PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC
102: 179–182, February 1990

TOWARD SELECTION OF INTERMEDIATE-MAGNITUDE POLARIZATION STANDARDS

D. P. CLEMENS*

Department of Astronomy, Boston University, 725 Commonwealth Avenue, Boston, Massachusetts 02215

AND

S. TAPIA†

Steward Observatory, University of Arizona, Tucson, Arizona 85721

Received 1989 September 15, revised 1989 October 19

ABSTRACT

We have used the Minipol optical polarimeter with a V-band filter to observe 16 summertime, intermediate-magnitude ($m_B \sim 9$) stars from the survey of Mathewson and Ford. These stars were chosen to span polarization percentages from zero to almost 6% and to cover a large range of polarization position angles; the 16 stars were previously used as polarization standards to derive instrumental polarizations and offset angles for CCD-based imaging polarimeters. The primary reason for reobserving these stars was to determine their V-band polarization properties and to identify polarization variables, which are unsuitable standards. Our Minipol observations showed that 12 of the stars had V-band polarizations that were very similar to the Mathewson and Ford B-band values. One star had a significantly different polarization position angle and two had significantly different percentage polarizations. One star, HD 161306, was wildly different in both percentage polarization and position angle. Hence, we present 12 useful standard stars, two of moderate usefulness because of differing polarization percentages, and two stars which should not be used as standards.

Key words: polarization–polarization standards

1. Introduction

Studies of magnetic-field directions in galactic gas clouds are typically based on analyses of linear polarization induced on the light from distant, unpolarized, background stars. The direction of the observed electric-field vector is generally taken as the direction of the embedded magnetic field, although the details of the alignment process acting on the differentially absorbing dust grains are not fully clear.

As the angular sizes of the regions of interest are decreased, it becomes necessary to measure the stellar polarizations of background stars in ever fainter and more crowded fields. In order to develop a detailed magnetic-field map for a galactic cloud, many hundreds of stellar polarizations must be measured. As polarizations of progressively fainter stars are sought, the integration time needed to make the measurements using a single-channel polarimeter becomes excessive.

CCDs offer a multiple detector advantage and, when combined with a polarization analyzing element (e.g., Savart plate or polaroid filter), can be used to simultaneously measure the polarizations of many stars. However, the high quantum efficiency of most CCDs can make observations of bright polarization standard stars (e.g., those of Hsu and Breger 1982) nearly impossible without the introduction of neutral density filters, which increase the scattered light within the optical apparatus.

Many users of CCD-based imaging polarimeters (Zaritsky *et al.* 1986; Heyer, Strom, and Strom 1987; Hodapp 1987; Clemens and Leach 1987, hereafter CL87) have adopted a more pragmatic approach to instrumental calibration. They typically select a few of the fainter, more polarized stars from the polarization survey of Mathewson and Ford (1970, hereafter MF) for observation using their CCD instruments. This technique often works well because the typical level of polarization uncertainty sought in magnetic-field mapping with CCDs amounts to 0.3%–1%, some 5–10 times less accurate than the average MF uncertainties for stars between $m_B = 6$ and 10 magnitudes. The much higher precision which could be obtained by using brighter, well-established polarization standard stars is simply not needed, and the brightness of the well-characterized standards is a serious problem for the CCDs.

*Also Steward Observatory, University of Arizona.
†Also Lincoln Laboratory, Massachusetts Institute of Technology.

However, the MF observations were performed in the *B* band, while most magnetic-field studies currently choose redder filters (*V*, *R*, and *I* are generally used). The MF stars have not been systematically checked for polarization variables or other problems, and their work remains a *survey* of stellar polarizations. So, before any particular star from their list can be used as a polarization standard for CCD work, it must be checked, preferably at the wavelength of interest for the CCD observing.

This paper presents observational results obtained using the Minipol optical polarimeter (Frecker and Serkowski 1976) of 16 summertime stars from the MF list which we used as potential polarization standards in our CCD imaging polarization work (CL87; Clemens, Leach, and Barvainis 1988). Twelve of the stars were found to be suitable standards and four were found to be of dubious value as standards.

2. Observations

The observations were performed during 1988 June 8–10 using Minipol on the 1.55-meter telescope of the University of Arizona Observatories on Mount Bigelow, Arizona. The weather conditions were excellent, and the sky was judged to be photometric throughout the run. All of the observations were performed through a filter which, when combined with the GaAs photomultipliers in Minipol, gave a spectral response very similar to a Johnson *V* band (mean $\lambda \sim 5388$ Å, $\Delta\lambda \sim 352$ Å, where both quantities are as defined for the Hubble Space Telescope (HST) system by Koornneef *et al.* 1986). The aperture chosen for the observations was 15″. A Glan prism was used to check the polarization efficiency, which was found to be stable at 98.2% during the run.

Observations of the star HD 155197 were used to establish the instrumental offset angle. This star was part of a group of stars specifically characterized for use as HST polarization standards (Tapia 1988). Here, we adopted the HD 155197 results of that study (P_V = 4.627% ± 0.020%, $\chi_V = 105.13 \pm 0.^\circ12$) and computed all of our position angles relative to this value. The combined angular uncertainty for our observations and those of Tapia (1988) give a total angular uncertainty for our HD 155197 angular registration of $0.^\circ35$.

Table 1 presents our polarization measurements and those of MF. Our data have not been corrected for the instrumental polarization efficiency (98.2%, from the Glan measurements) nor for the very small instrumental polarization of Minipol (0.0042% at *V* band; Tapia 1988). In the table, numbers listed in parentheses indicate the uncertainty of the final digits. In the "Notes" column we list any discrepancy between our measurements and those reported by MF. To be discrepant, the difference in the polarization percentage (or position angle) between our values and the MF values had to exceed the root square sum uncertainties of our and MF uncertainties by a factor of four (4σ). Entries in that column also indicate

TABLE 1

Observations Compared with Mathewson and Ford Values

HD	P [%]	χ [°]	P_{MF} [%]	χ_{MF} [°]	Notes[a]
94474	1.068 (80)	80.6 (2.1)	1.00 (3)	63.2 (9)	χ
109055	0.015 (31)	...	0.07 (7)	...	
127769	1.489 (21)	54.0 (4)	1.35 (8)	52.7 (16)	
142863	1.891 (63)	83.7 (10)	1.72 (6)	84.7 (9)	
155197	4.371 (50)	105.1[b] (0.35)[c]	3.99 (8)	103.9 (5)	
155528	4.849 (52)	93.7 (3)	4.57 (7)	93.5 (4)	
161306	1.252 (71)	75.7 (16)	3.70 (5)	67.6 (4)	P, χ
161753	4.171 (91)	46.6 (6)	4.10 (7)	45.1 (5)	
162061	3.177 (142)	65.8 (13)	3.14 (8)	65.4 (7)	
165175	1.801 (46)	53.9 (7)	1.92 (10)	53.1 (14)	
173133	1.562 (46)	19.7 (8)	1.31 (4)	18.7 (8)	P
181474	1.150 (15)	74.6 (4)	0.96 (7)	70.4 (20)	
183143	5.737 (32)	179.6 (2)	5.84 (3)	178.8 (1)	
185198	1.675 (35)	76.0 (6)	1.64 (4)	76.3 (6)	
197577	0.255 (52)	114.9 (16)	0.07 (4)	114.7 (160)	
208205	1.187 (65)	147.7 (16)	0.70 (7)	145.4 (28)	P

[a] An entry in this column denotes a difference between this work and MF exceeding 4σ. "P" indicates that the percent polarization is discrepant, "χ" indicates the position angle is discrepant.

[b] Assumed, to establish the instrumental offset angle.

[c] Combined observational (0.°33) and standard (0.°12; Tapia 1988) uncertainty.

the nature of the discrepancy, whether due to a polarization percentage difference (P) or due to a position angle difference (χ).

Twelve of the stars in Table 1 have both P and χ within 4σ of the MF values. This criterion was chosen because some differences are expected in the polarization properties due to the wavelength dependence of the polarization. Depending on whether the wavelengths of maximum polarization are bluer than the blue filter used by MF, or redder than the V filter we used, one would expect modest polarization differences. The effect of using this 4σ criterion across two different bands, separated by ~ 900 Å, is comparable to an inband 3σ test.

The four discrepant stars are distributed as follows: One has a serious position angle problem (HD 94474, which is 7.6σ discrepant); two have polarization percentage differences (HD 173133 at 4.1σ and HD 208205 at 5.1σ); and one star, HD 161306, has both P (28σ) and χ (4.9σ) discrepancies. We observed this last star on two nights to confirm the discrepancies. We suspect that HD 161306 has time-variable polarization.

3. Comparison with CCD Observations

Five of the newly observed polarization standard stars were also observed at the V band by CL87 using a CCD-based imaging polarimeter. They previously compared the CCD-derived polarization values to the MF values in Figure 2 of the CL87 paper.

In Figure 1 of this paper we show a new comparison of the CL87 CCD-derived polarization values and the V-band Minipol-derived polarization values from this work. The dashed line represents the best linear fit (with slope 0.98 ± 0.09 and intercept 0.13 ± 0.23). The correlation is somewhat better than that obtained for the earlier (CL87) MF comparison, and clearly shows that CCD-based imaging polarimeters can measure subpercent polarizations (~ 0.3% rms) and thereby probe magnetic fields in nearby gas clouds.

While achieving subpercent polarizations using CCDs has been demonstrated, it is worthwhile reiterating some important aspects of the application of CCDs to imaging polarimetry. In stellar polarimetry the typical polarizations are in the 1%–5% range. To be able to measure the polarization position angle of a 2% polarized star to an accuracy of 2° requires a signal-to-noise ($S{:}N$) level of at least 1000:1. If the observations are Poisson noise-limited, this implies detection of at least 10^6 photons by the CCD in the signal images. Additionally, for the calibrating flat-field frames to add negligible noise to the signal, the flat-field images must have $S{:}N$ greatly in excess of 1000:1. For the CL87 effort, 30 flat-field frames were acquired through each of eight polarimeter position angles. If the dark current of the CCD is important, or the sky background is bright enough to contribute to the total

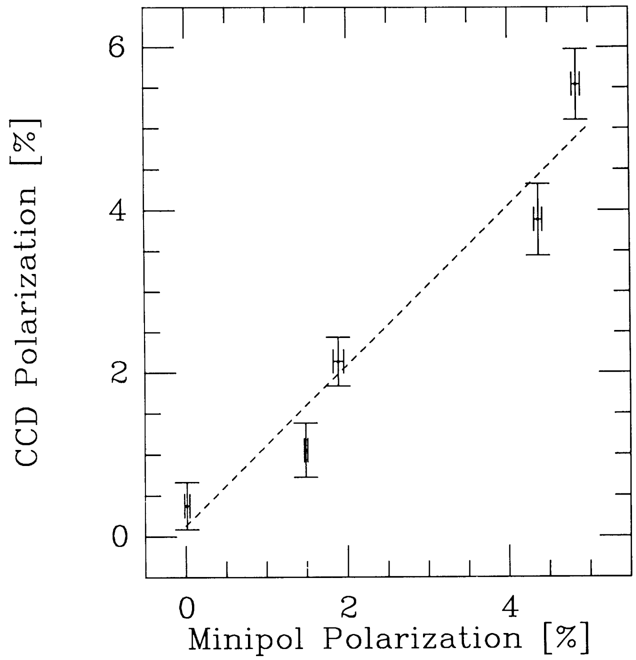

FIG. 1–Comparison of the percentage polarization measured for the stars HD 109055, HD 127769, HD 142863, HD 155197, and HD 155528 using Minipol (horizontal axis; this work) and using a CCD-based imaging polarimeter (vertical axis; Clemens and Leach 1987). The best linear fit is represented by the dashed line and has a slope of 0.98 ± 0.09 and an intercept of $0.13\% \pm 0.23\%$.

noise, the number of signal and flat-field photons required to achieve the same polarization position angle uncertainty increases. Hence, observations at V-band, where the sky is fairly dark, are often preferred to observations in the I-band, where background stars may be brighter (because of reddening by the cloud of interest) but where the sky brightness is quite high. Also, any technique which attempts to measure subpercent polarizations with CCDs must deal with possible low-level linear polarization response of individual pixels (a problem also present in photomultipliers—cf. Hoening and Cutler 1966). CL87 used a $\lambda/4$ plate *after* the linear polarizing element to convert the analyzed starlight, which was 100% linearly polarized, to circular polarization before detection by the CCD. Then, the detection of light by the CCD was independent of the position angle of the analyzing polarizer. Finally, short-term sky transmission variations must be removed to avoid polarization errors. With Minipol, sky chopping is performed by a quickly rotating half-wave plate (spinning at several tens of Hz). CL87 used on-chip back and forth charge shifting with synchronized rotation of the polarization analyzer to achieve 0.1 Hz chopping. In the latter, CCD technique, the further requirement of exceedingly high charge-transfer efficiency (CTE) is added to the instrumental design.

4. Summary

We have used Minipol to reobserve 16 intermediate-brightness ($m_B \sim 9$) stars from the survey of Mathewson and Ford (1970). Of these, 12 stars were found to be reasonable polarimetric standards, at least to the precision level needed for magnetic-field mapping using CCD-based imaging polarimeters. Four stars were not found to be suitable, though two of those had polarization position angles which agreed with the Mathewson and Ford values.

REFERENCES

Clemens, D. P., and Leach, R. W. 1987, *Opt. Eng.*, **26**, 923 (CL87).
Clemens, D. P., Leach, R. W., and Barvainis, R. 1988, in *Molecular Clouds in the Milky Way and External Galaxies*, ed. R. L. Dickman, R. L. Snell, and J. S. Young (New York: Springer-Verlag), p. 124.
Frecker, J. E., and Serkowski, K. 1976, *Appl. Optics*, **15**, 605.
Heyer, M. H., Strom, S. E., and Strom, K. M. 1987, *A.J.*, **94**, 1653.
Hodapp, K.-W. 1987, *Ap. J.*, **319**, 842.
Hoening, S. A., and Cutler, A. 1966, *Appl. Optics*, **5**, 1091.
Hsu, J. C., and Breger, M. 1982, *Ap. J.*, **262**, 732.
Koornneef, J., *et al.* 1986, *STSci Preprint*, No. 91.
Mathewson, D. S., and Ford, V. L. 1970, *Mem. R.A.S.*, **74**, 139 (MF).
Tapia, S. 1988, *Preprints of the Steward Observatory*, No. 831.
Zaritsky, D., Shaya, E. J., Scoville, N. Z., Sargent, A. I., and Tytler, D. 1986, *A.J.*, **93**, 1514.