the SDSS,” *A&A* 529, A162 (2011).

[37] S. B. Howell, *Handbook of CCD Astronomy* (2006).

[38] H. Kjeldsen and S. Frandsen, “High-precision time-resolved CCD photometry,” *PASP* 104, 413–434 (1992).

[39] F. Patat and S. Taubenberger, “Characterisation of the CAFOS linear spectropolarimeter,” *A&A* 529, A57 (2011).

[40] B. Rosner, “Percentage Points for a Generalized ESD Many-Outlier Procedure,” *Technometrics* 1, 8 (1983).

[41] K. Serkowski, D. S. Mathewson, and V. L. Ford, “Wavelength dependence of interstellar polarization and ratio of total to selective extinction,” *ApJ* 196, 261–290 (1975).

[42] D. C. B. Whittet, P. G. Martin, J. H. Hough, et al., “Systematic variations in the wavelength dependence of interstellar linear polarization,” *ApJ* 386, 562–577 (1992).

[43] J. von Neumann, “Distribution of the ratio of the mean square successive difference to the variance,” *Ann. Math. Statist.* 12, 367–395 (1941).

[44] T. Arasaki, Y. Ikeda, Y. Shinnaka, et al., “The Very precise Echelle SpectroPolarimeter on the Araki telescope (VESPolA),” *Publications of the Astronomical Society of Japan* 67, 35 (2015).

[45] R. Devaraj, A. Luna, L. Carrasco, et al., “POLICAN: A Near-infrared Imaging Polarimeter at the 2.1m OAGH Telescope,” *Publications of the Astronomical Society of the Pacific* 130, 055002 (2018).

[46] D. P. Clemens, A. F. Pinnick, and M. D. Pavel, “Polarimetric Calibration of Mimir and the Galactic Plane Infrared Polarization Survey (GPIPS),” *ApJS* 200, 20 (2012).

[47] R. C. Sprinthall, *Basic Statistical Analysis, Pearson Education* (2011).

[48] M. Karson, “Handbook of methods of applied statistics. volume i: Techniques of computation descriptive methods, and statistical inference. volume ii: Planning of surveys and experiments. i.
m. chakravarti, r. g. laha, and j. roy, new york, john wiley; 1967, $9.00.,” Journal of the American Statistical Association 63(323), 1047–1049 (1968).

[49] B. T. Jannuzi, P. S. Smith, and R. Elston, “Optical polarimetry and photometry of X-ray selected BL Lacertae objects,” ApJS 85, 265–291 (1993).

[50] I. Andruchow, G. E. Romero, and S. A. Cellone, “Polarization microvariability of BL Lacertae objects,” A&A 442, 97–107 (2005).

[51] R. A. Remillard, I. R. Tuohy, R. J. V. Brissenden, et al., “Two X-ray-selected BL Lacertae objects observed with the HEAO 1 scanning modulation collimator,” ApJ 345, 140–147 (1989).

[52] E. F. Schlafly and D. P. Finkbeiner, “Measuring Reddening with Sloan Digital Sky Survey Stellar Spectra and Recalibrating SFD,” ApJ 737, 103 (2011).