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ON STANDARD POLARIZED STARS

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ABSTRACT

Intensive linear polarimetric measurements have been made to improve the standard polarized stars north of $\delta = -35°$. Among the previously used standards, 55 Cyg (HD 198478), 9 Gem (HD 43384), and HD 183143 showed definite polarimetric variability on the time scale ranging from days to weeks. The amounts of change are in the order of 0.3% in p and/or $>1°$ in the position angles. These three stars are therefore not suitable as standards for accurate polarimetric observations.

The incidence of the short time-scale polarimetric variability seems to be higher among the supergiants of earlier spectral type than those of later spectral type.

The polarization values of some of the other standard polarized stars are determined to an estimated accuracy of ± 0.01% in p and $\pm 0\overset{\circ}{.}2$ in the position angles.

Subject headings: photometry — polarization — stars: supergiants

I. INTRODUCTION

The advance of the instrumentation in the past decade has made the accuracy on the level of 0.01% in astronomical polarimetry possible. There are, however, numerous considerations to be made when such an accuracy is pursued. Examples are precise determinations of the dead time of the photomultiplier and the associated electronics, the instrumental polarization, the instrumental depolarizing factor, and the accurate determination of the position angle of the system. The most realistic procedure to accomplish the calibration is made at the telescope. This philosophy is reflected in the setup of the polarized and the unpolarized standard stars compiled by Serkowski (1974*a*, hereafter SER). A list of the unpolarized standard stars was established by observing nearby nonvariable stars using the rotatable telescopes (Appendix 1 in SER). Serkowski also suggested a list of fainter nearby dwarf G stars to be used as unpolarized standards (Appendix 3 in SER). Most stars in both lists indeed have either a very small degree of or no polarization (<0.01%). Nevertheless, among these 35 stars, HD 202573[1] and χ Her (HD 142373) (Piirola 1977) have been noticed to exhibit a small degree of polarization. Therefore, these two nearby stars are not justified to be used for the intended purpose.

The highly polarized standard stars, on the other hand, were selected by their high polarization and brightness. Not surprisingly, these stars are mostly supergiants.

The uncertainties of the values of the polarization, p, and the position angle, θ, listed in SER are on the level of ± 0.1% and $\pm 1°$, respectively, for the polarized standards. Some improvements had been made for the determination of the p values to the level of ± 0.05% (Serkowski, Mathewson, and Ford 1975, hereafter SMF), but the accuracy of θ is still limited to the $\pm 1°$ level.

The uncertainty of θ, caused by the statistical randomness (predominantly photon statistics) is:

$$\Delta\theta = 28\overset{\circ}{.}65 \frac{\Delta p}{p}, \tag{1}$$

where $\Delta\theta$ and Δp are the uncertainties of θ and p, respectively. To reduce the uncertainty of θ to the level of, say, $0\overset{\circ}{.}3$, the value of p needs only to be determined to an accuracy of ± 0.03% for a star with 3% polarization. Notwithstanding, this accuracy is not generally achieved for the position angle measurements because: (1) the listed values of θ of the standard stars are not accurate to this level in the first place, and (2) there is no guarantee that the values of θ of the polarized standard stars are absolutely constant. Indeed, the polarimetric variability of several early-type supergiants has already been noticed (Serkowski 1968, 1970; Coyne 1971). Other systematic errors may also affect the precise determination of θ, and they will be discussed in § III.

A straightforward way to refine the values of θ is to make repeated observations of *all* the standard polarized stars in the same nights. This "network" type observation should be able to minimize the possible systematic

[1]A total number of 25 measurements in the V filter of the "unpolarized standard" HD 202573 were made during 1979 Feb., Oct., and Nov. These data indicate that HD 202573 has a small amount of polarization of 0.054 ± 0.010% with $\theta = 80° \pm 5$. Another eight measurements made at the B filter during the same runs show similar values of p and θ.

TABLE 1

EFFECTIVE WAVELENGTHS[a] OF THE FILTERS

Filter	Value	
U	$\lambda_{eff} = 3590 + 40\,(U-B)_0 + 26\,E(B-V) + 16\,(X-1)$	Å
B	$\lambda_{eff} = 4381 + 58\,(B-V)_0 + 40\,E(B-V) + 9\,(X-1)$	Å
V	$\lambda_{eff} = 5347 + 42\,(B-V)_0 + 45\,E(B-V) + 3\,(X-1)$	Å
R	$\lambda_{eff} = 6440 + 32\,(B-V)_0 + 43\,E(B-V) + 4\,(X-1)$	Å
[0.75]	$\lambda_{eff} = 7434 + 30\,(B-V)_0 + 41\,E(B-V) + 2\,(X-1)$	Å

[a] X = air mass.

TABLE 2

POLARIMETRIC MEASUREMENTS OF THE POLARIZED STANDARD STARS[a]

	U	B	V	R	[0.75]		U	B	V	R	[0.75]
HD 7927 (ϕ Cas)						HD 154445 (HR 6353)					
p(%)	3.04	3.30	3.34	3.19	2.93	p(%)	2.96	3.49	3.74	3.63	3.40
(m.e.)	±0.02	±0.01	±0.02	±0.02	±0.01	(m.e.)	±0.01	±0.01	±0.01	±0.01	±0.02
θ	93.7	93.0	92.3	91.7	91.7	θ	89.7	90.1	90.1	90.0	90.1
(m.e.)	±0.2	±0.2	±0.1	±0.1	±0.2	(m.e.)	±0.1	±0.1	±0.1	±0.1	±0.1
N	6	6	42	6	6	N	13	10	33	11	9
HD 14433 (BD+56°568)						HD 160529 (CD −33°12361)					
p(%)	3.43	3.77	3.87	3.69	3.45	p(%)	6.31	6.97	7.31	7.04	6.53
(m.e.)	±0.02	±0.01	±0.01	±0.01	±0.02	(m.e.)	±0.13	±0.03	±0.04	±0.01	±0.03
θ	113.3	112.8	112.5	112.4	111.9	θ	20.3	20.1	20.4	20.8	21.3
(m.e.)	±0.3	±0.3	±0.1	±0.2	±0.3	(m.e.)	±0.2	±0.1	±0.1	±0.1	±0.1
N	2	6	24	8	5	N	3	4	10	6	5
HD 21291 (2H Cam)						HD 183143 (BD +18°4085)					
p(%)	3.01	...	3.49	3.30	3.08	p(%)	4.86	5.89	6.10	5.90	5.43
(m.e.)	±0.01	...	±0.02	±0.02	±0.01	(m.e.)	±0.03	±0.04	±0.05	±0.05	±0.03
θ	116.6	...	116.6	116.5	116.3	θ	179.3	179.5	179.3	179.2	179.0
(m.e.)	±0.1	...	±0.2	±0.2	±0.3	(m.e.)	±0.2	±0.2	±0.2	±0.2	±0.2
N	6	0	3	6	6	N	6	8	27	12	9
HD 23512 (BD +23°524)						HD 187927 (η Aql)					
p(%)	1.73	2.04	2.26	2.29	2.13	p(%)	1.43	1.65	...	1.67	1.63
(m.e.)	±0.03	±0.01	±0.01	±0.02	±0.03	(m.e.)	±0.03	±0.02	...	±0.02	±0.01
θ	30.7	30.3	29.9	29.6	29.3	θ	95.4	94.4	...	93.3	92.6
(m.e.)	±0.5	±0.2	±0.3	±0.2	±0.3	(m.e.)	±0.1	±0.4	...	±0.3	±0.1
N	1	7	22	4	2	N	8	2	0	1	6
HD 43384 (9 Gem)						HD 198478 (55 Cyg)					
p(%)	2.58	2.83	2.94	2.86	2.71	p(%)	2.36	2.60	2.74	2.60	2.37
(m.e.)	±0.04	±0.05	±0.04	±0.03	±0.04	(m.e.)	±0.01	±0.01	±0.02	±0.03	±0.02
θ	169.8	169.3	169.8	170.7	170.3	θ	2.1	3.2	3.2	3.7	3.5
(m.e.)	±0.7	±0.7	±0.7	±0.7	±0.7	(m.e.)	±0.2	±0.2	±0.2	±0.2	±0.2
N	5	6	10	5	5	N	11	12	35	18	11
HD 147084 (o Sco)						HD 204827 (BD +58°2272)					
p(%)	2.77	3.50	4.18	4.44	4.42	p(%)	...	5.71	5.49	4.99	4.42
(m.e.)	±0.02	±0.01	±0.02	±0.02	±0.02	(m.e.)	...	±0.02	±0.02	±0.05	±0.04
θ	31.9	32.0	32.0	32.2	32.1	θ	...	58.7	59.3	59.9	60.2
(m.e.)	±0.3	±0.2	±0.1	±0.1	±0.2	(m.e.)	...	±0.1	±0.1	±0.1	±0.3
N	4	6	15	7	5	N	0	4	9	3	1

[a] N = number of measurements.

errors due to the different instrumentation and/or setup, the mechanical and optical imperfection, and the absolute position angle zero point problem. Also, if any of the standard polarized stars has variability in p and/or θ, it will stand out against all the other standard stars and therefore can be determined with greater confidence. One of the objectives of this paper is to use this "network" type observation to redetermine the values of p and θ of the polarized standard stars to the level of $\pm 0.01\%$ and $\pm 0\overset{\circ}{.}2$, respectively.

II. OBSERVATION

Due to the latitude of the observing site, we can only observe stars north of $\delta = -35°$. Therefore, three of the 15 SER polarized standard stars are not included because of their southern locations. They are HR 3708 (HD 80558), l Car (HD 84810), and HR 4876 (HD 111613). The main body of the data presented here was obtained during 1981 August 22–28 at McDonald Observatory with the 76 cm telescope. The rest of the data were obtained at various epochs ranging from 1978 to 1981 at the same observatory by using the 2.1 m, the 91 cm, and the 76 cm telescopes. The polarimeter and filter system used are described by Breger (1979). We will hereafter denote the five filters we used as U, B, V, R, and [0.75], respectively. The effective wavelengths of these filters have been calculated as a function of the observed stellar color and the airmass by using a mean atmospheric extinction curve, the mean interstellar extinction curve (Code *et al.* 1976) and stellar intensity distributions from the model atmospheres by Kurucz (1979). The effective wavelengths are listed in Table 1.

Since some of the polarized standard stars have different values of θ at different wavelengths, we prefer to establish the values of θ for the standard stars for a particular filter. This differs from the scheme used by SER where the values of θ are listed at $\lambda_{\max}$, the wavelength at which p has the maximum value, $p_{\max}$. We choose the V filter for the following reasons: (1) the V filter of our system is very similar to the V filter in the UBV system; (2) we do not have to rely on the value of $\lambda_{\max}$ to determine θ; and (3) the visual band usually transmits a sufficient number of photons. For this reason, measurements through the V filter were emphasized.

The average values of the measurements are listed in Table 2. Most *single* measurements used for the averages have the photon statistics uncertainty of less than 0.02% in p.

III. DISCUSSION OF POSSIBLE SYSTEMATIC ERRORS

a) Instrumental Polarization

Instrumental polarization was determined by repeated observations of the unpolarized standard stars given by SER. The amount of the instrumental polarization was usually on the level of 0.05% and fairly constant in each run with a scatter of $\pm 0.02\%$ for each single measurement. The instrumental polarization was then applied to all measurements.

b) Accurate Determination of the Dead Time

Due to the coincidence loss, the observed amount of polarization is reduced for bright stars. The true value of polarization $p_{\rm tr}$ can be obtained through the following approximation:

$$p_{\rm tr} = p_{\rm obs}(1 + \tau C), \tag{2}$$

where $p_{\rm obs}$ is the observed value of polarization, τ is the dead time, and C is the count rate. For a bright star with the count rate of 10^6 s^{-1} and $p = 3\%$, an uncertainty of only 10 ns in τ will cause a sizable error of 0.03% in p. This example demonstrates the importance of the accurate determination of τ. We use a nonlinear least squares algorithm to fit the double-sine curve (distorted by coincidence losses) produced by a calibration polaroid in front of the polarimeter, and obtain rather precise (± 2 ns) values of the dead time. A value of 70 ns is adopted for the EMI 9658 AR tube used at a voltage of 1650 V and the electronic circuitry in statu quo.

c) Depolarizing Factor

The calibration polaroid mentioned in the previous subsection can also be used to check the polarizing efficiency of the analyzer. The depolarizing factor for the Glan-Air prism in our polarimeter is determined to be 1.000 ± 0.0005 in all our filters, after the sampling depolarizing factor $(\pi/n)/\sin(\pi/n)$ ($= 1.00374$ for $n = 21$) is applied. This is in good agreement with the fact that the Glan-Air prism usually has an extinction ratio of 10^5 or larger.

d) Farady Effect

When linearly polarized light is passing through a medium in a direction parallel to the magnetic field presented in the medium, the plane of vibration is rotated. The amount of rotation is

$$\Delta\theta = VBl, \tag{3}$$

where $\Delta\theta$ is the amount of rotation, V is the Verdet constant, B is the magnetic field strength, and l is the distance traveled by the light in the medium. When we consider the polarized light going through the Earth's atmosphere, the geomagnetic field will enable the atmosphere to be optically active and therefore rotate the plane of vibration. Equation (3) can also be written as

$$\Delta\theta = VB_{\parallel}hX, \tag{4}$$

where $B_{\parallel}$ is the magnetic field component parallel to the

TABLE 3

POLARIMETRIC PARAMETERS OF THE POLARIZED STANDARD STARS

HD, Name	α(1985)	$\Delta\alpha/\Delta t$ (s/yr)	δ(1985)	$\Delta\delta/\Delta t$ (″/yr)	m_V	$B-V$	Sp.	p_{max}(%)	λ_{max}(μm)	θ_V(1985)	$\Delta\theta/\Delta t$ (°/100 yr)	$\Delta\theta/\Delta\lambda$ (°/μm)	Remarks
7927, ϕ Cas	$1^h19^m07\overset{s}{.}3$	3.78	+58°09′12″	+18.9	4.98	0.68	F0 Ia	3.41±0.02	0.515±0.006	92.3±0.1	+0.4	−5.7±1.1	
14433, +56°568	2 20 50.8	4.24	+57 10 31	+16.5	6.39	0.57	A1 Ia	3.91±0.03	0.519±0.007	112.5±0.1	+0.6	−3.0±0.7	
21291, 2H Cam	3 27 50.3	4.86	+59 53 24	+12.5	4.21	0.41	B9 Ia	3.53±0.02	0.521±0.003	116.6±0.2	+0.9	~0	
23512, +23°524	3 45 40.6	3.55	+23 34 45	+11.2	8.11	0.36	A0 V	2.29±0.01	0.600±0.006	29.9±0.3	+0.5	−3.6±0.2	
43384, 9 Gem	6 16 03.7	3.66	+23 44 52	−1.2	6.27	0.44	B3 Ia	3.01±0.04	0.531±0.011	169.8±0.7	+0.6	+2.5±1.3:	var. pol.
80558, HR 3708	9 18 12.5	1.98	−51 29 49	−15.2	5.91	0.54	B7 Iab	(3.32±0.02)	(0.61±0.01)	(162)	+0.6	(−5.7±1.8)	
84810, *l* Car	9 44 50.2	1.65	−62 26 17	−16.6	(3.3–4.0)	...	(F8–K0 Ib)	(1.62±0.01)	(0.57±0.01)	(100)	+0.7	(~0)	Cepheid
111613, HR 4876	12 50 23.6	3.56	−60 14 54	−19.6	5.74	0.38	A1 Ia	(3.14±0.06)	(0.56±0.01)	(81)	−0.2	(~0)	
147084, o Sco	16 19 43.8	3.61	−24 08 05	−8.7	4.54	0.84	A5 II	4.46±0.03	0.695±0.006	32.0±0.1	−0.6	~0	
154445, HR 6353	17 04 45.7	3.09	− 0 52 23	−4.9	5.63	0.16	B1 V	3.73±0.01	0.558±0.002	90.1±0.1	−0.5	~0	
160529, −33°12361	17 40 59.6	3.95	−33 29 52	−1.9	6.67	1.28	A2 Ia	7.31±0.02	0.543±0.003	20.4±0.1	−0.7	+3.5±0.6	
183143, +18°4085	19 26 46.5	2.66	+18 15 52	+7.3	6.87	1.22	B7 Ia	6.08±0.05	0.551±0.006	179.3±0.2	−0.5	~0	var. pol.
187929, η Aql	19 51 42.4	3.06	+ 0 57 57	+9.2	(3.5–4.3)	...	(F6–G2 Ib)	1.76±0.03	0.562±0.014	93.8±0.3	−0.5	−7.3±0.3	Cepheid
198478, 55 Cyg	20 48 25.6	2.04	+46 03 28	+13.4	4.83	0.40	B3 Ia	2.72±0.02	0.522±0.008	3.2±0.2	−0.6	~0	var. pol.
204827, +58°2272	21 28 31.7	1.73	+58 40 25	+15.8	7.93	0.79	B0 V	5.70±0.03	0.460±0.006	59.3±0.1	−0.7	+5.5±0.3	

direction of the line of sight, and X is the air mass. The absolute value of V is in the order of 10^{-5} arcmin gauss^{-1} cm^{-1}, (6.27×10^{-6} arcmin gauss^{-1} cm^{-1} for the air at 0° C, 760 mm Hg, at $\lambda = 5780$ Å; West and Carpenter 1963) and has higher values at shorter wavelengths. The geomagnetic field is a quantity which varies both in strength and orientation as a function of time (due to solar activities, etc.) in a rather random fashion. The value of 0.5 gauss will be used subsequently as a mean value of the geomagnetic field strength. The scale height of the atmosphere, h, is about 8 km. A further complication is introduced owing to the disagreement between the geomagnetic and geographic poles. For the sake of simplicity, we will assume the locations of the geomagnetic poles coincide with those of the geographic poles. With this simplified geometry, the sign of $\Delta\theta$ in equation (4) is positive if the declination of the observed object is north of the latitude of the observer and vice versa. For a star only 5° above the horizon (i.e., $X=10$) and which locates at the geomagnetic meridian, equation (4) yields $\Delta\theta = 40'$. This is in good agreement with Lyot (1929) who claimed $\Delta\theta = 45'$ under the same conditions.

Our observations of the standard polarized stars were all made with air masses less than 1.5; therefore, the values of $\Delta\theta$ are always less than 0°.1, and corrections are not performed.

e) *Refraction by the Atmosphere*

Another atmospheric effect which may rotate the position angle is refraction. The change of the position angle is (Born and Wolf 1970):

$$\Delta\theta = \tan^{-1}\{\tan\theta\cos\left[\alpha_i - \sin^{-1}(\sin\alpha_i/n)\right]\} - \theta, \quad (5)$$

where α_i is the angle of incidence, n is the refraction index of the air ($1+3\times10^{-4}$), and θ is the position angle relative to the plane of incidence. This effect turns out to be so small that even at 10 air masses, $\Delta\theta$ is on the level of 10^{-4}°.

f) *Change of Position Angle due to the Astrometric Motions*

The formulations of the secular changes of the position angles as the results of precession and proper motions are exactly the same as those of the visual binary systems. For stars not very close to the poles, the change of θ due to the precession is:

$$\Delta\theta = \theta_t - \theta_0 = +0.00557(t-t_0)\sin\alpha_0\sec\delta_0\ ^\circ\mathrm{yr}^{-1} \quad (6)$$

(van de Kamp 1967), where θ_t and θ_0 are the position angles at epochs t and t_0, respectively and (α_0, δ_0) is the celestial coordinates of the object at epoch t_0.

For an object at $\delta = 60°$, the change of position angle can be as high as 1° in 100 years! Accordingly, we include the values of $\Delta\theta/\Delta t$ due to precession in Table 3 and assign an epoch to the tabulated values of position angles.

The change of θ due to the proper motion is:

$$\Delta\theta = \theta_t - \theta_0 = +0.00417(t-t_0)\mu_\alpha\sin\delta_0\ ^\circ\mathrm{s}^{-1} \quad (7)$$

(van de Kamp 1967), where μ_α is the proper motion in right ascension. Since the standard polarized stars all have $\mu_\alpha < 0.003$ s yr^{-1} the values of $\Delta\theta$ are < 0°.1 in 10^4 yr, and are thus neglected. Equation (7) will have significant effect only for the objects having both high polarization and large proper motion.

g) *Absolute Zero Point of the Position Angle*

By definition, the absolute zero point of the position angle is in the direction toward the Celestial North Pole. Contrary to astrometrists' situation, this zero point is not readily accessible to the polarimetrists. Several methods have been suggested (see, for example, Serkowski 1974*b*) to obtain the zero point of θ, but it seems that systematic differences on the level of 1° are not uncommon when we compare values of the same stars from different publications. In our final reduction of the standard polarized stars, we *select* the absolute zero point of θ in such a way that the weighted average of the differences between our measurements and those in SER is zero. The uncertainty in this internal zero-point system should be 0°.25 or less. This is based on the fact that the values listed in SER are the result of a compilation merged from several different sources; therefore, the possible deviation of the zero point in any single source is reduced, if not removed.

IV. POLARIMETRIC VARIABILITY OF THE STANDARD POLARIZED STARS

Polarimetric variability of several standard polarized stars was noticed and will be discussed case by case.

a) *55 Cyg (HD 198478)*

Figure 1 shows the average value of the position angle (relative to their mean values) of all filters for several polarized standard stars on each night during the 1981 August run. The star 55 Cyg showed a definite change of θ by about 1° between August 23 and August 24. Meanwhile, the amount of the polarization showed a marginally small change during the same epoch. The largest change in p is less than 0.06%. Similar variability was also detected within the epochs of 1980 October 4–6, 1980 November 4–10, and 1981 September 15–18. Underhill (1960) and Granes and Herman (1971) noticed that the Hα profile of 55 Cyg showed noteworthy change within only a few days. This short time scale of spectroscopic change is consistent with the characteristic time scale of the polarimetric change, and both variabilities may share the same physical origin intrinsic to the star.

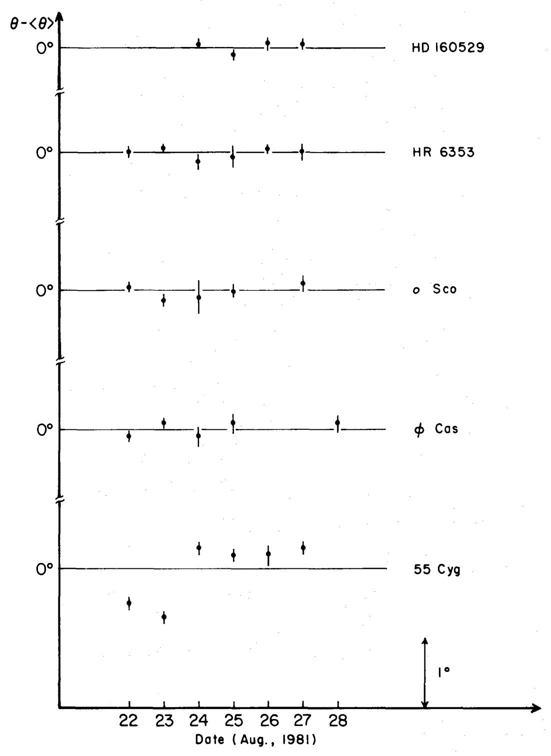

FIG. 1.—The daily average position angles of all filters of 55 Cyg (relative to the mean value of the entire observing run) during 1981 August. 55 Cyg showed a 1° change of θ between August 23 and August 24, while the other polarized standard stars showed no variation.

b) BD + 18°4085 (HD 183143)

This star was observed to have very constant values in both p and θ during the run of 1981 August 22–28. However, during the run of 1981 September 12–18, HD 183143 exhibited a $1^\circ\!.0 \pm 0^\circ\!.1$ decrease of position angle in both V and R filters, while the values of θ in *all* three other standard polarized stars showed no measurable change (Fig. 2). The p values obtained in 1981 September were also 0.29 ± 0.03% higher than those of 1981 August in both V and R bands (measurements were not made for HD 183143 in the U, B, and [0.75] filters during 1981 September). Measurements acquired on 1979 September 21, and 1981 October 10 and 12 also show the unmistakably higher (0.2%) values of p than those of 1981 August in *all* five filters.

The polarimetric constancy of HD 183143 during the run of 1981 August suggests that the time scale of the polarimetric variability is probably a few weeks.

c) 9 Gem (HD 43384)

Long term variations of both p and θ are noticed from the observations made in 1979 January, 1981 January, 1981 August, and 1981 December. The amounts of change are as large as 0.25% and 2° in p and θ, respectively. Short term variation of θ is marginally detected ($0^\circ\!.8 \pm 0^\circ\!.2$) in the V filter between 1981 November 3 and November 4. Coyne (1971) also detected the polarimetric variability of 9 Gem during 1969–1971. The amount of change was as large as 0.7% in p and 6° in θ.

The temporal polarimetric changes of these three stars are presumably due to the changes of their intrinsic polarization in view that all of the three stars are early-type supergiants. In addition, these three stars have the earliest spectral types among the observed standard polarized stars which are supergiants. This high incidence of short time-scale polarimetric variability among the early-type supergiants is probably a manifestation of a selection effect inasmuch as the standard stars were closely monitored only for a short span of time. If the polarimetric variation is indeed associated with the semi-periodic photometric change of supergiants whose period of variability increases from 17 days for a B2 Ia star to more than 80 days for a G0 Ia star (Burki, Maeder, and Rufener 1978), our observation schedules were in favor of finding variability for supergiants of the earlier spectral types.

The variability of 55 Cyg, 9 Gem, and HD 183143 makes them unsuitable for use as standard polarized stars for accurate polarimetric observations. Polarimetric variability of other standard polarized stars are also possible. In order to prevent the systematic error in position angle caused by unexpected variability of any of the standard stars, at least three polarized standards should be observed in every observing run. Establishment of more polarized standards, which are not variable supergiants, is desirable.

V. OTHER POLARIMETRIC CHARACTERISTICS OF THE STANDARD POLARIZED STARS

Serkowski (1973) suggested an empirical relation for the wavelength dependence of polarization due to the interstellar medium:

$$\ln(p/p_{\max}) = -K \ln^2(\lambda/\lambda_{\max}) \qquad (8)$$

where $K = 1.15$. We found that equation (8) makes excellent fits for most of the measurements we obtained, and mean errors of $\lambda_{\max}$ and $p_{\max}$ determined from our data have the uncertainties smaller than those listed in SMF by at least a factor of 2. The calculated values of $p_{\max}$ and $\lambda_{\max}$ of the polarized standard stars are listed in Table 3. A slightly different relation of $p(\lambda)$ has been proposed by Wilking *et al.* (1980) and Wilking, Lebofsky, and Rieke (1982). They suggested that the value of K in equation (8) should be a function of $\lambda_{\max}$ ($K = 1.86\lambda_{\max}$). This revised $p(\lambda)$ relation will slightly broaden or narrow the shape of the curve of equation (8), and the values of $p_{\max}$ and $\lambda_{\max}$ obtained by fitting our data with the revised relation remain almost unchanged.

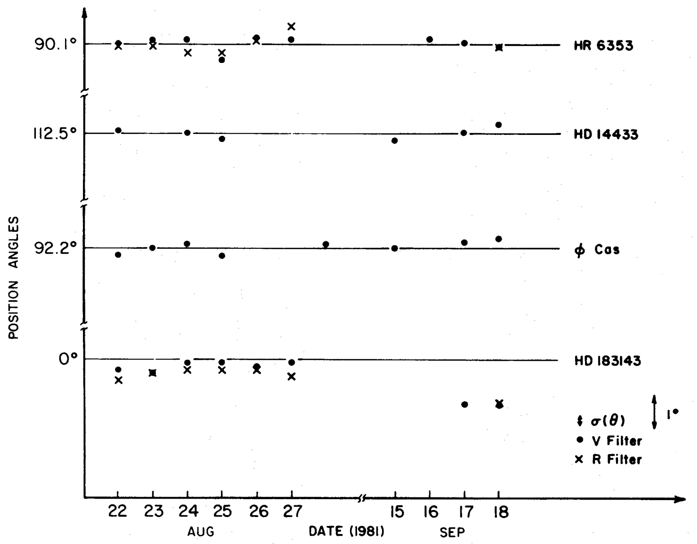

FIG. 2.—The change of the position angle of HD 183143 between 1981 August and 1981 September. All three other standards showed relatively constant values of θ.

For at least half of the standard polarized stars, the values of the position angle vary as a function of wavelength. No unique relation can be established for the wavelength dependence of the position angles, probably because it can be caused by several different mechanisms. The values of $\Delta\theta/\Delta\lambda$ are listed in Table 3 for the stars showing a definite wavelength dependence of θ to reflect the first-order behavior of the position angles as a function of wavelength *in the optical bandpass*. For the 3 southern stars which we did not observe, the values of $p_{\max}$ and $\lambda_{\max}$ as well as θ_V and $\Delta\theta/\Delta\lambda$ are adopted from SMF and are put in parentheses in Table 3.

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REFERENCES

Born, M., and Wolf, E. 1970, in *Principles of Optics* (4th ed.; Oxford: Pergamon), p. 45.
Breger, M. 1979, *Ap. J.*, **233**, 97.
Burki, G., Maeder, A., and Rufener, F. 1978, *Astr. Ap.*, **65**, 363.
Code, A. D., Davis, J., Bless, R. C., and Hanbury Brown, R. 1976, *Ap. J.*, **203**, 417.
Coyne, G. V. 1971, in *Colloquium on Supergiant Stars*, ed. M. Hack (Trieste: Osservatorio Astronomico Trieste), p. 93.
Granes, P., and Herman, R. 1971, in *Colloquium on Supergiant Stars*, ed. M. Hack (Trieste: Osservatorio Astronomico Trieste), p. 58.
Kurucz, R. L. 1979, *Ap. J. Suppl.*, **40**, 1.
Lyot, B. 1929, *Ann. Obs. Paris-Meudon*, **8**, 26.
Piirola, V. 1977, *Astr. Ap. Suppl.*, **30**, 213.
Serkowski, K. 1968, *Ap. J.*, **154**, 115.
______. 1970, *Ap. J.*, **160**, 1083.
______. 1973, in *IAU Symposium 52, Interstellar Dust and Related Topics*, ed. J. M. Greenberg and H. C. van de Hulst (Dordrecht: Reidel), p. 145.
Serkowski, K. 1974*a*, in *Planets, Stars and Nebulae Studied with Photopolarimetry*, ed. T. Gehrels (Tucson: University of Arizona), p. 135 (SER).
______. 1974*b*, in *Methods of Experimental Physics*, Vol. 12: *Astrophysics*, *Part A*, ed. N. Carleton (New York: Academic Press), p. 361.
Serkowski, K., Mathewson, D. S., and Ford, V. 1975, *Ap. J.*, **196**, 261 (SMF).
Underhill, A. B. 1960, *Pub. Dom. Ap. Obs. Victoria*, **11**, 353.
van de Kamp, P. 1967, in *Principles of Astrometry* (San Francisco: Freeman), p. 144.
West, C. B., and Carpenter, R. O'B. 1963, in *American Institute of Physics Handbook*, ed. D. E. Gray (New York: McGraw-Hill), p. 6-181.
Wilking, B. A., Lebofsky, M. J., Martin, P. G., Rieke, G. H., and Kemp, J. C. 1980, *Ap. J.*, **235**, 905.
Wilking, B. A., Lebofsky, M. J., and Rieke, G. H. 1982, *A.J.*, **87**, 695.

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