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CHARACTERISTICS OF AN IMAGING POLARIMETER FOR THE POWELL OBSERVATORY

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ABSTRACT

A dual-beam imaging polarimeter has been built for use on the 14-inch Schmidt-Cassegrain telescope at the ETSU Harry D. Powell Observatory. The polarimeter includes a rotating half-wave plate and a Wollaston prism to separate light into two orthogonal linearly polarized rays. A thermoelectrically cooled CCD camera is used to detect the modulated polarized light. We present here measurements of the polarization of polarimetric standard stars. By measuring unpolarized and polarized standard stars we are able to establish the instrumental polarization and the efficiency of the instrument. The polarimeter will initially be used as a dedicated instrument in an ongoing project to monitor the eclipsing binary star, Epsilon Aurigae.

Subject headings: Polarization — Stars: eclipsing binaries — Methods: observational — Techniques: photometric, polarimetry

1. INTRODUCTION

Polarization describes the orientation of a wave's oscillations. Concerning light, the direction of the wave's electric field is specified. As an EM wave, light is polarized by transmission, reflection, refraction, scattering, and magnetic fields. In linear polarization the electric field is oriented in a single direction and is perpendicular to the direction of the magnetic field and the wave propagation. In circular and elliptical polarization the orientation of the electric field rotates as the wave travels.

Studying polarized light can lead to a plethora of information concerning the object that emitted it. In particular, the geometry and physical mechanisms that generate the light can be ascertained. If a magnetic field is present there will be linear polarization (assuming the field is uniform) and circular polarization caused by the Zeeman effect. The scattering of light is a common mechanism in astronomy for producing polarization. An example of such scattering can be seen when light travels through the interstellar medium or the Earth's atmosphere. Starlight polarized by rotating or eclipsed stars or a magnetic field is polarized based on the magnitude of these characteristics.

Polarized light is described by the 4 Stokes parameters I, Q, U, and V. All 4 parameters measure intensity with I being the total intensity, Q being the difference in intensities between North-South and East-West linearly polarized components, U being the difference in intensities between linearly polarized components oriented at +45° and -45° from North, and V being the difference between right and left circularly polarized intensities (Hough 2005). These parameters correspond to a net polarization and a position angle given by

$$P = \sqrt{Q^2 + U^2} \tag{1}$$

and

$$\theta = 0.5 \arctan\left(\frac{U}{Q}\right). \tag{2}$$

The net polarization value represents the percentage of light polarized, and the position angle represents the orientation of the polarized vector, or the electric field with respect to the north direction, and increasing through the east (Gehrels 1974).

A polarimeter is used to measure the polarization of starlight. The instrument used requires careful calibration and testing. Polarimetry is made difficult by atmospheric conditions as well as the optics within the instrument itself. The optics of the telescope may not have perfect symmetry and internal reflections can produce spurious effects. Thus, even unpolarized light passing through the optics can interfere with the actual polarization of the star. Our goal is to determine the efficiency and the instrumental polarization of the system described here.

2. INSTRUMENTATION AND OBSERVATIONS

The polarimeter is mounted on the 14 inch Schmidt-Cassegrain telescope at the Harry D. Powell Observatory at East Tennessee State University. Cassegrain reflectors are ideal for polarimetry as they are highly symmetrical (Gehrels 1974). As illustrated in Figure 1, the beam of light from the telescope first enters the half-wave plate (HWP), then enters the Wollaston prism, and then passes through the various filters before converging on the CCD chip[2]. The axis of the HWP is initially aligned

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[2] This is a similar set-up to Appenzeller (1967) but instead of using two PMT's, the o and e rays are simultaneously imaged onto a CCD.

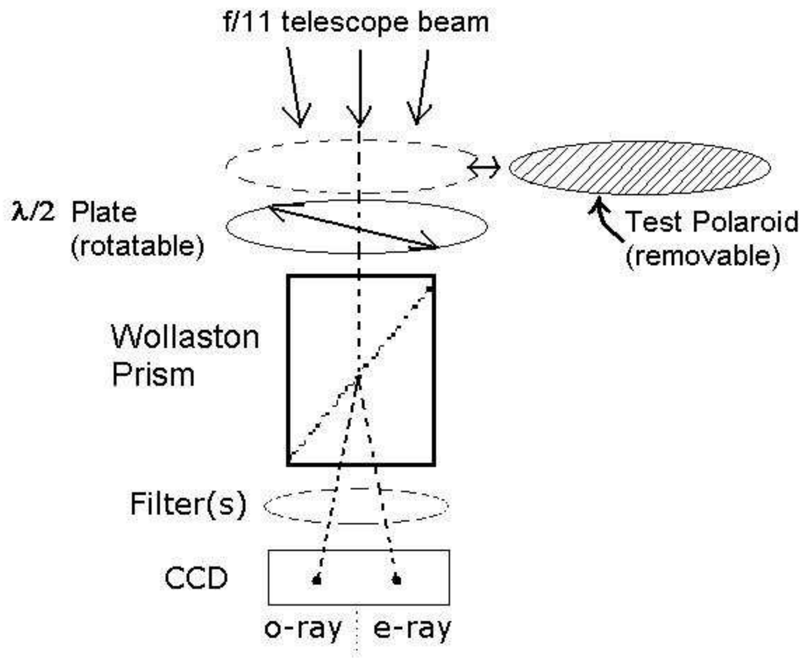

FIG. 1.— This is a schematic of the Polarimeter mounted on the 14 inch telescope at the ETSU Powell Observatory.

perpendicular to the axis of the Wollaston prism, which is aligned to the east-west axis of the telescope. The HWP rotates in steps of 22.5° (rotating the electric field vector by 45°) and the Wollaston prism (acting as an analyzer) produces two orthogonally polarized components (the ordinary and extraordinary rays, more commonly known as the *o* and *e* rays) which are imaged on the CCD.

All measurements presented here were taken through the broad band *V* filter plus a neutral density filter (1.0%T) to allow for measurements of bright stars. Due to camera hardware failures three CCD cameras (SBIG ST-9, Meade 416XT, and SBIG ST-8) were used during the time period of the observations presented here (July 2008 - July 2009). The current system has an SBIG ST-8 CCD camera as its dedicated detector which is controlled by MaxIm DL software.

The HWP rotation is controlled by a stepper motor and gear train precise to $\leq 0.1°$. A measurement unit consists of 4 waveplate positions. These positions are $+Q$, $+U$, $-Q$, and $-U$, and correspond to 0°, 22.5°, 45°, and 67.5°. We obtain three more measurement units, rotating the waveplate through a full rotation of 16 positions. The full waveplate rotation helps to average out spurious effects due to waveplate imperfections and very small misalignment of the optical elements with the light beam path.

The Wollaston prism acts as a dual beam analyzer and separates the incoming light into two orthogonal linearly polarized rays, an ordinary and extraordinary ray. Thus both polarizations fall on the CCD chip at the same time and are imaged simultaneously. Figure 2 shows the ordinary and extraordinary light rays from a single star. Since the calculation of the polarization depends upon the ratio of the intensity of the two star images, simultaneous measurement of the two rays eliminates susceptibility to slight atmospheric changes, seeing, and telescope guide errors.

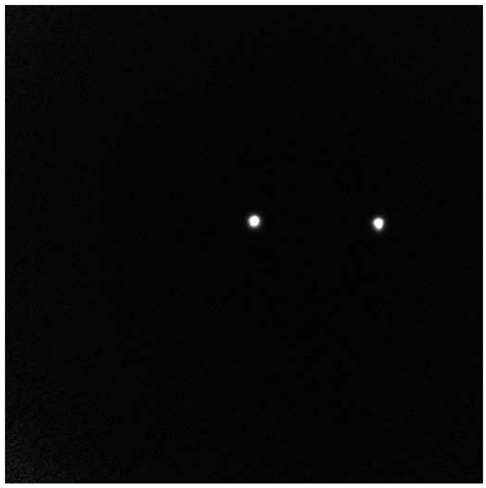

FIG. 2.— This is a sample image of the star Beta Cas.

2.1. *Measurement of Polarization*

A complete polarization measurement involves rotating the HWP through 16 positions. Although in theory only two HWP positions are required (yielding a single measure of Q and U), 16 positions yield 4 independent sets. This gives 4 sets of the 4 parameters: $+Q$, $-Q$, $+U$, and $-U$. Sixteen positions also represent a full rotation of the HWP, which should cancel out small spurious effects due to defects in the HWP or misalignment with the telescope light path.

Using MIRA software, each of the 16 images is then calibrated with bias, dark, and flat frames before aperture photometry is performed on the two star images. Although bias and dark frames are standard, flat-fields require special care. Due to the HWP rotations, we obtain two separate master flats with all optical components in the light path, one for the Q Stokes parameter and one for the U Stokes parameter (Patat & Romaniello 2006). Multiple flats are taken at all 16 HWP positions with all Q positions averaged and all U positions averaged into the separate masters.

The aperture photometry measurement yields the intensity for each star in the image. There are 32 total values of intensity which are then imported to a spreadsheet where the calculations of the net polarization and position angle are performed. These 32 values are labeled to represent ±Q and ±U, with 16 values representing each parameter. These measurements comprise 4 sets of $+Q$, $-Q$, $+U$, $-U$ values from which the polarization of the light is determined as described below.

First we calculate a corrective term for the systematic differences in the optical beam position for the instrument as well as its symmetry. This first term is of the form:

$$C_1 = \left[\frac{I_{o1}}{I_{e3}} \times \frac{I_{o3}}{I_{e1}} \times \frac{I_{o2}}{I_{e4}} \times \frac{I_{o4}}{I_{e2}}\right]^{\frac{1}{4}} \tag{3}$$

where I_o represents the intensity of the ordinary ray and I_e represents the intensity of the extraordinary ray. The subscripts 1, 2, 3, and 4 represent the image numbers in the sequence. Four total corrective terms are calculated using the 16 total images.

Next we determine a fractional polarization intensity value for each image. An example of the first value is:

$$P_1 = \left[\frac{1 - C_1\left(\frac{I_{e1}}{I_{o1}}\right)}{1 + C_1\left(\frac{I_{e1}}{I_{o1}}\right)}\right] \tag{4}$$

where C_1 was calculated previously. The values P_1 through P_4 use C_1, P_5 through P_8 use C_2, and so forth. A value of P is calculated for each image. Essentially this is a ratio of the ordinary and extraordinary ray intensities in each image. For unpolarized standard stars the intensities should be equal and the ratio 1. For polarized standard stars the intensities differ and the ratio shows the fractional polarization (Rautela et al. 2004).

The final step is to calculate the normalized Stokes parameters Q and U in order to find the net polarization value and position angle. To find the net value for Q we calculate for each measurement unit

$$Q = \frac{(Q^+ - Q^-)}{2}, \tag{5}$$

but average this for the 4 sets of $+Q$, $-Q$ pairs yielding

$$Q_{net} = \frac{\sum_{n=1}^{4}[P_{4n-3} - P_{4n-1}]}{8} \tag{6}$$

and similarly for U

$$U_{net} = \frac{\sum_{n=1}^{4}[P_{4n} - P_{4n-2}]}{8}. \tag{7}$$

Using the Stokes parameters Q and U the net polarization and the position angle are given by

$$P_{net} = \sqrt{Q_{net}^2 + U_{net}^2} \tag{8}$$

and

$$\theta = 0.5 \arctan\left(\frac{U_{net}}{Q_{net}}\right). \tag{9}$$

2.2. *Test Polaroid Efficiency Measure*

When inserted into the beam path (Figure 1) a test polaroid (TP) allows us to test the efficiency of the instrument (Kemp et al. 1981). The TP (type HNP'B Polaroid) has its transmission axis carefully aligned with the $+Q$ wave plate position. Here the HWP advances by 45° in the sequence yielding 8 images that give measurements for the parameters $+Q$ and $-Q$ only. For a TP image only one star image is present on the CCD frame since light passing through the HWP and prism is now 100% polarized. Aperture photometry is performed both on this star image and at the location where the second star image would appear.

We first calculate a corrective term of the new form:

$$C_1 = \left[\frac{I_{o1}}{I_{e2}} \times \frac{I_{o2}}{I_{e1}}\right]^{\frac{1}{2}}. \tag{10}$$

Then we calculate a polarization intensity, P, in the same form as equation (4).

The final step is to calculate the test polaroid signal in the Q Stokes parameter. In order to find the net value for Q we average the 4 pairs of $+Q$ and -Q similar to equation (3) before

$$Q_{TP} = \frac{\sum_{n=1}^{4}[P_{2n-1} - P_{2n}]}{8}. \tag{11}$$

This final result represents a fractional polarization which would equal 1 if the instrument were 100% efficient.

Test polaroid measurements were taken for all of the unpolarized and polarized standard stars observed for this paper. A total of 24 independent measurements were averaged. We find the net value for Q_{TP} to be 0.985±0.005. Thus, the efficiency of our instrument in detecting the presence of polarized light is 98.5%. We correct for this efficiency by dividing the calculated polarization values by 0.985.

2.3. *Standard Star Discussion*

We measured the Stokes parameters and found the net polarization and position angle for 12 unpolarized standard stars and 7 polarized standard stars in V band in the fashion stated above. The given values and our measured values for the unpolarized standard stars are presented in Table 1 and for the polarized standard stars in Table 2. These are all relatively bright stars with typical integration times of around 10 seconds per image. A measurement comprising a full HWP rotation represents a total integration time of approximately 3 minutes. Although the S/N ratio for the photometric intensity measurement of a star image on the CCD was very high, the S/N ratio for determining the corresponding fractional polarization would be extremely low. The error in the

TABLE 1
Unpolarized Standard Stars in V band

Star	R.A.	Dec.	Mag.	Sp.	Accepted $P_{\rm net}(\%)^a$	Observed $P_{\rm net}(\%)^b$	Accepted Θ^a	Observed Θ	Nights Observed
Altair	19 50 47.0	+08 52 05	0.77	A7V	0^c	0.10±0.10	0^c	113.1±21.9	2
Arcturus	14 15 39.7	+19 10 56	−0.04	K1.5III	0^c	0.14±0.14	0^c	80.3±42.4	3
Beta Cas	00 09 10.7	+59 08 59	2.3	F2III	0.04 ±0.02	0.06±0.04	72.5	76.5±52.4	4
Gamma Boo	14 32 04.7	+38 18 30	3.0	A7III	0.07 ±0.02	0.08±0.04	21.3	84.2± 0.8	4
HD114710	13 09 32.4	+28 07 52	4.3	GOV	0.018±0.014	0.22±0.13	116	80.3±42.3	3
HD142373	15 50 56.7	+42 35 26	4.6	F9V	0.012±0.009	0.24±0.12	31	85.9±37.6	5
HD165908	18 05 07.5	+30 33 13	5.0	F7V	0.002±0.007	0.52±0.47	39	93.4±84.7	3
HD185395	19 35 06.0	+50 06 16	4.5	F4V	0.003±0.007	0.18±0.12	139	102.7±83.1	3
HD188512	19 52 51.4	+06 16 36	3.7	G8IV	0.012±0.005	0.13±0.10	154	90.7±54.4	2
HD202573	21 13 44.5	+25 13 31	7.0	G5V	0^c	0.37±0.29	0^c	72.8±44.0	1
HD210027	22 04 40.8	+25 06 01	3.8	F5V	0.002±0.006	0.12±0.06	45	67.9±55.7	3
Vega	18 36 56.3	+38 47 01	0.03	A0V	0^d	0.15±0.09	0^d	82.5±54.5	5

[a] All accepted data can be found in Gehrels (1974)
[b] Polarization values have taken the 0.985 efficiency correction factor into account
[c] These stars are expected to have no polarization but have no published measurements
[d] Polarization values have been given for these stars using a 61 cm telescope and integration times up to 90 minutes per night. These values are within our error bars surrounding zero and for all intents and purposes can be ignored (Kemp et al. 1986b).

TABLE 2
Polarized Standard Stars in V band

Star	R.A.	Dec.	Mag.	Sp.	Accepted $P_{\rm net}(\%)^a$	Observed $P_{\rm net}(\%)^b$	Accepted Θ^a	Observed Θ	Nights Observed
HD7927[c]	01 16 55.1	+57 58 10	5.0	F0Ia	3.32±0.04	3.60±0.36	94	84.3± 0.8	3
HD21291	03 25 00.1	+59 46 05	4.2	B9Ia	3.5	3.56±0.12	115	120.6± 0.7	2
HD147084[c]	16 17 37.4	−24 03 02	4.6	A5II/III	4.3	4.11±0.27	32	34.4± 1.1	1
HD154445[c]	17 02 57.5	−00 49 30	5.7	B1V	3.67±0.05	3.81±0.69	90	90.1± 7.1	3
HD183143	19 25 13.2	+18 11 37	6.9	B7Ia	6.1	6.10±0.61	0	−2.5± 2.4	1
HD187929	19 49 55.5	+00 52 33	3.5-4.3	F6-G2Ib	1.8	1.59±0.19	93	91.6±11.2	1
HD198478	20 47 14.0	+45 55 40	4.9	B3Iae	2.8	2.77±0.27	3	6.1± 1.7	5

[a] All accepted data can be found in Gehrels (1974)
[b] Polarization values have taken the 0.985 efficiency correction factor into account
[c] Recent publications have shown these stars to be variable, thus explaining inconsistent data (Wiktorowicz & Matthews 2008)

observed P_{net} for an individual star measurement from a single full HWP rotation is thus relatively large (on the order of 0.10%). Even for bright stars, a total integration time of 3 minutes is insufficient to precisely detect the extremely small polarization levels present. In order to decrease the errors multiple sets of measurements, each consisting of a full HWP rotation, need to be averaged. A few of the most recent nightly observations presented here were performed obtaining such multiple sets. For those observations, the typical error was much more acceptable (on the order of 0.02%).

We have averaged the 32 independent unpolarized standard star observations represented in Table 1 to establish a value for the instrumental polarization of the system. For the individual Stokes parameters this gives a fractional polarization in Q of $-2\times10^{-4}\pm8\times10^{-4}$ and in U of $-6\times10^{-6}\pm9\times10^{-4}$. This yields an average value for the instrumental polarization of 0.18±0.12% with a corresponding position angle of $84.2^\circ \pm 11.3^\circ$.

In addition to establishing the instrumental polarization from observation of unpolarized stars we have also observed strongly polarized standard stars to verify the HWP alignment with respect to position angle (Table 2). Again, these measurements were made with minimal integration times so the errors in our observed P_{net} and θ values are relatively large. However, our values for P_{net} agree with the accepted values within the stated errors. For the position angle, only five of the seven stars have measured values that agree closely with the accepted values. We note that both HD7927 and HD21291 have been shown to have variable polarization (Wiktorowicz & Matthews 2008) which may explain this discrepancy. We plan to obtain further observations of better quality for many standard stars to better define the instrumental polarization.

3. DISCUSSION

The measurements of unpolarized standard stars indicate a small but consistent instrumental polarization for our polarimeter. Measurements of polarized standard stars are in agreement with the published values for these stars, but the errors in the measurements presented here are larger than desired. We note the need to establish the instrumental polarization more precisely so we are continuing measurements of standard stars using longer integration times. Initial measurements employing integration times of approximately 30 minutes per star have produced more reasonable errors. Our goal is to achieve reproducible errors on the order of 0.02% or less. This will allow us to reliably detect variable polarization in a star on the order of 0.1%.

The level of sensitivity for the instrument as described above is necessary for the study of the unique eclipsing binary system, Epsilon Aurigae. The instrument was built primarily to allow monitoring of the polarized light from this system during its current eclipse. This system consists of a bright FO Ia supergiant primary and an opaque cool disk suspected of being a pre-solar nebula. The supergiant star pulsates irregularly and the binary period is an extremely long 27 years with the eclipse lasting two years. The polarized light from the system was observed by one of the authors of this paper during the 1982-84 eclipse of this system (Kemp et al. 1986a). The next eclipse is beginning as this paper is being written and observations of the star with the polarimeter have already begun.

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