NO. 90 WAVELENGTH DEPENDENCE OF POLARIZATION. VIII. INTERSTELLAR POLARIZATION*

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ABSTRACT

Eighteen stars were observed primarily with an ultraviolet and an infrared filter in order to verify the previous discovery of a dependence of position angle on wavelength. The effect is confirmed. Observations were also made at five other wavelengths in the range 0.3–1.0 μ. The variability of the polarization of μ Cephei, discovered by K. A. Grigoryan in 1958, appears confirmed. These observations were made with the Catalina 21-in. and Steward Observatory 21-in. reflectors. The current data are combined with those previously reported in this series of papers, so that the total number of stars now is 36. The interpretation is in terms of the traverse of several discrete clouds having different particle sizes and different particle orientations. If the refractive index is 1.3, for example, various particle diameters occur in the range 0.17–0.4 μ. (Smaller particles may be present but they can be observed only at shorter wavelengths.) In a few regions, particle diameters near 1 μ are also found. (Larger particles can be observed only at longer wavelengths.) In general, there is no uniform law of the dispersion of interstellar polarization.

1. *Introduction*

LITTLE is known about the wavelength dependence of plane interstellar polarization. The present observational status was reviewed by Martel (1964). The topic was discussed at the IAU Colloquium on Interstellar Grains (Greenberg 1966) held at Troy, New York, in August 1965.

Circular interstellar polarization has been observed by Serkowski (1965b) for two stars that have no plane polarization and four stars that have strong plane polarization; no ellipticity exceeding 0.05% was found.

In this paper we present additional observations of the wavelength dependence of plane polarization on 18 stars. They were observed primarily at two wavelengths ($1/\lambda = 1.05$ and 2.79) in order to confirm the rotation of position angle with wavelength reported in Paper V. Observations at other wavelengths were also obtained, and all of the new observations are combined with the observations of Papers II, V, and VII (see Reference section).

A discussion is made of the variations for individual stars of the percentage polarization versus wavelength, and of the rotation of position angle. The correlation of percentage polarization and position angle with distance and with galactic longitude are also discussed.

An attempt is made to fit the calculations of van de Hulst (1957), for light scattering by long cylinders, to the observations. This, however, is only a first approximation, using single-particle sizes rather than size distributions and restricting the refractive index to that of dirty ices ($m \simeq 1.3$).

2. *The Observations*

Most of the observations reported here were obtained during the summer of 1965 with the Catalina 21-in. and the Steward 21-in. reflectors. The Catalina telescope is at 2510 m altitude in the Santa Catalina Mountains north of Tucson and is operated by the Lunar and Planetary Laboratory of The University of Arizona. The Steward telescope is in Tucson at 757 m altitude and it is operated by the Astronomy Department of The University of Arizona. The polarimeter is the same as used before (Gehrels and Teska 1960). The tubes and filters which define the effective wavelengths are described in Table I of Paper VII. We are indebted to Mrs. Tricia Coffeen, who assisted with much of the observing and who made the majority of the reductions.

In order to obtain corrections for instrumental polarization, at least six nonpolarized stars ($P < 0.023\%$) were observed twice. As usual, the resulting small corrections were applied at each analyzer angle before the computation by least squares of the cosine curve was made.

Table I gives the instrumental effects of the two telescopes. P is the percentage polarization (division by 46.05 gives the amount in magnitudes), and θ is the position angle in the equatorial reference frame. Under the $1/\lambda = 1.90$ heading is listed the average of observations at $1/\lambda = 1.85$ (green filter with RCA 7102 phototubes) and at $1/\lambda = 1.95$ (same filter with EMI 6255*S*). It is seen in Table I that the instrumental polarization is small even for the Steward mirrors for which no special precautions, to reduce polarization, in the aluminization had been taken.

The calibration of the polarization position angles (Gehrels and Teska 1960, p. 121) was carried out in the course of the observing runs.

TABLE I. Observed instrumental polarization.

Telescope		Amount and position angle observed at $1/\lambda =$ 1.05	1.19	1.39	1.90	2.33	2.79	3.04
Catalina	P (%)	0.09	0.13	0.09	0.07	0.13	0.14	0.21
	θ (deg)	90	107	106	87	94	99	102
Steward	P (%)	0.18	0.14	0.12	0.12	0.14	0.13	0.19
	θ (deg)	172	173	165	169	173	10	174

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TABLE II. Observed percentage of interstellar polarization. 1965 observations.[a]

HD	Percentage polarization observed at 1/λ= 1.05	1.19	1.39	1.95	2.33	2.79	3.04
147165	0.90	1.12;	1.96:	1.60	1.44	1.23	...
187929	1.16	1.42	1.64	1.50	1.65	...	...
198478	1.96;	1.84;	2.11;	2.94	2.65	2.31;	2.52;
206936	0.85	1.11:	1.55	2.28	2.44	...	...
207260	1.24	1.00	1.35	1.67	1.55	1.45	1.01;
217476	1.62	1.64:	2.14	...	...	...	...
224014	1.09	...	...	1.33	1.34	1.12	...
2905	0.95	...	...	1.62	1.49	1.28	1.40
7927	2.07	...	...	3.35	3.66	3.11	...
14489	1.54	...	...	...	...	2.43:	...
21291	2.54	2.64	3.24	3.56:	3.60	3.48:	2.73
21389	2.72	...	...	4.07:	3.61	...	...
30614	...	...	...	1.70	1.59	1.56	1.06:
25291	1.54	1.57	1.83	1.85	2.00	...	...
24398	0.95	0.92	1.08	1.19	1.19	0.96:	0.55
31964	1.46	1.58	1.89	2.01	1.88	2.02	1.28:
36371	...	...	1.56:	2.22	2.20	1.69	...
37202	1.36;	1.06;	1.21;	...	...	1.08;	...

[a] Semicolons are used for single observations and colons for uncertain observations.

The depolarization correction factor was determined anew, for all filters with 1/λ<2.3, and it was found to be 1.004 (±0.001 p.e.), independent of wavelength; the observed polarizations have been multiplied by 1.004 before entry in the tables. This determination of the depolarization is made with a Polaroid sheet immediately in front of the *polarimeter*, and it does not, therefore, include any depolarization effects of the telescope mirrors (we thank Mr. F. F. Forbes for a discussion of depolarization effects).

In 1965, the observations were primarily made with the *I* and *U* filters (see Table I of Paper VII) using, for both filters, one and the same phototube box (RCA 7102); these observations were to test the wavelength dependence of the position angles. As an incidental part of the work in 1965, observations were also made at the other wavelengths.

TABLE III. Observed position angles of interstellar polarization. 1965 observations.

HD	Position angles observed at 1/λ = 1.05	1.19	1.39	1.95	2.33	2.79	3.04
147165	164°7:	168°8:	176°6;	0°9:	179°9	8°8:	...
187929	91.4	90.5	90.0	88.7	95.9	...	...
198478	7.3:	1.3;	5.1:	3.3	2.8	0.6;	9°8:
206936	22.2	22.7	24.9	30.8	32.0	...	...
207260	48.8:	44.2:	41.6:	41.6	42.1	46.2	49.9;
217476	70.1	67.1	69.3	...	...	...	...
224014	58.5:	...	...	56.4	58.0:	53.4:	...
2905	80.9	...	...	82.9	84.9	84.8	90.9;
7927	91.0	...	...	92.5	...	94.2	...
14489	116.1:	...	...	...	...	110.5:	...
21291	115.9	115.2	115.9	116.5	116.8	117.3	107.6:
21389	118.9	...	...	120.3	120.9	...	...
30614	136.8	...	...	136.6	138.0	135.5:	137.0
25291	132.8	141.3:	133.2	131.8	133.1	...	...
24398	61.1	58.6	63.9	61.7	61.8	63.2:	72.7
31964	144.9	144.9	145.8	146.2	145.0:	144.4	143.3;
36371	...	...	176.4;	179.3:	178.8:	173.8	...
37202	...	28.2;	34.0;	...	...	...	...

TABLE IV. Observed percentage of interstellar polarization. All observations combined.

HD	Percentage polarization observed at 1/λ= 1.05	1.19	1.39	1.95	2.33	2.79	3.04
147165	1.10	1.18	1.55:	1.65	1.49	1.30	1.35
161056	2.89	...	4.24;	4.08	3.98;	3.00	3.07;
154445	2.62	...	3.75;	3.68	3.42;	2.87	2.60;
134335	0.39	0.61	0.58:	0.58	0.78	1.10	0.68
134320	0.69:	0.47	0.49	0.71	0.65:	0.57:	...
187929	1.16	1.42	1.64	1.50	1.65	...	...
183143	4.21;	...	5.99	6.08;	5.68	5.18:	4.28:
193443	1.54:	1.03:	2.00:	1.70	1.84:	1.71:	1.30:
198478	1.94	1.84;	2.45:	2.89	2.68	2.33	2.39
206936	0.85	1.11	1.55	2.28	2.44	...	...
207538	1.51:	1.58	1.92	2.12	2.23	2.12:	1.72
207260	1.08	1.15	1.30	1.60	1.56	1.48:	1.09;
217476	1.95:	2.18:	2.49:	2.64	2.53	2.49	2.85:
218342	1.85:	1.75	2.07	2.14	1.88	2.04	2.09:
224014	1.02	1.13	1.32	1.39	1.25	1.08	1.13:
2905	1.10	1.10	1.37	1.51	1.40	1.24	1.31
6675	1.48	1.46	1.69	1.66	1.44	1.44	1.73
7927	2.28	2.47	2.99	3.33	3.36	2.90	2.92
12301	2.01	2.37	2.41	2.80	2.72	2.58	2.14
12953	1.96	2.70	2.96	3.48	3.40	3.25	2.94
14489	1.44	1.55	1.80	2.10	2.03	2.05	1.87:
18326	2.51	2.51	3.88:	3.03	3.15	2.89	3.09
21291	2.39	2.72	3.16	3.48	3.43	3.09:	2.78
21389	2.49	2.75	3.18	3.72:	3.61	3.39	3.15
30614	0.89:	1.13	1.44	1.83	1.76	1.68	1.50:
22253	1.36	1.35	1.48	1.69:	1.58	1.76	1.67
25291	1.50	1.59	1.71	2.11	2.08	2.13	2.00
24431	1.57	1.60	1.34	2.14	1.87	2.12:	1.90
24398	0.93	0.98	1.13	1.20	1.11	0.88:	0.67
31964	1.46	1.60	1.83	2.04	2.00	1.99	1.76:
36371	1.52;	1.70;	1.87:	2.23	2.14	1.81	1.78
37202	1.37	1.23	1.21	1.46	1.53	1.01	0.68
41117	1.95	2.27;	2.50;	2.85	2.81	2.42	2.47
42379	1.88	2.07;	2.63;	2.92:	2.81;	2.98	2.44;
43753	2.18:	2.65	2.84:	2.80	2.59	2.28	2.51
37041	0.91	0.94	0.91	0.87	0.58	0.39	0.33

Table II lists the amounts of polarization observed in 1965. The stars are identified by their number in the Henry Draper catalogue, and they occur in the order of increasing galactic longitude. Corrections for red leaks of the ultraviolet filters have not been applied in any of our reductions of interstellar polarization. We have assumed that the effective wavelength for the ultraviolet filter with RCA 7102 tubes is the same as with EMI 6255S, so that 1/λ=2.79. Furthermore, we have combined (Tables IV and V, below) a few observations made at 1/λ=1.85 into those reported at 1/λ=1.95, and at 1.46 (Paper II) into those at 1/λ=1.39; resulting errors in the final values are always less than 0.03%.

The weighted mean values are listed in our tables, where the weights are equal to the reciprocal of the mean of the least-squares residuals. In practice, this is more realistic than applying the *square* of the mean residual. The number of observations per least-squares solution is small (of the order of 6 usually, and only

TABLE V. Observed position angles of interstellar polarization. All observations combined.

HD	Position angles observed at $1/\lambda =$ 1.05	1.19	1.39	1.95	2.33	2.79	3.04
147165	176°4:	170°1:	176°1	177°8:	179°2	183°9:	179°9
161056	68	...	65 ;	66	62 ;	68	63 ;
154445	89	...	86 ;	89	86 ;	89	87 ;
134335	64.0:	82.0:	62.8:	76.3:	72.6	...	...
134320	64.4:	75.6:	82.0:	75.3	77.7	...	...
187929	91.4	90.5	90.0	88.7	95.9	...	...
183143	0 ;	...	179	1 ;	1	0 :	0 :
193443	34 :	58 :	71	52	43	74	64 :
198478	2.3:	1.3;	3.0:	2.0	1.4	1.3	6.4:
206936	22.2	22.7	24.9	30.8	32.0	...	...
207538	49	55	57 :	59	59	56	63
207260	44.9:	39.9:	44.9:	41.0	41.6	42.0:	48.3
217476	69.5	69.3	68.8	70.5	70.1;	74.8:	70.0
218342	61 :	56	53	54	54	50	67 :
224014	52.3:	52.3	53.8	53.5:	54.9:	53.4:	...
2905	79.6	80.8	80.2:	83.2	85.5	86.4	91.8
6675	110	125	127	130	121	116	130
7927	90.6	91.4	90.8	93.7	94.8;	94.6	97.8
12301	108.1	109.1	109.6	112.2	112.2	113.0	114.6
12953	103.5	107.5	107.0	110.1	110.8	112.2	112.9
14489	108.1:	112.2	110.5	113.8	115.0	115.5:	121.1
18326	118	109	120 :	115	119	116	119
21291	116.9	115.6	116.3	115.8	114.6	115.5	115.5:
21389	118.9	119.4	119.6	121.1	121.8	121.9	122.3
30614	134.2	136.0	136.9	138.4	139.1	138.4:	138.4
22253	128	129	128	122	122	113	112
25291	133.2	133.8:	132.7	132.8	133.0	131.0	134.3
24431	125	121	120	113	119	117	110
24398	60.8	57.4	61.0	60.8	61.0	61.5:	67.6:
31964	144.3	145.2	145.0	145.3	144.2	144.2	145.5
36371	177.6;	176.5;	177.8	175.9:	175.2:	171.0	168.9
37202	30.4;	30.6	33.8	26.0	27.5	23.3	17.6
41117	179.9	177.8;	179.9;	174.9	172.8	174.6:	172.6:
42379	170.0	172.7;	181.0;	169.5:	168.0;	169.9	168.1;
43753	176 :	164	150 :	166	168	166	161
37041	96.7:	104.5:	89.6:	105.6	100.4:	96.6:	...

in the case of I and U observations in 1965 of the order of 18) and the mean residual is, therefore, statistically not a good indicator (for details of the least-squares solutions, see Gehrels and Teska 1960).

Table III lists the weighted mean value of the position angles observed in 1965.

Table IV gives the combination of all our observations of the percentage polarization. The results of Papers II, V, and VII, and those of the present Table II are included. The probable error, determined from repetition of observations, of the values without a colon in Table IV is ±0.08%.

Table V gives the combination of all our observations of the equatorial position angle. The probable error of the values without a colon is ±0°9 (when the polarization is about 2%), except for the stars from Paper VII, marked with asterisks in Table IX, for which the probable error is ±4°. The relative weights in Table II–V are with the reciprocal of the mean residual, as described above. Colons are used in the tables when the values appear uncertain by about three times the probable error. Semicolons are used to indicate that there is only one observation.

Table VI has some of the fundamental data for the observed stars. The *Catalogue of Bright Stars* (Hoffleit 1964) was used as a general reference, and especially for the parallactic distances; "neg" indicates zero or negative parallax. The photometric data are from Johnson and Mitchell (personal communication). We are indebted to Mitchell for several helpful discussions. The intrinsic photometric data for the classical Cepheid η Aquila were taken from Kraft (1963). The values of the ratio of total to selective absorption, $R = A_v/E_{B-V}$, were obtained from Fig. 41 of Johnson (1966). The absolute magnitudes are from Blaauw (1963). When in the second column the BD number is given, the star is not in the bright-star catalogue and the photometric data then are from Hiltner (1956), or Serkowski (1965a). Because the present distance determinations are poor—as seen in the lack of agreement of the parallactic and photometric distances—it is more practical to designate a few well-established distances by "near" and "far." The distances in the footnote of Table VI are based on the R values of Johnson, whereas in Paper V the old value $R=3$ was used. For reference in Sec. IV we have P_{vis} in Table VI, which is equal to the weighted mean (colons and semicolons halfweight) of the polarizations at $1/\lambda = 1.39$, 1.95, and 2.33 in Table IV. "Var." in the last column of Table VI indicates that the brightness is variable.

3. *Intrinsic Variations*

Because of motion of dust clouds and stars in the galaxy, the interstellar polarization is not invariable. Small changes in particle characteristics can cause strong changes in the observed polarization. Furthermore, in some cases we may be observing a polarization that is intrinsic to the star, or caused by material that is close to the star. Since the discovery of interstellar polarization in 1949, too few years have passed to expect sufficient changes in the relative motions of clouds and stars. But a quick reconnaissance of the problem may be useful, and the comparison of the work of various observers is always interesting.

Tables VII and VIII give the difference between our observations, made mostly in the years 1961–1965, with those of other observers. The catalogues were used of Hiltner (1956 and references given in that paper), Hall (1958, the "Hall" columns), and Behr (1959). The "Serkowski 1960–65" observations were supplied directly to us by Serkowski who applied a depolarization correction to the ones with the Belgrade refractor (publications are by Serkowski 1965a, 1965b, 1966a, 1966b, and Kruszewski 1962). Hall's measurements were compared with those of our blue filter ($1/\lambda = 2.33$), Hiltner's with our green filter ($1/\lambda = 1.95$), Behr's with the weighted (colons and semicolons halfweight) mean of our green and blue filters, while the average is listed for the differences of Serkowski's yellow filter with our green, his blue with ours, and—in 1965—his ultraviolet with ours.

The systematic difference between the various observers is determined by taking the straight average. The mean residual—without regard to sign—is also

TABLE VI. Various data on the stars observed in this program.

HD	Name	Galactic long	Galactic lat	Sp	V	$B-V$	E_{B-V}	R	Distance in kpc Phot.	Distance in kpc Par.	Distance in kpc Rel.[a]	P_{vis} (%)	Remarks
147165	σ Sco	351°	+17°	B1 III	$2^{m}89$:	$+0^{m}14$	$0^{m}40$	3.6	0.15	···	*n*	1.57	Sp. bin. Var.
161056	BS 6601	19	+12	B3 Vn	6.2	···	0.61:	3.6	0.14:	···	*n*	4.10	
154445	BS 6353	19	+23	B1 V	5.6	···	0.51:	3.6	0.30:	···	*n*	3.63	
134335	BS 5640	38	+59	gK1	5.8	···	···	···	···	···		0.66	
134320	46 Boo	39	+60	gK2	5.6	···	···	···	···	···		0.61	
187929	η Aql	41	−13	F6: Ib	3.50:	+0.80	0.13:	3.6	0.24:	0.20	*n*	1.60	Class. Ceph
183143	+18°4085	53	+ 1	B7 Ia	6.87	+1.24	1.30	3.6	0.72	···	*f*	5.88	
193443	+37°3879	76	0	O9 III	7.24	+0.41	0.71	3.6	1.19	···	*f*	1.81	
198478	55 Cyg	86	+ 2	B3 Ia	4.87	+0.43	0.57	3.9	0.78	0.08		2.72	Double
206936	μ Cep	101	+ 4	M2 Ia	4.13:	+2.26	0.62	4.6	0.45	0.08		2.09	Var.
207538	+59°2420	102	+ 4	B0 V	7.31	+0.33	0.63	4.6	0.58	···		2.09	
207260	ν Cep	102	+ 6	A2 Ia	4.29	+0.51	0.46	4.6	0.86	0.11		1.49	Var. ?
217476	BS 8752	108	− 3	G0 Ia	5.13	+1.55	0.85	4.9	0.62	neg.	*f*	2.58	
218342	+62°2170	111	+ 3	B0 IV	7.38	+0.41	0.71	5.0	0.53	···		2.03	
224014	ρ Cas	115	− 4	G0 Iap	4.59:	+1.26	0.56:	5.2	0.86:	0.06		1.32	Var.
2905	κ Cas	121	0	B1 Ia	4.16	+0.14	0.36	5.4	0.58	···		1.43	Var. ?
6675	+68°74	124	+ 7	B0.5 III	6.90	+0.31	0.59	5.6	0.46	···		1.60	
7927	φ Cas	127	− 4	F0 Ia	4.99	+0.68	0.49	5.6	1.41	neg.	*f*	3.23	
12301	53 Cas	131	+ 3	B8 Ib	5.58	+0.38	0.41	5.7	0.59	···		2.64	
12953	BS 618	133	− 3	A1 Ia	5.68	+0.61	0.58	5.8	0.84	···	*f*	3.28	
14489	9 Per	136	− 5	A2 Ia	5.17	+0.37	0.32	5.8	1.45	···	*f*	1.98	
18326	+59°578	138	+ 2	O8	7.82	+0.38	0.69	5.9	0.78:	···	*f*	3.25	
21291	BS 1035	142	+ 3	B9 Ia	4.21	+0.41	0.42	5.9	0.58	···		3.36	Var. ? Double
21389	BS 1040	142	+ 2	A0 Ia	4.54:	+0.56	0.55	5.9	0.48	···		3.46	Sp. bin.
30614	α Cam	144	+14	O9.5 Ia	4.29	+0.03	0.33	6.0:	0.50:	neg.		1.68	
22253	+56°824	145	+ 2	B0.5 III	6.53	+0.33	0.61	6.0	0.33	···		1.56	
25291	BS 1242	146	+ 5	F0 II	5.08	+0.50	0.30	6.0	0.14	···	*n*	1.97	
24431	+52°726	150	0	O9 IV–V	6.72	+0.38	0.69	6.0	0.34	···		1.78	
24398	ζ Per	162	−17	B1 Ib	2.85	+0.12	0.34	6.1	0.20	0.14	*n*	1.15	Var. ?
31964	ϵ Aur	163	+ 1	F0 Iap	3.00:	+0.54	0.35:	6.1	0.75:	0.25		1.96	Ecl. sp. bin.
36371	χ Aur	176	+ 1	B5 Iab	4.77:	+0.35	0.45	6.0	0.47	···		2.12	Sp. bin.
37202	ζ Tau	186	− 6	B2 IVp	3.03:	−0.19	0.05:	6.0	0.16:	neg.		1.40	Sp. bin. Shell
41117	χ^2 Ori	190	− 1	B2 Ia	4.63	+0.28	0.46	5.9	0.55	0.04		2.76	Var. ?
42379	+21°1143	190	+ 3	B1 II	7.37	+0.35	0.58	5.9	0.62	···	*f*	2.79	
43753	+23°1297	190	+ 5	B0.5 III	7.90	+0.30	0.58	5.9	0.68	···	*f*	2.72	
37041	θ^2 Ori	209	−19	O9.3 Vp	5.10:	−0.11	0.19:	5.2	0.55:	neg.		0.79	Sp. bin.

[a] In the relative-distance column, *near* stands for 0.1–0.3 kpc and *far* for 0.6–1.5 kpc.

given at the bottom of Tables VII and VIII. The values in brackets were not included for these determinations.

HD 206936 is already now suspected of intrinsic variation. On the other hand, HD 224014 is well observed and good agreement is seen. Additional and repeated observations are obviously needed. We are indebted to Dr. Serkowski for a discussion on this topic. The variations of HD 206936, μ Cephei, were first noticed by Grigoryan (see Serkowski 1965a, p. 85).

4. *Wavelength Dependence*

Table IX is designed to reveal any dependence of position angle on wavelength and to show any differences among the stars in this dependence. For each star the weighted (half-weight for colons and semicolons) mean value of the position angles is determined and the difference with the values of Table V is listed in Table IX. The stars marked with an asterisk have a much lower precision in the position angle as the observations had been made mainly for the percentage polarization (Paper VII).

Table IX shows that at least one-third of the stars show a marked dispersion of position angles, they are indicated with exclamation marks. The findings of Paper V are thereby confirmed. More stars may have some dispersion of the position angles, detectable at better precision and/or greater wavelength range. As for the dependence on galactic longitude, the effect is not so often found from Ophiuchus through Cygnus. But in the range of 120°<long<145° (Cassiopeia), 7 of the 10 observed stars show an increase in position angle with increasing $1/\lambda$. There is a sudden reversal as 5 of the 10 stars within the range 144°<long<191° (from Perseus to Orion) show a decrease of θ with increasing $1/\lambda$.

Table X lists normalized values of the percentage polarization. For each star the straight average of the polarizations at $1/\lambda=1.95$ and 2.33 is set equal to 100.0. The probable errors of the values without a colon now are about $\pm 4\%$. Colons and semicolons are transferred from Table IV.

Table X shows a variety of shapes in polarization-wavelength dependence (see also the third and fourth columns of Table XI, Sec. V). Paper II concluded to a general shape ("characteristic curve") with a maximum near $1/\lambda=1.5$ or 1.6, a gradual decrease toward greater $1/\lambda$ value and a sharp drop toward smaller $1/\lambda$. Nearly half of the stars show this same general shape although some may have the maximum apparently shifted, in most cases towards larger value of $1/\lambda$.

HD 37041 is peculiar. The maximum of the amount of polarization occurs near $1/\lambda=1.2$. In addition to HD 37041, HD 37202 also shows an abnormally large decrease towards the ultraviolet. A few stars show an abnormally large decrease toward the infrared; HD 206936 is noteworthy in this respect.

Some of the stars of Table X show a rise to a *second* maximum near the limits of the observed wavelength range. For example, such a secondary rise occurs in the ultraviolet for HD 22253, and in the infrared for HD 37202. HD 6675 has little wavelength dependence of polarization.

An intercomparison of Tables IX and X is now made. In the case of HD 2905, the maximum in percentage polarization coincides with the mean value of the position angle. In other cases, such as HD 206936, the percentage polarization maximum coincides with the maximum value of the position angle. For HD 206936 the abnormally low value of percent polarization at $1/\lambda=1.05$ corresponds to a large difference of

TABLE VII. Our percentage polarization minus that of other observers.

HD	Hall 1949–54	Hiltner 1949–54	Behr 1956–58	Serkowski 1960–65
147165	+0.06	···	+0.08	+0.16
161056	(−1.09;)	···	···	+0.09
154445	+0.10;	···	···	−0.04
134335	···	···	+0.07	···
134320	···	···	+0.04	···
187929	···	···	−0.05	···
183143	(−0.91)	+0.09;	+0.03	+0.04
193443	+0.50:	+0.13	···	···
198478	−0.45	+0.08	−0.08	+0.10
206936	···	(+0.67)	···	(+2.01)
207538	+0.02	0.00	···	···
207260	−0.10	−0.10	···	−0.05
217476	−0.14	−0.31	···	−0.21
218342	+0.36	+0.25	···	···
224014	−0.09	+0.01	+0.08	+0.01
2905	−0.12	+0.04	+0.17	···
6675	−0.08	0.00	···	···
7927	+0.14	−0.08	+0.15	+0.08
12301	−0.09	+0.45	−0.12	−0.03
12953	−0.10	+0.07	···	−0.07
14489	+0.05	−0.16	···	···
18326	+0.57	−0.19	···	···
21291	+0.11	+0.03	+0.07	+0.07
21389	−0.21	+0.27:	(+0.48)	+0.20
30614	+0.10	···	···	···
22252	+0.01	−0.15:	···	···
25291	···	···	+0.11	···
24431	−0.43	+0.25	···	···
24398	+0.14	−0.14	+0.02	···
31964	···	···	+0.07	−0.08
36371	−0.44	···	+0.16	+0.08
37202	+0.19	···	···	···
41117	−0.18	···	(+0.62)	+0.21
42379	−0.60;	+0.16:	···	···
43753	+0.43	+0.08	···	···
37041	−0.11	···	···	···
Syst. Diff.	−0.01	+0.04	+0.05	+0.04
Mean Res.	0.21	0.14	0.09	0.09

TABLE VIII. Our position angle minus that of other observers

HD	Hall 1949–54	Hiltner 1949–54	Behr 1956–58	Serkowski 1960–65
147165	+ 3°	···	0°	− 1:°
161056	0;	···	···	− 6
154445	− 2;	···	···	− 2
134335	···	···	−4	···
134320	···	···	−4	···
187929	···	···	−4	···
183143	+ 2	+2°;	+3	+ 2
193443	−10	−4	···	···
198478	− 3	−3	0	− 2
206936	···	(−7)	···	(+17:)
207538	− 1	−2	···	···
207260	+ 6	−5	···	− 4
217476	− 3;	+1	···	− 1
218342	− 4	−4	···	···
224014	+ 5:	+3:	−1	− 1
2905	+ 2	0	−2	···
6675	− 4	+7	···	···
7927	− 1;	+1	0	+ 1
12301	+ 1	+2	+2	+ 2
12953	+ 2	+2	···	+ 1
14489	− 3	0	···	···
18326	0	−2	···	···
21291	0	−1	0	− 3
21389	− 2	0	+1	+ 1
30614	− 2	···	···	···
22253	0	−5	···	···
25291	···	···	+2	···
24431	− 2	−5	···	···
24398	+10	−1	−1	···
31964	···	···	+1	+ 1
36371	− 4:	···	−1	0
37202	+ 5	···	···	···
41117	− 4	···	−2	0
42379	− 8;	−1:	···	···
43753	+ 7	+5	···	···
37041	− 2:	···	···	···
Syst. Diff.	− 0.4	−0.5	−0.6	− 0.8
Mean Res.	3.3	2.5	1.6	1.8

TABLE IX. Residuals of position angles.

HD[a]	Observed minus average for each star, at $1/\lambda =$ 1.05	1.19	1.39	1.95	2.33	2.79	3.04
147165!	− 2°:	− 8°:	− 2°	0:°	+ 1°	+ 6°:	+ 2°
161056	+ 2	···	− 1;	0	− 4;	+ 2	− 3;
154445	+ 1	···	− 2;	+1	− 2;	+ 1	− 1;
134335	− 8:	+10:	− 9:	+5:	+ 1	···	···
134320	−11:	0:	+ 7:	0	+ 2	···	···
187929	0	− 1	− 1	−3	+ 5	···	···
183143	0;	···	− 1	+1;	+ 1	0:	0:
193443*	−24:	0:	+13	−6	−15	+16	+ 6:
198478	0:	− 1;	+ 1:	0	− 1	− 1	+ 4:
206936!	− 4	− 4	− 2	+4	+ 5	···	···
207538*!	− 8	− 2	0:	+2	+ 2	− 1	+ 6
207260	+ 3:	− 2:	+ 3:	−1	− 1	0:	+ 6
217476	− 1	− 1	− 1	0	0;	+ 5:	0
218342*	+ 6:	+ 1	− 2	−1	− 1	− 5	+12:
224014	− 1:	− 1	+ 1	0:	+ 2:	0:	···
2905!	− 5	− 3	− 4:	−1	+ 1	+ 2	+ 8
6675*	−13	+ 2	+ 4	+7	− 2	− 7	+ 7
7927!	− 3	− 2	− 2	0	+ 2;	+ 1	+ 5
12301!	− 3	− 2	− 2	+1	+ 1	+ 2	+ 3
12953!	− 6	− 2	− 2	+1	+ 2	+ 3	+ 4
14489!	− 6:	− 2	− 4	0	+ 1	+ 1:	+ 7
18326*	+ 2	− 7	+ 4:	−1	+ 3	0	+ 3
21291	+ 1	0	+ 1	0	− 1	0	0:
21389!	− 2	− 1	− 1	0	+ 1	+ 1	+ 2
30614!	− 3	− 1	0	+1	+ 2	+ 1:	+ 1
22253*!	+ 6	+ 7	+ 6	0	0	− 9	−10
25291	0	+ 1:	0	0	0	− 2	+ 1
24431*!	+ 7	+ 3	+ 2	−5	+ 1	− 1	− 8
24398	0	− 4	0	0	0	+ 1:	+ 7:
31964	− 1	0	0	+1	− 1	− 1	+ 1
36371!	+ 4;	+ 2;	+ 4	+2:	+ 1:	− 3	− 5
37202!	+ 4;	+ 4	+ 7	−1	+ 1	− 4	− 9
41117!	+ 4	+ 2;	+ 4;	−1	− 3	− 1:	− 3:
42379	− 1	+ 2;	+10;	−2:	− 3;	− 1	− 3;
43753*	+11:	− 1	−15:	+1	+ 3	+ 1	− 4
37041	− 3:	+ 5:	−10:	+6	+ 1:	− 3:	···

[a] The stars with exclamation mark (!) show appreciable wavelength dependence of the position angles. The stars marked with an asterisk (*) have low precision in position angle.

position angle. The same is true for HD 37202 in $1/\lambda = 3.04$. For HD 22253, abnormally large values of percent polarization at $1/\lambda = 2.79$ and 3.04 correspond to large differences in position angle. Improved precision may be necessary to substantiate these conclusions.

5. *Interpretations*

For a constant value of the refractive index we tend to see at shorter wavelengths the effects of clouds with smaller mean particle sizes and at longer wavelengths clouds with larger mean particle sizes. If the difference in the mean particle sizes for two clouds is sufficiently great, we may expect to see two maxima in the $P(\lambda)$ curve, indicating the superposition of two distinct $P(\lambda)$ curves, each characteristic of a given mean particle size (various characteristic curves are shown in Paper VI). If, in addition, the particle alignment in the two clouds is different, we should expect to find a dependence of the polarization position angle θ with wavelength λ, since the relative contribution to the polarization from each cloud will vary with wavelength.

Variations of position angle with wavelength might be explained by assuming that the starlight traverses two or more discrete clouds of interstellar particles in which the characteristics and the alignments of the particles differ. The illuminating star must be far away enough so that the light traverses at least two different particle clouds and at least two different orientations of the galactic magnetic field.

It is, however, not established observationally that the stars with rotation are always at great distances. For instance nearby σ Scorpionis may show some rotation. Another puzzle is in the systematic trends of rotation (Table IX), with one direction at longitudes smaller than 144° and the opposite direction at greater longitudes. Longitude 144° is probably the direction perpendicular to the local spiral arm. Some effect alike

TABLE X. Normalized polarizations.

HD	Normalized percentage polarization at $1/\lambda =$ 1.05	1.19	1.39	1.95	2.33	2.79	3.04
147165	70	75	99:	105	95	83	86
161056	72	···	105;	101	99;	74	76;
154445	74	···	106;	104	96;	81	73;
134335	57	90	85:	85	115	162	100
134320	101:	69	72	104	96:	84:	···
187929	74	90	104	95	105	···	···
183143	72;	···	102	103;	97	88:	73:
193443	87:	58:	113:	96	104:	97:	73:
198478	70	66;	88:	104	96	84	86
206936	36	47	66	97	103	···	···
207538	69:	73	88	97	103	97:	79:
207260	68	73	82	101	99	94:	69
217476	75:	84:	96:	102	98;	96	110:
218342	92:	87	103	106	94	101	104:
224014	77	86	100	105	95	82	86:
2905	76	76	94	104	96	85	90
6675	95	94	109	107	93	93	112
7927	68	74	89	100	100	87	87
12301	73	86	87	101	99	93	78
12953	57	78	86	101	99	94	85
14489	70	75	87	102	98	99	91:
18326	81	81	126:	98	102	94	100
21291	69	79	91	101	99	89:	80
21389	68	75	87	102:	98	92	86
30614	50:	63	80	102	98	94	84:
22253	83	83	91	103:	97	108	102
25291	72	76	82	101	99	102	95
24431	78	80	67	107	93	106:	95
24398	81	85	98	104	96	76:	58
31964	72	79	91	101	99	99	87:
36371	70;	78;	86:	102	98	83	81
37202	92	82	81	98	102	68	45
41117	69	80;	88;	101	99	86	87
42379	66	72;	92;	102:	98;	104	85;
43753	81:	98	105:	104	96	85	93
37041	126	130	126	120	80	54	46

TABLE XI. Ratio of polarization to total absorption, of visual to infrared, and of visual to ultraviolet polarizations. Approximate particle sizes.

HD	$\frac{p_{vis}}{RE_{B-V}}$	$\frac{P_{vis}}{P_{ir}}$	$\frac{P_{vis}}{P_{uv}}$	Particle diameters (μ)		
147165	0.024	1.38	1.18	···	0.3	0.2
	±.006	±.03	±.03		±.1	
161056	.041:	1.42:	1.35	···	.3	···
154445	.043:	1.39:	1.33	···	.3	···
134335	···	1.32:	0.74:	···	.2	.17
134320	···	1.05:	1.07:	···	.2	···
187929	.074:	1.24	···	···	.3	.2
183143	.027	1.40:	1.24	···	.3	···
193443	.015	1.41	1.20	···	.3	···
198478	.027	1.44	1.15	···	.2	···
206936	.016	2.13	···	···	···	···
207538	.016	1.35	1.09	···	.3	.2
207260	.015	1.34	1.16	···	.3	···
217476	.013	1.25	0.97	···	.3	.17
218342	.012	1.13	0.98	···	.3	.17
224014	.010:	1.23	1.19	···	.3	···
2905	.016	1.30	1.12	···	.3	.2
6675	.011	1.09	1.01	1.1	.3	.17
7927	.026	1.36	1.11	···	.3	.2
12301	.025	1.21	1.12	···	.3	.2
12953	.021	1.41	1.06	···	.3	.2
14489	.023	1.32	1.01	···	.3	.2
18326	.017	1.29	1.09	···	.3	.17
21291	.029	1.32	1.14	···	.3	···
21389	.023	1.32	1.06	···	.3	.2
30614	.018:	1.66	1.06	···	.2	.17
22253	.009	1.15	0.91	1.1?	.3	.17
25291	.024	1.28	0.95	···	.2	.17
24431	.009	1.12	0.89	···	.3	.17
24398	.012	1.20	1.48	···	.3	.2
31964	.020:	1.28	1.05	···	.2	···
36371	.017	1.32	1.18	···	.3	.2
37202	.101:	1.08	1.66	1.1	.3	···
41117	.022	1.31	1.13	···	.3	.2
42379	.018	1.41	1.03	···	.3	.17
43753	.017	1.13	1.14	···	.3	0.17
37041	0.017:	0.85	2.19	···	0.4	···

a Faraday rotation may play a role. Faraday rotation itself has been estimated by Greenstein (1960) to be completely negligible in optical measurements of interstellar polarization. Additional observations, with high precision in θ and distance, and a detailed study of the $\theta(\lambda)$ rotation appear in order.

Systematic trends of $P(\lambda)$ with galactic longitude are predicted by Greenberg and Shah (1966). For refractive index $m=1.33$ they studied the effects of aspect for fast spinning cylinders. When the spin is seen edge-on the computed polarization—wavelength dependence is steep. When the spin is seen nearly pole-on, the polarization-wavelength curve is considerably flattened, especially at shorter wavelengths.

Table XI lists the ratio of polarization versus total extinction p_{vis}/RE_{B-V} based on the values given in Table VI ($p_{vis}=P_{vis}/46$). Also listed are the ratios of visual versus infrared polarizations and visual versus ultraviolet polarizations. The infrared polarization P_{ir} is the straight mean of the percentage polarization (Table IV) at $1/\lambda=1.05$ and 1.19; the ultraviolet polarization, P_{uv}, at $1/\lambda=2.79$ and 3.04. The estimated probable errors are in the second line. Colons are used when a blank occurs in Table IV or when the ratio appears poorly established because of colons or large differences in Table IV.

The polarization versus total-extinction ratio may be an indicator of alignment because the polarization is maximum when the particle spin is seen edge-on, and zero when the spin is seen pole-on, both for about the same amount of extinction. There is no obvious correlation of either Table IX (residuals of position angles) or Table X (normalized polarizations) with the p_{vis}/RE_{B-V} values of Table XI. Stars which show a significant dependence of the polarization position angle on wavelength have both large and small values of p_{vis}/RE_{B-V}. Stars with values of $p_{vis}/RE_{B-V}\geq 0.020$ show characteristic polarization curves with one or two maxima. Stars with $p_{vis}/RE_{B-V}\leq 0.013$ also show characteristic polarization curves with one or two maxima.

As the flattening predicted by Greenberg and Shah (1966) is primarily in the ultraviolet, we should look primarily at the fourth column of Table XI. No correlation with galactic longitude or with p_{vis}/RE_{B-V} can be seen. Instead, the ratios vary in an irregular fashion from star to star, also in P_{vis}/P_{ir}. From star to star the ratios may change by more than three times their probable error.

A selection effect must be kept in mind as we have always chosen the most strongly polarized stars for the observing program. With a greater number of stars observed, it may be possible to find flattening superposed on the scatter. In the meantime, the scatter is explained by transverse of the starlight through various clouds having various particle sizes and field orientations.

In the last three columns of Table XI an estimate is made of the particle sizes that may predominate the polarization of various clouds. Five steps, (1)–(5), underlie this first approximation.

(1) While we realize that the interstellar particles may be composite and irregular in shape, it is assumed here that they are homogeneous and that all grains have the same index of refraction, $m=1.3-\epsilon i$, where ϵ is small. The shape is assumed to be that of long cylinders. Therefore, the only variables remaining are the size and size distribution.

(2) Each traversed interstellar cloud is assumed to have a *narrow* distribution of sizes about a mean diameter $2a$.

(3) Each mean diameter gives a characteristic shape of polarization versus $1/\lambda$, as follows: a well-defined maximum at $(1/\lambda)_0$, a steep decrease toward longer

wavelengths, and a gradual decline toward shorter wavelengths. The *characteristic curve* is seen in the calculations (Figs. 2–6 of Paper II; Paper VI) as well as in the observations (e.g. HD 21291 in Table X).

(4) Where there is an appreciable wavelength dependence in the position angles, the light apparently traverses at least *two* interstellar clouds having different particle size as well as different orientation of the magnetic field. For example, the wavelength dependence of HD 36371 would be interpreted with at least two particle sizes, even though our curve has only a single maximum. (With several narrow filters one could perhaps detect greater detail.)

(5) From the apparent maxima of each star in Table X, values of the above defined $(1/\lambda)_0$ are estimated. Particle diameters $2a$ are computed from

$$2\pi a(1/\lambda)_0(m-1)=C, \qquad (1)$$

where C is a constant (see Fig. 67 of van de Hulst 1957). From the figures of Paper II it is found that $C\simeq0.4$. With the above assumption of refractive index m, expression (1) reduces to a simple relation between $(1/\lambda)_0$ and the diameter. For example, the light from HD 36371 may be traversing a cloud with $(1/\lambda)_0 \simeq1.4\mu^{-1}$ and one with $2.0\mu^{-1}$, and the particle diameters are $2a\simeq0.3\ \mu$ and $0.2\ \mu$, listed in Table XI.

A few stars show an excess of polarization at filters $1/\lambda=1.05$ and 1.19, for example HD 37202; others show an excess at $1/\lambda=2.79$ and 3.04, for example HD 217476. We need far-infrared and far-ultraviolet polarimetry to study these. In the meantime an estimate of $2a$ is made as follows. In visual light the polarization of HD 37202 shows a characteristic curve for $2a\simeq0.3\ \mu$. But a rise—over and above that characteristic curve—becomes noticeable certainly for filter 1.05, and perhaps already for filter 1.19. The rise is explained as the short-wavelength "tail" of another characteristic curve but in the far-infrared, belonging to a large particle. The short-wavelength tail of the characteristic curve for $2a\simeq0.3\ \mu$ would become noticeable at $1/\lambda\simeq4.5$. The ratio 4.5/1.19, referring to expression (1), gives the ratio of $2a/0.3$; the $1.1\ \mu$ diameter for HD 37202 in Table XI is thus estimated.

Incidentally, μ Cephei shows an exceptionally steep shape of $P(\lambda)$. Furthermore, the amount of polarization appears to be variable with time (Sec. III), and the star should, therefore, not be considered in a general discussion of interstellar particles. It is also noted that μ Cephei shows rotation of the plane of polarization. This case certainly merits a special study.

If the difference of HD 134335 and 134320 is real, it would be amazing. These two stars in the north galactic spur are close together and yet their observed polarization dispersions differ appreciably. However, the amounts of polarization are small and the apparent difference may, therefore, be due to errors of observation.

The particle diameters in Table XI should not be taken too seriously. They are intended merely as an indication of how the variations in the $P(\lambda)$ curves for different stars may be interpreted in terms of the traverse of discrete clouds with different particle characteristics. It must be recalled that we have not taken into account the variation of shape nor of refractive index nor variations in the distribution of particle sizes for different clouds.

Greenberg and Shah (1966) compute for a distribution of particle sizes and orientations and for $m=1.33$ a $P(\lambda)$ curve that is similar to that for HD 21291. The maximum in their curve occurs near $2\pi a/\lambda=2.4$ while the observed maximum for HD 21291 occurs near $1/\lambda=1.7\ \mu^{-1}$, and the resulting grain size is $2a=0.45\ \mu$. Compared to our value of $2a=0.3$ in Table XI, it may be an indication of the effects of distributions that should be taken into account in closer approximations.

From the present first approximation, we draw the following conclusions:

(1) The wavelength dependence of the position angles, and the variations in the wavelength dependence of the percentage polarization from star to star, indicate that various interstellar clouds have various grain characteristics.

(2) The increase in polarization observed with our extreme infrared filters moreover indicates that some interstellar clouds have large particles. Incidentally, the Orion region is exceptional (HD 37041) with larger particles than usual, predominant even in the visual range.

(3) The increase in polarization observed with our ultraviolet filters indicates that some interstellar clouds have small particles.

The dispersion of interstellar polarization is nonuniform. This conclusion is similar to the one made in photometry where it has become clear (Johnson and Borgman 1963) that there is no uniform law of interstellar reddening.

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