Measuring the continuum linear polarization
with ESPaDOnS*

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ABSTRACT

Aims. Our goal is to test the feasibility to obtain accurate measurements of the continuum linear polarization from high-resolution spectra using the spectropolarimetric mode of ESPaDOnS.

Methods. We used the new pipeline OPERA to reduce recent and archived ESPaDOnS data. A couple of standard polarization stars and several science objects were tested. Synthetic broad-band polarization was computed from the ESPaDOnS continuum linear polarization spectra and compared with published values to quantify the accuracy of the instrument.

Results. The continuum linear polarization measured by ESPaDOnS is consistent with the broad-band polarimetry measurements available in the literature. The polarization degree accuracy is better than 0.2\% considering the full sample. The accuracy in polarization position angle using the most polarized objects is better than 5\°. Our results suggest that measurements of the continuum linear polarization using ESPaDOnS are viable.

Key words. polarization – instrumentation: polarimeters – techniques: polarimetric – stars: pre-main sequence

1. Introduction

ESPaDOnS is a bench-mounted high-resolution echelle spectrograph and spectropolarimeter which was designed to obtain a complete optical spectrum from ultraviolet to near-infrared wavelengths in a single exposure (Donati 2003, Manset & Donati 2003). This is

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installed at the 3.6m Canada-France-Hawaii Telescope (CFHT) in Hawaii. Three operational modes are available in ESPaDOnS: object spectroscopy, sky and object spectroscopy and spectropolarimetry. The first mode reaches a resolving power of 80,000 and the others, up to 65,000.

Polarimetry with ESPaDOnS was initially conceived to detect linear and circular polarization along line profiles (see, for example, Wade et al. 2005 and Harrington & Kuhn 2008). The evaluation of the feasibility to measure the continuum polarization during the earlier ESPaDOnS commissioning was not conclusive. A high cross-talk between the Stokes parameters associated to the ESPaDOnS optics and losses of light over the entrance of the optical fibers were claimed by the ESPaDOnS team as factors which would play against reliable continuum polarization measurements. In consequence, the Libre-ESpRIT pipeline (Donati et al. 1997), which was routinely applied to ESPaDOnS data over the last years, gave priority to the line effect detection offering as default spectropolarimetry with the continuum removed.

In this work, we present new results on the continuum linear polarization measurements using ESPaDOnS. A sample of objects, including polarimetric standard stars and science objects with polarization measured previously, was used for this purpose. The new reduction software for ESPaDOnS data OPERA (Martioli et al. 2012) was intensively used in these tests. This pipeline offers the possibility to compute the continuum polarization for ESPaDOnS data.

Sect. 2 describes the data used in this work including archived and original measurements. The steps of the reduction process by OPERA are explained in Sect. 3. The mathematical procedures used by OPERA to compute the Stokes parameters are shown in Sect. 4. The results on the continuum linear polarimetry are presented in Sect. 5 along with the computed synthetic broad-band polarimetry for the sample. A comparison between the different methods implemented by OPERA to compute the polarization is also shown. The conclusions are summarized in Sect. 6.

2. Data description

In this section, we describe the data used to demonstrate the feasibility of measuring the continuum linear polarization using ESPaDOnS. The data set is composed by original observations of Herbig AeBe (HeAeBe) stars gathered with ESPaDOnS at CFHT on semesters 2011A and 2011B (Proposal IDs 11AB04 and 11BB05). This program was initially proposed to measure the linear polarization across the Hα line. The results concerning the Hα measurements will be published in a separate paper. A total of nine HeAeBe stars were measured and a log of observations is shown in Table 1. All the HeAeBe stars have optical linear polarization published (Rodrigues et al. 2009) which allows us to do a proper comparison. HeAeBe stars are known to exhibit variable polarization. However, the objects

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1 http://www.cfht.hawaii.edu/Instruments/Spectroscopy/Espadons/
2 http://www.cfht.hawaii.edu/Instruments/Spectroscopy/Espadons/ContiPolar/
3 OPERA: Open-source Pipeline for Espadons Reduction and Analysis, is an Open Source software reduction pipeline for the ESPaDOnS spectro-polarimeter at the Canada France Hawaii Telescope.
Table 1. Log of observations and archived data.

| Object | Other name | Date       | Proposal ID<sup>a</sup> | Type    | $V$<sup>b</sup> (mag) | Observ. mode | Detector | IT<sup>c</sup> <br />(sec) | S/N<sup>c</sup> |
|--------|------------|------------|-------------------------|---------|-----------------------|--------------|----------|----------------|----------------|
| HD 144432<sup>d</sup> | PDS 078    | 2009/02/14 | 09AH10                  | HeAeBe  | 8.2                   | Fast         | EEV1     | 360  | 70             |
| HD 150193<sup>d</sup> |           | 2009/05/07 | 09AH10                  | HeAeBe  | 8.9                   | Fast         | EEV1     | 600  | 128            |
| PDS 069 N<sup>e</sup> | Hen 3-949 | 2011/03/16 | 11AB04                  | HeAeBe  | 9.7                   | Fast         | Olapa    | 650  | 84             |
| PDS 395    | HD 139614  | 2011/07/03 | 11AB04                  | HeAeBe  | 8.2                   | Fast         | Olapa    | 537  | 245            |
| PDS 545    | HD 174571  | 2011/07/05 | 11AB04                  | HeAeBe  | 9.4                   | Fast         | Olapa    | 463  | 212            |
| HD 144668  | V856 Sco   | 2011/07/10 | 11AB04                  | HeAeBe  | 7.0                   | Fast         | Olapa    | 145  | 222            |
| PDS 080    | HD 145718  | 2011/07/14 | 11AB04                  | HeAeBe  | 8.9                   | Fast         | Olapa    | 463  | 175            |
| PDS 225    | HD 50083   | 2011/11/13 | 11BB05                  | HeAeBe  | 6.9                   | Normal       | Olapa    | 336  | 298            |
| HD 76543 S<sup>f</sup> |       | 2012/01/05 | 11BB05                  | HeAeBe  | 8.0                   | Normal       | Olapa    | 952  | 267            |
| PDS 021    | V791 Mon   | 2012/01/08 | 11BB05                  | HeAeBe  | 10.4                  | Normal       | Olapa    | 1740 | 203           |
| PDS 281    | SAO 220669 | 2012/01/11 | 11BB05                  | HeAeBe  | 8.9                   | Normal       | Olapa    | 1232 | 301            |
| 73 Cet     |            | 2012/01/10 | 11BE95                  | std. unpol.| 4.3                  | Normal       | Olapa    | 15   | 267            |
| HD 19820   |            | 2012/01/10 | 11BE95                  | std. pol.| 7.2                  | Normal       | Olapa    | 60   | 159            |

<sup>a</sup> PI names: 09AH10 - D. M. Harrington; 11AB04 and 11BB05 - A. Pereyra; 11BE95 - N. Manset.

<sup>b</sup> Integration time by individual frame.

<sup>c</sup> Signal-to-noise ratio per CCD pixel by single frame for order # 35 as appeared in headers generated by Libre-ESpRIT.

<sup>d</sup> From CFHT archive.

<sup>e</sup> North component.

<sup>f</sup> South component.

of our sample shown a consistent stability in polarization (see Sect. 5) which helped to test the quality of the continuum linear polarization measured by ESPaDOnS.

In addition, two polarimetric standard stars from the Atlas of HST Polarimetric Calibration Objects (Turnshek et al. 1990) were measured using the same instrument configuration by ESPaDOnS in the 2011B semester as part of an independent program (Proposal ID 11BE95). One of them is the unpolarized star 73 Cet and the other one is the polarized star HD 19820. In order to test the capability of the OPERA software to reduce archived data of ESPaDOnS and enlarge our sample, we selected a couple of HeAeBe stars from the CFHT database<sup>4</sup> (Proposal ID 09AH10). These stars (HD 144432 and HD 150193) also have optical polarimetry already published (Rodrigues et al. 2009). This additional four objects are also included in Table 1.

Our sample spans $V$ magnitude between 4.3 and 10.4 mag. The archived data (observed in 2009A) and the 2011A HeAeBe stars were observed using the fast readout mode of ESPaDOnS. The rest of our sample (2011B) were observed using the normal readout mode, which includes a slightly larger overhead between individual exposures. The archived data

<sup>4</sup> http://www.cfht.hawaii.edu/ObsInfo/Archive/
were taken using the old ESPaDOnS detector EEV1 and the rest of the sample with the new and enhanced detector Olapa. The integration time (IT) by individual frame is also indicated in Table 1. Considering that a set of eight frames are needed to characterize completely a linear spectropolarimetric measurement with ESPaDOnS, this time must be multiplied by eight to obtain the total observation time (without overheads).

The signal-to-noise ratio (S/N) per CCD pixel for the order # 35 (centered at 647 nm and near the Hα line) is also shown in Table 1. This S/N is computed by single frame using the Libre-ESpRIT pipeline and recorded in the image headers. All the objects of our sample except three have S/N higher than 150.

As mentioned before, our sample has previous published broad-band polarization and the full polarization range goes from 0.04% (PDS 080) to 4.8% (HD 150193 and HD 19820) - see Table 2. We believe that this interval is appropriate for testing the continuum linear polarization in most common polarization levels of astrophysical objects.

3. Reductions with OPERA

The OPERA software was used to reduce the ESPaDOnS data. We installed and run OPERA in a Ubuntu 12.03 Linux system. An overall description of the reduction steps for OPERA can be found in Martioli et al. (2012). The complete source software is available in the OPERA webpage.

For extracting the flux from the two polarized beams, OPERA implements the optimal extraction algorithm by Horne (1986) and Marsh (1989) using an oversampled tilted aperture. The aperture for extraction consists of a tilted rectangle, where the tilt angle is measured from a two-dimensional instrument illumination profile obtained from a calibration Fabry-Perot alignment exposure. An oversampled tilted aperture for flux extraction is required for ESPaDOnS, since it has an image slicer, which produces a tilted pseudo-slit as the dispersing element. In addition, ESPaDOnS has a limited CCD pixel size that undersamples the spectrum. The detailed algorithms for calibration and reduction of ESPaDOnS data implemented in the OPERA pipeline are thoroughly described in another paper in preparation (Martioli et al. 2014).

A typical calibration set for the observations presented here is composed by three bias frames, one Th-Ar lamp calibration frame, one alignment frame (Fabry Perot), and a sequence of 20 halogen lamp flat frames. For each science frame, a proper reduced calibration set must be generated considering the same observation mode (Fast, Normal, or Slow) and detector (EEV1 or Olapa).

Each Stokes parameter ($Q_\lambda$ or $U_\lambda$) is obtained reducing four single frames in proper positions of the retarders. After this process, OPERA yields the $Q_\lambda$ and $U_\lambda$ spectra and the associated errors. These spectra were conveniently adapted to be read by the specpol package, which allowed us to show multiplots including intensity ($I_\lambda$), polarization ($P_\lambda$), and position angle ($PA_\lambda$) spectra. This package allows spectra binning using a variable bin

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5 Version 2013/Oct/21.
6 http://sourceforge.net/projects/opera-pipeline
7 specpol was originally written by A. Carciofi and is available in PCCDPACK (Pereyra et al. 2000)
Fig. 1. ESPaDOnS spectropolarimetry of the HeAeBe stars HD 144432 and HD 150193 gathered from the CFHT archive. The spectra show the normalized total flux (top), polarization level (middle), and polarization position angle (bottom, $\theta = PA$) binned using a variable bin size with a constant polarization error per bin of 0.1%.

4. Measuring the linear polarization

A detailed description of the procedure to measure the linear polarization using a simple polarimeter can be found in Bagnulo et al. (2009). In summary, two different methods are available to obtain the linear polarization and its angle: the ratio and difference methods. These two methods are implemented in the OPERA software. The linear polarization is a function of two Stokes parameters: $Q$ and $U$. Each of these parameters is computed using four independent exposures gathered in different positions of the retarders, which rotate the polarization plane of the incident beam. The polarimetric mode of ESPaDOnS used a combination of three Fresnel rhombs as retarders. Two of them rotate (with angles $\phi_1$ and $\phi_3$) and define the net polarization plane to be measured. In each exposure two spectra are recorded with orthogonal polarization states following the splitting done by the analyser.

It can be shown that the transmitted intensity of light passing through the polarimetric unit of ESPaDOnS, which is composed by two rotatable and one fixed retarder followed by a Wollaston prism as analyser, is given by:

$$I_{\pm}(\phi_1, \phi_3) = \frac{I_*}{2} \left[ 1 \pm Q \cos 4\phi_1 \cos 4\phi_3 \right.$$
$$\left. \pm U \sin 4\phi_1 \cos 4\phi_3 \mp V \sin 4\phi_3 \right]$$

where $I_*$ is the incident intensity, and $\phi_1$ and $\phi_3$ are the directions of the retarder’s optical axes. The $+$ and $-$ signal indicates the intensities of the measured orthogonal beams produced by the analyser splitting. All these directions are measured with respect to the orientation of the instrument. As this work is focused on linear polarimetry, the $V$ parameter will not be considered.
In this sense, a combination of four pairs of rotations of the retarders $(\phi_1/\phi_3 = 0^\circ/0^\circ$, $90^\circ/45^\circ$, $45^\circ/90^\circ$, and $135^\circ/135^\circ$) are needed to measure $Q_\lambda$ and additional four combinations ($22.5^\circ/0^\circ$, $112.5^\circ/45^\circ$, $67.5^\circ/90^\circ$, and $157.5^\circ/135^\circ$) are used to measure $U_\lambda$. This procedure yields a set of eight spectra for each computed Stokes parameter.

Following the ratio method, we define the ratio between the orthogonal polarization intensities in a given combination of the retarders position as follows:

$$r_{\phi_1, \phi_3} = \frac{I_+ (\phi_1, \phi_3)}{I_- (\phi_1, \phi_3)}$$

Then, the Stokes parameters can be obtained from:
Fig. 3. As Fig. 1 for the HeAeBe stars gathered with ESPaDOnS in 11BB05 proposal.

\[ Q = \frac{R_Q - 1}{R_Q + 1}, \quad \text{being } R_Q^4 = \left( \frac{r_{0.0}}{r_{90.45}} \right) \left( \frac{r_{135.135}}{r_{45.90}} \right), \quad \text{and} \]

\[ U = \frac{R_U - 1}{R_U + 1}, \quad \text{being } R_U^4 = \left( \frac{r_{22.5.0}}{r_{112.5.45}} \right) \left( \frac{r_{157.5.135}}{r_{67.5.90}} \right). \]

The degree \((P)\) and the position angle \((\text{PA})\) of the linear polarization are determined from the following expressions:

\[ P = \sqrt{Q^2 + U^2} \quad ; \quad \text{PA} = \frac{1}{2} \arctan \left( \frac{U}{Q} \right). \]
In the same way, the difference method can be applied if we define the ratio between the difference and the sum of the two orthogonal polarization intensities in a given combination of the retarders position, as follows:

$$r_{\phi_1,\phi_3} = \frac{I_{+}(\phi_1,\phi_3) - I_{-}(\phi_1,\phi_3)}{I_{+}(\phi_1,\phi_3) + I_{-}(\phi_1,\phi_3)}.$$ 

Then, the Stokes parameters can be obtained from:

$$Q = \frac{1}{4}[(r_{0,0} - r_{90,45}) - (r_{45,90} - r_{135,135})], \text{ and}$$

$$U = \frac{1}{4}[(r_{22.5,0} - r_{112.5,45}) - (r_{67.5,90} - r_{157.5,135})].$$

In this work, the ratio method was used to compute the continuum linear polarization using OPERA. A comparison between the two methods is presented in Sect. 5.

5. Results

Figures 1-4 show the results for the spectropolarimetry of our sample (Table 1). The spectra are binned to enhance the signal-to-noise ratio. We selected a polarimetric error of 0.1% per bin as a good compromise to show properly the data.

Our sample include HeAeBe stars with typical very low polarization levels as HD 144432, PDS 395, and PDS 080. Interestingly, the mean level of the binned polarization spectrum of PDS 395 (Fig. 2) is lower than 0.1%, which is a good example of the capabilities of ESPaDOnS to detect low polarizations. On the other hand, high polarization levels (up to \(\sim 5\%\)) are well sampled as are the cases of the HeAeBe star HD 150193 (Fig. 1) and the standard polarized stars HD 19820 (Fig. 4). As expected, all the HeAeBe stars except one show H\(\alpha\) in emission. As commented before, many HeAeBe stars are time-variable in flux and polarization. Hence caution must be taken when comparing measurements, because possible differences may be intrinsic to the object and not due to observational uncertainties. We looked for previous broad-band polarization measurements of our HAeBe sample to check for variability and only in one case confirmed variability was found (see below).

In order to facilitate the comparison with the literature and test the quality of the continuum linear polarization from ESPaDOnS, we calculate synthetic \(VRI\) broad-band polarization averaging the Stokes parameters \((Q_\lambda\) and \(U_\lambda\)) between the cut-on and cut-off wavelengths associated to these standard broad-band filters. The intervals were 5070–5950\(\AA\), 5890–7270\(\AA\), and 7315–8805\(\AA\) for \(V\), \(R\), and \(I\) filters, respectively. The synthetic values are shown in Table 2 along with the literature values when available.

All the HeAeBe stars of our sample have optical polarization (at \(V\) filter) previously measured by Rodrigues et al. (2009). The two polarimetric standard stars (73 Cet and HD 19820) have published values by Schmidt et al. (1992).

In Figure 5, we compare the polarization level at \(V\) band of the objects of our sample with their published values \((P_{lit})\) as appeared in Table 2. The polarization degree compar-
Fig. 5. Comparison of synthetic $V$ broad-band polarization from ESPaDOnS and literature values. (a) The abscissa is the polarization degree ($P$) measured using ESPaDOnS. The ordinate is the literature value ($P_{\text{lit}}$). The dashed line represents $P_{\text{lit}} = P$. (b) The residual ($P_{\text{lit}} - P$). The gray zone indicates a 1-sigma dispersion around the mean value: $0 \pm 0.23\%$ (dashed line). (c) The abscissa is the polarization position angle (PA) measured using ESPaDOnS. The ordinate is the literature value ($PA_{\text{lit}}$). The dashed line represents $PA_{\text{lit}} = PA$. The black dots are objects with $P > 0.5\%$ and crosses with $P < 0.5\%$. The PA variable HD144668 is labelled. (d) The residual ($PA_{\text{lit}} - PA$) only for objects with $P > 0.5\%$. The gray zone indicates a 1-sigma dispersion around the mean value: $-3.3 \pm 4.3^\circ$.

Comparison (Fig. 5a) shows a good agreement between ESPaDOnS data and the results published in the literature. The polarimetric accuracy is preserved for lower and higher values of polarization. The slope one is included to help the comparison. Considering all objects in the sample, the residual of the polarization measurements (Fig. 5b) has a mean zero with a 1-sigma dispersion of 0.23%. This result gives us confidence that accuracies as low as 0.2–0.3% can be obtained measuring the continuum linear polarization with ESPaDOnS. Consistent with this, the wavelength ($\lambda_{\text{max}}$) for maximum polarization ($P_{\text{max}}$) for the polarized standard star of our sample (HD 19820) computed from the ESPaDOnS spectra ($\lambda_{\text{max}} = 5298\AA$, $P_{\text{max}} = 4.63\%$) is in excellent agreement with the published values by
Schmidt et al. (1992, $\lambda_{\text{max}} = 5235$ Å, $P_{\text{max}} = 4.76\%$). In this case, the consistency in $P_{\text{max}}$ is better than 0.15%.

The polarization degree measured by ESPaDOnS for the unpolarized standard star 73 Cet deserves a special comment. A consistent 0.5% level is present along the full spectrum (Fig. 4, left). This level is well above the published polarization (0.1%, Schmidt et al. 1992) considering our quoted errors. The S/N for this object (see Table I) is similar to other well sampled objects of our sample and this does not seem to be the origin of the discrepancy. However, an inspection on the integration times reveals that this object is the only one of our sample with a small IT (15 sec). Similar ITs were used by the ESPaDOnS team during the earlier commissioning. Their results were not conclusive about the capability of the instrument to measure the continuum polarization. Probably, this is the case for 73 Cet and small ITs must play against a reliable measurement of the continuum polarization. We believe that such short ITs are not sufficient to take the time to average out the modal noise present in the optical fibers. ESPaDOnS has a fiber agitator at the entrance of the spectrograph, which is a device that agitates the fiber at frequency of 30 Hz and amplitude of 1 mm. Interestingly, a minimum of 30 sec was suggested by the ESPaDOnS team for a proper remotion of the modal noise present in the optical fibers. This procedure must guarantee a S/N ratio compatible with the photon noise. Nevertheless, this issue needs to be confirmed in the future.

We also computed the residuals between the ESPaDOnS polarization position angle and the published values (Fig. 5c). Caution must be taken in this comparison because low polarization levels cause high indetermination in the PA. For this reason, we computed the residuals in PA only for objects with high polarization degree (larger than 0.5%, Fig. 5d). Using this criterion, five objects were removed from the subsequent analysis.

In particular, the PA residual of HD 144668 ($\sim 30^\circ$) also fitted our criteria of higher $P$. Nevertheless, this object is the only source of our sample that seems to show historical

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8 http://www.cfht.hawaii.edu/Instruments/Spectroscopy/Espadons/ContiPolar/
intrinsic variability in PA \citep{Hutchinson1994, Bhatt1996} and it was not included in Fig. 5d.

The residuals in PA have a mean of $-3\pm4^\circ$. Therefore, the accuracy in PA for measurements of the continuum linear polarization using ESPaDOnS is better than 5$^\circ$.

In particular, the constancy of the PA along the spectra for the polarized standard star (HD 19820, Fig. 4, right) and its comparison with the published broad-band values (see Table 2) indicate a very reliable result.

In general, the comparison of the optical synthetic broad-band polarimetry indicates that accurate continuum linear polarization measurements are feasible using ESPaDOnS. The measured polarizations are consistent with the literature values.

A comparison between the two methods implemented by OPERA (see Sect. 4) to compute the polarization was done for the high polarized object HD 150193. Figure 6 shows the residuals between the ratio and difference methods computed in polarization degree and position angle. The residual in polarization degree is $0.02\% \pm 0.05\%$ and in polarization angle is $-0.01^\circ \pm 0.13^\circ$. These values imply that both methods yield similar results, whose differences are below 0.05% in polarization and 0.2$^\circ$ in PA. Hence, the results using OPERA are independent of the method used to compute the polarization.

6. Conclusions

We demonstrated the ESPaDOnS capability to measure continuum linear polarization. A sample composed mainly by HeAeBe stars with known optical polarization along with a couple of polarimetric standards was selected to obtain the wavelength dependence of the continuum polarization level and their position angle. Data reduction was done using the new OPERA pipeline for ESPaDOnS data. Well sampled continuum linear polarization spectra were measured with polarization levels ranging between 0 and 5%.

Synthetic broad-band linear polarization computed from the ESPaDOnS spectra was compared with published values to quantify the accuracy of the instrument. The continuum linear polarization measured by ESPaDOnS is fully consistent with the broad-band polarimetry measurements already published. Our tests yielded a polarization degree accuracy around 0.2%. In turns, the accuracy in polarization position angle resulted better than 5$^\circ$. Our results suggest that high quality measurements of the continuum linear polarization are feasible with ESPaDOnS.

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References

Bagnulo, S., Landolfi, M., Landstreet, J. D., Landi Degl’Innocenti, E., Fossati, L., Sterzik, M., 2009, PASP, 121, 993

\footnote{See legends of Table 2}
Bhatt, H. C., 1996, A&AS, 120, 451
Donati J.-F., Semel, M., Carter, B. D., Rees, D. E., Collier Cameron, A., 1997, MNRAS, 291, 658
Donati J.-F., 2003, in Trujillo-Bueno J., Sanchez Almeida J., eds, ASP Conf. Ser. Vol. 307, Solar Polarization 3. Astron. Soc. Pac., San Francisco, p. 41
Harrington, D. M., & Kuhn, J., 2008, PASP, 120, 89
Horne, K., 1986, PASP, 98, 609
Hutchinson, M. G., Albinson, J. S., Barrett, P., Davies, J. K., Evans, A., Goldsmith, M. J., & Maddison, R. C., 1994, A&A, 285, 883
Manset, N. & Donati, J.-F., 2003, in Polarimetry in Astronomy, Fineschi, S., ed., Proceedings of the SPIE 4843, 425
Marsh, T. R., 1989, PASP, 101, 1032
Martiole, E., Teeple, D., Manset, N., Devost, D., Withington, K. et al., 2012, in Software and Cyberinfrastructure for Astronomy II, Proc. SPIE 8451, 84512B
Pereyra, A., 2000, Ph.D. Thesis, Instituto Astronômico e Geofísico, Universidade de São Paulo
Rodrigues, C. V, Sartori, M. J., Gregorio-Hetem, J., & Magalhães, A. M., 2009, ApJ, 698, 2031
Schmidt, G. D, Elston, R., & Lupie, O. L., 1992, AJ, 104, 1563
Turnshek, D. A., Bohlin, R. C., Williamson, R. L., Lupie, O. L., Koornneef, J., Morgan, D. H., 1990, AJ, 99, 4
Wade, G. A., Drouin, D., Bagnulo, S., Landstreet, J. D., Mason, E., Silvester, J., Alecian, E., Böhm, T., Bouret, J.-C., Catala, C., Donati, J.-F., 2005, A&A, 442, L31

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Table 2. Synthetic optical broad-band polarimetry using ESPaDOnS data and literature values.

| Object     | band | ESPaDOnS   | Literature\(^a\) |
|------------|------|------------|-------------------|
|            |      |            |                   |
|            |      | \(P\) (%) | \(PA\) (°)       | \(P\) (%) | \(PA\) (°) |
| HD 144432  | \(V\) | 0.27 (0.02) | 33.9 (2.5)        | 0.37 (0.06) | 14.5       |
|            | \(R\) | 0.27 (0.03) | 25.7 (2.8)        |           |            |
|            | \(I\) | 0.25 (0.02) | 16.0 (2.7)        |           |            |
| HD 150193  | \(V\) | 5.12 (0.05) | 56.1 (0.3)        | 4.78 (0.11) | 56.7       |
|            | \(R\) | 5.14 (0.07) | 56.2 (0.4)        |           |            |
|            | \(I\) | 4.83 (0.13) | 56.2 (0.8)        |           |            |
| PDS 069 N  | \(V\) | 0.48 (0.05) | 153.2 (3.3)       | 0.68 (0.04) | 147.0      |
|            | \(R\) | 0.65 (0.05) | 149.2 (2.0)       |           |            |
|            | \(I\) | 0.70 (0.03) | 149.1 (1.4)       |           |            |
| PDS 395    | \(V\) | 0.04 (0.03) | 96.2 (24.2)       | 0.06 (0.11) | 147.6      |
|            | \(R\) | 0.04 (0.02) | 121.4 (19.1)      |           |            |
|            | \(I\) | 0.04 (0.03) | 131.2 (21.3)      |           |            |
| PDS 545    | \(V\) | 2.69 (0.02) | 81.7 (0.2)        | 3.04 (0.03) | 78.6       |
|            | \(R\) | 2.56 (0.08) | 81.7 (0.9)        |           |            |
|            | \(I\) | 2.23 (0.10) | 81.5 (1.3)        |           |            |
| HD 14468\(^b\) | \(V\) | 0.77 (0.02) | 16.2 (0.9)        | 0.58 (0.02) | 166.5      |
|            | \(R\) | 0.81 (0.03) | 16.2 (0.9)        |           |            |
|            | \(I\) | 0.79 (0.04) | 17.5 (1.3)        |           |            |
| PDS 080    | \(V\) | 0.22 (0.02) | 82.4 (2.7)        | 0.04 (0.05) | 45.8       |
|            | \(R\) | 0.28 (0.04) | 87.5 (4.6)        |           |            |
|            | \(I\) | 0.44 (0.07) | 90.0 (4.3)        |           |            |
| PDS 225    | \(V\) | 1.03 (0.03) | 32.9 (0.9)        | 0.97 (0.04) | 26.3       |
|            | \(R\) | 0.96 (0.03) | 31.8 (1.0)        |           |            |
|            | \(I\) | 0.84 (0.04) | 32.0 (1.3)        |           |            |
| HD 76543 S | \(V\) | 0.54 (0.03) | 137.9 (1.8)       | 0.47 (0.02) | 127.4      |
|            | \(R\) | 0.63 (0.04) | 138.3 (1.7)       |           |            |
|            | \(I\) | 0.68 (0.03) | 138.1 (1.4)       |           |            |
| PDS 021    | \(V\) | 1.44 (0.04) | 33.9 (0.7)        | 1.60 (0.02) | 29.7       |
|            | \(R\) | 1.31 (0.06) | 32.7 (1.4)        |           |            |
|            | \(I\) | 1.05 (0.07) | 32.7 (2.0)        |           |            |
| PDS 281    | \(V\) | 1.17 (0.04) | 159.0 (1.0)       | 1.38 (0.04) | 160.2      |
|            | \(R\) | 1.16 (0.04) | 162.8 (1.0)       |           |            |
|            | \(I\) | 1.04 (0.07) | 166.3 (1.8)       |           |            |
| 73 Cet     | \(V\) | 0.46 (0.02) | 69.4 (1.3)        | 0.09 (0.02) | 114.4      |
|            | \(R\) | 0.49 (0.02) | 69.8 (1.4)        |           |            |
|            | \(I\) | 0.54 (0.03) | 71.0 (1.5)        |           |            |
| HD 19820   | \(V\) | 4.61 (0.02) | 115.1 (0.1)       | 4.79 (0.03) | 114.9      |
|            | \(R\) | 4.42 (0.09) | 115.1 (0.6)       | 4.53 (0.03) | 114.5      |
|            | \(I\) | 3.88 (0.13) | 115.1 (1.0)       | 4.08 (0.03) | 114.5      |

Errors in parenthesis.

\(^a\) All objects from Rodrigues et al. (2009) except 73 Cet and HD 19820 (from Schmidt et al. 1992).

\(^b\) This object presents confirmed variability in polarization (specially in PA). Hutchinson et al. (1994) reported \(P(V) = 1.19\%\ (0.08\%)\) at \(PA = 134^\circ\ (5^\circ)\), and Bhatt (1996) \(P(V) = 0.58\%\ (0.11\%)\) at \(PA = 168^\circ\ (5^\circ)\). Our result is more consistent with Hutchinson et al. (1994), and Rodrigues et al. (2009) with Bhatt (1996).
