Polarimetry: From the Sun to Stars and Stellar Environments
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Commissioning Results of a New Polarimeter: Denver University Small Telescope Polarimeter (DUSTPol)

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Abstract. DUSTPol is a dual-beam polarimeter that operates in optical wavelengths, and was built to promote the study of linear polarimetry with smaller telescopes. DUSTPol's performance has demonstrated low instrumental polarization at $0.05 \pm 0.02\%$. This poster presents commissioning results as well as early science observations, and describes software used for data reduction. Recent polarimetric results of RS CVn systems and Wolf-Rayet stars, discussed herein, indicate shape and interaction parameters. By promoting the development of similar polarimeters at other institutions, DUSTPol will serve to establish new collaborative surveys of cool active stars, as well as systems showing evidence of containing complex stellar environments.

Keywords. polarization, instrumentation: polarimeters, standards, stars: Wolf-Rayet, stars: activity, stars: general

1. Introduction

The broken symmetry of light from a celestial body is ultimately what causes stellar polarization. This can occur due to innately asymmetric geometries in eclipsing binaries, non-spherical stars and extended bodies such as nebulae. Other than geometric considerations, net polarization can also be induced by scattering off gas and dust within the environment of the object (such as stellar envelopes), or between the object and Earth (dust in the interstellar medium). The amount of polarization produced can provide information regarding the nature of the scatterers themselves, such as size and composition. Furthermore, detected polarization from scattered light can at times be due to *aligned* scatters (such as dust), and measurements can constrain the alignment mechanisms in play, from magnetic fields to radiative torque (Clarke 2010).

Polarimetry can therefore provide details on many different types of celestial bodies as well as different physical mechanisms in astronomy, which are otherwise hidden to photometry and spectroscopy. The asymmetric environments mentioned above may be inherently present within Wolf-Rayet and RS CVn systems, which are currently being explored by DUSTPol. As such, supporting the development of polarimeters for research institutions will be very valuable to the field. The goal of DUSTPol is to encourage institutions already equipped with astronomical resources, such as CCD cameras and even small-scale telescopes, to build polarimeters in an effort to establish a larger network of instruments, and operate under ideals of cooperation and consistency of method.

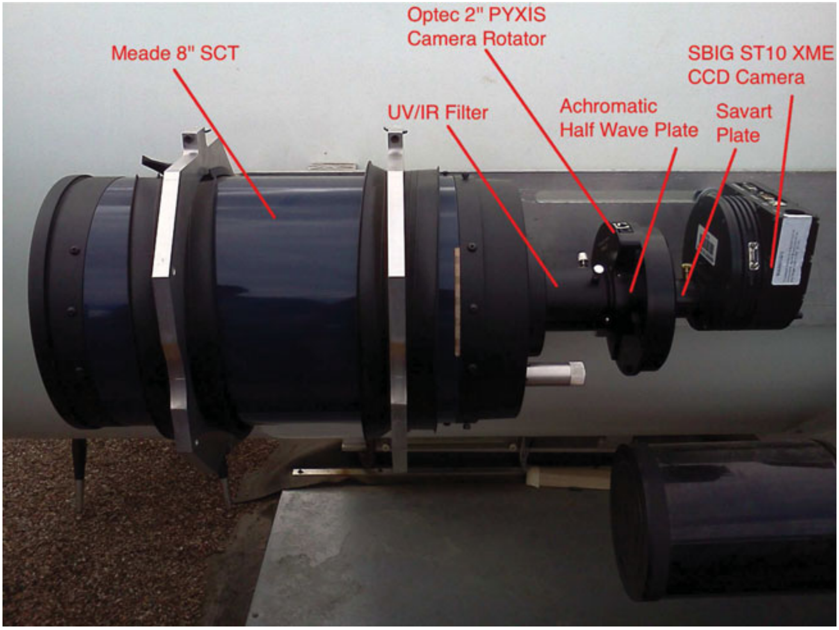

Figure 1. Photograph of DUSTPol with individual components labeled.

2. The Polarimeter

DUSTPol, as pictured in Figure 1, is a broadband optical dual-beam linear polarimeter. It utilizes a Meade 8" Schmidt-Cassegrain, co-mounted with the University of Denver's Student Astronomy Lab Telescope (DU-SALT, Mellon *et al.* 2004) to provide a robust computer-controlled pointing system. The polarimetric optics operate via passing the collected light through a rotatable achromatic half wave plate and polarizing beam-splitter known as a Savart plate. This produces a doubled image of orthogonal polarization states, which are then imaged simultaneously by a single SBIG ST-10 XME CCD camera. This is a very similar configuration to polarimeters developed by Masiero *et al.* (2007) and Cole (2010), and the dual-beam approach allows for simultaneous probing of the Q & U Stokes parameters.

The half wave plate, produced by Bolder Vision Optik, functions between wavelengths 400nm and 700nm. In order to allow and control the rotation of the wave plate, a customized Optec PYXIS 2" camera rotator was purchased for the wave plate to be seated in. PYXIS rotators typically rotated attachments on the back-end of the device, but the customization implemented by Optec for the polarimeter allows *internal* components of the PYXIS to rotate, and involves an O-ring that holds the wave plate in place.

The Savart plate created by United Crystals operates similarly to a Wollaston prism. Two pieces of crossed calcite split light into two orthogonally polarized beams with equal path-lengths, allowing the original polarization of the light to be measured by analyzing the brightness of each beam. However, the Savart produces parallel beams, as opposed to the divergent beams split by a Wollaston. While similar dual-beam polarimeters have made use of Wollaston prisms with single detectors (Topasna *et al.* 2013), the parallel beams produced by the Savart offers greater freedom of placement with respect to the detector.

In addition to these items, an Astronomik UV-IR blocking filter was purchased to ensure that each image contains polarimetric information according to the appropriate

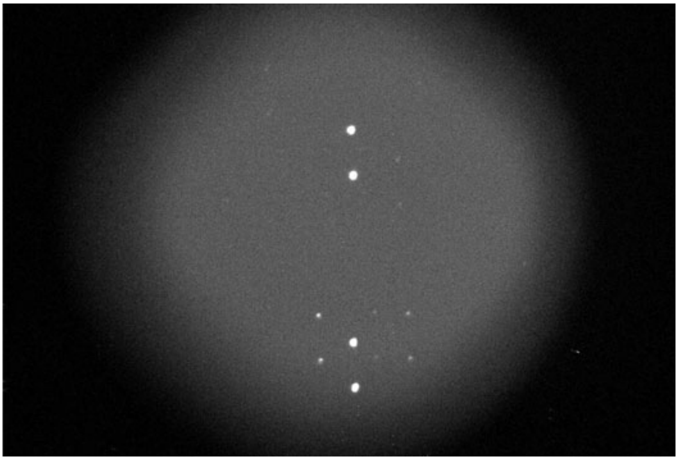

Figure 2. DUSTPol first light image of stars in the vicinity of Regulus.

wavelength range that the wave plate operates as designed. While no B, V, or R filters are in use at this time, these will be purchased and commissioned with the instrument in the future. Some periphery items such as adapters needed to assemble the instrument were also purchased from standard astronomy equipment retailers. Since the telescope and CCD camera were resources already owned by the University of Denver's Physics and Astronomy Department, the total cost of the polarimeter itself was under \$2500, making the instrument very affordable to many astronomy institutions with access to similar resources.

DUSTPol saw first light in May of 2014. Figure 2 shows an example image from this test. The heavy vignetting is caused by the Savart plate, creating a useable field of view of about 6 arc minutes.

While dual-beam linear polarimeters can typically measure Q and U parameters in as few as 2 images, DUSTPol employs a technique that involves taking four images, at wave plate angles 0°, 22.5°, 45°, and 67.5° (Pickering 1874). For a given exposure such as the one shown in Figure 2, the brightnesses (signals) of the top and bottom images (extraordinary and ordinary rays produced by the Savart plate) of an object pair are measured using aperture photometry. Once the brightness for images at each of the four wave plate angles of Pickering's Method are measured in this way, signals S_{0°, $S_{22.5^\circ}$, S_{45° and $S_{67.5^\circ}$ are now known for both the ordinary and extraordinary rays. Angles 0° and 45° contain information about Stokes I & Q, while angles 22.5° and 67.5° contain information about Stokes I & U.

These signals can then be used to calculate the following:

$$R_q = \frac{S^o_{0^\circ}}{S^e_{0^\circ}} \Big/ \frac{S^o_{45^\circ}}{S^e_{45^\circ}}, \qquad R_u = \frac{S^o_{22.5^\circ}}{S^e_{22.5^\circ}} \Big/ \frac{S^o_{67.5^\circ}}{S^e_{67.5^\circ}},$$

where superscripts o and e correspond to measurements made on the ordinary and extraordinary rays, respectively. These can then be used to find *normalized* stokes q and u, in accordance with derivations similar to di Serego Aligieri (1997) and equations found in Tinbergen *et al.* (1992) and Clarke (2010):

$$q = \frac{\sqrt{R_q} - 1}{\sqrt{R_q} + 1}, \qquad u = \frac{\sqrt{R_u} - 1}{\sqrt{R_u} + 1}.$$

From these equations, the linear polarization can then be computed as $p = \sqrt{q^2 + u^2}$, and the position angle can be calculated with $\zeta = \frac{1}{2} \arctan \left(\frac{u}{q} \right)$.

Because the light signals detected on a CCD chip can be expressed as a function of wave plate angle and Stokes parameters modified by *factors* involving instrument gain, airmass, and optical effect, these factors are in essence canceled when determining the normalized stokes parameters. As such, typical time-consuming image calibration techniques such as flat fielding and airmass measurements are not needed (Masiero *et al.* 2007). In fact, this benefit also offers more incentive for other institutions to commission similar polarimeters, as any efforts in cooperative observations would not suffer from differences in image calibration techniques.

Measurement uncertainty ultimately involves photon statistics, as the initial measurements of signal are entirely photometric. Thus, the uncertainties in the polarimetry are simply propagated from the photometric measurements using standard statistical equations. Additionally, bias inherent in polarization percentages is removed using the Wardle-Kronberg estimator (Wardle & Kronberg 1974). These methods are shared by Topasna *et al.* (2013), and all representations of measurement uncertainty shown in this paper were calculated this way.

3. Calibration and Observations

For any polarimeter, observations of standardized calibration stars is very important. Prior to being able to make any claims about the polarization of light from astronomical sources, the polarization (or depolarization) introduced by the instrument itself must be measured. For ideal polarimeters, instrumental offsets are constant and can simply be subtracted out of all subsequent measurements once obtained via calibration. In fact, the similar polarimeters developed by Masiero *et al.* (2007) and Cole (2010) show nearly constant instrumental polarization, and as such similar offsets in quantity and consistency are expected for DUSTPol.

Standard calibrators, polarized and unpolarized, can be obtained from published sources. A list of bright standards compiled by Serkowski (1974) is typically used for instrument calibration. Additionally, a useful database of Northern sky calibrators has been compiled by Berdyugin *et al.* (2014), and can be accessed via the VizieR Astronomical Database. DUSTPol calibrations are based on stars observed from these lists.

Instrumental polarization signals measured for standard, unpolarized calibration stars during DUSTPol observations are consistently low, at a current estimate of $0.05 \pm 0.02\%$. While DUSTPol's calibration involved observations of these stars, there is some question as to whether historically-accepted calibrators such as Serkowski's list are actually constant in their polarization levels (Bastien *et al.* 2007). The assumption that they have remained constant should be avoided, and more attempts to re-observe these standards to look for change should be made, and frequently. To help off-set any errors in determining DUSTPol's instrumental polarization from these standards, the standards will be re-observed frequently by the DUSTPol team, and its instrumental polarization re-evaluated when needed. Results of observations of Serkowski standards are provided in Table 1. Position angle calibration of the instrument is in the process of being re-analyzed.

In addition to calibrators, DUSTPol observations have focused on Wolf-Rayets and RS CVns. Wolf-Rayet stars in particular offer an interesting target for broadband polarimetry, as complex and asymmetrical stellar environments created by their characteristic winds can induce a polarized signal. Polarimetry may be used to detect or constrain rotation speed of these stars. This is of interest to Gamma Ray Burst studies, as

Table 1. Results of instrumental polarization calibration for Serkowski standards. Published values are from Serkowski (1974).

Date of Observation (mm/dd/yyyy)	Star	m_V	%p	Published %p
08/12/2014	HD 165908	5.07	0.00 ± 0.01	0.002
08/18/2014	HD 204827	7.94	5.40 ± 0.12	5.7
08/12/2014	HD 187929	3.80	1.66 ± 0.02	1.8
08/12/2014	HD 7927	4.98	3.20 ± 0.14	3.4

Table 2. Preliminary data on WR 137 and RS CVn variable II Peg.

Date of Observation (mm/dd/yyyy)	Star	m_V	%p
10/06/2014	WR 137	7.91	1.20 ± 0.03
10/29/2014	II Peg	7.18	0.08 ± 0.04

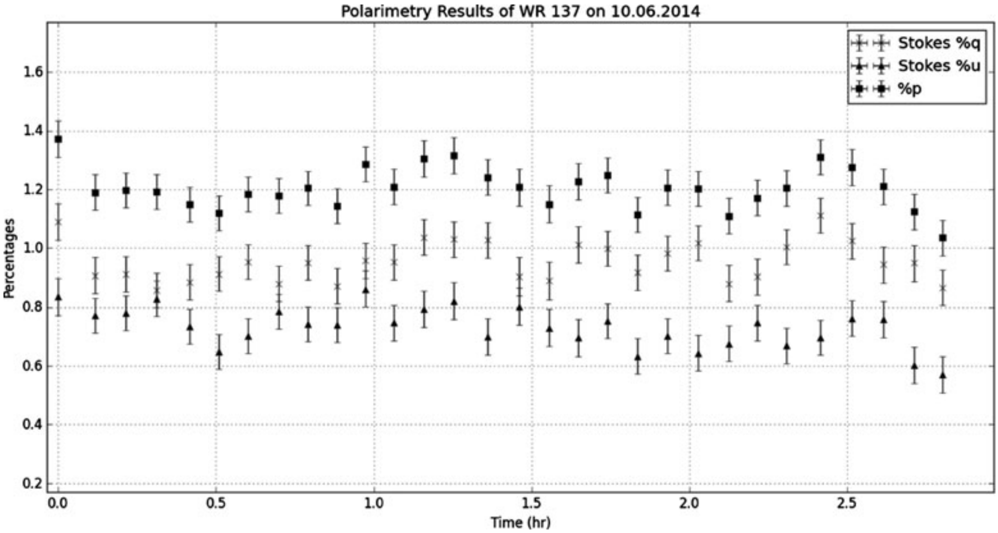

Figure 3. Time series polarimetry data of WR 137 from October 6, 2014, 4:30 (UT).

fast-rotating Wolf-Rayets are possible candidates for progeny of these explosive events (Vink *et al.* 2011). A first look at WR 137 indicates polarization levels consistent with prior results.

Additionally, interacting binary variables of RS CVn type (such as II Peg) have been known to show variable linear polarization in spectral data, as detected by Kochukhov *et al.* (2013) and Rosén *et al.* (2013). *Broadband* linear polarization measurements may indicate shape parameters for these interacting systems, the presence of star spots, as well as potential cumulative Zeeman effects in the optical. An initial attempt to detect this in the optical wavelength regime has been carried out on RS CVn star II Peg.

Table 2 summarizes the results of WR 137 and II Peg. A time-series evaluation of the WR 137 results, shown in Figure 3, offers an interesting perspective of the star. While any actual variability has not been verified due to the level of uncertainties in the measurements, visual trend seen in the graph has not been seen in data on other stars. More observations of WR 137 are needed to confirm whether this is some previously unseen fast variation in polarization.

4. Discussion and Future Work

Thus far, DUSTPol has produced results largely consistent with prior measurements. Inconsistencies present in some of the polarization levels measured of calibration stars shown in Table 1 are being analyzed. They could be the result of spurious polarization effects introduced by unwanted wandering of the stellar images across the CCD array for those observations.

The polarization levels of WR 137 shown in Table 2 and Figure 3 are consistent with measurements made by Akras *et al.* (2013), and exhibit a curious trend, albeit not necessarily real. More data taken by DUSTPol, currently being analyzed, will help determine whether this star shows any actual variability in polarization on short-term time scales.

The data for II Peg indicates a possibly marginal polarization level. More statistically rigorous methods should be used in constraining this low-level result.

Instruments like DUSTPol can be easily built by many institutions and amateur astronomers that already own telescopes with computer-operated mounts, regardless of their size. Thus, we extend an open invitation to any other institutions who may wish to collaborate in studies of astronomical polarimetry. Our current look into software solutions can also be shared among collaborators in order to provide those who are interested with means of automating their observations. Establishing a network of calibrated polarimeters can facilitate larger-scale, collaborative surveys in polarimetry, and create a vast database in an effort to help standardize the field and constrain the physics of many different objects. Additionally, it seems timely to propose an IAU Commission to address polarimetry standards and calibration.

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