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Interstellar polarization at high galactic latitudes from distant stars

III. Distribution of the polarization vectors – evidence for distinct zones

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Abstract. We make a map of interstellar polarization direction around the North Galactic Pole and study the distribution of the revealed magnetic field lines. We study in detail Markkanen's (1979) cloud and other local features apparent in the polarization map, and compare them with the IRAS 100 micron map. The elongated Markkanen's cloud (at a distance of 100–200 pc) and its magnetic field lines coincide with IRAS filaments. The cloud throws a shadow in soft (0.25 keV ROSAT) X-rays, as expected from its close distance. Another interesting feature is the polarization alignment around $l \approx 190^\circ, b \approx 75^\circ - 83^\circ$, with the direction about perpendicular to that of Markkanen's cloud, hence also perpendicular to the Local Spiral spur. This feature is shown only by stars more distant than 300 pc, and in the IRAS map it is located in a region of enhanced brightness. The differing polarization directions partially overlap in the sky, suggesting the existence of two kinds of clouds with different magnetic field directions.

The IRAS 100 micron map is faint towards the sector $40^\circ < l < 135^\circ$. Only in this region with little nearby diffuse matter is there some signature of the global magnetic field (parallel with $l \approx 78^\circ$).

Key words: polarization – ISM: dust, extinction – Galaxy: solar neighbourhood

1. Introduction

The present study continues our series on interstellar polarization at high northern galactic latitudes. The previous results have been published by Berdyugin et al. (1995; Paper I) and Berdyugin & Teerikorpi (1997; Paper II).

The aim of this programme is to investigate the interstellar polarization over the North Galactic Pole (NGP) region ($b > 70^\circ$) from observations of distant stars. These results are applied for the determination of the amount of interstellar extinction and the structure of the Galactic magnetic field in this area. Papers I and II were mainly concerned with the distance dependence of polarization, up to $Z \approx 1000$ pc. Maps of polarization directions were also presented. In the present paper we study especially the distribution of the polarization direction (the plane of vibration), complementing the data in Papers I and II with our more recent unpublished measurements. We also use older measurements of closer stars by other authors to construct a representative polarization map.

2. The sample of stars and data

Our first star sample was based solely on the catalogue by Hill et al. (1982), listing the stars in the region of the NGP ($b > 75^\circ$). The polarization data for the brightest stars have been obtained with the 60 cm telescope of Tuorla Observatory and with the 1.25 m telescope of the Crimean Astrophysical Observatory (52 stars, Paper I).

The next sample of the more distant and fainter stars was observed on the NOT, La Palma (20 stars, Paper II). Starting from 1997 we have complemented our sample with stars from the unpublished list by Knude (see e.g. Knude 1996). Up to now we have obtained with NOT polarization data for 94 more stars. The details of our observation techniques and data reduction can be found in Papers I and II.

In addition, we use in some parts of the analysis older polarization measurements by Appenzeller (1968), Markkanen (1979), Haikala (1979) and Korhonen & Reiz (1986). These measurements were concerned with bright and rather close stars. All available polarization data for the NGP region, in different wavelength bands and with additional analysis, will be published in the compendium by Berdyugin et al. (2000).[1]

When our programme was started, only photometric distances were available for most of the stars in the studied area. Presently many close stars in the NGP region have accurate parallaxes from the HIPPARCOS. Whenever possible, we use in our new analysis the distances derived from parallaxes (when

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[1] The data especially used in the present paper are available in electronic form from andrei@deneb.astro.utu.fi

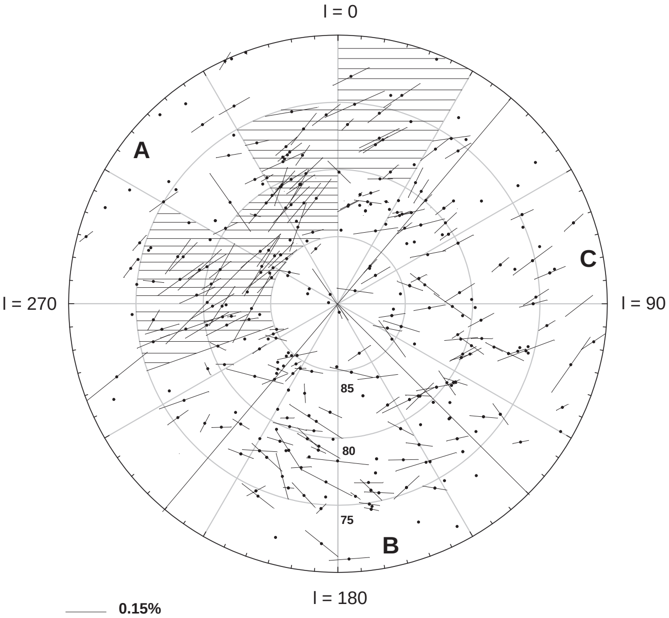

Fig. 1. The polarizations of the stars around the NGP. The length of the bars give the amount of polarization, their directions give the directions of the polarization plane. The dots are stars with very small or zero polarization. The sectors A, B, and C are separated by the lines having the longitudes 40°, 135°, and 220°. The shaded area shows the approximate location of Markkanen's cloud.

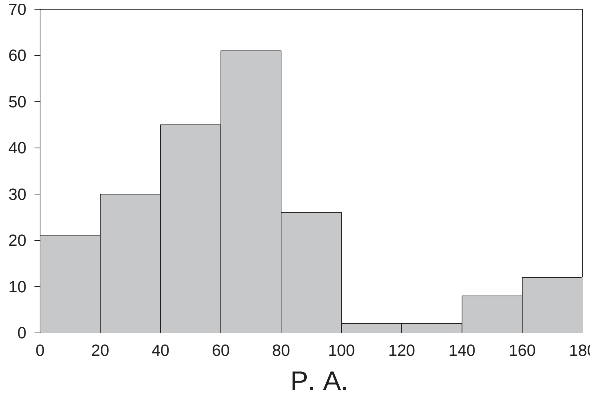

Fig. 2. The distribution of the equatorial position angle of polarization vector all over the polar cap. Note the maximum between 60° and 80°, and the "hole" around 110°. Recall that the direction of the inner edge of the Local Spiral spur ($l \approx 60^\circ$) corresponds to P.A. $\approx 63^\circ$, and the standard direction of the global magnetic field ($l \approx 78^\circ$) is towards P.A. $\approx 45^\circ$.

$\pi > 2\sigma_\pi$) also for stars from the older samples where polarimetry has been made by our predecessors. Thus for about 90% of stars which are closer than 300 pc we have now a reliable distance estimation from the HIPPARCOS, while for more distant stars ($d > 400$ pc) the estimates come mostly from photometry.

Comparison with HIPPARCOS parallaxes shows that generally at small distances the agreement between photometric and parallax distances is rather good. At large distances, the photometric distances tend to be larger than parallax distances. At present we do not claim to understand this effect, though one notes that two factors might be involved: 1) an underestimation for extinction would increase the photometric distance, and 2) the bias of the Lutz-Kelker (1973) type in trigonometric parallaxes tends to increase the average observed parallax, thus decrease the average HIPPARCOS distances, especially at large distances where the random errors are large. Though the distance uncertainties affect the study of the distance dependence of interstellar polarization, they are not critical for the present investigation. However, one should be aware about the distance problem.

3. The map of the polarization direction

In our analysis of polarimetric data we have used the same accuracy criterium as before. All data with $P > 2\sigma_P$ are kept. For $P < 2\sigma_P$, datum is retained only if $\sigma_P < 0.05$ percent. Under this restriction the error in the derived direction angle is $\leq 14^\circ$.

In astrophysical polarimetry the polarization vector usually is defined in the frame of the standard equatorial coordinate system, where the polarization angle is measured counterclockwise from the line pointing to the North. It is useful to remember that in the galactic coordinate frame this direction is given by the longitude $l = 123^\circ$. The reader may consult Appenzeller (1968) on the question of the position angle (P.A.) and how it is transformed into galactic coordinates.

3.1. Polarization map

Fig. 1 shows all the available data on the polar map, with the direction angle and amount of polarization indicated by the direction and length of the bar. Stars without detectable polarization are shown as points. In Paper I we noted some systematic features in the polarization map (at that time based on only about 50 stars), which suggested a division of the polar cap into three sectors A, B, and C. Their original borders are indicated in Fig. 1.

The sector division still appears relevant with the extensive data. In particular, A is dominated by Markkanen's cloud (Sect. 4), with the cloud itself and the magnetic field lines parallel to about $l \approx 45^\circ$. What we called B, contains an alignment of field vectors about perpendicular to that of Markkanen's cloud. Finally, C is seen to contain stars with the polarization directions pointing roughly between the directions dominating in A and B.

3.2. Distribution of position angle

Fig. 2 shows the histogram of the position angle for all the stars in Fig. 1. One notes the maximum around 70° and the apparent gap around 120°. These features confirm the visual impression from Fig. 1 about preferred alignments of the polarization vectors. The gap corresponds to the absence of vertically directed vectors in Fig. 1, i.e. the absence of radial field lines in the Galactic plane.

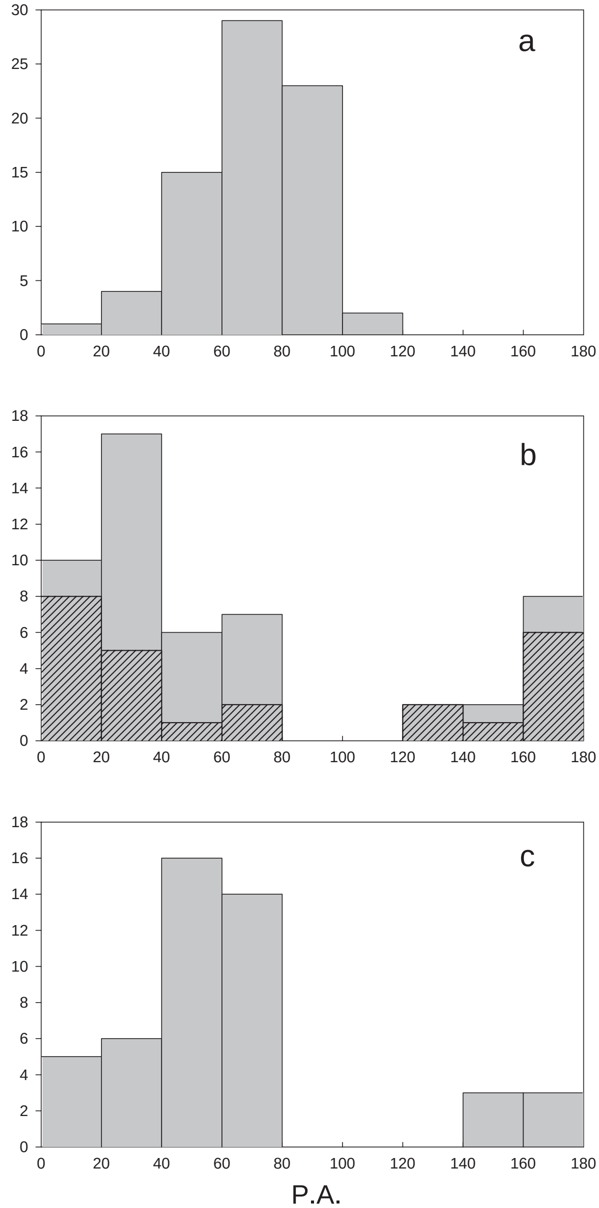

Fig. 3a–c. The distribution of the equatorial position angle of polarization: **a** for the region of Markkanen's cloud, **b** for sector B, **c** for sector C. The hatched part of the histogram for B refers to the half-sector inside B containing the patch of aligned polarization (Sect. 6).

4. Background for interpretation: local and global Galactic structure

4.1. Local Spiral spur at high latitudes

It is useful to summarize what is known or supposed about our close Galactic environment. In the scale of hundreds of parsecs, the distribution of young stars and other spiral arm tracers in the Galactic plane is dominated by the Local Spiral (or Orion) spur (LS). The maps made of spiral tracers show that our Sun is located close to the inner edge of the LS (e.g. Humphreys 1976). The edge points at about $l \approx 60°$. Besides from the plots of low-latitude spiral tracers, which originally revealed it, the position of the LS may be seen at high latitudes from the counts of galaxies. So in north polar Lick counts the direction from $l \approx 220° - 245°$ to $40° - 75°$ shows about zero gradient, but perpendicular to this direction there is a general decrease towards $\approx 140°$ (Fig. 3 in Teerikorpi & Haarala 1987). On this trend is, however, superimposed a pit of $\Delta logN \approx 0.15$ just where Markkanen's cloud is located (Sect. 5). The decrease of galaxy counts towards the general direction of the LS was interpreted by Teerikorpi & Haarala as an increase of average extinction, due to dust clouds concentrated in the spiral arm. Though there is also other evidence for excess dust in the LS at high and intermediate latitudes (e.g. the dust complex revealed by Schlosser & Görnandt 1984, reddenings of radio selected quasars as discussed by Teerikorpi 1981), the situation at very high latitudes has been controversial. The average extinction in the polar cap $b > 70°$ must still be regarded as an open question (e.g. Knude 1996). The things are complicated by a bias in stellar reddenings (Teerikorpi 1990) and the fact that there may be a population of very cold clouds which are not detected by IRAS.

In the scale of tens of parsecs, there is the "Local Bubble" around us (Cox & Reynolds 1987, Ferlet 1999), a relatively empty and hot place, where the stars apparently do not show polarization (e.g. Leroy 1993).

4.2. Global magnetic field

In external spiral galaxies the global magnetic field closely follows the spiral pattern formed by young stars, gas and dust. As Vallée (1995) emphasizes, thus the determination of the magnetic field lines in our own Galaxy should also give a determination of the spiral arms. In his review, Vallée concludes from studies using different methods (those concerned with the magnetic field being based on the Faraday rotation) that our global spiral pattern is best described as a four-armed logarithmic spiral, with the pitch angle about $-12° \pm 1°$. Locally, this would mean that the global pattern is directed towards $l = 78°$.[2]

In principle, looking perpendicular to the Galactic plane (as we do) should allow one to see from the polarization vectors almost directly the orientation of the magnetic field. However, this would require that the field lines are not distorted locally, and Fig. 1 reveals that there must be such distortions. In fact, field line distortions from the Local Bubble were seen first in Fig. 2 of Vallée & Kronberg (1973). Then the question arises whether one may detect the global pattern outside of the distortions? Another interesting question relates to the Local Spiral spur, which deviates from the global pattern. Can one see its presence in the local magnetic field lines?

[2] A somewhat different result was obtained by Heiles (1996) who analyzed optical polarization data for a large sample of stars, distant, but close to the Galactic plane. From the "railroad track" convergence of polarization directions he derived that the local inclination angle is $-7° \pm 4°$, when one takes into account the curvature of field lines. Heiles concludes that the local direction of the magnetic field disagrees with the generally adopted spiral arm angle of $-12.5°$. However, each different tracer of the spiral arm has a different bias, so a multi-tracer study is to be preferred.

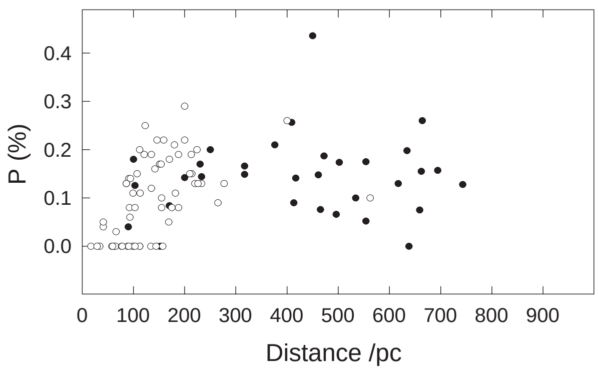

Fig. 4. Polarization vs. distance in the region encompassing Markkanen's cloud. We have added older observations by Appenzeller, Markkanen, and Haikala as open circles.

It is useful to know a few reference directions: (1) the longitude $l = 90°$ corresponds to the equatorial direction angle $123° - 90° = 33°$, (2) the direction of the inner edge of the local spiral spur is about $60°$, which corresponds to the equatorial direction angle $63°$, and (3) the expected global magnetic field direction is $123° - 78° = 45°$.

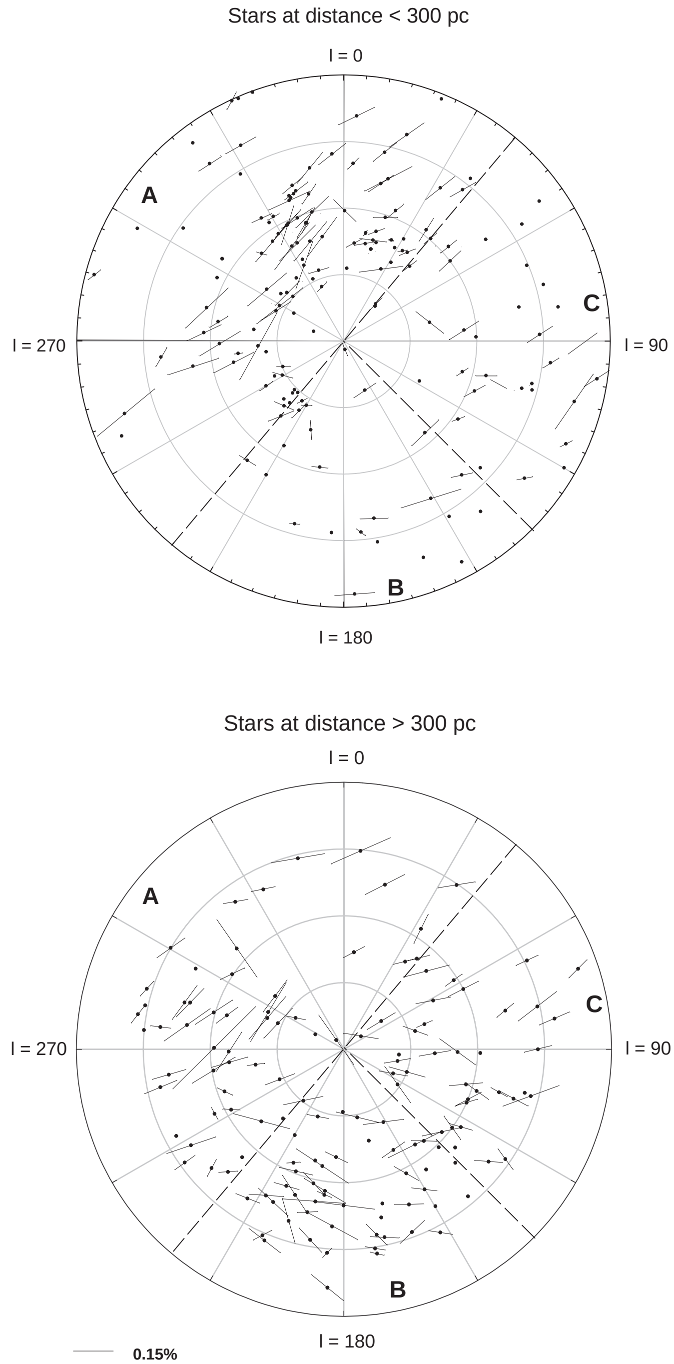

Fig. 5. Polarization maps for close (< 300 pc) and distant (> 300 pc) stars.

5. Revisiting Markkanen's cloud

In an important early polarimetric study of the NGP region, for stars generally brighter than 9 mag and closer than 250 pc, Markkanen (1979) concluded that "in the last quadrant $l = 270° - 360°$ there is a cloud or cloud complex with $A_V \geq 0\overset{\mathrm{m}}{.}1$ at a distance of about 100–200 pc." This agreed with an earlier conclusion based on stellar reddenings (Hilditch et al. 1976). Furthermore, Markkanen noted that the cloud, seen as an area of high (up to 0.3 percent) polarization, coincided with an area of denser neutral hydrogen, elongated generally parallel to the magnetic field in that area. With our much more extensive data it is interesting to take a new look at Markkanen's cloud, the polarization that it causes, and to determine more accurately the magnetic field direction inside it.

Markkanen's observations were mainly restricted to $b > 80°$. Later Haikala (1979; also Berdyugin et al. 2000) observed with the same telescope 50 more stars. These measurements showed that Markkanen's high polarization region extends towards $l = 0°$ at least down to $b \approx 75°$. On the other hand, our map shows that the region of high and aligned polarization extends below $b = 80°$ also towards the third quadrant. Hence we have defined an extended area which encompasses Markkanen's original cloud.[3] It is elongated roughly parallel to $l \approx 50°$, making it almost along the Local Spiral spur, and as noted in Paper I, close to its inner edge.

Fig. 3a shows the histogram of polarization position angle inside the region of thus defined Markkanen's cloud. The maximum around $70°$ corresponds to an equatorial direction parallel to $l \approx 123° - 70° = 53°$. Note the near absence of position angles in the range $100° - 180° - 20°$.

Fig. 4 shows the polarization percentage versus distance for the stars in Markkanen's region. At about 100 pc the polarizations rather abruptly increase, both the older measurements by Markkanen and others and the few new measurements by ourselves. Hence the cloud begins at a distance of about 100 pc. The IRAS map suggests a filamentary structure (Sect. 7) with

[3] $250° < l < 300°$, $75° < b < 85°$ & $300° < l < 330°$, $80° < b < 85°$ & $330° < l < 360°$, $75° < b < 85°$ & $0° < l < 30°$, $70° < b < 80°$.

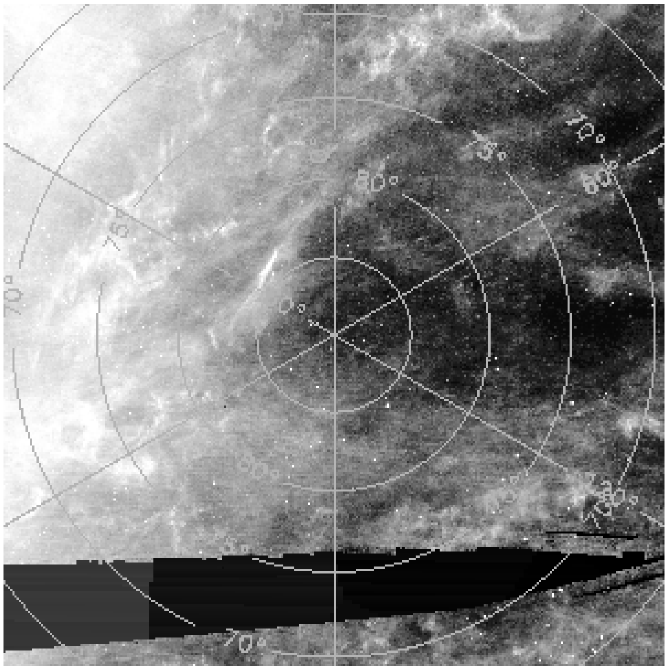

Fig. 6. The IRAS 100 micron map around the North Galactic Pole, down to $b = 70°$ (Wheelock et al. 1991). One may in many places see a correspondence between polarization alignments and filamentary structure.

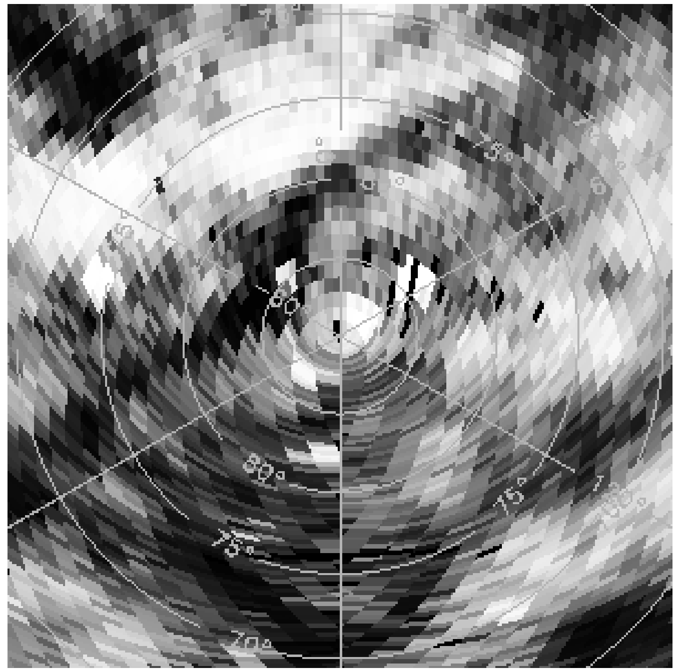

Fig. 7. The soft X-ray (0.25 keV) ROSAT map of the northern galactic polar region (same scale as in Fig. 6). Reference: Snowden et al. 1995. Note the deep shadow cast by Markkanen's cloud and other structure.

the filaments about 1–2 deg wide, at 100 pc corresponding to about 5 pc.

The existence of zero-polarization stars in Markkanen's region above 100 pc (Fig. 4) may be due to such a structure (plus the nearly empty Local Bubble in the foreground), allowing one to see some stars between the filaments. Note that beyond 170–180 pc all stars have non-zero polarization, hence every line of sight traverses some filament.

6. What happens around $l \approx 190°, b = 75° - 83°$?

A group of distant stars (> 300 pc; Fig. 5) in Sector B show a well defined alignment of polarization vectors. The distribution of their position angle is shown as hatched in Fig. 3b, the subsector defined as one half of B: $220° > l > 173.5°$. Closer stars in this region are almost unpolarized. This suggests that there is little diffuse dust up to 200–300 pc, beyond which a cloud is encountered. It produces about the same amount of polarization as Markkanen's cloud, but the polarization direction is roughly perpendicular. Note that this same direction is visible also for several stars in Sector C, close to the border between B and C. This existence and partial overlap of two quite different polarization directions close to the inner edge of the Local Spiral spur is very interesting. It seems that in their purest these directions are revealed by Markkanen's cloud and by the more distant source of polarization in Sector B, respectively. Neither of these directions corresponds to the global magnetic field, but more nearly to the LS and almost perpendicular to it.

7. Comparison with the IRAS map

The IRAS/ISSA full-sky maps of infrared emission at different wavelengths have provided a wealth of information on the diffuse Galactic dust having the temperature of about 20 K. At high latitudes the 100 micron map is correlated with neutral hydrogen HI emission, and has been used as a means of deriving reddening corrections (Schlegel et al. 1998). We reproduce the IRAS map around the North Pole, down to $b = 70°$, in Fig. 6. One may immediately note the following features:

* Markkanen's alignment coincides with elongated filamentary structure on the IRAS map. The filaments have about the same direction as the polarization vectors. They make a border between the bright diffuse emission region and the much fainter area which extends towards the 1st and 2nd galactic quadrants in the direction of the LS (i.e. to the right on the map).
* The region around $l = 190°$, $b = 75° - 83°$ where we find a concentration of distant stars with a good polarization angle alignment is also relatively bright on the IRAS map. It is probably inside the Local Spiral spur, being away from the Sun towards the Galactic anticentre.
* If anywhere, only in the faint IRAS region ($\approx$ Sector C) the polarization vectors of distant stars tend to suggest some alignment in the direction of the global magnetic field (parallel to $l \approx 78°$). In fact, if one takes Sector C and the right half of Sector B (the unhatched part of the histogram in Fig. 3b plus the histogram in Fig. 3c) there is a pronounced maximum centered in the P.A. direction $40° - 60°$, containing the global direction $45°$.

8. Discussion and conclusions

Markkanen (1979) already noted that the HI map had an elongated feature coinciding with the polarizing cloud that he identified. The IRAS 100 micron map shows the same thing and enforces the impression of filamentary structure in this part of the polar region. Our polarization map confirms that the direction of the magnetic field follows well the filaments, which seem to belong to the category termed by Vallée (1997) as "narrow magnetized features".

8.1. The soft X-ray shadow of Markkanen's cloud

The inferred proximity of Markkanen's cloud, apparently on the border of the Local Bubble, makes one expect that its HI gas would reveal itself via the absorption of soft X-rays arriving beyond it. Such shadowing effects have been found for compact clouds (e.g. Snowden et al. 1991, Burrows & Mendenhall 1991, Snowden et al. 1993) and there is generally an anticorrelation between HI emission and soft X-ray background. In order to see, at least qualitatively, the effect of Markkanen's cloud and other structure's on soft X-rays, we have produced the polar portion of the ROSAT RASS 0.25 keV map in Fig. 7.

Indeed, Markkanen's cloud is very well revealed by its X-ray shadow. It is seen to extend all across the polar cap, and what we call Markkanen's cloud is actually a part of a long narrow structure. The polarized patch in sector B also coincides with a faint X-ray area, so the cloud at the inferred distance of about 300 pc seems to absorb soft X-rays as well. In fact, just below $b = 75°$ there is a clear elongated shadow in the direction of typical polarization of the patch. Unfortunately, the polarization measurements are scarce towards lower latitudes. It will be important to fill this and other gaps in the polar region with new polarization measurements.

8.2. Different field directions

Our original division of the polar region (in Paper I) into the three sectors A,B, and C, purely on the basis of polarization directions, has not lost its relevance when the data has increased. Sector A contains the nearby Markkanen's cloud, B contains many distant stars with about perpendicular polarization direction to that of Sector A, and C which according to the IRAS map contains little nearby diffuse dust shows a signature of the global magnetic field.

It is noteworthy that the different dominating polarization directions partly overlap. This should mean that there are two populations of clouds with different internal magnetic field directions. The line of sight mostly intersects only one cloud, hence on the map different directions may overlap. In fact, the magnetic field pattern classification by Vallée & Bastien (1996) contains among its 11 subclasses also cases where perpendicular to each other field directions may coexist. The cloud's magnetic field may be perpendicular to the regional magnetic field (Class D). In a filament of clouds, the magnetic field in individual clouds may be perpendicular to the field of the filament (Class H, if the field of the filament is aligned along the filament; Class I, if the field of the filament is perpendicular to the filament). Naturally, it requires more polarization measurements and better distance estimates to make a more detailed analysis of the magnetic field configuration. In fact, there are still several tens of NGP stars with HIPPARCOS parallaxes, for which polarization has not been measured. Our work has, on its part, confirmed that the north pole region is a rich source of information and deserves to be studied with all available means.

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