Boletim da Sociedade Astronômica Brasileira, **36**, no. 1, 186-187

Polarimetric Characterization of SPARC4

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Abstract. SPARC4 is an imager capable of observing in four optical bands (g, r, i, z) simultaneously and in photometric and polarimetric modes. Its first light was in 2022, commissioning and scientific verification missions were carried out in 2023, and from the first half of 2024 it became part of the facilities offered at the Observatório do Pico dos Dias. Therefore, its characterization is essential so that users can correctly calibrate and interpret the measurements. Thus, we propose to analyze all calibration observations made in polarimetric mode and obtain the characterization of the polarimetric efficiency and instrumental polarization. To do this, we will use a pipeline, which uses ASTROPOP, a software written in Python. Here we describe the status of this ongoing project.

Resumo. A SPARC4 é um imageador capaz de observar em quatro bandas ópticas (g, r, i, z) de forma simultânea e nos modos fotométrico e polarimétrico. Este instrumento teve sua primeira luz em 2022, no ano de 2023 foram realizadas missões de comissionamento e verificações científicas e a partir do primeiro semestre de 2024 passou a fazer parte das facilidades oferecidas no Observatório do Pico dos Dias, portanto, a sua caracterização é fundamental para que os usuários possam calibrar e interpretar as medidas corretamente. Assim, propomos analisar todas as observações de calibração feitas no modo polarimétrico e obter a caracterização da eficiência polarimétrica e da polarização instrumental. Para isso, vamos utilizar uma pipeline que utiliza o ASTROPOP, um software escrito em Python. Aqui descrevemos o status deste projeto em andamento.

Keywords. Instrumentation: photometers – Instrumentation: polarimeters – Methods: observational – Techniques: polarimetric

1. Introduction

SPARC4, the Simultaneous Polarimeter And Rapid Camera in four bands, is capable of observing in the photometric and polarimetric modes simultaneously in g, r, i and z bands. Many scientific cases can benefit from the SPARC4 polarimetric mode, such as interacting binaries, exoplanets, circumstellar envelopes, star-forming regions, blazars, and open clusters (Rodrigues et al., 2012, 2024). Therefore, it is important to characterize the instrument polarimetrically.

The SPARC4 commissioning runs started in November 2022 and continued throughout the year 2023. In this year, 2024, SPARC4 became part of the facilities of the Pico dos Dias observatory. Some objectives of the commissioning runs were to verify the instrument performance in polarimetry; to test instrument and pipeline stability for polarimetry; to assess the instrumental efficiency and polarization; and to measure the position of the fast axis of the quarter-wave retarder. These data will also be used to produce reference polarization for standard stars in the SDSS griz bands. In this work, we present how the polarimetry works on SPARC4, the data reduction, the preliminary results, the conclusion, and perspectives.

2. Observations

Photometric and polarimetric data were obtained at the Observatório do Pico dos Dias (OPD), using the SPARC4 camera attached to the 1.6 m Perkin-Elmer telescope. The SPARC4 polarimeter is composed of a retarder plate and a Savart prism, responsible for dividing the beam into ordinary and extraordinary components. The waveplate has 16 positions, separated by 22.5 degrees (Rodrigues et al., 2012). For each waveplate position, we collected one or more images, depending on the band and exposure time. To perform calibration measurements, we can add a polarizer or a depolarizer to the setup.

Our observations include 24 polarized standard stars, of which 19 were observed more than once, and 9 unpolarized stars, see Table 1. In this sample, we have data from commissioning runs and from collaborator's scientific runs.

3. Preliminary Results

We have already perfomed the data reduction for 11 nights. For that we use the ASTROnomical Photometry and Polarimetry Pipeline (ASTROPOP, Campagnolo 2018). ASTROPOP is an open source package written in Python. ASTROPOP can perform image preprocessing, source detection, photometric and polarimetric reduction, and astrometric and photometric calibration. Since we are working with polarimetric frames, where we have the ordinary and extraordinary beams, the code matches the pairs before performing the aperture photometry. In this step, it allows us to obtain aperture photometry for all pairs identified using a range of aperture radii, calculated proportionally to the full width at half maximum (FWHM) of the images. We can obtain the Stokes parameters from the ordinary and extraordinary fluxes ($F_o(\phi)$ and $F_e(\phi)$, respectively) using the Stokes Least Squares (SLS) method, where ϕ is the angle of position of the waveplate. This method calculates the normalized flux difference between the fluxes,$Z(\phi)$, for each ϕ (Rodrigues et al., 1998). $Z(\phi)$ is a function of the Stokes parameters (Q, U, and V), which, in turn, are related to linear polarization (p) and position angle (θ).

$$Z(\phi) = \frac{F_o(\phi) - F_e(\phi) \cdot k}{F_o(\phi) + F_e(\phi) \cdot k}, \tag{1}$$

Table 1. Observed polarimetric standards objects.

Star ID	V (mag)	Type	N° of observations 2022	2023	2024
NGC 2024 1	12.17	polarized	1	2	-
HD 111579	9.12	polarized	-	7	1
Hilt 652	10.61	polarized	-	5	5
HD 126593	8.65	polarized	-	4	5
Vela1 95	12.12	polarized	-	2	2
HD 298383	9.75	polarized	-	2	2
Hilt 781	10.71	polarized	-	5	-
HD 155528	9.60	polarized	-	2	2
HD 316232	10.17	polarized	-	2	1
Hilt 715	9.56	polarized	-	2	-
Hilt 785	10.20	polarized	-	1	-
HD 10038	8.14	unpolarized	-	2	-
HD 13588	7.9	unpolarized	-	3	-
WD 2039-202	12.4	unpolarized	-	3	3
WD 2149+21	12.74	unpolarized	-	2	2
HD 98161	6.24	unpolarized	-	-	1
HD 110984	9.03	polarized	-	-	1
HD 97698	7.09	unpolarized	-	-	1
HD 176425	6.21	unpolarized	-	-	2
WD 1620-391	11.03	unpolarized	-	-	2
WD 2007-303	12.24	unpolarized	-	-	3
BD-13 5073	10.20	polarized	-	-	2
BD-12 5133	10.71	polarized	-	-	2
HD 187929	3.80	polarized	-	-	1

where k is a normalization factor (for $\lambda/2$, $k = \frac{\sum F_o(\phi)}{\sum F_e(\phi)}$) (Magalhaes et al., 1984).

We also have a well-developed pipeline based on ASTROPOP (Martioli, 2025). We intend to continue the polarimetric characterization of SPARC4 using this pipeline. In Figure 1, we have an example of the reduction using the SPARC4 pipeline. The object is the polarized standard star HD 126593 observed in g, r, i, and z bands using the half-wave plate. In the figure, the black dots in the top panel show $Z(\phi)$ as a function of the position of the retarder plate, and the red dashed line is a model for $q = Q/I$ and $u = U/I$ (where I is the light intensity), from 0 to 360 degrees. The bottom panel presents the residuals of the observations with respect to the model. This figure shows some information at the top of the panel, such as the object ID, the observed date and mode, the index, according to the stack image, the chosen aperture radii, the χ^2, the RMS, the theoretical error (σ_t), k, the zero of the waveplate (ψ_0), the Stokes parameters values q and u, P and θ.

The polarization error is in the same order as the theoretical errors. Also, the residuals are around zero, attesting to the good quality of the fit and, consequently, of the data.

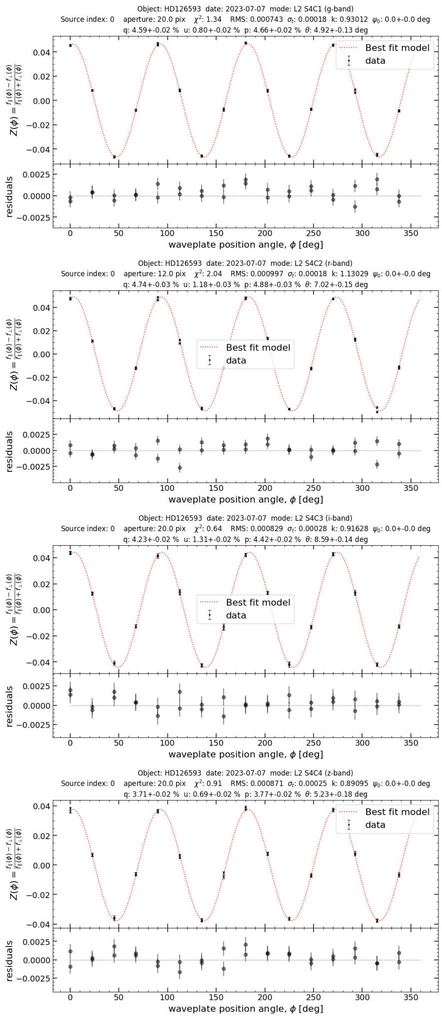

Figure 1. Polarization adjustment for the HD 126593 in g, r, i and z bands. The black dots, at the top panel, show $Z(\phi)$ as a function of the retarder plate position, and the red dashed line is a model for q and u, from 0 to 360 degress. The bottom panel presents the residuals of the observation relative to the model

4. Conclusion and Perspectives

We use ASTROPOP and the SPARC4 pipeline to perform data reduction. Both perform well. The uncertainties are compatible with expectations. Polarimetric characterization of SPARC4 is a work in progress. It will provide the accuracy and precision limits of the polarimetric modes of the SPARC4 instrument. Our work will also provide the polarization of standard polarimetric stars in the griz bands of the SDSS photometric system.

Acknowledgements. This paper uses data obtained with the Simultaneous Polarimeter and Rapid Camera in 4 bands (SPARC4), installed on the 1.6-m telescope at the Observatório do Pico dos Dias (OPD), managed by the Laboratório Nacional de Astrofísica (LNA) under the Ministério da Ciência, Tecnologia e Inovação (Brazil). SPARC4 was funded by Financiadora de Estudos e Projetos - Finep (Proc: 0/1/16/0076/00), Agência Espacial Brasileira - AEB (PO 20VB.0009), Fundação de Amparo à Pesquisa do Estado de São Paulo - FAPESP (Grant 2010/01584-8), Fundação de Amparo à Pesquisa do Estado de Minas Gerais - FAPEMIG (APQ-00193-15 & APQ-02423-21), Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq (Grant #420812/2018-0) and INCT-Astrofísica. A.C.M thanks to CNPq (382618/2021-1, 150737/2024-6), INPE for the opportunity and supervision, and OPD-LNA for the observations. C.V.R. thanks the support from AEB (PO 20VB.0009) and CNPq (310930/2021-9). E.M. acknowledges funding from FAPEMIG (APQ-02493-22) and CNPq for a research productivity grant number 309829/2022-4 awarded by the CNPq, W.S. acknowledges financial support from CNPq/Brazil (Proc. 318052/2021-0, 300343/2022-1, 300834/2023-3, 301366/2023-3, 300252/2024-2 and 301472/2024-6).

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