

Polarization Surveys of the Galaxy

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Abstract. We report on sensitive $\lambda 21$ cm and $\lambda 11$ cm polarization surveys of the Galactic plane carried out with the Effelsberg 100-m telescope at arcmin angular resolution and some related work. Highly structured polarized emission is seen along the Galactic plane as well as up to very high Galactic latitudes. These observations reflect Faraday effects in the interstellar medium. Polarized foreground and background components along the line of sight, modified by Faraday rotation and depolarization, add in a complex way. The amplitudes of polarized emission features are highly frequency dependent. Small-scale components decrease in amplitude rapidly with increasing frequency. We stress the need for sensitive absolutely calibrated polarization data. These are essential for baseline setting and a correct interpretation of small-scale structures. Absolutely calibrated data are also needed to estimate the high-frequency polarized background. A recent study of polarized emission observed across the local Taurus-Auriga molecular cloud complexes indicates excessive synchrotron emission within a few hundred parsecs. These results suggest that possibly a large fraction of the Galactic high latitude total intensity and polarized emission is of local origin.

SURVEY HISTORY

Survey work has a tradition at the Max-Planck-Institut für Radioastronomie in Bonn. At first there are the all-sky surveys at 408 MHz ($\lambda 73$ cm, Haslam et al. [1]) and the recently completed $\lambda 21$ cm all-sky survey (Reich [2], Reich & Reich [3] and Reich et al. [4]). Both surveys have a comparable angular resolution of 0.8° or 0.6° . Their sensitivities of 2 K or 0.05 K match for spectral studies of the Galactic synchrotron emission. Higher angular resolution surveys at $\lambda 21$ cm and $\lambda 11$ cm were carried out with the Effelsberg 100-m telescope, but had to be limited to the Galactic plane because of the large amount of observing time needed. These and other survey data including all references are accessible via the internet at <http://www.mpifr-bonn.mpg.de/survey.html>.

Although a number of new total intensity surveys were carried out in the last two decades, polarization measurements were still just available from a number of long wavelengths surveys, where $\lambda 21$ cm is the shortest wavelength. These surveys were carried out in the sixties with the Dwingeloo 25-m telescope (Brouw & Spoelstra [5]). Although these data have rather moderate angular resolution they are quite carefully absolutely calibrated. The Dwingeloo surveys cover large sections of the northern sky, although they are not fully sampled. Large fractional polarizations are noted at high Galactic latitudes and a fairly smooth intensity and vector distribution is seen. Rotation Measures (RMs) are small in general. These results did not immediately trigger survey projects aiming for higher angular resolution.

The motivation for systematic polarization work at the Effelsberg telescope is mainly based on the unexpected $\lambda 11$ cm polarization results of Junkes et al. [6], which came out as a byproduct of the first section on the Effelsberg $\lambda 11$ cm Galactic plane survey (Reich et al. [7]). Beside polarized sources, like supernova remnants, these data show polarized emission patches with no apparent corresponding total intensity structure. These have to be associated to the unresolved diffuse background emission. It could be demonstrated by the anticorrelation of diffuse thermal emission and integrated polarized emission that a fraction of the emission must originate at a few kpc distance in the Galactic disk (Junkes et al. [8]). This indicates a highly structured interstellar medium, where "holes" with low Faraday effects allow a study of the Galactic magnetic field at large distances.

Sensitive high resolution polarization observations at $\lambda 90$ cm by Wieringa et al. [9] with the Westerbork telescope showed filamentary features on degree scales at high latitudes. Their origin has to be local. The total absence of enhanced synchrotron emission calls for an explanation by a local Faraday screen modifying the polarized background.

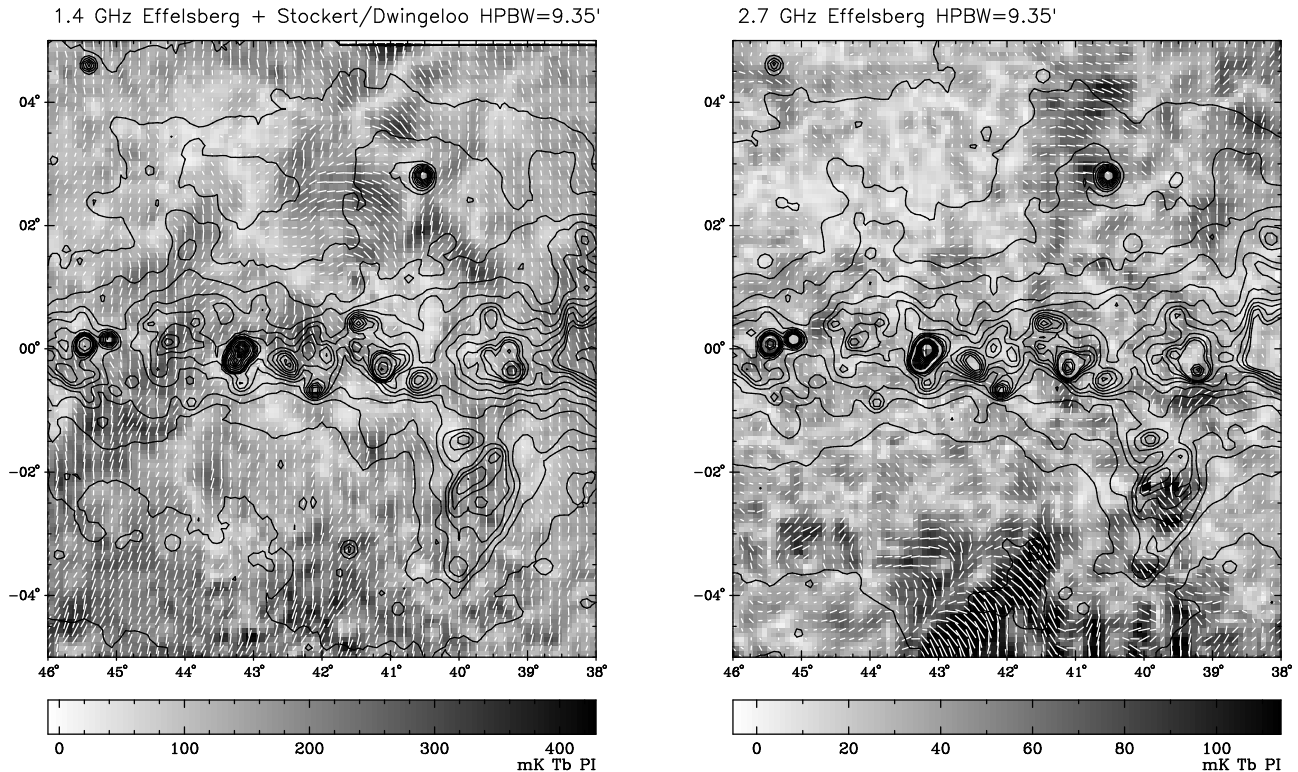


FIGURE 1. Section of the Galactic plane at $\lambda 21$ cm and $\lambda 11$ cm shown at the same angular resolution. The $\lambda 21$ cm map was absolutely calibrated both for total intensity and polarization using Stockert (Reich & Reich [3]) and Dwingeloo (Brouw & Spoelstra [5]) data, while the $\lambda 11$ cm map is not on an absolute scale. Polarized structures vary largely in intensity and angle.

However, a quantitative analysis has some difficulties. The detected filaments at $\lambda 90$ cm disappear at shorter wavelengths, which again strengthens the case of a Faraday screen. Because of the λ^2 dependence of the Faraday rotation even small RMs have large effects at long wavelengths. We refer to Sokoloff et al. [10] for a detailed discussion of Faraday effects.

GALACTIC PLANE SURVEYS INCLUDING POLARIZATION

From the Junkes et al. [6] $\lambda 11$ cm data it is obvious that low resolution data miss details of Galactic polarized emission. It is also clear that the fine structure is quite weak. The $\lambda 11$ cm survey data need some smoothing to obtain a sufficient signal-to-noise. Since the distribution of polarized emission is not predictable from total intensity we started in 1994 the " $\lambda 21$ cm Medium Galactic Latitude Survey" to map the Galactic plane within $\pm 20^\circ$ at $9'35''$ (HPBW) with a sensitivity equivalent to the total intensity confusion limit of 7 mJy/beam or ~ 15 mK T_b . This sensitivity was reached with an integration time of 2 sec per $4'$ pixel. Thus the surveyed area of ~ 7600 deg² needs ~ 1000 h of net integration time. Observations were exclusively done at night time otherwise polarized solar emission shows up, which was picked up by far sidelobes. Varying interference sometimes forces to stop observations for several months. Nevertheless, in September 2001 the survey is observed to $\sim 95\%$. Of course, the completion of data reduction needs some more time. Basic data of the survey are listed in Table 1.

The observing and calibration methods of the " $\lambda 21$ cm Medium Galactic Latitude Survey" were already described in detail by Uyaniker et al. [11]. These include some additional steps to the standard Effelsberg reduction, in particular reduction of spurious polarization from cross-talk and absolute calibration using Dwingeloo survey data (Brouw & Spoelstra [5]), where available. First maps of typical regions ranging from the first quadrant towards the Galactic anticentre region are shown by Uyaniker et al. [12]. The characteristics of the total intensity are a smooth dominating background with faint ridges, arcs and complex emission regions superimposed. Diffuse polarized emission is seen

TABLE 1. Basic observational parameters of the Effelsberg $\lambda 21$ cm and $\lambda 11$ cm polarization surveys of the Galactic plane

| Frequency [GHz] | 1.4 | 2.695 |
|-----------------|-----------------------------|------------------------|
| HPBW | 9'35 | 5'1 |
| RMS PI [mK] | 8 | 11 |
| L-Coverage | $\sim 30^\circ - 220^\circ$ | $4^\circ 9 - 76^\circ$ |
| B-Coverage | $\pm 20^\circ$ | $\pm 5^\circ$ |

everywhere. There are numerous polarized features without any associated total intensity structures. In particular remarkable depolarized loops, arcs and straight filaments are seen. These are most pronounced towards the anticentre direction, where the absolute intensities are low and the line of sight out of the Galaxy is short. The standard interpretation is the assumption of a highly polarized smooth background, which is seen through spatially varying Faraday screens. We refer to Uyaniker et al. [12] for maps illustrating these findings. A section of the Galactic plane is shown in Fig. 1.

In addition the work of Junkes et al. [6] was continued by analysing more polarization data of the Effelsberg $\lambda 11$ cm survey of the first quadrant, which was extended from the initial latitude coverage of $\pm 1.5^\circ$ to $\pm 5^\circ$ (Reich et al. [13]). The results of the analysis of the polarization data were published by Duncan et al. [14]. Figure 1 shows some data from that work at the angular resolution of the $\lambda 21$ cm survey. Duncan et al. [14] made also some comparison with the Parkes $\lambda 13$ cm polarization survey of the fourth quadrant (Duncan et al. [15]). The $\lambda 11$ cm maps show a clear increase of polarized emission with Galactic latitude where depolarization is smaller. This result strengthens the conclusion of Junkes et al. [8] on the kpc-origin of some polarized emission. Duncan et al. [14] noted an anticorrelation of polarized emission at longitudes between 20° and 45° with H I gas at kinematic distances in the range 2 kpc – 2.5 kpc, which requires the polarized emission to originate at the same or larger distances.

SOME FOLLOW-UP WORK

Meanwhile some follow-up observations of $\lambda 21$ cm and $\lambda 11$ cm polarization features have been started at $\lambda 6$ cm, although the required typical sensitivities of 1 mK and below limit observations to a few fields only. Some first results have been described by Reich et al. [16]. In brief: towards the first Galactic quadrant the situation appears rather complex. $\lambda 21$ cm, $\lambda 11$ cm (see Fig. 1), but also $\lambda 6$ cm polarization maps might differ largely in the sense that features visible at one wavelength disappear at the other, while new features show up. This indicates a superposition of numerous emission layers along the line of sight across the Galaxy, which is quite plausible when looking at the structured polarized emission towards the anticentre at $\lambda 21$ cm (Uyaniker et al. [12]), where the line of sight is much shorter. For a decomposition of these components observations at a denser sampling in wavelengths are required, but these are not yet available. Of course, narrow-band polarimetry within each available band will be quite helpful as well.

Towards the Galactic anticentre Reich et al. [16] find the situation to be less complex. For example: a ring-like structure of $\sim 1^\circ$ in diameter centered at $l, b = 192.2, 9.4$ was also visible in polarization at $\lambda 11$ cm and $\lambda 6$ cm, although it becomes very faint. A RM of $\sim 120 \text{ rad m}^{-2}$ was derived. RM is calculated from: $\text{RM} [\text{rad m}^{-2}] = 0.81 n_e [\text{cm}^{-3}] B_{\parallel} [\mu\text{G}] l [\text{pc}]$. Assuming distances between 0.5 kpc and 3 kpc for this feature, its size l is between 9 pc and 52 pc. Here a spherical shape is assumed. Upper limits for the electron density are 1.5 cm^{-3} or 0.6 cm^{-3} from the emission measure of less than 20 pc cm^{-6} set by the noise of the $\lambda 6$ cm total intensity signal. The magnetic field component along the line of sight calculates lower limits between $11 \mu\text{G}$ and $5 \mu\text{G}$. It is not clear what processes create such unusual magnetic-ionic structures high above the Galactic plane. We note that for this and similar features the spectrum of the polarized signal is steeper than the total intensity spectrum.

The Taurus-Auriga region and the local synchrotron emissivity

The $\lambda 21$ cm Medium Galactic Latitude Survey data from longitudes 150° to 190° and latitudes from -4° to -20° have recently been reduced and analysed by Wolleben [17]. This region includes the well studied Taurus-Auriga

and Perseus molecular cloud complexes, which are located at distances of ~ 140 pc and 350 pc. The molecular clouds are partly seen in superposition. CO survey data and IRAS data show highly structured emission across this area. Molecular gas and dust clouds are partly well correlated. There is an enhancement of polarized emission in the direction of these molecular cloud complexes. However, the total intensity smoothly increasing towards the Galactic plane but there is no indication of enhanced synchrotron emission. A number of discrete polarized features ranging between $\sim 0.3^\circ$ and 1° in diameter could be identified adjacent to molecular and dust clouds. This association suggests the existence of a Faraday screen at the same distance. Polarized emission originating behind the molecular material gets modified and adds with the foreground polarization in a different way than outside the Faraday screen. Wolleben [17] noticed for a number of polarized structures a clear systematic dependence of the polarization angle with polarized intensity. Nine objects including their surroundings were modelled assuming regular foreground and background polarization. The background emission is then subject to Faraday modulation towards the polarized feature. Pure Faraday rotation as well as Faraday rotation with correlated depolarization were considered and fitted to the polarization angle–polarized intensity relation. RMs of up to $\sim 30 \text{ rad m}^{-2}$ were derived, quite much for clouds of a maximum extent between 0.7 pc and 2.4 pc (distance 140 pc) or 1.8 pc to 6 pc (distance 350 pc). For a number of polarized features both models fit the data quite well and a second frequency is needed for a distinction between both models. The average of $\lambda 21$ cm polarized intensities in front and behind the nine the Faraday screens near the molecular clouds have values of ~ 220 mK at polarization angle 25° and 290 mK at -35° for the foreground and background components, respectively. Both components are related to a regular magnetic field. Both values are uncertain by ~ 100 mK and $\sim 20^\circ$, respectively. Interestingly, a rather similar jump in polarization angle is seen from stellar polarization data (Heiles [18]) in the range up to 200 pc and 200 pc to 500 pc. The E-vectors agree on average within 20° with those from the radio data, where the internal scatter is about the same.

Polarized intensity of ~ 0.5 K from a regular magnetic field originating within 0.5 kpc requires a total intensity synchrotron component of at least 0.7 K. This is a lower limit from the intrinsically polarized regular field. Estimates for the fraction of the regular magnetic field component range from 60% to 70% of the total field (see Beck [19] for a review and references). If these estimates also hold for the very local magnetic field the $\lambda 21$ cm synchrotron component raises to ~ 1 K within 0.5 kpc.

Beuermann et al. [20] have unfolded the $\lambda 73$ cm all-sky survey (Haslam et al. [1]) for a three-dimensional radio emission model of the Galaxy. They quote a local synchrotron emissivity of ~ 11.7 K/kpc, which they found to be in agreement with previous studies. This scales to ~ 0.3 K/kpc at $\lambda 21$ cm, which is significantly below the 1.4 K/kpc to 2 K/kpc for the local emissivity towards the Taurus-Auriga complex. In this direction the total Galactic emission above the cosmic microwave background is at the 2 K level. However, this very local synchrotron component depends strongly on the magnetic field direction and therefore is unlikely isotropic. It is interesting to note that the recently derived average local emissivity at 22 MHz by Roger et al. [21] is about three times higher than the value adopted by Beuermann et al. [20]. The Roger et al. [21] result is based on emission towards extended opaque HII regions at distances between 400 pc and 2.2 kpc.

Enhanced local emissivity implies that emission at high Galactic latitudes is more affected by small scale fluctuations in the interstellar medium. This is expected to be the case in particular for polarized emission. The thick disk shrinks in size and its smooth intensity distribution is less dominant. Cosmic microwave studies at high Galactic latitudes should take this result into account.

ABSOLUTE CALIBRATION

The Effelsberg survey maps have a relative offset resulting from the assumed "zero" at the edges of each individual observed field. Each field is observed twice in Galactic longitude and latitude direction. Just the strong emission of the Galactic ridge in the first quadrant requires to scan along latitude direction only. The fields at $\lambda 21$ cm and $\lambda 11$ cm have typical sizes of $\sim 10^\circ \times 10^\circ$ or $\sim 3^\circ \times 3^\circ$, respectively. The combined observations have an "average zero" at their boundaries. As described by Uyaniker et al. [11] the total intensity and polarization data were absolutely calibrated by available lower angular resolution data from the Stockert and the Dwingeloo 25-m telescopes. While the total $\lambda 21$ cm intensities could be completely corrected, the polarization data could not because of incomplete mapping, undersampling and low sensitivity. The correction effects at low latitude are largest for total intensities and low for polarization, while at high latitudes the situation is reverse. This is problematic, because the correct zero level in polarization is much less predictable than for total intensities. Stokes U and Q may have positive or negative values depending on the polarization angle $\phi = 0.5 \text{ atan}(U/Q)$ and the polarized intensity calculates from

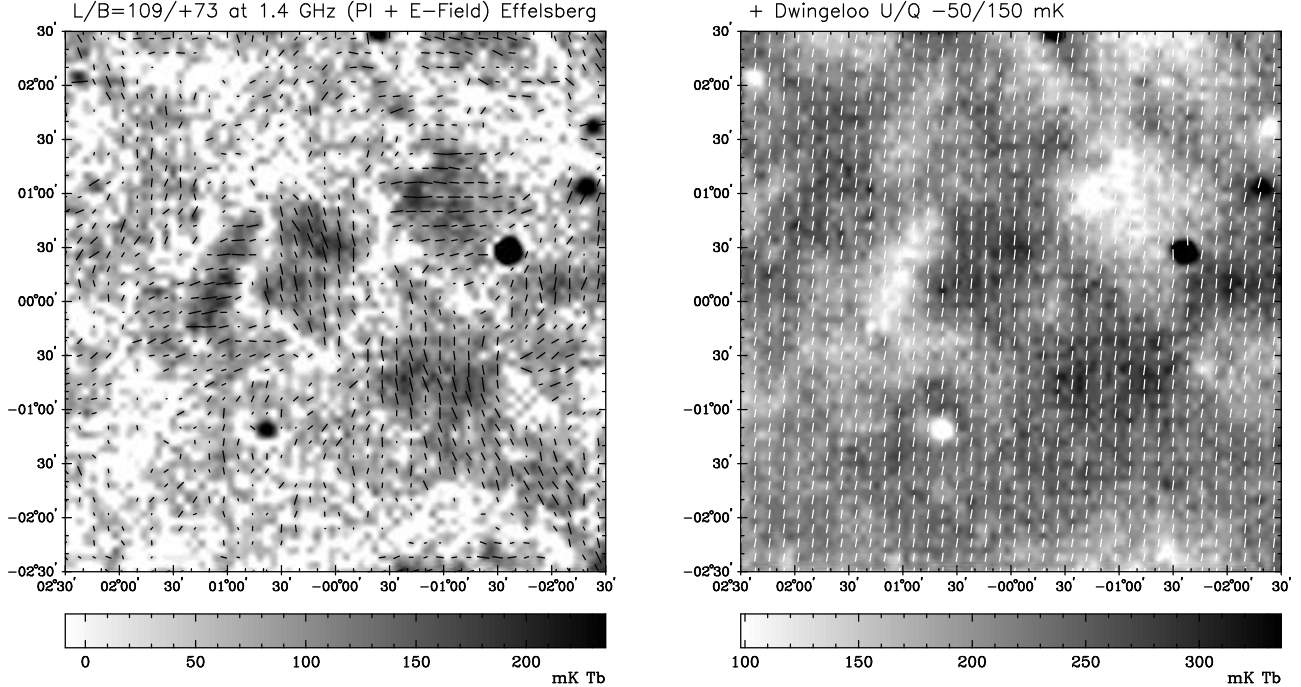


FIGURE 2. High latitude polarized emission at 1.4 GHz without (left) and with (right) large-scale structure added. Low-resolution absolutely calibrated Dwingeloo data were used to estimate the missing large-scale components of the Effelsberg data. Due to severe undersampling of the Dwingeloo data just constant offsets for U (-50 mK) and Q ($+150$ mK) have been added to the Effelsberg data. Depending on their polarization angle relative to the large-scale emission small-scale structures appear as enhancements or depressions superposed on the large-scale structure. A number of polarized sources are visible. The total intensity (not shown here) shows many compact sources in the field but no extended structures possibly related to the polarized features.

$(U^2 + Q^2)^{0.5}$. Adding large-scale dominating U and Q components with the same or the opposite sign converts a small-scale polarized emission feature into enhanced or reduced emission within the large-scale structure. Figure 2 shows an example of this effect: A high Galactic latitude $\lambda 21$ cm Effelsberg map with relative zero levels and with the large-scale components added. The large-scale structure entirely dominates. The average polarized emission from the Effelsberg map is about 8 mK, which is just 5% of the large-scale emission. However, the large-scale structure is estimated from a few data points near the observed field. These U and Q values were averaged and used to adopt the level of the Effelsberg U and Q maps. The uncertainty of the large-scale amplitudes is at least 30%. In addition, possible gradients in U and Q or fluctuations on scales of a degree or larger could not be taken into account.

The $\lambda 11$ cm total intensity data could be corrected for missing large-scale emission ($\geq 10^\circ$), while the polarization data from all fields were adjusted relative to each other. In fact it was shown by Duncan et al. [14] that the $\lambda 13$ cm Parkes data contain emission from larger scales, because the survey was combined from larger individual fields. The only indirect method to adopt large-scale polarized structure at shorter wavelengths than $\lambda 21$ cm is to extrapolate by assuming a spectral index for the polarized emission and to adopt a long wavelength RM in part available from the work of Brouw & Spoelstra [5]. New absolutely calibrated data at $\lambda 21$ cm at mK-sensitivity are needed, which may use the already existing Dwingeloo data for adjustment purpose, as was discussed by Reich & Wielebinski [22]. Also plans for sensitive $\lambda 6$ cm observations exist, where the angular resolution of a 25-m telescope matches that of the Effelsberg $\lambda 21$ cm observations. At $\lambda 6$ cm and shorter wavelengths extrapolation from the Brouw & Spoelstra [5] data seem irrelevant.

CONCLUDING REMARKS

We have discussed some work on polarized Galactic emission from the Effelsberg $\lambda 21$ cm and $\lambda 11$ cm surveys including some follow-up observations and analysis. Small-scale Faraday modulation causes highly fluctuating polarized or

depolarized structures. The origin of the corresponding magneto-ionic structures – enhancement of thermal electron density or compression of the magnetic field – remains open so far. Small-scale emission becomes rather faint at shorter wavelengths. The dominating polarized background appears to be smooth on degree scales and larger. It is likely the dominating component at short wavelength. Its investigation requires very sensitive absolutely calibrated measurements. This needs substantial efforts and much telescope time, but can be done with small (25-m class) telescopes. At high latitudes the contribution from polarized synchrotron emission originating within a few hundred parsecs appears to be larger than previously assumed and fluctuations in polarization are also visible at high latitudes not much different from those seen at low latitudes.

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