

# Characterisation of the CAFOS linear spectro-polarimeter<sup>★</sup> (Research Note)

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## ABSTRACT

**Aims.** This research note presents a full analysis of the CAFOS polarimeter mounted at the Calar Alto 2.2m telescope. It also provides future users of this mode with all necessary information to properly correct for instrumental effects in polarization data obtained with this instrument.

**Methods.** The standard stars BD+59d389 (polarized) and HD 14069 (unpolarized) were observed with CAFOS in November, 2010, using 16 half-wave plate angles. The linear spectropolarimetric properties of CAFOS were studied using a Fourier Analysis of the resulting data.

**Results.** CAFOS shows a roughly constant instrumental polarization at the level of  $\sim 0.3\%$  between 4000 and 8600 Å. Below 4000 Å the spurious polarization grows to reach  $\sim 0.7\%$  at 3600 Å. This instrumental effect is most likely produced by the telescope optics, and appears to be additive. The Wollaston prism presents a clear deviation from the ideal behavior. The problem is largely removed by the usage of at least 4 retarder plate angles. The chromatism of the half-wave plate causes a peak-to-peak oscillation of  $\sim 11$  degrees in the polarization angle. This can be effectively corrected using the tabulated values presented in this paper. The Fourier analysis shows that the  $k \neq 0,4$  harmonics are practically negligible between 3800 and 7400 Å.

**Conclusions.** After correcting for instrumental polarization and retarder plate chromatism, with 4 half-wave plate angles CAFOS can reach an rms linear polarization accuracy of about 0.1%.

**Key words.** Techniques: polarimetry - Instrumentation: polarimeters

## 1. Introduction

In the course of the observational campaign on the bright Supernova 2010jl we obtained spectropolarimetry of this object using the Calar Alto Faint Object Spectrograph (CAFOS), mounted at the 2.2 m telescope in Calar Alto, Spain (Meisenheimer 1998). The results were published in Patat et al. (2010). The polarimetric mode of CAFOS has not been used very extensively, and mostly in imaging mode (see Greiner et al. 2003 for an example). As we could not find a proper characterisation of the instrumental effects in the literature, during the campaign on SN 2010jl we ran a full analysis of the instrument. This is presented here with the aim of making it available to a wider community, who might find it useful for future spectropolarimetric observations with this instrument.

Dual-beam polarimeters like CAFOS are composed by a half-wave retarder plate (HWP) followed by the analyzer, which is a Wollaston prism (WP) producing two beams with orthogonal directions of polarization, usually indicated as ordi-

nary (O) and extraordinary (E) beams. With this instrumental setup, the Stokes parameters  $Q$  and  $U$  are derived measuring the intensities in the O and E beams ( $f_{O,i}$ ,  $f_{E,i}$ ) at a given set of HWP angles  $\theta_i$  (for a general overview see Patat & Romaniello 2006, and references therein).

This is typically achieved through the normalized flux differences  $F_i$ ,

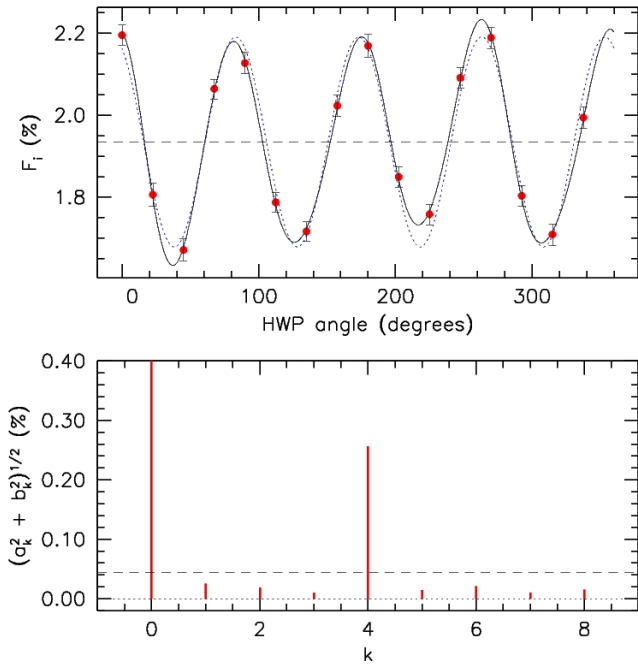
$$F_i = \frac{f_{O,i} - f_{E,i}}{f_{O,i} + f_{E,i}}.$$

For an ideal polarimeter, the normalized flux differences obey to the following relation:  $F_i = P \cos(4\theta_i - 2\chi)$ , where  $P = \sqrt{Q^2 + U^2}$  is the polarization degree, and  $\chi = \frac{1}{2} \arctan(U/Q)$  is the polarization position angle. Although any set of angles  $\theta_i$  is in principle suitable for obtaining  $Q$  and  $U$ , the optimal choice is  $\theta_i = \frac{\pi}{8}i$ . In these conditions one has that:

$$Q = \frac{2}{N} \sum_{i=0}^{N-1} F_i \cos\left(\frac{\pi}{2}i\right)$$

$$U = \frac{2}{N} \sum_{i=0}^{N-1} F_i \sin\left(\frac{\pi}{2}i\right),$$

<sup>★</sup> Based on observations collected at the German-Spanish Astronomical Center, Calar Alto, jointly operated by the Max-Planck-Institut für Astronomie Heidelberg and the Instituto de Astrofísica de Andalucía (CSIC).



**Fig. 1.** Fourier analysis applied to the unpolarized standard star HD 14069 at 5500 Å (200 Å bin). **Top:** normalized flux differences. The curves trace the partial reconstruction using 8 harmonics (solid) and the fourth harmonic only (dotted). The dashed horizontal line is placed at the average of the  $F$  values ( $a_0$ ). **Bottom:** harmonics power spectrum. The dashed line indicates the 5-sigma level of the uncertainty.

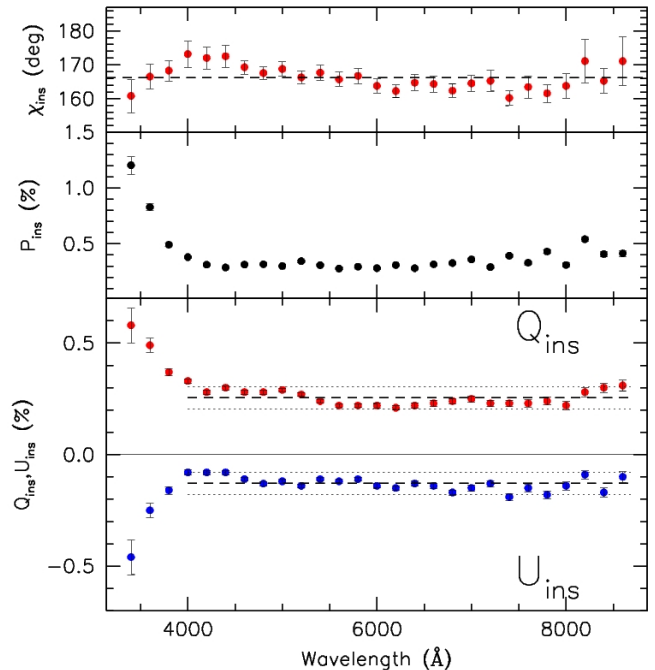
where  $N$  is the number of HWP angles. As  $F_i$  can be thought as a co-sinusoidal signal modulated by the rotation of the HWP with a fundamental period  $2\pi$ , these can be rewritten as a Fourier series (see Fendt et al. 1996):

$$F_i = a_0 + \sum_{k=1}^{N/2} \left[ a_k \cos\left(k \frac{2\pi i}{N}\right) + b_k \sin\left(k \frac{2\pi i}{N}\right) \right], \quad (1)$$

where  $a_k$  and  $b_k$  are the Fourier coefficients. The Fourier analysis is particularly useful when  $N=16$ ; under these circumstances, the polarization signal is carried by the  $k=4$  component. In an ideal system, all other components are rigorously zero. Therefore, non-null Fourier coefficients for  $k \neq 4$  signal possible problems in the polarimeter. For the meaning of the various components the reader is referred to Fendt et al. (1996).

## 2. Observations and data reduction

The observations were carried out with CAFOS (Meisenheimer 1998). In this multi-mode instrument, equipped with a 2K×2K SITE-1d CCD (24 μm pixels, 0.53 arcsec/pixel), polarimetry is performed by introducing into the optical path a WP (18" throw) and a super-achromatic HWP, between the collimator and the grism. For our study we observed the polarized star BD+59d389 ( $P(V)=6.70\pm 0.02\%$ ,  $\chi=98.1$  degrees; Schmidt et al. 1992), and the unpolarized star HD 14069 ( $P(V)=0.02\pm 0.02\%$ ; Schmidt et al. 1992) on 2010, November



**Fig. 2.** CAFOS instrumental polarization. **Upper panel:** instrumental polarization position angle. The dashed line indicates the average value. **Mid panel:** instrumental polarization degree. **Lower panel:** instrumental Stokes parameters. The dashed lines indicate the average value of  $Q$  and  $U$  in the wavelength range 4000–8600 Å, while the dotted lines mark the  $\pm 0.05\%$  deviations from the average value.

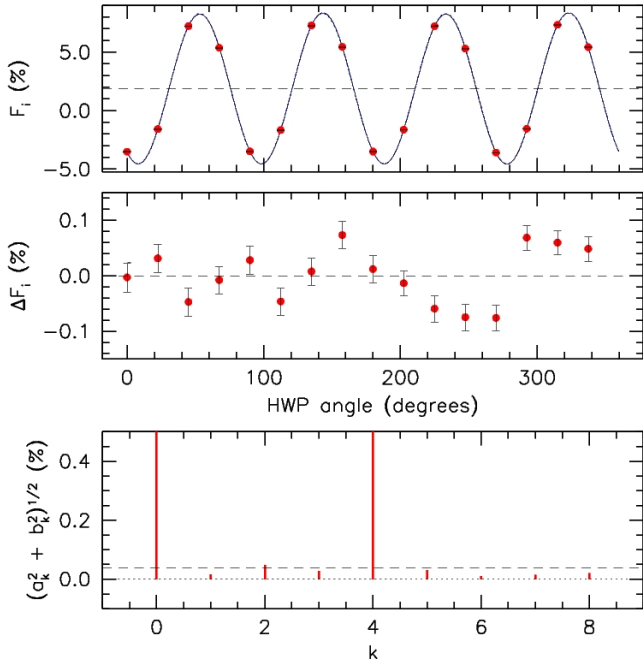
18.8 UT. All spectra were obtained with the low-resolution B200 grism coupled with a 1.0 arcsec slit, giving a spectral range 3300–8900 Å, a dispersion of  $\sim 4.7$  Å px<sup>-1</sup>, and a FWHM resolution of 14.0 Å. The slit was aligned along the N-S direction. To enable the Fourier analysis up to the 8-th harmonic we used  $N=16$  half-wave plate angles (0, 22.5, ..., 337.5). The exposure times were 180 seconds per HWP angle for both standard stars.

Data were bias and flat-field corrected, and wavelength calibrated using standard tasks within IRAF<sup>1</sup>. The Fourier analysis was carried out using specific routines written by us.

## 3. Instrumental polarization

To characterize the instrumental polarization of CAFOS, we first analyzed the data obtained for the unpolarized standard star. The result of the Fourier analysis is presented in Fig. 1 for a 200 Å wide bin centered at 5500 Å. The normalized flux differences show a marked modulation (upper panel), well reproduced by a sinusoidal function. The power spectrum (lower panel) displays a neat peak at the  $k=4$  overtone, corresponding to a linear polarization signal (see Sec. 1), reaching  $P=0.26\%$  (the  $k=0$  term is also non null, but we will discuss this in

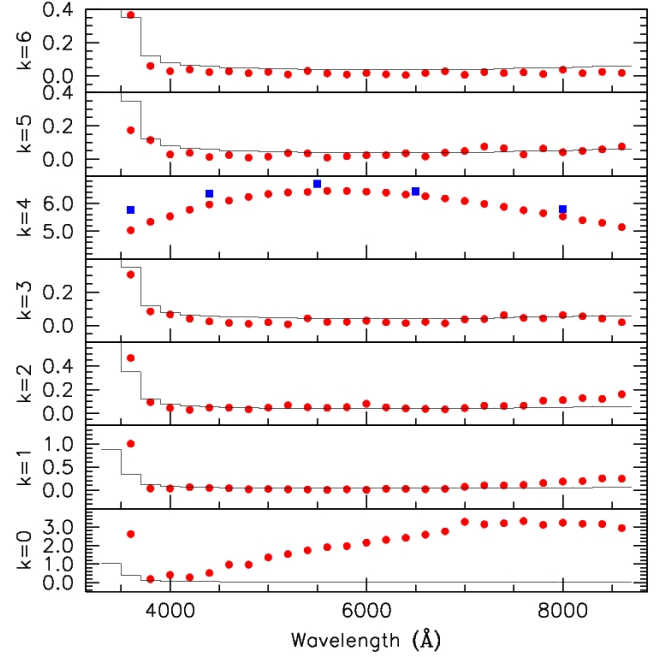
<sup>1</sup> IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, under contract with the National Science Foundation.



**Fig. 3.** Fourier analysis applied to the polarized standard star BD+59d389 at 5500 Å (200 Å bin). **Top:** normalized flux differences. The curves trace the partial reconstruction using 8 harmonics (solid) and the fourth harmonic only (dotted). The dashed horizontal line is placed at the average of the  $F$  values ( $a_0$ ). **Middle:** residuals from the reconstruction using the  $k=4$  harmonic. **Bottom:** harmonics power spectrum. The dashed line indicates the 5-sigma level uncertainty.

Sect. 4). The fact that the signal is modulated by the retarder plate rotation implies that the source of instrumental polarization precedes the HWP along the optical path. Therefore, most likely the observed polarization arises within the collimator and/or the telescope mirrors. For instance, inhomogeneities in the mirror coatings can break circular symmetry, and lead to an incomplete cancellation of the linear polarization generated by reflections (see Tinbergen 1996 and Leroy 2000 for general introductions to the subject). Such a system would behave as a partial polarizer, characterized by a certain position angle ( $\chi_{ins}$ ) that does not depend on wavelength, but only on the geometry of the system asymmetry. In general, the effect of the instrumental polarization depends on the Stokes vector that characterizes the input signal, and this makes the correction for instrumental polarization particularly difficult. However, when the instrumental polarization is much smaller than 1, the effect is additive, and the spurious signal can be removed subtracting it vectorially from the measured one (see for instance Patat & Romaniello 2006 for the case of VLT-FORS1).

The presence of a constant position angle is confirmed by the Fourier analysis run across the whole wavelength range covered by our observations. In Fig. 2 we present the values of  $Q_{ins}$  and  $U_{ins}$  derived within 200 Å wide bins between 3400 and 8600 Å (lower panel), and the implied position angle  $\chi_{ins}$  (upper panel). The average value of  $\chi_{ins}$  is 166.3 degrees, and the RMS deviation of the single measurements is 3.6 degrees.



**Fig. 4.** Power spectrum of the first 6 harmonics as a function of wavelength (ordinate scale is in %). The solid thin lines trace the 5- $\sigma$  confidence level. The filled squares in the  $k=4$  plot are the broad-band polarization measurements by Schmidt et al. (1992).

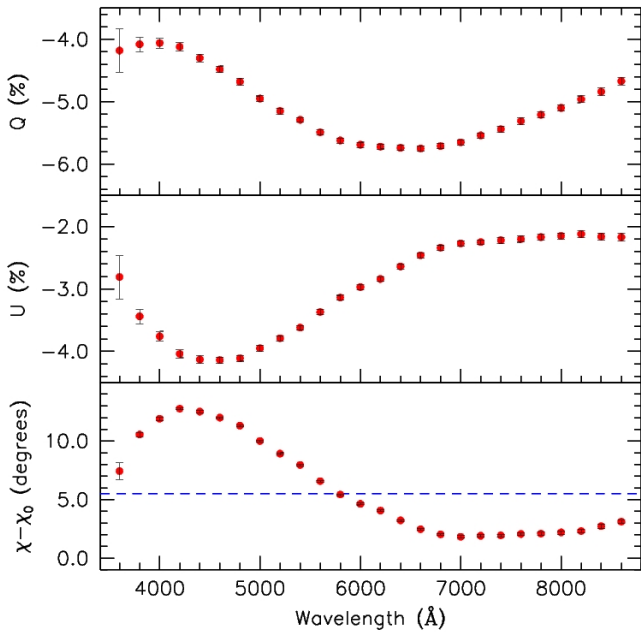
The smooth oscillation seen in the position angle is related to the chromatism of the HWP retardance (see Sect. 5). As far as the polarization is concerned, this reaches  $0.74 \pm 0.08\%$  at 3400 Å, and it rapidly decreases to  $0.33 \pm 0.01\%$  at 4000 Å, to remain constant to within 0.05% up to 8600 Å. The reason for the marked increase seen bluewards of 4000 Å is not clear, but it might be related to the decrease of efficiency in the anti-reflexion coatings of the collimator lenses.

The average values of the instrumental Stokes parameters above 4000 Å are  $\langle Q_{ins} \rangle = +0.25 \pm 0.03\%$ , and  $\langle U_{ins} \rangle = -0.13 \pm 0.03\%$  respectively, leading to an average polarization  $P_{ins} = 0.28 \pm 0.03\%$ . The wavelength range below 3800 Å is affected by other instrumental problems which make it hardly usable with the typical set of 4 HWP angles (see next section). Therefore, this constant correction is sufficient to guarantee the removal of the instrumental polarization with a maximum error of 0.05%, which is comparable to the maximum accuracy one can reach with CAFOS with 4 HWP angles (see next section).

We remark that the instrumental polarization correction derived here is strictly valid only for an object placed on the CAFOS reference pixel used for the acquisition onto the 1.0 arcsec slit. With the present analysis we cannot exclude position-dependent effects, similarly to what happens in the FORS instruments (Patat & Romaniello 2006).

#### 4. Fourier analysis

For the Fourier analysis of the CAFOS polarimetric performances we have used the data obtained for the polarized stan-



**Fig. 5.** Instrumental polarization corrected Stokes parameters  $Q$  (top panel) and  $U$  (mid panel) for BD+59d389. The bottom panel shows the phase retardance variation as a function of wavelength.

dard star. Fig. 3 shows an example for a 200 Å wide bin centered at 5500 Å. The only components which show a statistically significant power are  $k=0$  and  $k=4$ ; there is a hint of a non-null  $k=2$  component, which is related to the so-called pleochroism (Fendt et al. 1996; Patat & Romaniello 2006), but this is only marginally significant at the  $5\text{-}\sigma$  level. The original signal can be reconstructed using only the  $k=4$  harmonic, with maximum residuals  $\Delta F_i$  of  $\sim 0.1\%$ . This implies that 4 HWP angles are sufficient to derive the Stokes parameters with a maximum error of this order. The polarization degree derived using 16 HWP angles at 5500 Å is  $6.43 \pm 0.01\%$ . After applying the instrumental polarization correction described in the previous section this value becomes  $6.6 \pm 0.1\%$ . This is fully consistent with the reference value  $6.70 \pm 0.02\%$  measured in the V passband (Schmidt et al. 1992).

In the example illustrated in Fig. 3 we find  $a_0 = 1.88 \pm 0.01\%$  (the corresponding value derived from the unpolarized standard is  $1.93 \pm 0.01\%$ ; see also Fig. 1, upper panel). This indicates that the WP deviates from the ideal case, in that an unpolarized incoming beam is not exactly split into two identical fractions (see Patat & Romaniello 2006, their Sect. 7). As a consequence, using only 2 HWP angles (which is the minimum set needed to fully reconstruct the Stokes vector) would lead to a very significant error on the final result.

To study the instrumental performance as a function of wavelength, we have run the same analysis within 200 Å wide bins between 3400 and 8600 Å. The result for the first 6 harmonics is shown in Fig. 4. The  $k=0$  component is always significant, exceeding  $\sim 3\%$  at 7500 Å, but this is fairly well corrected if the data set includes at least 4 HWP positions. As for compo-

$\lambda$ (Å)	$\Delta\chi$ (deg)	$\sigma$ (deg)	$\lambda$ (Å)	$\Delta\chi$ (deg)	$\sigma$ (deg)
3600	7.44	0.71	6200	4.06	0.08
3800	10.55	0.20	6400	3.22	0.09
4000	11.90	0.12	6600	2.46	0.09
4200	12.76	0.09	6800	2.02	0.10
4400	12.51	0.07	7000	1.82	0.10
4600	12.00	0.07	7200	1.91	0.10
4800	11.31	0.07	7400	1.93	0.12
5000	10.00	0.07	7600	2.06	0.13
5200	8.91	0.07	7800	2.09	0.13
5400	7.95	0.06	8000	2.19	0.13
5600	6.57	0.07	8200	2.30	0.15
5800	5.42	0.07	8400	2.72	0.16
6000	4.63	0.08	8600	3.11	0.16

**Table 1.** HWP retardance variation as a function of wavelength.

nents  $k=1$  and 2, these are detected at a significant level below 3800 Å and above 7000 Å. At 3600 Å the usage of 4 HWP angles leads to errors larger than 0.3%, making data bluewards of 3800 Å hardly usable. At the red edge, deviations are below 0.2% bluewards of 7400 Å, while they can exceed 0.3% above 8200 Å.

As the  $k=4$  component of the power spectrum is the linear polarization degree, its wavelength dependence can be directly compared to the broad band values available in the literature (Schmidt et al. 1992). These are overplotted in the  $k=4$  panel of Fig. 4 (filled squares). As expected based on the estimates of the instrumental polarization (see Sect. 3), there is a difference of about 0.3% above 4000 Å. The value corresponding to the  $U$  passband shows a larger deviation (0.7%), which is consistent with the increase of the instrumental polarization seen below 4000 Å (see Fig. 2). It is worth noting that, as the polarization signals of the star and the instrument are close to orthogonal, the corrected value is higher than the measured one.

## 5. HWP chromatism

Although the retarder plate deployed in CAFOS is superachromatic, the phase retardance is expected to deviate from an ideal behavior as a function of wavelength. To quantify this effect we have used the polarized standard as reference. For this star the polarization position angle is constant to within 0.1 degrees in the UBVRI domain, the average value being  $\chi_0 = 98.2 \pm 0.1$  degrees (Schmidt et al. 1992). Therefore, if  $Q_{obs}$  and  $U_{obs}$  are the measured Stokes parameters, the phase retardance variation across the wavelength range can be computed as  $\Delta\chi = \chi - \chi_0$ , where  $\chi = \frac{1}{2} \arctan[(U_{obs} - U_{ins}) / (Q_{obs} - Q_{ins})]$ . The result is plotted in Fig. 5, and the values listed in Table 1.

Having these values at hand, the corrected Stokes parameters  $Q_c$  and  $U_c$  can be obtained by the following rotation:

$$Q_c = Q \cos 2\Delta\chi + U \sin 2\Delta\chi$$

$$U_c = U \cos 2\Delta\chi - Q \sin 2\Delta\chi,$$

where  $Q$  and  $U$  are the instrumental polarization corrected Stokes parameters. Alternatively, the position angle obtained from  $Q$  and  $U$  can be corrected subtracting  $\Delta\chi$ .

Usually the zero-point of the HWP angle is set so that  $\theta=0$  corresponds to a null astronomical position angle in the plane of the sky around the central wavelength. This is not the case in CAFOS, as the deviation at 6000 Å is about 5.5 degrees, and it is never zero between 3600 and 8600 Å (Fig. 5, bottom panel). However, given the way we have computed  $\Delta\chi$ , this correction will give position angles in the plane of the sky, with  $\chi=0$  corresponding to the N-S direction.

## 6. Conclusions

In this note we presented a full analysis of the linear polarization properties of CAFOS. Although the instrument appears to suffer from a significant spurious polarization, this can be removed to within  $\sim 0.1\%$ . The effect appears to be additive, and can be therefore easily corrected by vectorially subtracting the instrumental component on the Stokes  $Q, U$  plane.

As is typical of other dual-beam polarimeters (see for instance the case of FORS1, Patat & Romaniello 2006), the Wollaston prism departs from the ideal case. In the worst case the fraction of light in the ordinary and extraordinary beams for an unpolarized incoming signal deviates by  $\sim 2\%$  from the theoretical 50/50 ratio. However, this defect is largely removed by the adoption of 4 retarder plate angles during the observations. Using the minimum set (2 HWP angles) leads to large errors, especially in the case of low polarizations ( $\sim 1\%$ ), and it is therefore strongly discouraged.

The Fourier analysis shows that all harmonics with  $k \neq 0, 4$  are negligible in the wavelength range 3800–7400 Å, where a rms accuracy of 0.1% can be reached with a sufficient signal-to-noise. This can be considered as the instrumental limit attainable with CAFOS with 4 HWP angles, and within this spectral range. Below 3800 Å the polarimetric properties rapidly degrade, requiring a larger number of HWP angles. The same applies, though to a smaller extent, to the region redwards of 8200 Å.

For this work we have used data obtained with the B200 grism. Because of its tilted surfaces, the grism can act as a poor linear polarizer. Since in CAFOS this is placed after the analyzer, the spurious polarization produced by transmission is not modulated by the HWP rotation, and hence the redundancy in the retarder-plate position effectively removes it (see Patat & Romaniello 2006). The exact effect produced by the grism depends on its properties. However, the conclusions reached in this paper do not depend on the grism, provided that the data are obtained using at least 4 HWP angles.

In general, CAFOS appears to be perfectly suitable for linear polarization studies aiming at accuracies of a few 0.1%, making it a valid instrument for bright objects. As a term of reference, an accuracy of  $\sim 0.1\%$  per resolution element ( $\sim 50$  Å) was reached for SN 2010jl ( $V \sim 13.5$ ), with 4 exposures of 40 minutes each (Patat et al. 2010).

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