Polarimetry of Early Emission Line Stars.
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Citation for published version (APA):

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Appendix A

AnyPol: A Generic Linear Polarimeter

ABSTRACT

AnyPol is a high quality broadband optical linear polarimeter for astronomy, assembled from components that have become commercially available as a result of recent advancements in technology. Its design and construction are described in detail, and observations of standard stars are presented to verify its proper operation. It is currently being used on the 0.4 m telescope at Limber Observatory to monitor the variable polarization of bright Be stars.

1. Motivation

AnyPol was built in 1993–94 to study the linear polarization of bright Be stars with the 0.4 m telescope at Limber Observatory, a private observatory in the Texas Hill Country near San Antonio. The purpose was to relocate and continue the ongoing project of annual polarization monitoring of Be stars begun in 1985 (McDavid 1999) using the Breger polarimeter (Breger 1979) on the 0.9 m telescope at the University of Texas McDonald Observatory. The change was necessary because of the decommissioning of the McDonald telescope, and it was made possible by the rapidly growing commercial availability of research grade scientific instrumentation.

A comprehensive review on Be stars has been given by Slettebak (1988). Their intrinsic polarization comes from Thomson scattering of the starlight by free electrons in a rotationally flattened circumstellar envelope, with a wavelength dependence due to absorption by neutral hydrogen. The envelope is also the source of the erratically variable emission lines which are the distinguishing characteristic of the Be stars. By studying the polarization we can hope to learn more about the geometry and the physical conditions of the envelope, and variability of the polarization may give clues to the basic processes which lead to envelope formation and dissipation.
2. Design and Construction by Subsystem

The Limber Observatory polarimeter is called AnyPol because of its common generic simplicity. It is basically a miniaturized and technologically upgraded copy of the Breger polarimeter mentioned earlier.

The polarimeter system consists of a main head unit which is mounted on the telescope tailpiece, an electronics interface unit, two power supplies, and a control computer. The Physical/Mechanical, Optical, Electronic, and Control/Data Acquisition subsystems are described in detail in the following subsections.

2.1. Physical/Mechanical

The polarimeter head is constructed of 0.25 in aluminum plates which interlock by a tongue-and-groove system to make a light-tight box. The top plate is 0.375 in thick and is drilled for 0.375 in bolts to serve as a flange for mounting on the telescope tailpiece. The compactness of the polarimeter head unit was achieved by offsetting the optical axis by 2.125 in from the center toward the front plate (Figure 1). See Figure 2 for an exploded diagram of the head.

The head (Figure 3) contains two removable modules: the polarization analyzer assembly (Figure 4) and the filter wheel assembly (Figure 5). The analyzer assembly consists of a cylindrical cell for the optical components, mounted in ball bearings and rotated by a stepper motor through a belt drive. The filter wheel assembly uses an identical stepper motor and a similar belt drive to rotate a custom-made filter wheel with 8 positions on a circle, mounted in ball bearings with a 0.25 in shaft. Both drive motors are double-shafted to carry encoders and are mounted in slots to allow for tensioning of the belts.

There is an aperture slide before the analyzer and a dark slide after the filter wheel, both operated from the front plate by knobs controlling rack-and-pinion mechanisms with detent grooves engaged by adjustable ball plungers. A 1.25 in helical focuser for the viewer eyepiece is also mounted on the front plate.

Light passes through a Fabry lens into an enclosed lower chamber of the head which contains the uncooled end window photomultiplier tube and associated wiring, with a cap over the protruding part of the tube. A signal conditioning unit is mounted on the side of the head with aluminum brackets.

The electronics interface is a separate box constructed of 0.125 in aluminum plates with a 0.25 in base plate. It contains an AC power bus, the power supplies and microstepping drivers for the stepper motors, and a push-pull pair of cooling fans.

The high voltage power supply for the photomultiplier tube and the power supply for the signal conditioning electronics are both standalone units. A dedicated PC is used for the interactive control, data acquisition, data processing, and display functions.
Fig. 1.— AnyPol attached to the 0.4 m telescope at Limber Observatory.
Fig. 2.— Exploded diagram of the polarimeter head.
Fig. 3.— Inside the polarimeter head.

Fig. 4.— The polarization analyzer assembly.
2.2. Optical

The polarimeter was designed to be mounted on the 0.4 m telescope at Limber Observatory, which has f/12 classical Cassegrain optics. The entrance hole to the instrument is 2.0 in in diameter, and the aperture slide is located at the optimal focal plane, 3.25 in behind the external surface of the tailpiece. It has three available apertures with angular diameters of 4' (for finding), 1' (for centering), and 30" (for measurement). The material used for the slide is black acrylate, to block both infrared and ultraviolet light and to avoid spurious polarization from metallic edges. The apertures are backlit by a pair of red LEDs.

The analyzer is a Glan-Taylor prism, rotated continuously at 10 Hz to modulate the intensity of the incoming light according to the degree of polarization. Following it in the same cylindrical mounting cell is a Lyot depolarizer, to eliminate any polarization dependent response of the rest of the optical system.
The filter wheel carries a set of $UBVRI$ filters which closely match the Johnson-Cousins system when used with a photomultiplier with the standard S-20 response curve. This color system was chosen to match by prescription the color system which had been previously used for monitoring Be stars with the Breger polarimeter at McDonald Observatory. The filter materials and bandpasses of the system are shown in Table 1. One of the 8 positions in the filter wheel holds a right angle prism through which the apertures may be seen for finding and centering with the postviewer eyepiece via a transfer lens.

An image of the telescope objective is focused as a spot of 2 mm diameter on the cathode of the photomultiplier by a fused silica plano-convex Fabry lens. Due to the beam deviation of the spinning Glan-Taylor prism, this spot moves in a small circle of diameter $\sim 0.02$ mm on the nonuniform surface of the photocathode, causing a sinusoidal intensity modulation of less than 1% at the rotation frequency of the analyzer. This effect, known as “tilt” since it could be caused by a deviation from normal incidence of the light on the photocathode, is easily separable from the actual modulation due to polarization, which has double the frequency.

### 2.3. Electronic

The analyzer and the filter wheel are driven by identical size 23 double shafted stepper motors with 4 windings rated at 2.6 A DC, wired in a bipolar parallel configuration as 2 pairs of parallel windings to generate the least possible heat. They have 200 steps per revolution and are operated by optically isolated bipolar choppers at 10 microsteps per step, with 28 V DC, 4 A power supplies. Each motor carries an incremental optical shaft encoder with a resolution of 500 parts and one index pulse per revolution. The chopper opto-isolators and the encoders are powered by 5 V DC from an external power supply.

The photomultiplier tube is an end-window type with an S-20 photocathode (extended

<table>
<thead>
<tr>
<th>Filter</th>
<th>Schott Glass Components</th>
<th>Effective Wavelength (Å)</th>
<th>Bandpass (fwhm) (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U$</td>
<td>UG2(2mm) + BG18(2mm)</td>
<td>3650</td>
<td>700</td>
</tr>
<tr>
<td>$B$</td>
<td>BG12(2mm) + GG385(2mm)</td>
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<td>1000</td>
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<td>$V$</td>
<td>GG495(2mm) + BG18(2mm)</td>
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<td>900</td>
</tr>
<tr>
<td>$R$</td>
<td>OG570(2mm) + KG3(2mm)</td>
<td>6400</td>
<td>1500</td>
</tr>
<tr>
<td>$I$</td>
<td>RGN9(3mm)</td>
<td>7900</td>
<td>1500</td>
</tr>
</tbody>
</table>
red spectral response). It is operated in a grounded anode configuration with -1000 V DC applied to the cathode from an external high voltage power supply. The output of the tube is converted to a stream of 10 ns TTL pulses by a signal conditioning unit which includes a pulse amplifier, discriminator, and pulse shaper.

2.4. Control/Data Acquisition

The polarimeter is controlled by a C program running on a 66 MHz 486 DOS PC with a stepper motor interface card and a multichannel scaler card. A virtual control panel constructed with a graphical widget set allows point-and-click selection of operating parameters and functions, including analyzer rotation start/stop, filter setting, integration time, target identification, star or background sky mode, count rate, ratio of the current count rate to that at the beginning of the integration, output data file, and abort (Figure 6). There are also two macro buttons that start preprogrammed observing sequences of either one set of UBVRI filter measurements or 3 repeated measurements in a single filter.

![Fig. 6.— The AnyPol computer control panel.](image)

The specified integration time is divided into the appropriate number of 10 s counting loops, with the analyzer spinning at 10 Hz. For each 10 s loop, the multichannel scaler accumulates signal pulses for 100 revolutions of the analyzer in 50 channels per revolution as triggered by the encoder index pulse. After each 10 s loop the total pulse count per channel is updated and a graph of the cumulative data buffer cnt(i) is displayed. After removal of the tilt by subtracting a least squares fit to a sine wave, a least squares fit to a double sine wave is made to determine the normalized Stokes
parameters $q$ and $u$, the degree of polarization $p$, and the polarization position angle $\theta$, according to

\begin{align*}
q &= \frac{2}{25} \sum_{i=0}^{24} [(c(i)/m - 1) \cos \beta(i)], \\
u &= \frac{2}{25} \sum_{i=0}^{24} [(c(i)/m - 1) \sin \beta(i)], \\
p &= \sqrt{q^2 + u^2},
\end{align*}

(A1)

(A2)

(A3)

and

\begin{align*}
\theta &= \frac{1}{2} \arctan \frac{u}{q},
\end{align*}

(A4)

where

\begin{align*}
c(i) &= \text{cnt}(i) + \text{cnt}(i + 25), \\
m &= \frac{1}{25} \sum_{i=0}^{24} c(i),
\end{align*}

(A5)

(A6)

and

\begin{align*}
\beta(i) &= \frac{2\pi i}{25}.
\end{align*}

(A7)

The instrumental error in $q$, $u$, and $p$ is estimated by the variance of the double sine wave fit:

\begin{align*}
dp^2 &= \frac{2}{250} \sum_{i=0}^{24} [(c(i)/m - 1)^2 - q^2 - u^2].
\end{align*}

(A8)

The error in $\theta$ (in degrees) is then estimated as

\begin{align*}
d\theta &= 28.65 \frac{dp}{p}.
\end{align*}

(A9)

After these calculations are completed, the control panel display is updated with the latest cumulative results and another 10 s loop is started. This process repeats until the end of the integration time. A record of the data is then written to a disk file for further reduction off line.
3. Performance

On the 0.4 m telescope at Limber Observatory the photon count rates are comparable to those obtained with the 0.9 m telescope at McDonald Observatory with a neutral density filter of 10% transmission which was necessary for the bright stars ($V = 2-5$) in the Be star monitoring program. Observational error estimates are derived from the repeatability of multiple independent measurements, and they are in general agreement with checks based on the residuals in the fit to the modulated signal and the uncertainty derived from photon counting statistics. Typical errors are on the order of 0.05% in the degree of polarization and 2° in position angle. One of the main sources of error is a slight variation in the speed of the motor driving the analyzer, which becomes significant at the level of a few hundredths of a percent in the degree of polarization. All observations are corrected for an instrumental polarization on the order of 0.10%, tracked by repeated observations of unpolarized standard stars from the list of Serkowski (1974). The position angle is calibrated by observing polarized standard stars from the list of Hsu & Breger(1982).

One individual measurement consists of 3 cycles through all 5 filters with a 200 s integration time on each filter. If there is a bright Moon, a sky cycle is taken to correct for the background polarization. The result for each single filter is taken to be the mean and standard deviation of the 3 integrations in that filter. (The standard deviation is a more conservative error estimate than the standard deviation of the mean, but it may be more realistic because 3 measurements is a very small sample.)

It is interesting to compare the Limber Observatory system with the system used previously at McDonald Observatory. For this purpose Table 13 of McDavid (1994) is reproduced here as Table 2, and Table 15 of McDavid (1999) is reproduced here as Table 3. In both tables, $q/dq$, $u/du$, $p/dp$, and $\theta/d\theta$ are the mean and standard deviation over four annual observing runs. Quantities in angled brackets are similar four-year means, including $dpi$ and $d\theta i$, which are estimates of the internal precision of a single measurement. The grand averages, denoted by $GAV$, are averages of these data over all 5 filters.

These observations of polarized standard stars show very clearly that the two systems match extremely well. The only outstanding difference is the typical precision of a single observation, which is higher in the McDonald system. This is readily understood since the McDonald estimates were based on theoretical photon counting statistics, while the Limber estimates are based on experimental scatter in repeated measurements. With a larger value for the error in a single observation, the Limber system is sometimes a less sensitive detector of variability, but it may also give more realistic results.

I wish to thank Michel Breger and Santiago Tapia for introducing me to the art of stellar polarimetry and Paul Krueger for his valuable design advice and excellent machine work.
Table 2. Polarized Standard Star Summary (Limber)

<table>
<thead>
<tr>
<th>Star</th>
<th>Filter</th>
<th>q/dq (%)</th>
<th>&lt;dq&gt; (%)</th>
<th>u/du (%)</th>
<th>&lt;du&gt; (%)</th>
<th>p/dp (%)</th>
<th>&lt;dp&gt; (%)</th>
<th>θ/dθ (°)</th>
<th>&lt;dθ&gt; (°)</th>
<th>&lt;dpi&gt; (%)</th>
<th>&lt;dθi&gt; (%)</th>
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</thead>
<tbody>
<tr>
<td>2H Cam</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>U</td>
<td></td>
<td>-1.83/0.09 0.04</td>
<td>-2.41/0.06 0.04</td>
<td>3.03/0.07 0.03</td>
<td>116.5/ 0.8</td>
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<tr>
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Table 3. Polarized Standard Star Summary (McDonald)

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REFERENCES

Slettebak, A. 1988, PASP, 100, 770