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Interstellar Polarization in the Immediate Solar Neighbourhood*

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Summary. About 180 stars within 35 pc have been observed for interstellar linear polarization with a precision of about 7 10^{-5} (degree of polarization). The results, combined with those of Piirola (1977), establish the following points:

Section 5a: Within 35 pc of the Sun the dust content is very low indeed: visual extinction over 35 pc is $A_v = 0.002$ mag *or less*.

Section 5b: The polarizations are inconsistent with a uniform magnetic field throughout the 35-pc sphere observed.

Section 5c: There is evidence for a region with a very regular field, near $l=0°$, $b=-20°$. Its distance is less than 20 pc, its angular extent 30°–60°.

Section 5d: Six stars in the sample are *not* suitable for use as zero-polarization standards.

Section 5e: Stars of spectral type F 0 and later are suspected of intrinsic linear polarization at the 10^{-4} level. This polarization seems to be variable in time.

Key words: interstellar dust – magnetic field (interstellar) – linear polarization

1. Introduction

One of the ways of investigating the structure of the interstellar magnetic field is to measure the linear polarization of starlight. Necessary conditions are that the distance of the stars in the sample are known well enough and that the polarimetry is sufficiently accurate. The large-scale features of the local galactic field have been studied in this way, using photometric stellar distances (e.g. Behr, 1959; Mathewson and Ford, 1970), and in some cases a projection of the field structure has been studied, using stellar clusters as background sources. Small-scale (≈10 pc) three-dimensional structure has so far not been studied extensively (but see Appenzeller, 1966, 1974), since the necessary conditions mentioned cannot generally be met simultaneously. This situation will change dramatically when the data from the planned HIPPARCOS satellite become available, but at present the only volume of space that might be suitable for such a study is the solar neighbourhood, out to the limit of earthbased trigonometric parallaxes. The question is: can we measure the very low polarizations expected for these stars? The present paper is a report on a (partially successful) attempt to do this.

* Based partly on observations collected at the European Southern Observatory, La Silla, Chile

The investigation had another, more technical, aim, viz. to provide a greater selection of near-zero-polarization stars to use as standards in polarimetry. A few such stars have been sufficiently well observed with the rotatable telescopes (see Serkowski, 1974, for a list), but more of them would be welcome, particularly if they are evenly spread over the sky and cover a range in brightness. This aspect of the investigation has already been reported on (Tinbergen, 1979)

The chosen limit for "reliable" trigonometric parallaxes was 0".03, 2 or 3 times the mean error for the parallaxes quoted in the Bright Star Catalogue (see Nørgaard-Nielsen, 1977). If one 'interpolates to zero' Behr's (1959) polarimetric results for distances of 100 pc and more (where the polarizations are large enough to be readily observable), one expects at least some stars at 35 pc to show a degree of polarization of 5 10^{-4}. I had good reason to think that I could keep systematic errors down to 10^{-4} (Tinbergen, 1973); to push photon noise down to the same level, the programme was limited to stars brighter than magnitude 5 and the bandwidth used was of the order of 100 nm (one needs 10^5 times as many photons as for photometry to an accuracy of 0.01 mag). Since interstellar polarization extends smoothly over a broad wavelength range, and we have to content ourselves in this case with a very rough measurement of it, there is no objection to such a wide band; in fact, I used 2 bands and combined the results for greater weight. After rejecting stars with 'peculiar' spectral type or known emission (to avoid intrinsic polarization as far as possible) and double stars with companions near the diaphragm edge, I was left with about 180 stars, all in the Yale Bright Star Catalogue (Hoffleit, 1964).

Since these stars are spread all over the sky, I needed two observing periods each in the Northern and in the Southern hemisphere. I used three F/15 Cassegrain telescopes, the 30-cm in Leiden, the ESO 50-cm on La Silla, Chile, and the 36-inch at the Leiden Southern Station (at that time near Hartebeespoortdam, S. Africa). I shall describe rather extensively the details of observation and reduction. The reason for this is that we are looking for a meaningful pattern in the distribution over the sky of very weak polarizations. We must avoid imposing a spurious pattern and therefore must be especially careful in merging the data from the three telescopes into one survey.

The polarimeter is similar to the prototype I have described before (Tinbergen, 1973). The main difference is that it allows observations in 3 spectral ranges simultaneously (Fig. 1). To check on instrumental constancy, certain bright standard stars were observed every night, both directly and with a 6% calibration polarizer in the beam. Longer runs on a few stars were done on a number of nights to search for change of instrumental polarization

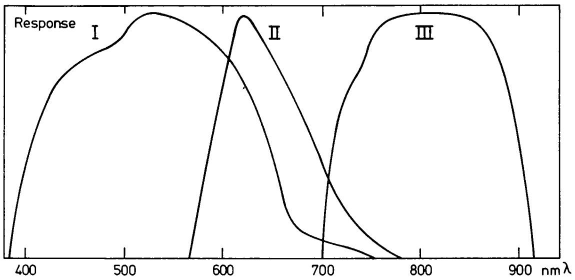

Fig. 1. The passbands. The ordinate has simply been labeled "response", to indicate that the whole concept of passband shape is vague when the bands are as broad as the present ones. The effective system passband depends on the spectrum of the star being observed. This does not matter in the present investigation, as explained in the text. The "response" shown is in fact photocathode sensitivity, as modified by filters, and normalised separately for each band

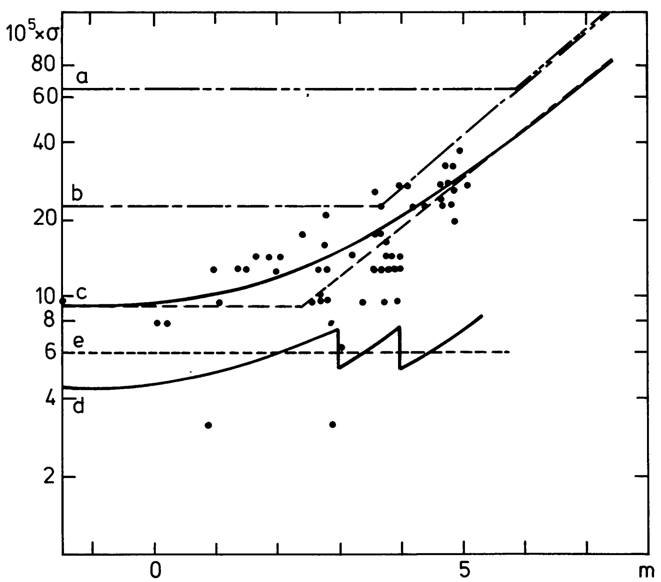

Fig. 2. Random noise as a function of stellar magnitude for the observations with the ESO 50-cm telescope on La Silla. Horizontal part of each curve: scintillation-limited; sloping part: photon-limited; for curve *c*, the quadratic sum is also shown. *a* Estimated for a DC single-channel polarimeter, based on $m=6$ as break-even point (Serkowski, 1974, p. 387, corrected for polarimeter transmission of 40 %). The other curves are all for 100 Hz modulation: *b* channel I only (reconstructed from *a* and *c*); *c* average of channels I and II (single observations, a best fit to the experimental points shown); *d* survey data, averages of 4 nights' observations, integration times doubled for $m>3$ and again for $m>4$; *e* nominal survey accuracy (Table 1)

with telescope position; none was found. To make the material homogeneous as far as photon noise is concerned, integration times were adjusted to the size of the telescope and the brightness of the star. However, a minimum of 1 min was adhered to, even for the brightest stars, so that remaining scintillation noise for these would never exceed the photon noise for the faintest stars in the sample. An observation consisted of 4 integrations, at 45° intervals in the orientation of the first quarter-wave plate, followed by either 4 sky integrations, or one dark current, depending on the relative brightness of star and sky and on sky polarization. Such an observation yields the *Q* and *U* Stokes parameters, in a degree-of-polarization scale (Tinbergen, 1973). Polarization angle was calibrated by observing standard stars from Serkowski (1974), Behr (1959), Appenzeller (1966), Matthewson and Ford (1970), and Schröder (1976). Calibration of the degree of polarization was by reference to an HN22 polaroid in the green and by using the theoretical wavelength-dependence of the 6 % polarizer, which consists of two oppositely inclined plates of fused silica, to transfer the calibration to other wavelengths. Angle and degree of polarization are thus calibrated more than adequately. The only points that needed special attention were noise and instrumental zero point; these are treated in Sects. 2 and 3 respectively. Each star was observed on at least 4 nights, as far as possible at different hour angles. Some stars were observed from more than one station.

The general course of the reduction was as follows: certain of the nearest stars in the sample, of various spectral types, were assumed, until proved otherwise, to be essentially unpolarized (some in fact have been *proved* to be so by the rotatable telescopes). These defined the intrumental polarization, which was then subtracted from all observations. The rotation to the equatorial reference frame was performed next, followed by averaging of the results for each star, separately for each telescope. The results in the overlap regions and for the stars assumed to be unpolarized then give the final estimate for the consistency of the whole procedure, as opposed to the possibly flattering *internal* agreement per star.

All results are presented in terms of the normalized Stokes parameters *Q* and *U*, which have the dimension of degree of polarization. Section 4 contains the catalogue, from which measurements of low weight have been deleted. Section 5 presents the astronomical conclusions which I feel justified in drawing; the general reader may proceed to that section immediately.

2. Noise

Three kinds of noise are of importance in this investigation: photon noise, scintillation noise, and noise from instability of the equipment.

Photon noise can be estimated from the bandwidth, telescope aperture, total quantum efficiency etc., as in photometry. One should, however, remember that linear polarization is characterized by two Stokes parameters, each of which is again the difference of two intensities. These intensities must each be measured with $\sqrt{2}$ greater accuracy than the final result and the total integration time required is therefore 8 times that for photometry of the same accuracy.

Scintillation noise dominates for the brighter stars. It is reduced by the 100 Hz modulation employed in the Leiden polarimeter. The scintillation noise in a single channel was found to be equal to the photon noise roughly at magnitude 3.7 with the 50-cm ESO telescope (Fig. 2). Serkowski (1974) gives (p. 387) 7[th] magnitude as the break-even point for a single-detector DC parameter and a 40-cm telescope. This difference in break-even point, corrected for polarimeter transmission, corresponds to a reduction factor for scintillation noise of nearly 3, which agrees with a prediction by Young (unpublished, quoted by Serkowski, 1974, p. 391). Further reduction by a factor 2.5 was achieved by combining the results for channels I and II, which use oppositely polarised beams (polari-

Table 1. Unweighted average internal r.m.s. errors of the mean Stokes parameters as listed in the catalogue, according to station and channel (average for Q and U; units: 10^{-5})

Channel	Station LaSilla	Hartebeespoortdam	Leiden
(I+II)/2	6	6	9
I	8	7	12
II	12	11	17
III	24	25	54

Table 2. Nearby stars used for determination of instrumental polarization

Star	HR	Distance (pc)	Leiden	La Silla	Hartebees-poortdam
β Cas	21	14	×		
α Eri	472	33			×
α Aur	1708	14	×		
α CMa	2491	3	(×)	×	
α CMi	2943	3	(×)	×	
α Leo	3982	26	×	×	
α UMa	4301	22	(×)		
a Boo	5340	11	×	×	×
α Cen	5459/60	1		×	×
36 Oph	6401/2	5			×
α Lyr	7001	8	×		
α Aql	7557	5			×
ε Cyg	7949	23			×
ι Peg	8430	14			×
α PsA	8728	7			×

zation modulation in antiphase, scintillation in-phase). This worked well, even though the passbands were centred on different wavelenghts.[1] Figure 2 is a schematic illustration of these considerations for the ESO telescope.

Noise from instability of the equipment was mostly absent. During 1975 in Leiden, however, an electronic instability was present in channel II, which made it necessary to discard results in that channel for most of the year. It is unfortunate that I did not detect this until after the programme was complete; it is a consequence of working below the noise for single observations and (at that time) without on-line reduction.

To keep the noise in the survey results as homogeneous as possible, the integration time and number of observations were increased whenever the observations were expected to be severely photon-limited. For the Southern part of the survey this worked very well; for the Leiden results, the scatter is larger than I had expected. I can only attribute this to the much worse observing conditions (city lights, seeing, clouds). The final average internal r.m.s. errors for each station are listed in Table 1. In Sect. 3a, the conclusion is reached that for the Southern part of the survey these internal errors are consistent with the external errors found, but that for the Leiden results the real external errors may be larger.

1 The total reduction is a factor 7, which could also have been obtained from a classical Wollaston polarimeter (Serkowski, 1974, p. 388). The only way to obtain a large improvement at the same telescope would be to increase the modulation frequency considerably, as has been done by Kemp (1969), Angel and Landstreet (1970) and others

Table 3. Consistency of the results from the 3 observing stations; average of channels I and II. The unit for Q and U is 10^{-5} (degree of polarization). The following quantities are listed: Δ_Q, Δ_U: the differences between the Q and U values obtained at the two stations, averaged over the overlap stars. $(\mathrm{r.m.s.})_Q, (\mathrm{r.m.s.})_U$: the r.m.s. deviations, in Q and U, from these average differences. Σ: the quadratic sum of the internal r.m.s. errors derived for each station separately (average for Q and U). If all errors are internal, this quantity should be equal to those in the two rows above; see text for further comment. n: the number of stars involved in each comparison

	Leiden minus La Silla	Leiden minus Hartebees-poortdam	La Silla minus Hartebees-poortdam
Δ_Q	$-$ 5.6±3.1	+ 7.6±6.5	+ 0.2±2.7
Δ_U	+ 5.1±8.0	+ 7.3±4.7	$-$ 2.4±2.4
$(\mathrm{r.m.s.})_Q$	6.2	19.5	8.9
$(\mathrm{r.m.s.})_U$	15.9	14.0	7.9
Σ	10.8	11.4	8.5
n	4	9	11

3. Instrumental Polarization

In this section I shall conclude that the instrumental polarization has been eliminated to about 3 10^{-5} (Table 4; see also Fig. 1 of Tinbergen, 1979).

a) Determination

The instrumental polarization was determined by observing very nearby stars which were also bright enough for the observations not to be photon-limited. Table 2 shows the stars used at the 3 observing stations. The determinations were done separately for the 3 stations, but on the same principle: the average for these bright stars should be zero. Since the samples are different, the results need not be identical, if one or more of the stars happen to be noticeably polarized. A number of programme stars have been observed from more than one station, so that the mutual consistency of the adopted systems may be tested. Table 3 gives the results of these comparisons. We may draw the following conclusions from this table:

1. the instrumental polarization has been eliminated in a consistent way, at least to a level of 10^{-4} in degree of polarization (5 10^{-5} for the Southern part: 95% confidence statements). The possibility of undiscovered systematic polarization for the whole sky remains, and should be tested by comparison with rotatable-telescope results.

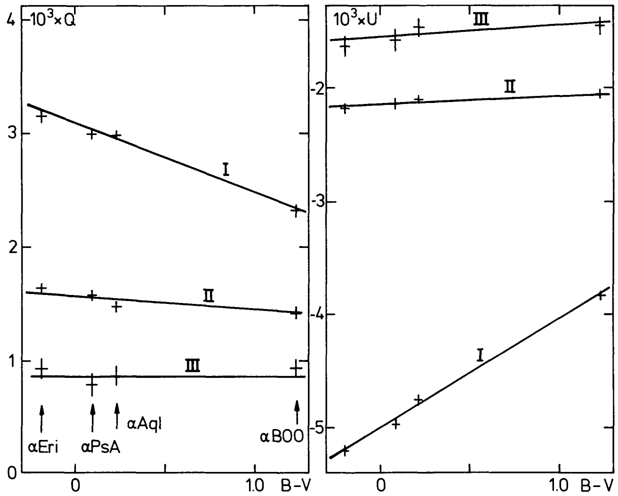

Fig. 3. Instrumental polarization at Hartebeespoortdam, as a function of $B-V$, for each of the three channels. Though the effect is large, it is stable and well-determined. 1σ errors of the observations are indicated. Lower-weight observations of other stars have also been used in deriving the straight lines, which represent the adopted corrections

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2. the r.m.s. scatter of the difference between 2 stations is almost entirely accounted for by the measured internal errors for each station. Undiscovered errors which are systematic per station per star, but vary from star to star for one station or vice versa, would show up in this test. In the results for Hartebeespoortdam and La Silla, there are no such errors. For Leiden, it would seem that the real error level could be as high as 14 10^{-5} rather than the 9 10^{-5} quoted in Table 1 as "internal per star". Comparison with Piirola's (1977) results, however, indicates that 10 10^{-5} is the correct figure (Sect. 3b). The possibility of an error systematic per star for all stations remains, but is unlikely, due to the different orientations of the polarimeter with respect to the sky. *A conservative conclusion is therefore that the Southern part of the survey (results from Hartebeespoortdam and La Silla, for a total of 145 stars) is internally consistent to 5 10^{-5}, the total survey to 15 10^{-5}.* Since the differences between stations are statistically not very significant, the 3 sets of results have been combined without further corrections.

Since the instrumental polarization in Hartebeespoortdam was both strong and wavelength-dependent, I shall describe its elimination in more detail than given above.

Observations in 8 narrower bands (50 nm) show that the instrumental degree of polarization varied from 0.002 at 820 nm to 0.013 at 420 nm, the polarization angle being almost constant. The mirror coatings were 20 years old and the mirrors were covered with mineral dust at the time of my observations. However, I was not in a position to do anything about it and proceeded with the survey, since the instrumental polarization seemed to be systematic and constant to a sufficient degree.[2] As the final accuracy I wished to obtain was about 1% of the instrumental polarization, I have depended on 1% stability of the, partly analogue, electronic system. The results show that it performed adequately, to say the least.

Since all the programme stars are in the Bright Star Catalogue (Hoffleit, 1964), it was possible to use $B-V$ as a measure of the colour of the star (*MK* type converted into $B-V$ in rare cases; the stars are unreddened). Figure 3 shows the observations of the nearby calibration stars in the 3 channels, plotted against the $B-V$ of the star. The adopted relations for correction of all observations are also shown. The results are acceptable for 2 reasons:

a) in the Q, U diagram, the cluster of points representing stars observed in Hartebeespoortdam does not show any elongation in the direction of the intsrumental polarization that was eliminated.

b) the results for overlap stars do not indicate any residual error for Hartebeespoortdam.

One final point should be mentioned. Since the instrumental polarization is a function of the colour of the star, it must also be a function of the zenith distance for each star separately. To test for this, α Boo (K2) and α Vir (B1) were observed alternately while they went through an extreme range of zenith distance. No effect could be found, i.e. any systematic variation with zenith distance was less than 5 10^{-5} and could be neglected.

b) Comparison with Other Observers

For comparison I have selected 2 Southern and 2 Northern surveys (Serkowski et al., 1970, Table 2; Schröder, 1976; Behr, 1959; Piirola, 1977), plus a mixed list recommended as standards (Serkowski, 1974). These are all expected to have a systematic error less than about 10^{-4}, though their random-error levels are different. Behr and Schröder used non-rotatable telescopes and equated the average of stars within 10 pc to zero. I followed a similar procedure, but some of my stars are at larger distances and the sample is different (Table 2). Serkowski, 1974 and Serkowski et al., 1970 list stars observed with rotatable-tube telescopes; these results also need not be entirely free of instrumental polarization, but they are independent of any assumptions about the nearby stars. Finally, Piirola forces the average of his entire survey to zero (stars at less than 25 pc). It is clear that the zero points of these various lists need not be identical. The passbands of all these polarimeters are different, but at such low levels of polarization this is of no importance.

The results of the comparisons are given in Table 4. We may conclude from this table that in 5 of the surveys (including the present one) the internal random errors have been correctly determined, but that Behr (1959) has underestimated his random errors (this is not a new fact, but I mention it since I want to use some of his results in my interpretation; see Sect. 5). We may also conclude that remaining instrumental polarization in any of the 6 surveys is indeed less than 10^{-4}, which is adequate for most purposes.

The comparison which has most statistical significance is that with Schröder (1976). It shows that our two surveys are not entirely consistent (a 99% confidence statement); the difference is about 5 10^{-5} in both Q and U. The results of 3 of the 4 other comparisons, though separately not very significant, support Schröder. For most purposes differences of this size are unimportant. However, if it should be desirable to improve on the remaining level of uncertainty, this could be done by using a strain-birefringence modulator and a rotatable halfwave plate in a polarimeter mounted on a rotatable-tube telescope. Such an instrument, if properly used, would be free of scintillation noise, telescope polarization, detector sensitivity to polarization, and effects due to flexure and magnetic fields. Of course, with an accuracy of about 10^{-5} on a 60-cm telescope and with the 100 nm bandwidth required by the modulator, one could only hope to reach magnitude 4 in reasonable observing time (3 h). Further improvement would require large telescopes, which for this purpose would need to have a mounting other than equatorial.

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2 After thorough cleaning later, the instrumental polarization had not changed. After recoating by ESO, it has virtually disappeared. Thus, reassuringly, the coatings were responsible and the assumption of constancy over a period of 2 months was a good one

Table 4. Consistency of the present survey with others. The unit for Q and U is 10^{-5} (degree of polarization). The following quantities are listed: $\bar{\Delta}_Q$, $\bar{\Delta}_U$: the differences, in Q and U, between the results in the two surveys, averaged over the overlap stars. $(\mathrm{r.m.s.})_Q$, $(\mathrm{r.m.s.})_U$: the r.m.s. deviations, in Q and U, from these average values. Σ: the quadratic sum of the internal errors of the two surveys involved (average for Q and U). If all errors are internal, this quantity should be equal to those in the two rows above; see text for further comment. Whenever the error varies from star to star in a survey, I have used the r.m.s. of the quoted internal errors for the actual sample of overlap stars. n: the number of star involved in each comparison

	Schröder minus Tinbergen	Serkowski minus Tinbergen	Serkowski et al. minus Tinbergen	Behr minus Tinbergen	Piirola minus Tinbergen (Leiden)	Piirola minus Tinbergen (Hart'dam and La Silla)
$\bar{\Delta}_Q$	$-\ 5.4\pm1.5$	$-\ 3.3\pm2.9$	$-\ 8.0\pm4.3$	$-\ 6.8\pm4.9$	$+\ 0.6\pm2.6$	$+\ 0.3\pm3.1$
$\bar{\Delta}_U$	$+\ 4.9\pm1.9$	$+\ 1.2\pm3.6$	$-\ 0.7\pm3.7$	$+\ 7.1\pm5.4$	$+\ 2.1\pm4.1$	$+\ 2.3\pm2.1$
$(\mathrm{r.m.s.})_Q$	7.5	11	17	39	10	15
$(\mathrm{r.m.s.})_U$	9.5	14	15	44	15	10
Σ	9	13	14	29	12	12
n	26	14	16	65	13	24

Piirola's survey (1977) covers the same region of sky as the Northern part of mine and forms a consistent set with the Southern part (Table 4). For use in Sect. 5, I have combined our two surveys, according to the following weights:

Tinbergen (Southern) : 3

Piirola : 2

Tinbergen (Northern) : 1

These weights are roughly inversely proportional to the internal mean square errors of the surveys. A list of these combined results has already been published for use as zero-polarization standards (Tinbergen, 1979). No correction has been made for the systematic error of about $3\ 10^{-5}$ which might still be present in 'Tinbergen + Piirola'.

4. Catalogue

The final results of the survey are given in Table 5. The following quantities are listed:

HD, HR – Star number in the Henry Draper and Yale Bright Star Catalogues.

STN – Observing station: L: Leiden, S: La Silla, H: Hartebeespoortdam. For the nominal errors for each station, see Table 1.

I, II, III, (I+II)/2 – Q, U for channels I, II, III and average of I and II [N.B. (i)]. The unit is 10^{-5} (degree of polarization). Q positive, U zero: electric vector North-South (equatorial system).

R – Remarks: 1. Parallax $>0\farcs030$, but star is not suitable for use as a zero-polarization standard; see Sect. 5d. 2. Used for determination of instrumental polarization (see Table 2). 3. High-polarization star, used for angle calibration. 4. Double star, both components within diaphragm.

N.B. (i) The value for (I+II)/2 is the average of those observations for which this combination could be made. Whenever I or II could not be used in one or more obsevations, the average of I and II in the catalogue need not be the same as the catalogue value of (I+II)/2.

(ii) Entries were omitted whenever the number of observations was less than three quarters of the number planned for a uniform noise level.

(iii) For the overlap stars, the result is given separately for each station.

5. Conclusions

In this section I shall use the combined results of Piirola (1977) and myself. See the end of Sect. 3 for details.

a) Variation of Average Polarization with Distance

The first (technical) conclusion one may draw from the results is that almost all stars closer than 30 pc can literally be used as sources of unpolarized light, down to a level of $2\ 10^{-4}$. Those stars in the survey that are *not* suitable for this have been identified in the remarks column of Table 5 and are listed in Sect. 5d. For use of the survey stars as low-polarization standards to about $5\ 10^{-5}$, see Tinbergen, 1979.

Next one may note that the polarizations within the first 35 pc are noticeably less than one would expect from those beyond 100 pc (Fig. 4 and Tables 6 and 7). This presumably indicates a lower dust content locally. Such an effect has been reported many times, but on this scale precision polarimetry is the only technique capable of giving direct proof. The results indicate that the extinction in the first 35 pc is of the order of $A_v = 0.002$ mag, which is even lower than obtained in previous (polarimetric) determi-

Table 5.

HD	HR	STN	I		II		III		(I+II)/2		R
432	21	L	1	19			0	1			2
496	25	H	14	-30	-7	17	-1	-9	3	-6	
693	33	H	-1	-11	22	-17	-20	-11	9	-14	
1581	77	H	14	-30	-12	3	-14	-6	1	-12	
2151	98	H	-3	-26	14	25	3	-15	6	0	
2261	99	H	4	-23	6	9	4	-25	6	-7	4
2262	100	H	-6	-28	0	12	-4	3	-3	-7	
4128	188	H	9	-12	1	0	1	1	4	-6	
5015	244	L	11	-3			-14	107			
5448	269	H	-20	36	14	-49	-19	-28	-3	-6	
5448	269	L	30	17	23	26	6	136	26	22	
6805	334	H	19	-19	9	9	-11	15	14	-4	
6860	337	H	-6	-1	-14	-19	-17	4	-11	-9	
6860	337	L	-14	-9	3	20	-6	-3	-4	6	
7570	370	H	14	-19	19	7	-17	7	15	-4	
7927	382	L	-3189	-306							3
8512	402	H	6	-25	-6	6	7	-14	0	-9	
9826	458	L	15	-1	0	30	31	58	9	4	
10144	472	H	-3	-3	4	0	7	4	1	-1	2
10307	483	L	22	-11							
11353	539	H	14	-15	17	3	11	4	15	-6	
11443	544	H	-19	26	0	-11	41	6	-9	7	
11443	544	L	17	-3	-23	-4	-1	31	-3	-3	
11636	553	H	0	25	11	-20	0	11	4	1	
12311	591	H	-7	-22	14	20	3	-23	3	-1	
12929	617	H	1	7	15	-31	-3	7	7	-11	
12929	617	L	-17	-22	20	20	9	-31	1	0	
13974	660	H	-14	9	3	-19	-25	-87	-6	-4	
13974	660	L	13	-11			49	-170			
16620	781	H	6	-6	19	-23	-4	-12	12	-14	4
17206	818	H	11	-20	14	9	1	-11	12	-4	
17573	838	L	9	11	-14	23			-1	17	
18978	919	H	4	0	14	-15	12	-17	9	-7	
19373	937	L	-1	1							
20630	996	H	-9	3	17	-22	3	4	3	-9	
20794	1008	H	0	-17	19	-9	-9	3	9	-14	
21291	1035	L	-1976	-2684			-1976	-2397			3
22001	1083	S	-7	0	0	-20	34	52	-3	-9	
22049	1084	H	26	-1	15	3	31	-17	22	0	
22484	1101	H	-3	-20	4	-9	12	19	0	-14	
23249	1136	H	9	-9	4	19	15	-23	6	4	
23754	1173	H	-4	-4	14	12	1	-23	4	3	
23817	1175	H	6	-11	28	31	19	-26	17	9	
23817	1175	S	3	6	4	-15	20	63	4	-4	
24398	1203	H	-696	1008	-662	983	-578	907	-678	995	3
26965	1325	S	-1	-6	-4	1	-7	6	-3	-3	
27290	1338	S	-9	-20	7	-19	31	9	0	-20	
28307	1411	H	14	14	4	-44	9	1	9	-15	
28527	1427	L	0	0			-223	-31			
29139	1457	L	3	3			1	-19			
29503	1481	H	-1	-14	15	0	4	-22	7	-7	4
29503	1481	S	-4	7	-3	0	-4	15	-4	4	4
30652	1543	L	6	-15			33	17			
32923	1656	L	-17	-9			-31	-280			4
33111	1666	H	1	9	14	-11	0	7	7	0	
33111	1666	S	6	9	22	-26	-12	63	14	-7	
33262	1674	S	-11	9	19	-1	22	58	3	3	
34029	1708	L	14	4	-25	-17	15	9	-1	-1	2
34411	1729	L	6	-11			-14	-84			
36079	1829	H	15	-4	-11	3	6	-11	1	0	
36079	1829	S	1	1	-3	-12	-34	20	-1	-6	
38393	1983	S	9	7	15	-25	25	33	12	-9	
38678	1998	S	-11	1	14	-1	-34	38	1	0	
39060	2020	S	-20	-3	3	-7	-58	68	-7	-6	
39425	2040	S	-7	39	19	-38	-3	61	4	1	
39587	2047	L	29	-3							
40136	2085	S	0	3	26	-23	-3	58	12	-11	
43834	2261	S	1	28	31	-19	-36	52	15	4	
47105	2421	S	26	-14	-44	12	39	-23	-9	-1	
47205	2429	S	-4	12	23	-15	-7	22	9	-1	
48737	2484	S	-9	-22	22	7	-15	-6	6	-7	
48915	2491	S	1	0	-1	-7	-3	7	0	-4	2
48915	2491	L	-17	0			-79	12			2
50241	2550	S	-1	12	-9	-23	25	39	-4	-4	
50310	2553	S	-17	41	30	-47	-1	76	6	-3	
52089	2618	S	6	11	4	-39	11	9	6	-14	4
58207	2821	L	23	4							
58946	2852	L	20	-4							
61421	2943	S	3	-4	0	-3	-6	-12	1	-4	2
62509	2990	S	1	-14	-3	-14	12	26	0	-14	
62644	2998	S	-4	31	3	-23	42	-1	0	3	
63032	3017	S	759	-766	734	-778	785	-746	746	-772	3
68456	3220	S	3	36	7	-36	-20	99	4	0	
71878	3347	S	-19	23	20	-25	-9	50	1	0	
73752	3430	S	-7	19	14	-41	-44	20	3	-11	4
76943	3579	L	-1	-33	-11	50	12	-9	-15	6	4
78045	3615	S	20	12	-6	-26	-1	57	7	-7	
78154	3616	L	23	23							4
80007	3685	S	3	30	-6	-45	-22	65	-1	-7	
81797	3748	S	6	11	0	-7	-15	-9	3	1	
82328	3775	L	-7	-7	11	12	44	-7	1	3	
82434	3786	S	6	6	7	-11	1	52	6	-3	4
84117	3862	S	-7	-1	23	-17	-74	-1	7	-9	
84810	3884	H	-1474	-564	-1476	-521	-1341	-510	-1474	-542	3
84810	3884	S	-1457	-515	-1476	-577	-1367	-467	-1466	-547	3
85123	3890	S	-98	421	-114	442	-130	464	-106	431	3
87901	3982	S	3	1	-1	-11	9	-9	0	-4	2
87901	3982	L	0	-6	1	0	-3	-3	-4	-4	2
89449	4054	S	-7	-14	20	-4	-26	-55	6	-9	
89758	4069	L	0	7	9	3	20	42	4	6	
90589	4102	S	-9	36	15	-39	-42	44	3	-1	
90839	4112	L	33	-22							
92139	4167	S	6	15	-15	-14	9	33	-4	0	4
93497	4216	S	12	57	-4	-66	-14	85	3	-4	4
94510	4257	S	1	25	7	-23	20	44	4	1	
95128	4277	L	34	6							
95418	4295	L	20	-1	-7	-30	65	22	3	-22	
95689	4301	L	22	-14			20	1			2
97603	4357	S	-4	-25	3	3	-33	-57	-1	-11	
97633	4359	H	-1	28	-6	-14	-11	-4	-3	6	
97633	4359	L	-36	-23	-15	25	-4	-82	-33	1	
98230	4374	H	-9	39	7	-7	22	7	0	15	4
98430	4382	S	1	15	20	-22	33	33	11	-3	
99028	4399	S	3	7	11	-19	30	3	6	-4	4
102365	4523	S	-14	15	11	-15	4	82	-1	0	
102647	4534	H	-6	0	9	-3	-12	19	1	-1	
102647	4534	S	-9	-6	33	12	-22	-36	12	3	
102870	4540	S	6	25	1	-20	-1	14	4	3	
103287	4554	L	9	9			33	20			
105211	4616	S	-7	22	42	-20	-1	38	17	0	
105452	4623	S	1	-12	17	-22	-61	14	9	-17	
106591	4660	L	9	-28	-4	1	7	-22	3	-14	
109358	4785	L	3	-15			107	9			
109379	4786	H	7	-9	-1	9	-9	-3	3	0	
109379	4786	S	12	-3	12	-3	11	41	12	-3	
110379	4825	S	-20	-12	34	30	-47	17	6	7	4
113226	4932	S	-17	-26	31	15	-41	-22	6	-6	
114613	4979	S	-12	25	12	-9	-19	49	0	7	
114710	4983	L	6	-30	7	50	44	-50	7	11	
115617	5019	S	1	1	7	-6	-12	44	4	-1	
115892	5028	H	11	3	-15	19	12	4	-3	11	
115892	5028	S	4	30	-15	-45	36	68	-6	-7	
116658	5056	H	-28	7	-15	-9	-25	1	-22	-1	
116658	5056	S	-23	-3	-6	-9	-4	0	-15	-6	
116976	5068	H	-14	-31	-49	-20	4	-34	-31	-26	1
116976	5068	S	-53	-22	-22	-42	-26	31	-38	-33	1
118098	5107	S	-15	-25	-9	33	-22	-57	-12	4	
121370	5235	S	-14	6	1	-30	17	6	-6	-12	
123123	5287	H	22	-1	3	11			12	4	
123139	5288	H	15	-9	-15	22	20	-4	0	6	
124897	5340	H	0	-3	0	0	6	-3	0	-1	2
124897	5340	S	3	-12	-4	14	-9	-28	-1	1	2
124897	5340	L	-7	-20	7	9	-4	-11	-1	-6	2
125288	5358	H	-1219	967	-1227	934	-1105	834	-1219	975	3
125288	5358	S	-1218	997	-1224	978	-1197	899	-1221	988	3
126660	5404	L	6	-28			14	-44			
128167	5447	H	-1	14	-15	-31	-22	19	-9	-9	
128620	5459	H	-14	-1	-3	6	12	-6	-7	3	
128620	5459	S	-9	12	12	3	0	36	1	7	2
129502	5487	H	-7	9	-17	-15	-39	25	-12	-3	
131873	5563	L	6	-1			-1	15			
133216	5603	H	-280	15	-177	-3	-158	-3	-229	6	1
134083	5634	H	-12	-1	-6	20	-14	49	-9	9	
135722	5681	L	-50	-3	53	33	-9	14	1	15	
137759	5744	L	23	-20	38	41	3	3	30	9	
139063	5794	H	4	-4	-7	30	7	12	-1	12	4
139664	5825	H	-20	-11	-4	-4	-17	-28	-12	-7	
140573	5854	H	11	-12	-9	11	19	-4	1	0	
141004	5868	H	1	-1	-6	-11	12	-15	-3	-6	
141891	5897	H	-3	-6	-6	17	16	-3	-4	4	
142373	5914	L	-20	-36			-128	-28			
142860	5933	H	-9	-9	-11	-6	19	-5	-9	-7	
144470	5993	H	-591	-896	-658	-932	-594	-905	-624	-915	3
144470	5993	S	-607	-875	-642	-973	-580	-862	-624	-924	3
146791	6075	H	3	-26	-9	6	3	-7	-3	-11	
147084	6081	H	1749	3690	1906	4073			1827	3891	3
147084	6081	S	1779	3677	1987	4101	1852	4309	1884	3888	3
147165	6084	H	1471	-79	1519	-174	1336	-260	1495	-126	3
147584	6098	H	-7	-25	6	25	-38	-101	0	0	
147675	6102	H	-22	3	-12	-20	15	0	-17	-7	
150798	6217	H	-25	-45	-50	4	-26	-42	-38	-20	1
150997	6220	L	-31	-22			-95	-41			
151680	6241	H	15	-14	-3	-3	14	-3	6	-9	
152786	6285	H	320	347	283	388	287	326	302	367	1
153597	6315	L	9	-47			-26	112			
155125	6376	H	-3	12	1	-17	0	6	-1	-3	4
155203	6380	H	-6	22	9	-4	4	30	1	9	
155885	6401	H	28	-17	3	-1	7	4	15	-9	4
156897	6445	H	-3	0	9	0	-22	-14	3	0	4
157244	6461	H	662	540	631	578	591	534	647	559	3
159561	6556	H	-4	6	14	3	1	-1	4	4	
159561	6556	L	-4	-6			-6	-39			
160915	6595	H	-4	0	-6	-9	-969	-981	-4	-4	
161471	6615	H	2174	198	2193	198			2183	198	3
161868	6629	H	-3	30	28	1			12	15	
161892	6630	H	19	-31	15	-6	12	-12	17	-19	
163588	6688	L	-36	-41			-9	112			
165024	6743	H	978	147	1026	182	905	158	1002	164	3
165777	6771	H	-11	15	9	-23	20	-12	0	-4	
167618	6832	H	30	-36	-19	15	12	-26	4	-11	4
168454	6859	H	-1	-76	-22	-26	-15	-50	-11	-52	1
168723	6869	H	11	-25	-3	12	41	-19	4	-6	
169916	6913	H	6	-23	11	-6	12	1	9	-15	
170153	6927	L	-22	-31			-47	-14			
172167	7001	H	-33	25	-1	-14	-6	7	-17	6	
172167	7001	L	-6	0	15	7	-9	1	11	7	2
177241	7217	H	1	-36	12	-4	38	-22	7	-20	
177716	7234	H	7	-30	7	-12	-15	-34	7	-20	
181577	7340	H	19	-17	-1	-23	23	28	9	-20	
182640	7377	H	-4	1	-4	7	-7	-3	-4	4	
183143		H	6031	-344	6067	-385	5300	-317	6050	-364	3
185144	7462	L	-9	-19			1	-52			
187642	7557	H	1	4	-6	-3	-1	-1	-1	0	2
187642	7557	L	15	0			17	6			
187929	7570	H	-1674	-220	-1673	-206	-1512	-161	-1673	-212	3
188376	7597	H	12	-12	11	-7	23	0	12	-9	
188512	7602	H	9	-22	7	1	-6	-15	7	-9	4
190248	7665	H	11	-19	-3	-11	9	14	4	-15	
196171	7869	H	11	-52	-4	1	4	-36	3	-25	
197051	7913	H	-4	-9	1	3	-25	-19	-1	-3	
197345	7924	L	136	340	117	369	133	294	111	361	3
197692	7936	H	0	-17	42	7	-14	-6	20	-4	
197989	7949	H	-4	3	-4	-9	4	-1	-4	-3	
198149	7957	L	6	-12			36	-34			
202275	8123	H	-7	-12	7	1	1	28	0	-6	4
202444	8130	H	-26	-4	19	-9	-4	31	-4	-6	4
203280	8162	L	20	-9			-30	-28			
203608	8181	H	14	-6	-38	20	-12	1	-12	6	
205478	8254	H	-3	-25	-17	-7	11	1	-11	-15	4
205637	8260	H	742	-720	724	-734	659	-772	734	-727	3
207098	8322	H	-19	-4	7	-4	-20	0	-4	-4	
209100	8387	H	-3	-38	1	-7	-1	-19	0	-23	
209952	8425	H	-3	-6	-12	9	6	-3	-7	1	
210027	8430	H	-19	0	9	-22	-33	9	-4	-11	
210418	8450	H	1	-9	1	-19	6	11	1	-14	
215789	8675	H	-11	-28	17	4	14	-17	3	-11	
216228	8694	L	19	3			-4	12			
216627	8709	H	0	-9	0	3	7	19	0	-3	
216956	8728	H	1	-4	1	1	-1	-6	1	-1	2
217782	8766	H	-126	0	-69	-20	-107	82	-98	-11	1
217782	8766	L	-104	-28	-179	36	-382	172	-141	4	1
218045	8781	H	3	9	1	-23			1	-7	
218045	8781	L	9	-36			-88	-1			
219571	8848	H	-7	-33	7	-3	-12	6	0	-19	
222404	8974	L	9	-3			-17	-3			

Table 6. Mean square degree of polarization $\overline{P_0^2}$ (see appendix) as a function of distance. The following quantities are listed: $Q_{\mathrm{r.m.s.}}$, $U_{\mathrm{r.m.s.}}$: r.m.s. *observed* polarization. ε: r.m.s. error adopted (identical for Q and U; see Sect. 3). $\overline{P_0^2}$: mean square *true* polarization, computed as follows: $\overline{P_0^2}=\overline{Q_0^2}+\overline{U_0^2}=(Q_{\mathrm{rms}})^2+(U_{\mathrm{rms}})^2-2\varepsilon^2$. $\bar{r}$: mean distance of the stars in the group. n: number of stars in the group. For $r>50$ pc, the data are mainly from Behr (1959); I have applied a higher correction for random errors and tabulate $\overline{P_0^2}$ rather than Behr's P_σ, which corresponds to (Q_0)rms or (U_0)rms or $\sqrt{2}(P_0)$rms (Behr omits this factor of $\sqrt{2}$ when transforming to A_v via p_0). Appenzeller (1975) does not quote Q_{rms}, U_{rms}; I have used his $\bar{p}$ and corrected this for observational error using the $p \gg \varepsilon$ approximation (see appendix). In computing Q_{rms}, U_{rms} for "Tinbergen + Piirola", I have excluded the 6 stars with anomalously high polarization (Fig. 7). The Markkanen (1979) NGP sample has been split at $r=125$ pc, since at this distance the polarization suddenly increases (at least in his area II). His results for the Coma cluster presumably indicate dust within or near the cluster and are of minor interest here

Sample	Distance (pc)	Author	$10^5\times$			$10^{10}\times\overline{P_0^2}$	$\bar{r}$ (pc)	n
			Q_{rms}	U_{rms}	ε			
All-sky	0– 10	Tinbergen + Piirola	9.0	9.0	7	+63	7	29
	10– 20		7.3	8.1	7	+22	16	78
	20– 35		7.1	8.7	7	+27	24	62
Northern sky	50– 100	Behr	144	96	40	$2.7\ 10^4$	70	110
	100– 250		294	408	40	$2.5\ 10^5$	138	127
	250– 500		519	482	40	$5.0\ 10^5$	343	43
	500–1000		1055	1000	40	$2.1\ 10^6$	722	47
NGP	0– 125	Markkanen	37	41	34	660	84	7
	125– 400		165	85	39	$3.2\ 10^4$	250	7
NGP	140– 200	Appenzeller	—	—	23	$8\ 10^3$	≈160	16
SGP	>100		—	—	41	$1.6\ 10^4$	≈115	13
Coma cluster	0– 125	Markkanen	43	42	20	$2.8\ 10^3$	80	16

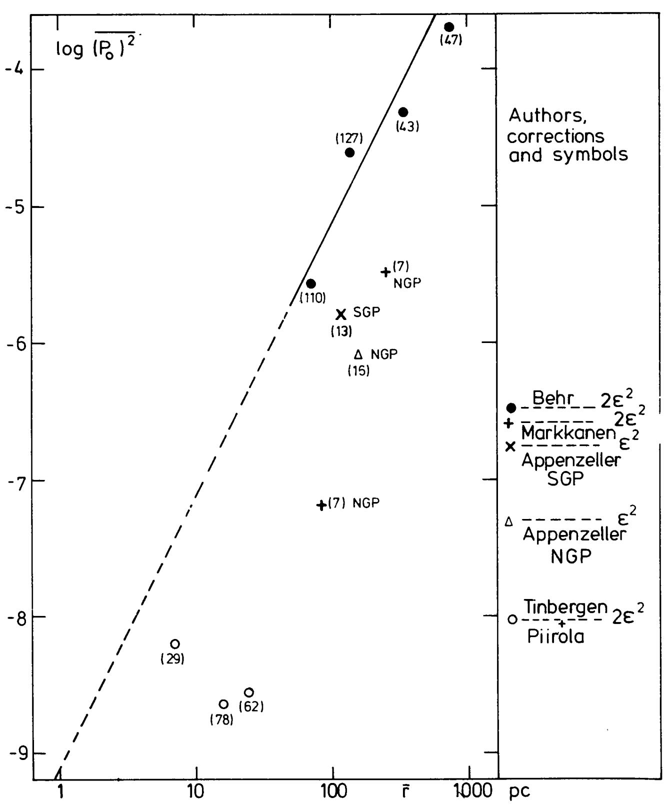

Fig. 4. Interstellar polarization (corrected for observational error) as a function of distance. Average square of the degree of polarization over the whole sky (Tinbergen + Piirola), for the North Galactic Pole (Markkanen) and over the Northern sky (Behr, 1959); square of the average for both Galactic Poles (Appenzeller, 1975). I have plotted the square of the degree of polarization, since this can very simply be corrected for observational error, even when $P \ll \varepsilon$ (see appendix). The straight line has a logarithmic slope of 2 (polarization proportional to distance) and has been drawn by eye through Behr's points (distances 50–1000 pc). In brackets the numbers of stars involved in each distance group. The applied correction for observational error for each data source is denoted by ε^2 or $2\varepsilon^2$, depending on the author's method of reduction (see legend to Table 6)

Table 7. Summary of polarization and implied extinction data for the first 35 pc, compared with recent photometry and contrasted with data for greater distances. r is an indication of the stellar distance group, P/r is r.m.s. degree of polarization for the group, divided by an estimated mean distance. A_v/r is simply P/r multiplied by (2.17/0.065) mag

Author	r (pc)	P/r (pc^{-1})	A_v/r (mag/pc)	Notes
Behr (1959)	12– 25	$5\ 10^{-6}$	0.0002	Northern Sky; redetermination allowing for larger observational errors
Walborn (1968)	<25	$5\ 10^{-6}$	0.00016	One-third of Northern Sky. Result too high (correction for observational error insufficient)
Piirola (1977)	<25	$4\ 10^{-6}$	0.00012	Northern Sky. Sub-sample of that in present paper. Slightly different correction for observational error
Tinbergen + Piirola (present study)	10– 35	$2.5\ 10^{-6}$	0.00008	Upper limit True value can be much lower
Knude (1979b)	20–150		≈0.00006	Intercloud medium. *uvby* Hβ; A and F stars
Markkanen (1979) (incl. Appenzeller, 1975)	125–200	$7\ 10^{-6}$	0.0002	North Galactic pole
Appenzeller (1975)	90–150	$1.1\ 10^{-5}$	0.0003	South Galactic pole
Behr (1959)	50–100 100–250	$2.3\ 10^{-5}$ $3.6\ 10^{-5}$	0.0008 0.0012	Northern Sky; emphasis on Galactic plane. Redetermination, allowing for larger observational errors
Neckel and Klare (1980) (Fig. 8)	1000	—	0.0005 to 0.003	Galactic plane. *UBV+MK* (Hβ) O, B, A stars. 1 kpc average

nations (see Table 7) and is comparable to Knude's (1979b) "intercloud extinction". Note that the lower values of P/r in the present study are obtained by correctly allowing for observational error (see Appendix) in an already high-precision survey; if the error were to be equated to zero, I would obtain $P/r \approx 5\ 10^{-6}\ pc^{-1}$, as do some of the other authors in Table 7. On the other hand, it requires an increase of the error by only 10–15% to make the derived quantity $\overline{P_0^2}$ negative and P/r indeterminate. No great confidence should therefore be given to the exact value quoted for P/r, but it is certainly much lower than hitherto accepted. It is also a factor of at least 10 lower than one might expect from Behr's data for 100–250 pc, at which distances his results are indisputable. The r.m.s. procedure, and Behr's sampling, imply that his results for the more distant groups refer primarily to the higher polarizations, in the Galactic Plane; Appenzeller's and Markkanen's data for the Galactic Poles are also clearly lower than Behr's for the same distance group. The general picture, then, is as follows: *really very low dust content near the Sun* ($r \lesssim 35$ pc)*, with an increase at distances of 50–100* pc*, more pronounced in the Galactic plane than outside it.* Some evidence for patchiness can be found in Markkanen's (1979) data and more may emerge when surveys of 10^{-4} precision become more general.

Of course, in a sense, polarization gives a lower limit to the extinction, since degree and direction of alignment are unknown. If polarization is below a certain value for the whole sky, however, the "lower limit" based on this value is unlikely to be much exceeded. In another sense, the value given is an upper limit: the results are dominated by noise, the real polarization is a fraction of that "measured". Under these circumstances, an underestimate of the noise may dramatically increase the "real" polarizations one obtains. A case in point is the pioneering study by Behr (1959). For the first 25 pc he obtains $A_v \approx 0.02$ mag (Eqs. 32, 33), stating that the value depends very much on the error level assumed. I have shown in Sect. 3b that in Behr's results there is greater scatter than is accounted for by his stated errors; his real random error level is $4\ 10^{-4}$ rather than 2.5 or $3\ 10^{-4}$, as he obtained. This serves to illustrate that a result as marginal as my present one is likely to be an upper limit: one never overestimates one's own errors. Finally, the quantity I have used is mean-square degree of polarization; since the dust may be distributed non-uniformly, this also leads to an upper limit to the mean extinction.

The unusually low extinction of $A_v \lesssim 0.00008\ \mathrm{mag\ pc^{-1}}$ is quite compatible with Knude's (1979b) "intercloud extinction" (inferred from the lower envelope of colour excesses as a function of distance). It is also compatible with hydrogen column densities derived from extreme ultraviolet and Lyman α observations of the nearby stars. Using the average relation preferred by Knude (1979a):

$$N(\mathrm{H}) = 7.5\ 10^{21}\ E(B\text{–}V)\ \mathrm{atoms\ cm^{-2}}$$

one obtains

$$N(\mathrm{H})/r \approx 2\ 10^{17}\ \mathrm{atoms\ cm^{-2}\ pc^{-1}}\ (\approx 0.07\ \mathrm{atoms\ cm^{-3}}).$$

For distances to 100 pc Cash et al. (1979) quote an observed "average" of $1.8\ 10^{17}\ \mathrm{atoms\ cm^{-2}\ pc^{-1}}$, which for distances less than 50 pc is also more of an upper limit than an average (see their Fig. 2). The picture emerging from these various types of observation is consistent within the observational errors. One should add, however, that these errors are considerable.

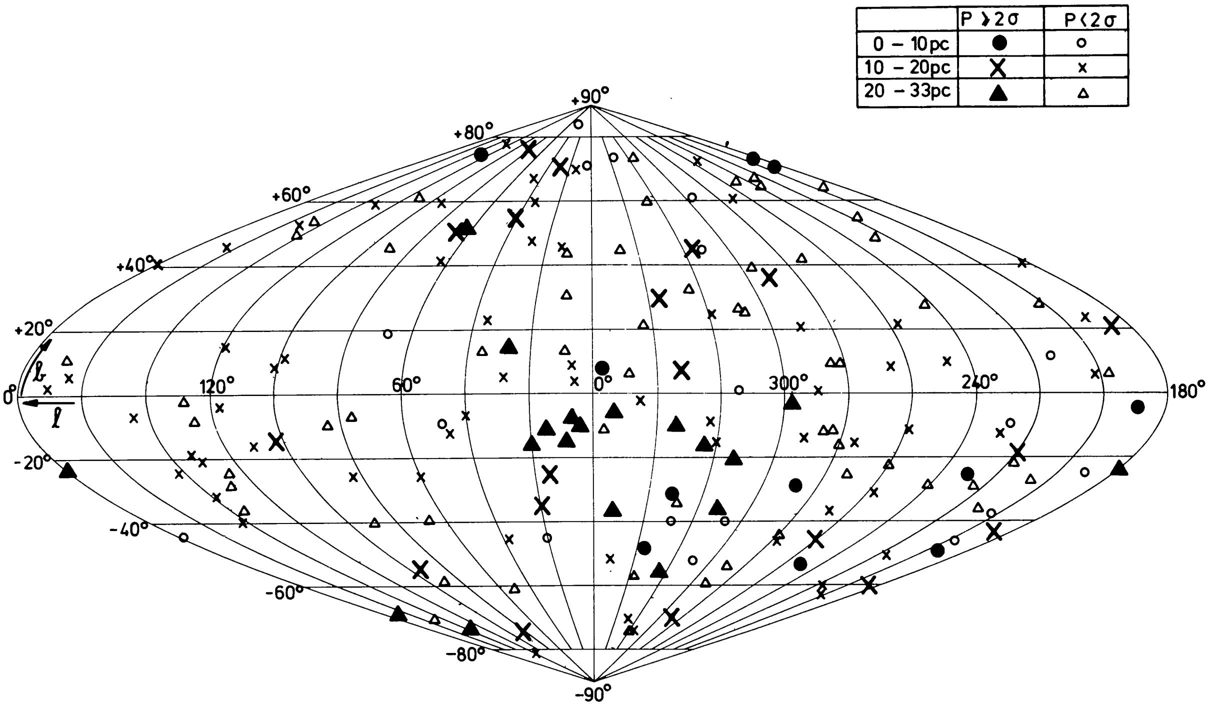

Fig. 5. All-sky representation of the interstellar polarization for nearby stars. Large symbols denote degrees of polarization exceeding 14 10^{-5} ($>2\sigma$, i.e. 95 %-confidence non-zero), small symbols polarizations less than this value. Rough distances are indicated by the choice of symbol. Data from Piirola (1977) included. For a discussion see Sect. 5b

Reductions by a factor of 3 or 10 would make several of the "observables" unobservable by present techniques; selection effects therefore operate and rough agreement is not completely unexpected.

One may ask why the 0–10 pc group should have an r.m.s. polarization about 1.6 times *higher* than the 10–35 pc remainder of the sample. Considering all the uncertainties, this at first sight unexpected result does not disturb me; possible explanations are:

1. A few of the stars in the 0–10 pc group could happen to be slightly polarized intrinsically. The precautions I have taken against intrinsic polarization (see Sect. 1) are not absolute.

2. The dust is almost certainly not evenly distributed. A few nearby stars could happen to lie behind relatively dusty regions, while by chance fewer 10–35 pc stars lie behind such regions.

The 0–10 pc group has less than half the number of stars of either of the other two groups, so it would require fewer stars to affect the result for this group significantly.

b) Distribution of Polarization over the Sky

In the previous subsection we have looked at all-sky averages, ignoring everything but distance structure. We shall now look for patterns on the celestial sphere. If we find such a pattern, it would suggest that the polarizations are not "intrinsic" to the stars, a question which has not really been settled for this sample.

Figure 5 shows the Tinbergen + Piirola data on an all-sky projection. I have arbitrarily divided the stars into two groups: polarization greater than and less than about twice the r.m.s. error; a further subdivision seems uncalled for. It is of course questionable whether a galactic coordinate system is appropriate to such nearby stars, but it is one of the things one tries and the results are suggestive: there seems to be a band of just detectable polarizations centred on $l=340°$ ($\pm 10°$?), which extends over all latitudes. A magnetic field in the Galactic plane (or the plane of the Gould belt) and in general direction $l=70°$ could produce such a band (the fact that at $l \simeq 160°$ we do not see the other half of the band does not, in itself, contradict the notion of a regular field, since it could be caused by lack of dust). It is interesting to note that Appenzeller (1975), from stars at the Galactic poles (distance > 100 pc), obtains $l=64°$ (NGP) and $l=83°$ (SGP) as the direction of the projected magnetic field. I have looked for evidence of Appenzeller's preferential directions in the Tinbergen + Piirola data for high-latitude stars ($|b|>50°$), but I can find none, even though for some of the stars the r.m.s. error of the polarization angle is only 10°–15°. Another discordant feature is that the polarizations for the low-latitude ($|b|<50°$) stars show more scatter in polarization angle than one would expect from the observational error (Fig. 6).

I have examined the pattern for other than Galactic influences and have not been able to find any. In particular, there is no evidence for a relation with the equatorial coordinate system (undetected instrumental errors?), nor with the ecliptic coordinate system (Zodiacal Light particles?). We must conclude that, while on the average the field direction seems to agree with what is found at greater distances, the present observations are inconsistent with a single field direction throughout the volume sampled (≈ 35 pc radius). When parallaxes from the planned HIPPARCOS satellite become available in the future, it will become very worthwhile to extend the present type of survey to distances of 150 pc, where the polarizations are considerable relative to the errors of modern polarimetry (Appenzeller, 1968; Markkanen, 1979, and Knude, 1979b).

As an alternative explanation of the band we might consider dust associated with the proposed H I shell centred on the Sco-Cen

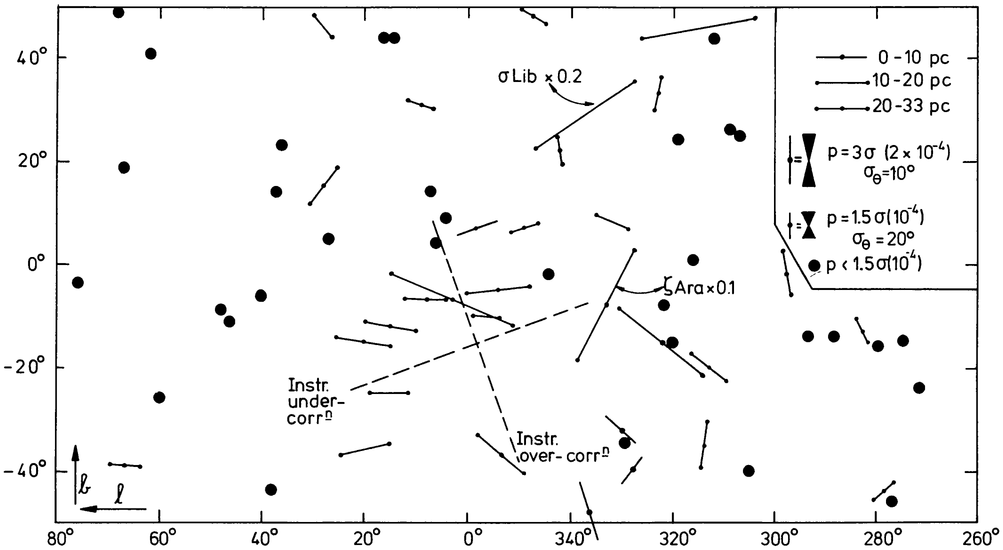

Fig. 6. The local dust patch, as shown by interstellar polarization. Rough stellar distances are indicated (see inset). The r.m.s. error of the polarization angle varies with the degree of polarization; two examples are given in the inset. σ Lib and ζ Ara have very high polarization; they are anomalous and are discussed in Sect. 5d. The dotted lines indicate the directions of the polarization I would have obtained by overcorrecting or undercorrecting for instrumental polarization (through an error in $B-V$, or very abnormal atmospheric extinction) in Hartebeespoortdam, where the data in this figure were obtained

association (Weaver, 1979). However, the polarized band is most in evidence at Southern Galactic latitudes, while the Sco-Cen bubble is centred at $b \approx +15°$. A second objection is that the observed polarizations correspond to only 5–10% of the H I column density of the shell (Davelaar et al., 1980), while the polarized stars are at distances ranging from 10 to 35 pc. The thickness of the "shell" would thus be of the same order as its radius of 150 pc. We conclude that an explanation in terms of the Sco-Cen bubble is unrealistic.

c) A Local Patch of Dust

There exists one area, $l = 350°$ to $20°$, $b = -40°$ to $-5°$ (Fig. 6), in which there does seem to be evidence for a very uniform field, situated somewhere between 0 and 20 pc. I shall call this area of higher dust content ($A_v \approx 0.01$ mag) a 'patch', to distinguish it from the standard cloud, which has $A_v \approx 0.1$ mag [e. g. Knude, 1979a, c; the obscuring feature in Markkanen's (1979) area II at the North Galactic Pole is a cloud rather than a patch]. The minimum angular extent of this dust patch is about 30°.

The question arises whether this is not an artefact due to abnormal atmospheric extinction, combined with broad passbands and a wavelength-dependent instrumental polarization at Hartebeespoortdam (see Sect. 3a), where these particular observations were made. The dotted lines in Fig. 6 indicate the 2 possible preferential polarization angles if this had been the case; I conclude that the results are not spurious, at least not from this cause. To exclude the possibility of an artefact still further, I have examined the original data for the 9 stars in this area. The mean value of the internal error is 6 10^{-5}, which is the standard value for Hartebeespoortdam. The data for these 9 stars come from altogether 14 different nights, and there are no suspicious data in the sample. I have also examined the published stellar data and again there is nothing suspicious: they do not have common notion, they are of various spectral types and luminosities and some, but not all, are multiple stars (none of them such as to influence the process of measurement). Lastly, even if I were to adjust the zero-point of the survey to coincide with Schröder's (an extreme measure; see Sect. 3b), the feature would not disappear; the polarization angles would hardly change, but the degrees of polarization would decrease by 7 10^{-5}, 30% of their average length. I conclude, therefore, that the regularity of the projected field over this area of sky is established. The regular-field area (as opposed to the dust patch) could conceivably be about twice as large as quoted above, but the observed polarizations are too small to be able to tell.

It is worthwhile considering whether this patch of regular field and higher dust content can be recognized by any other technique. Colour excess data are no help at this level. Although the H I column density normally associated with such a low extinction (1–2 10^{19} atoms cm^{-2}; e.g. Knude, 1979a) would also be almost invisible on the maps of Colomb et al. (1980), these maps were inspected. There is an abundance of "zero-velocity" hydrogen in the area, completely masking any very faint features that might be present.

One might attempt to interpret the "patch" in terms of Table 1 and Fig. 2 of McKee and Ostriker (1977). From its equivalent hydrogen column density one might suppose it to be a small "cold core" (radius ≈ 0.5 pc); its angular extent of roughly 1 radian then puts it at a distance of 1 pc. This is a distinct possibility. The closest star within the patch is HD 155885 (36 Oph) at 5 pc and it shares the common polarization angle; McKee and Ostriker's typical cloud number density of 6 10^{-3} pc^{-3} is not at all in conflict with discovering only one such patch when one is forced to use a sample of stars with sky density of 15 $steradian^{-1}$ and demands similar polarizations in at least 3 or 4 adjacent stars for a detection. The alternative of a "warm ionized component" is difficult to assess; the state of the dust particles in such a medium and possibly the extent to which the dust has expanded with the gas depend on the time elapsed since ionization took place.

It is manifestly stretching a point to compare a single observed object with a "typical" statistical quantity. It is therefore worthwhile to pursue the polarization mapping at the present precision to greater distances and higher sky density. A telescope of the 150-cm class is suitable; stellar distances of high precision are an important desideratum.

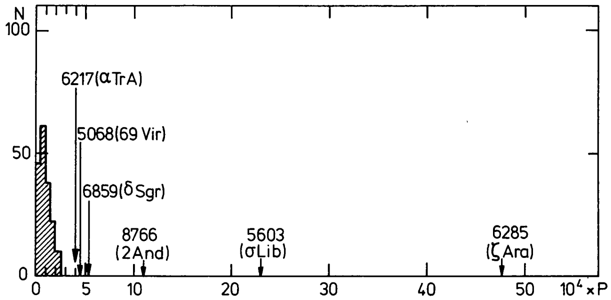

Fig. 7. Distribution of observed degree of polarization in the sample of supposedly nearby stars. 181 stars are in the histogram on the left. They form a statistical population to which the other 6 evidently do not belong; these 6 are described in Sect. 5d

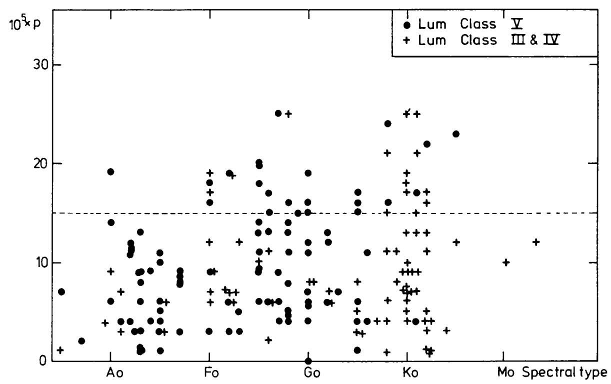

Fig. 8. Observed degree of polarization plotted against spectral type. Data Piirola and Tinbergen. The broken line is at 15 10^{-5} ($p \approx 2\varepsilon_p$)

Table 8. R.m.s. error of polarization (average of Q and U), averaged for various categories of stars in the sample

Category		$10^5 \cdot \bar{\sigma}$	n
III to V	A	6.1±0.4	29 (24 are V)
	F	6.6±0.3	35
	G	6.2±0.4	28
	K	5.2±0.3	35 (only 4 are V)
B to *M*	V	6.3±0.3	64
	III and IV	5.6±0.2	68
B to *M* and III to V	$p \leq 15\ 10^{-5}$	5.6±0.2	106
	$p > 15\ 10^{-5}$	7.0±0.4	26

d) Six Individual Stars with Abnormal Polarization

The stars listed in this section, though nominally closer than 35 pc, have polarizations which distinguish them from the general run of nearby stars (Fig. 7).

1. HR 5068 (HD 116976, 69 Vir; K 1 III). Gliese (1969) gives a trigonometric parallax of 0.″057 and a spectroscopic parallax of 0.″013. Polarization possibly interstellar.

2. HR 5603 (HD 133216, σ Lib; M 4 III); Gliese (1969) gives a trigonometric parallax of 0.″062 and a spectroscopic parallax of 0.″018. From 8-colour polarimetry I find that the maximum of the linear polarization must lie below 400 nm. In view of this and of its spectral type, I conclude that the polarization is probably circumstellar.

3. HR 6217 (HD 150798, αTrA; K4III). The Bright Star Catalogue gives a trigonometric parallax of 0.″024. Included in the sample on the strength of a rough spectroscopic parallax. Polarization probably interstellar.

4. HR 6285 (HD 152786, ζ Ara; K 5 III). This star is a puzzle. The 8-colour wavelength-dependence of the polarization roughly fits an interstellar curve with $\lambda_{max} \approx 600$ nm, but both trigonometric parallax and MK luminosity class would have to be wrong. A separate report is planned (Van Paradijs and Tinbergen).

5. HR 6859 (HD 168454, δ Sgr; K 2 III). Gliese (1969) gives a "best" parallax of 0.″043, which seems well established. Polarization probably interstellar (see Fig. 6; $l = +3°$, $b = -7°$). The star is a multiple system.

6. HR 8766 (HD 217782, 2 And; A 2). Gliese (1969) only lists a trigonometric parallax, of 0.″052. Binary. Cause of polarization unknown. Spectroscopic examination might be worthwhile.

e) Intrinsic Polarization

The very lack of interstellar dust that hampered the investigation of magnetic field structure makes it possible to push the search for intrinsic polarization of starlight to very low levels. This was recognised by Piirola (1977), who plotted the degree of polarization against spectral type for his sample of stars. In Fig. 8 I have done this for the combined sample and I confirm Piirola's observation that the higher polarizations are almost entirely confined to stars of spectral type F and later: 13 out of 77 have $p_0 > 15\ 10^{-5}$ in Piirola's sample and all are F 0 and later; in the larger Tinbergen plus Piirola sample 32 out of 181 have *observed* degree of polarization $> 15\ 10^{-5}$ and all but one of these are F 0 and later. I do not think this can be an instrumental effect, since so much care was taken to keep the error level independent of apparent magnitude and since the effect is present in Piirola's data as well as my own. There is also a suggestion of higher polarizations for luminosity class V than for III and IV (95% confidence). If the polarizations were interstellar, one would expect this to be the other way round, since the sample was selected partly on the basis of apparent magnitude. The effect must, I feel, be intrinsic to the stars themselves.

I have searched for evidence of variability of the polarization by investigating how the r.m.s. scatter per star varied with spectral type, luminosity class and average degree of polarization of the star (Table 8). There does seem to be more variability in the stars with the larger polarizations (99% confidence), but that is about all one can say.

The sum total of the evidence then amounts to a suspicion that, amongst stars of F 0 and later, 15–25% show intrinsic polarization at the 10^{-4} level, and that this polarization varies with time (days). A possibility, of course, is that *all* stars later than F 0 have variable polarization, which for 15–25% of the time (on a time scale of months or longer) is greater than about 15 10^{-5}. This, or some intermediate situation, would be in agreement with the idea that the polarization arises in solar-type active magnetic regions through linear Zeeman splitting of many narrow but saturated absorption lines. This exciting possibility has been reported on separately (Tinbergen and Zwaan, 1981).

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Appendix

There is some confusion in the literature on how best to average observations of linear polarization. When the observed polarization (p) is large compared with its r.m.s. error (ε_p), one may average the degree of polarization and the polarization angle separately.

When $p \approx \varepsilon_p$, this procedure is not valid, since p is always positive and is not distributed normally. Serkowski (1958) shows how the average ($\bar{p}$) is biased in this case. The Stokes parameters Q and U are distributed normally; taking their averages and combining them to form an average vector degree of polarization $\langle \tilde{p} \rangle$ is always valid:

$$p = |\langle \tilde{p} \rangle| = (\bar{Q}^2 + \bar{U}^2)^{1/2}, \quad \theta = 0.5 \arg \langle \tilde{p} \rangle = 0.5 \arctan (\bar{U}/\bar{Q}).$$

However, the *average* polarization *vector* may not be the astronomically significant quantity; one may wish to derive some sort of unbiased *average degree of true polarization* for a sample of stars for which the polarization angles are unknown and probably widely scattered. In such a case it is legitimate to compute the *mean-square true degree of polarization* $\overline{(p_0)^2}$, as follows:

$$p^2 \equiv Q^2 + U^2 = (Q_0 + \varepsilon_Q)^2 + (U_0 + \varepsilon_U)^2.$$

Taking means and rearranging:

$$\overline{(P_0)^2} \equiv \overline{(Q_0)^2} + \overline{(U_0)^2} = \overline{P^2} - 2\,\overline{\varepsilon^2} \qquad (\varepsilon_Q = \varepsilon_U = \varepsilon).$$

This holds for all values of p relative to ε.

One may now ask how this can agree with the oft-quoted formula for correcting for observational error:

$$(P_0)^2 = (\bar{P})^2 - (\varepsilon_p)^2.$$

This formula is valid only for $p \gg \varepsilon_p$; under these circumstances $\varepsilon_p = \varepsilon_Q = \varepsilon_U = \varepsilon$ and the two correction formulae would seem to differ by a factor of 2. The difference lies in the use of the mean-square and square-mean observed degree of polarization respectively. Writing out these two quantities in full shows that both formulae are in fact correct (however, the second one is often misapplied to the case $p \approx \varepsilon$, where it produces undercorrection).

One is often faced with handling a sample in which, through lack of photons, the error of observation varies from star to star. In deriving mean-square true polarization one should use the r.m.s. value of ε rather than its mean.

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