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Absolutely calibrated radio polarimetry of the inner Galaxy at 2.3 GHz and 4.8 GHz

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ABSTRACT

We present high sensitivity and absolutely calibrated images of diffuse radio polarisation at a resolution of about 10' covering the range 10° < l < 34° and |b| < 5° at 2.3 GHz from the S-band Parkes All Sky Survey and at 4.8 GHz from the Sino-German λ6 cm polarisation survey of the Galactic plane. Strong depolarisation near the Galactic plane is seen at 2.3 GHz, which correlates with strong Hα emission. We ascribe the depolarisation to spatial Faraday rotation measure fluctuations of about 65 rad m⁻² on scales smaller than 6–9 pc. We argue that most (about 90%) of the polarised emission seen at 4.8 GHz originates from a distance of 3–4 kpc in the Scutum arm and that the random magnetic field dominates the regular field there. A branch extending from the North Polar Spur towards lower latitudes can be identified from the polarisation image at 4.8 GHz but only partly from the polarised image at 2.3 GHz, implying the branch is at a distance larger than 2–3 kpc. We show that comparison of structure functions of complex polarised intensity with those of polarised intensity can indicate whether the observed polarised structures are intrinsic or caused by Faraday screens. The probability distribution function of gradients from the polarisation images at 2.3 GHz indicates the turbulence in the warm ionised medium is transonic.

Key words: ISM: magnetic fields – polarisation – radio continuum: general – radio continuum: ISM

1 INTRODUCTION

Polarised radio emission provides information on both the magnetic field at locations where the emission is generated and the magnetic field that pervades the ionised interstellar medium through which the emission then propagates. Therefore radio polarisation observations provide a unique probe of the Galactic magnetic field coupled with both thermal and relativistic electrons.

The magneto-ionic medium (MIM) modulates the linearly polarised emission that propagates through it via Faraday rotation. The polarisation angle of the emission is rotated by an amount proportional to the wavelength squared, with the coefficient defined as rotation measure (RM). RM is calculated as the integral of the magnetic field strength parallel to the line of sight weighted by thermal electron density and the integral is assessed from the source to the observer. Diffuse polarised emission at different locations along the line of sight or across the observation beam can experience different rotations, and adding up all the emission can thus cancel partly or completely the polarisation (“depolarisation”; e.g. Sokoloff et al. 1998).

The degree of depolarisation clearly depends on observational frequency. The higher the frequency, the weaker the depolarisation and the deeper we can thus penetrate into the Galactic interstellar medium. This implies that multi-
frequency polarisation observations can let us extract a series of slices from the MIM and thus gain a 3D view of the MIM.

Depolarisation also depends on direction. In the Galactic plane, particularly towards the inner Galaxy, RMIs and their spatial variations are both very large (e.g. Brown et al. 2007) because lines of sight cross many spiral arms. Therefore high frequency observations are required to detect diffuse polarised emission coming from large distances near the Galactic plane. In contrast, towards high Galactic latitudes, RMs are much smaller (Taylor et al. 2009) and diffuse polarised emission can be observed at low frequencies (e.g. Bernardi et al. 2013, at 189 MHz).

Currently there are many radio polarisation surveys available covering a broad frequency range. Examples of Galactic plane polarisation surveys are the Sino-German A6 cm polarisation survey (e.g. Sun et al. 2011), the Effelsberg 2.7 GHz survey (Duncan et al. 1999), the Parkes 2.4 GHz survey (Duncan et al. 1997), the Canadian Galactic Plane Survey at 1.4 GHz (CGPS, e.g. Landecker et al. 2010), and the Southern Galactic Plane Survey at 1.4 GHz (SGPS, e.g. Haverkorn et al. 2006). Examples of all-sky radio polarisation surveys including the Galactic plane are the WMAP all-sky surveys (Hinshaw et al. 2009), the S-band Polarisation All Sky Survey (S-PASS, Carretti 2010), and the 1.4 GHz all-sky survey (Wolleben et al. 2006; Testori et al. 2008). Ongoing surveys such as the Galactic Magnetic Medium Survey (GMIMS, Wolleben et al. 2010) and the Galactic Arecibo L-band Feeds Array Continuum Transit Survey (GALFACTS, Taylor & Salter 2010) using multichannel polarimetry and RM synthesis (Brentjens & de Bruyn 2005), will be able to reveal polarised emission at a wide range RMs, and therefore will further advance our understanding of the Galactic interstellar medium.

All the Galactic plane surveys share a common feature – most of the structures seen in polarisation, such as “voids”, “canals” and “patches”, do not have corresponding structures in total intensity, irrespective of frequency, resolution and telescope (whether single dish or synthesis array). Broadly, there are two possible mechanisms for these structures. The first possibility is that the random magnetic fields dominate over the regular fields in the emitting region and produce the observed polarised intensities (e.g. Sun et al. 2011). The random fields can be either anisotropic (e.g. Fletcher et al. 2011; Jaffe et al. 2011; Jansson & Farrar 2012) or isotropic but with a non-zero energy spectrum (Sun & Reich 2009). The second possibility is that the background polarised emission is smooth in spatial distribution, but foreground Faraday screens impose Faraday rotation and hence produce the structures in polarisation. The Faraday screens could be either diffuse warm ionised medium with jumps or cusps in electron density caused by MHD turbulence (Gaensler et al. 2011) or discrete objects such as Hi regions and others whose properties still remain unclear (Gaensler et al. 2001; Sun et al. 2011). The first scenario is intrinsic to the emitting regions and the second is extrinsic. The two mechanisms are best diagnosed at high and low frequencies, respectively. This reinforces the importance of having a wide frequency coverage to simultaneously investigate both mechanisms.

In this paper, we focus on the region $10^\circ < l < 34^\circ$ and $|b| < 5^\circ$, which is covered by both S-PASS (Carretti 2010) and the Urumqi survey (Sun et al. 2011) providing absolutely calibrated, high resolution and sensitivity observations at 2.3 GHz and 4.8 GHz. This is the only part of the Galactic plane where such kinds of dataset are currently available, allowing us to investigate different layers of the MIM. These two frequencies are ideal as the high frequency ensures intrinsic polarised emission can be detected while the low frequency results in depolarisation, so that different layers can be separated.

The paper is organised as follows. We show the observational data and describe the polarisation images in Sect. 2. We present the discussions on diffuse polarised emission, the branch extending from the North Polar Spur (NPS) and statistical studies of the polarisation images in Sect. 3. We give our conclusions in Sect. 4. Throughout the paper, all coordinates are Galactic and the intensities are presented as main beam brightness temperatures (see e.g. Wilson et al. 2012).

2 OBSERVATIONAL DATA

We show both total intensity and polarisation data in this section, but most of the discussion will be focused on polarisation. We mainly use 2.3 GHz data taken from the S-PASS (Carretti 2010) observed with the Parkes 64-m telescope and 4.8 GHz data taken from the Sino-German A6 cm polarisation survey of the Galactic plane (Sun et al. 2011) observed with the Urumqi 25-m telescope. The polarisation data at both 2.3 GHz and 4.8 GHz have been absolutely calibrated to cover structures of all angular scales down to the resolution. We also investigate 2.7 GHz data taken from the Galactic plane survey (Duncan et al. 1999) with the Effelsberg 100-m telescope.

2.1 The Parkes 2.3 GHz data

A brief introduction to S-PASS was given by Carretti (2010) and a detailed description as well as the data release will be presented in a forthcoming paper (Carretti et al. in prep.). The observations were conducted in fast long azimuthal scans and were absolutely calibrated by modelling variations of $U$ and $Q$ versus parallactic angle (Carretti 2010). The original resolution was 8.9. In this paper $I$, $Q$ and $U$ data have all been slightly smoothed to 10/75, and the resulting rms sensitivity in polarised intensity is about 0.3 mK per beam-sized pixel.

2.2 The Urumqi 4.8 GHz data

The Sino-German A6 cm polarisation survey of the Galactic plane\(^1\) was summarised by Han et al. (2012) and the results for the longitude range $10^\circ < l < 60^\circ$ were presented by Sun et al. (2011). The observations consist of many longitude scans of typical size $2^\circ \times 10^\circ$ and latitude scans of typical size $7^\circ \times 2^\circ$. The final maps after combining these orthogonal scans miss structures larger than about $10^\circ$. Absolute calibration was derived by tying the levels of large-scale structures in $U$ and $Q$ to the WMAP K-band (22.8 GHz) data, through a process described in detail by Sun et al. (2011).

\(^1\) http://zmtt.bao.ac.cn/6cm
In this paper, we redo the absolute calibration using the recently released nine-year WMAP data (Bennett et al. 2013). The original resolution is 9.5. We have slightly smoothed the data to the same resolution as the Parkes 2.3 GHz data. The sensitivity in polarisation is about 1 mK.

### 2.3 The Effelsberg 2.7 GHz data

The Effelsberg 2.7 GHz survey (Reich et al. 1990; Duncan et al. 1999) extended the earlier survey by Junkes et al. (1987) from $|b| = 1.5$ to $|b| = 5^\circ$. The data are public at...
the MPIfR Survey Sampler\(^2\). The observations were composed of many sections of $3^\circ \times 3^\circ$. The intensity levels of the final maps were set to satisfy the average of $U$ and $Q$ to be zero. No absolute calibration has been made to the data. The original resolution was 4'. The data have also been smoothed to a resolution of 10'.75 and the sensitivity in polarisation is about 6 mK.

2.4 Main features

The total intensity maps for the Parkes 2.3 GHz, the Effelsberg 2.7 GHz and the Urumqi 4.8 GHz data are shown in

\(^{2}\) http://www.mpif-bonn.mpg.de/survey.html
Fig. 1 from top to bottom. With the exception that more diffuse emission at high latitudes can be seen at 2.3 GHz than at 2.7 GHz and 4.8 GHz, the three maps show nearly the same features. Discrete sources including extragalactic sources, H ii regions and supernova remnants are embedded in a bright ridge extending from the middle Galactic plane to high latitudes.

The images of linearly polarised emission \( p = \sqrt{Q^2 + U^2} \) from the three surveys are displayed in Fig. 2. The thin layer of polarised intensity at 2.3 GHz around the Galactic plane is caused by instrumental polarisation leakage. The two bright polarisation blobs appearing in all the images at \((15^\circ, -0^\circ)\) and \((16^\circ, +0^\circ)\) are residuals of off-axis instrumental polarisation leakage from the bright H ii regions Sh 2-45 and Sh 2-49, which is less than 1.5% at 2.3 GHz and less than 1% at 4.8 GHz. The on-axis polarisation leakage is about 0.4% at 2.3 GHz (e.g. Carretti et al. 2010) and 0.7% at 4.8 GHz. A detailed description of the instrumental polarisation for S-PASS will be presented in a forthcoming paper (Carretti et al. in prep.). For diffuse emission, the instrumental polarisation leakage is generally not important.

We can see little resemblance between the total intensity and polarisation images at each individual frequency, as has already been noted in many previous surveys. In contrast with total intensity, polarisation images show totally different morphologies at different frequencies.

Polarisation patches as well as low polarisation voids and canals prevail in the Urumqi 4.8 GHz data. In contrast, in the Parkes 2.3 GHz and Effelsberg 2.7 GHz data, there is nearly no polarisation near the Galactic plane. Polarised emission towards a branch which is the low latitude extension of the North Polar Spur (NPS) can be identified in the Urumqi 4.8 GHz data from \((2^\circ 3^5, +5^\circ)\) to \((2^\circ 7, +2^\circ 7)\) (Fig. 2). However, in the Parkes 2.3 GHz data, only fragments of the upper part of the polarised branch are visible. It is also interesting to note that the Effelsberg 2.7 GHz image looks very similar to the Parkes 2.3 GHz image although the former is not absolutely calibrated. These points will be discussed in Sect. 3.

3 DISCUSSION

In this section, we try to answer the following questions: What causes the polarised structures in the Parkes 2.3 GHz and the Urumqi 4.8 GHz data? Can we constrain properties of the Galactic magnetic field from these polarised structures? Is the NPS local or much further away? Why do the 2.7 GHz data without absolute calibration look similar to the 2.3 GHz data with absolute calibration? Are the 2.3 GHz and 4.8 GHz data statistically different?

3.1 The origin of polarised structures

3.1.1 Polarised structures in the Urumqi 4.8 GHz data

Sun et al. (2011) argue that the polarised emission in the longitude range \(10^\circ < l < 60^\circ\) near the Galactic plane at 4.8 GHz originates from a distance less than about 4 kpc. We collected data of pulsars falling in the range \(10^\circ < l < 34^\circ\) and \(|b| < 5^\circ\) from the ATNF pulsar catalogue (Manchester et al. 2005), version 1.45. RMs of these pulsars versus their distances calculated using the NE2001 thermal electron density model (Cordes & Lazio 2002) are shown in Fig. 3. It is clear that pulsar RMs start to exhibit large fluctuations at a distance of about 4 kpc. These fluctuations \(\sigma_{RM} \approx 500 \text{ rad m}^{-2}\) are sufficient to completely destroy polarised emission from beyond 4 kpc at 4.8 GHz either through depth or beam depolarisation (Sokoloff et al. 1998). The argument is also supported by simulations based on 3D-emission models of the Galaxy (Sun et al. 2008; Sun & Reich 2010) showing that polarised emission stops increasing beyond a distance of about 4 kpc (Sun et al. 2011, their Fig. 4). We therefore conclude that the polarised emission at 4.8 GHz originates from within 4 kpc.

In Fig. 4, we indicate the longitude range \(10^\circ < l < 34^\circ\) covered by both the Parkes 2.3 GHz data and the Urumqi 4.8 GHz data on a sketch of the spiral arm pattern of the Milky Way Galaxy which was constructed in 2008 according to most of the known observational data (e.g. Urquhart et al. 2011). The distance of 4 kpc towards this direction corresponds to the middle or the inner edge of the Scutum arm. We will show in Sect. 3.1.2 that the polarised emission at 4.8 GHz actually is confined to the Scutum arm instead of being distributed uniformly along lines of sight.

The polarised emission at 4.8 GHz manifests itself as patchy structures. One explanation involving Faraday effects is that the polarised emission is smoothly distributed with total intensity. However, there might be larger foreground RM fluctuations towards some regions arising from irregularities in the interstellar medium, and these cause depolarisation in the form of voids or canals. The smooth background polarised emission is thus broken into patches. According to Fig. 3, the RMs for pulsars within 4 kpc have a standard deviation of only 44 rad m\(^{-2}\) (the outlier of \(-303 \text{ rad m}^{-2}\) was discarded). These RM fluctuations only produce polarisation angle fluctuations of about \(10^\circ\), which is too low to cause depolarisation at 4.8 GHz. This means that foreground Faraday screens cannot produce the polarisation patches observed.

Most of the polarised structures at 4.8 GHz therefore must be intrinsic, and either caused by fluctuations in cosmic ray electrons or magnetic fields. With a typical lifetime of about \(10^7\) yr for cosmic ray electrons emitting at 4.8 GHz in a magnetic field of several \(\mu G\) and a diffusion coefficient of...
where $\bar{s}$ sight, and of average regular magnetic field perpendicular to the line of
is assumed to be netic fields. Here the spectral index of synchrotron emission
not correspond to smooth total intensity. There are three
patches should be around zero at 4.8 GHz. This, however, is
2008), it is expected that polarisation angles towards all the
inter-arm regions. We therefore ascribe the polarised struc-
tion length of about 3 kpc. This means cosmic ray electrons
by Sokoloff et al. (1998), we
Figure 4. Artist’s conception of the Milky Way (R. Hurt:
about $10^{28}$ cm$^2$ s$^{-1}$ (Fletcher et al. 2011), we derive a diffusion
length of about 3 kpc. This means cosmic ray electrons are
nearly uniformly distributed across the spiral arm and
inter-arm regions. We therefore ascribe the polarised structures to
to magnetic fields. Following Sokoloff et al. (1998), we
represent total intensity ($I$) and polarised intensity ($p$) as
\begin{equation}
I \propto B_x^2 + B_y^2 + \sigma_x^2 + \sigma_y^2
\end{equation}
where $B_x$ and $B_y$ stand for the two orthogonal components of
average regular magnetic field perpendicular to the line of
sight, and $\sigma_x$ and $\sigma_y$ stand for the strength of random mag-
netic fields. Here the spectral index of synchrotron emission is
assumed to be $\alpha = -1$ for simplicity, but the discussions below
will not be affected if the spectral index is different.
According to Equation (1), we shall keep $I$ constant and let $p$
varies in order to generate polarised patches which do
not correspond to smooth total intensity. There are three
ways to achieve this:

- Regions where regular magnetic fields dominate produce polarised patches, while regions where isotropic random magnetic fields ($\sigma_x = \sigma_y$) dominate cause low polarisation
voids or canals. For all the regions, the sum of squared
regular and random fields are similar so that the total inten-
sity is smooth. Since the polarised patches correspond to
regular magnetic fields which are coherent over a large spa-
tial scale and mainly parallel to the plane (e.g. Sun et al.
2008), it is expected that polarisation angles towards all
the patches should be around zero at 4.8 GHz. This, however, is
not supported by the polarisation angle map presented by
Sun et al. (2011). This scenario is thus not favoured.
- The random magnetic field is dominant and anisotropic.
If the field is isotropic, no polarisation is generated. If to-
wards some regions the field is anisotropic, namely $\sigma_x \neq \sigma_y$,
polarised patches will be produced. The anisotropy can be
caused by compression or shear motions of gas (Jaffe et al.
- The random magnetic field is dominant and isotropic.
The field also has a non-zero, such as Kolmogorov-like (spect-
tral index is $-11/3$), energy spectrum so that coherent struc-
tures such as polarised patches could be formed over the
inertial scale of the turbulence (Sun & Reich 2009). Canals
actually mark the overlap regions of patches where polarised
emission partly or completely cancels.
The last two scenarios are both possible and they both re-
quire the random magnetic fields to be much stronger than the
regular fields.

3.1.2 Polarisated structures in the Parkes 2.3 GHz data
There is much less polarised emission near the Galactic plane
in the Parkes 2.3 GHz data than in the Urumqi 4.8 GHz
data (Fig. 2), indicating strong depolarisation at 2.3 GHz.
The depolarisation depends on frequency and therefore must
stem from Faraday rotation effects (Sokoloff et al. 1998).
Faraday rotation is related to thermal electrons that can be
._cised by Hα emission. We extract the Hα image from the
synthetic all-sky map by Finkbeiner (2003) which is mainly
from SHASSA (Gaustad et al. 2001) in this direction. In
Fig. 5 we show the Parkes 2.3 GHz data overlaid with the
Hα emission.

The anti-correlation between Hα emission and polarised intensity is very pronounced in Fig. 5. This indicates that the
warm ionised gas traced by the Hα emission acts as Far-
day screens to impact the depolarisation, although strong
extinction in the Galactic plane means only nearby ionised
gas has been observed. Several Hii regions bright at both ra-
dio total intensity (Fig. 1) and Hα are located at distances
of 2–3 kpc such as Sh 2-45 (15'0, $-0\circ6$7) at about 2.2 kpc, Sh
2-49 (16'9, +0'8) at about 2.6 kpc and Sh 2-54 (18'6, +1'9)
at about 2.5 kpc. However, the Hii region at (18'2, $-0\circ3$) at
a distance of 3.8 kpc is only visible in radio total intensity
maps but not in Hα probably due to extinction. All the
distances are from the compilation by Hou et al. (2009) with a
Galactocentric solar radius of $R_0 = 8.5$ kpc. In the following
discussions, we assume all the Hα emission is from a distance
of 2–3 kpc, which could be located in either the Sagittarius
arm or the Scutum arm (Fig. 4). A similar analysis has been
carried out by Carretti et al. (2013).

Faraday rotation mainly causes two types of depolarisa-
tion relevant in our observations: depth depolarisation and
beam depolarisation (Sokoloff et al. 1998). Depth depolaris-
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Figure 5. Polarised intensity from the Parkes 2.3 GHz data in cyan overlaid with Hα intensity from Finkbeiner (2003) in red.

Figure 6. Depolarisation factor (DF) calculated from the Parkes 2.3 GHz and the Urumqi 4.8 GHz data according to Equation (2). Regions where the polarised intensity at 4.8 GHz is less than 5σ are masked.

The Hα emission in Fig. 5 mainly consists of discrete structures which can be related to HII regions. Therefore there is no mixture of thermal and non-thermal medium, and only beam depolarisation accounts for the depolarisation in the Parkes 2.3 GHz data. We can then conclude that the fluctuation scale for RMs is smaller than 6–9 pc given the beam width of 10′.75 and the distance of 2–3 kpc. This fluctuation is probably induced by stellar sources in the arms with an energy injection scale of about 10 pc (Haverkorn et al. 2008).

To quantitatively describe depolarisation at 2.3 GHz, we define the depolarisation factor (DF) as

\[
DF = \frac{p_{2.3}}{p_{4.8}} \times \left( \frac{4.8}{2.3} \right)^\beta, \tag{2}
\]

where \(p_{2.3}\) and \(p_{4.8}\) are polarised intensity at 2.3 GHz and 4.8 GHz, respectively, and \(\beta\) is spectral index for brightness temperature \((T \propto \nu^\beta)\). The depolarisation factor describes how much of the polarised emission extrapolated from 4.8 GHz is observed at 2.3 GHz. The smaller the depolarisation factor, the more significant the depolarisation is.

The DF maps calculated from the Parkes 2.3 GHz and the Urumqi 4.8 GHz data are shown in Fig. 6. Here we have followed Sun et al. (2011) to take \(\beta = -3.1\) which is calculated from the WMAP 22.8 GHz and 33 GHz polarised intensity. The mean depolarisation factor measured from the low polarisation area at 2.3 GHz overlapping with Hα emission (Fig. 5) is about 10%. This means that 90% of the polarised emission has been depolarised at 2.3 GHz and thus must be located behind the warm ionised gas at 2–3 kpc traced by Hα emission (Fig. 5). We also know that polarised emission is produced within 4 kpc from Sect. 3.1.1. This means towards \(10^\circ < l < 34^\circ\) most of the polarised emission at 4.8 GHz comes from the Scutum arm at a distance of 3–4 kpc and the turbulent magnetic field dominates over the regular field in the arm to cause the patchy structures seen at 4.8 GHz (Fig. 2).
intensities corresponding to a spectral index $\beta$.

Figure 7. Polarisation images covering the NPS low latitude extension from the Parkes 2.3 GHz data (left) and the Urumqi 4.8 GHz data (right) overlaid with bars indicating $B$ vectors (polarisation angle plus 90$^\circ$). The two colour ranges have been scaled so that polarised intensities corresponding to a spectral index $\beta = -3.1$ have the same colours.

For beam depolarisation, the fraction of polarisation is proportional to $\exp(-2\sigma_{\text{RM}}^2 \lambda^2)$ (e.g. Burn 1966), where $\sigma_{\text{RM}}$ is the RM fluctuation within the beam. We can then represent the depolarisation factor as

$$\text{DF} = \exp(-2\sigma_{\text{RM}}^2 (\lambda_2^2 - \lambda_1^2)).$$

(3)

The depolarisation factor of about 10% implies an RM dispersion $\sigma_{\text{RM}} \approx 65$ rad m$^{-2}$ on scales of less than 6–9 pc. Gaensler et al. (2001) obtained a value of 35–50 rad m$^{-2}$ towards the region (332$^5$, +1$^2$) based on the depolarisation factor of 0.3–0.5 from the 2.4 GHz survey by Duncan et al. (1997) and a fluctuation scale less than about 2 pc based on the SGPS data. In our analysis, the depolarisation factor and thus the RM fluctuation are more robust as the high frequency data at 4.8 GHz are included. However, the fluctuation scale is loosely constrained to an upper limit at best, because of the much coarser angular resolution compared to the SGPS.

### 3.1.3 Summary

According to the discussion in Sects. 3.1.1 and 3.1.2, at 4.8 GHz the observed polarised structures are intrinsic, and caused by random magnetic field in the emitting medium at a distance of 3–4 kpc. However, at 2.3 GHz the observed polarised structures are extrinsic, and are caused by foreground Faraday screens composed of warm ionised gas at a distance of 2–3 kpc.

### 3.2 The branch extending from the North Polar Spur: a feature far away?

The North Polar Spur (NPS) is one of the most prominent structures in the radio sky, protruding from the Galactic plane at longitude about 30$^\circ$ and reaching a latitude as high as +80$^\circ$ (e.g. Berkhuijsen 1971). It has been widely accepted that the NPS is part of an old supernova remnant at a distance of about 100 pc based on optical star light polarisation and the relation between surface brightness and distance for supernova remnants (Salter 1983, and references therein). Recently, Wolfeben (2007) modelled the NPS as two shells at distances of 78 pc and 95 pc respectively. In contrast, Sofue & Reich (2000) interpreted the NPS as a shock front formed by about $10^5$ supernovae 15 million years ago in the Galactic centre. Bland-Hawthorn & Cohen (2003) proposed that the bipolar wind from the Galactic centre produces the NPS.

The key to understanding the nature of the NPS is to constrain its distance, for which polarisation observations can help. Sofue & Reich (1979) mapped the NPS in total intensity and presented the results in an image covering $16^\circ < l < 35^\circ$ and $-6^\circ < b < +20^\circ$ at 1420 MHz with a resolution of 10$^\prime$. By applying unsharp masking, they found that a ridge extends from the NPS towards lower Galactic latitudes and splits into two branches at (22$^5$, +3$^6$) and one branch reaches (21$^5$, +2$^3$). These two branches can be clearly seen in the Urumqi 4.8 GHz total intensity map but not well seen in the Parkes 2.3 GHz total intensity image because of confusion from strong background emission (Fig. 1). In Fig. 7 we display polarisation structure at 2.3 and 4.8 GHz in small areas including the total-intensity branches (which are indicated by arrows in Fig. 2). Note that polarised intensities scaled with a spectral index $\beta = -3.1$ have the same colour in both images. The spectral index is consistent with that for the NPS between 408 MHz and 1420 MHz derived by Reich et al. (2004). In the Urumqi 4.8 GHz data, polarised emission from one of the branches can be firmly identified from $b = +5^\circ$ to $b = +2^\circ$6. Whether the branch can be traced further is very uncertain because many polarised fragments appear below $b = +2^\circ$6. In the Parkes 2.3 GHz data, the part above the latitude of about $+3^\circ$8 roughly matches the 4.8 GHz data, but the rest has significantly lower intensities than that extrapolated from the 4.8 GHz data with $\beta = -3.1$.  

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The depolarisation at 2.3 GHz below a latitude of about $+3^\circ$ towards the branch extending from the NPS indicates that the branch is far away. We first investigate the cause for depolarisation. At 4.8 GHz, the magnetic field vectors well align with the ridge (Fig. 7) meaning the intrinsic RM is very small, which rules out depth depolarisation at 2.3 GHz. Beam depolarisation is therefore the main mechanism for depolarisation. However, there is no strong Hα emission above the latitude of about $+2^\circ$6 towards the branch (Fig. 5). The warm ionised gas producing large RM fluctuations is probably further away than that at lower latitudes, so that extinction prevents detection of strong Hα emission. This implies that the branch is located at a distance larger than 2–3 kpc.

It is not yet clear whether the branch extending from the NPS is physically associated with the NPS. If these two structures are physically connected, the distance to the NPS must be much further than the distance of 100 pc that was proposed decades ago. The NPS would intercept the Galactic plane at longitude of about 20° if we linearly extend the polarised branch at the Urumqi data towards the Galactic plane (Fig. 2). These facts agree very well with the scenario proposed by Sofue (2000), namely that the NPS traces a shock front formed in the Galactic centre about 15 My ago and the tangential direction of the gaseous ring in the plane formed by the blast wave is about $\pm20^\circ$. The Galactic wind model proposed by Bland-Hawthorn & Cohen (2003) is not favoured because the NPS would be thermal and aligned with the Galactic centre in their model.

It is also possible that the NPS and the branch are independent structures and uncorrelated with each other. In this case we cannot constrain the distance to the NPS. A detailed study of the NPS using GMIMS (Wolleben et al. 2010) data is underway.

### 3.3 Polarisation in the Effelsberg 2.7 GHz data

The baselines of the Effelsberg 2.7 GHz $U$ and $Q$ data were set by subtracting zeroth- or first-order fits so that the averages of all the pixels are zero (Duncan et al. 1999). This might limit the use of the dataset in studying large-scale polarised structures for which absolute calibration is required to warrant a reliable interpretation (e.g. Reich 2006). The Parkes 2.3 GHz data have an absolute level and therefore allow us to assess to what extent the large-scale structures were missed in the Effelsberg data.

We obtained longitude profiles of $U$ and $Q$ averaged over $+2^\circ < b < +5^\circ$ and $-5^\circ < b < -2^\circ$ for both the Parkes 2.3 GHz and Effelsberg 2.7 GHz data and the results are shown in Fig. 8. We have scaled the Effelsberg 2.7 GHz data by using a spectral index $\beta = -3.1$ The Galactic plane was skipped due to strong depolarisation. Except for the discrepancy that appears in $U$ at $15^\circ < l < 20^\circ$ and $-5^\circ < b < -2^\circ$ where a polarised filament was observed in the Parkes 2.3 GHz data, the profiles generally agree with each other. This is actually what we expect because the strong depolarisation near the plane breaks up large-scale coherent polarised structures as has been seen at lower frequencies (Haverkorn et al. 2003b). It is thus possible that towards the inner Galaxy the Effelsberg 2.7 GHz data without absolute calibration roughly approximate the Parkes 2.3 GHz data with absolute calibration.

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**Figure 9.** Structure functions for complex polarised intensity $P = Q + iU = p \exp(2i\psi)$ and polarised intensity $p = |P|$ are defined as

$$\text{SF}_P(\delta \theta) \equiv \langle |P(\theta) - P(\theta + \delta \theta)|^2 \rangle$$

$$\text{SF}_p(\delta \theta) \equiv \langle |p(\theta) - p(\theta + \delta \theta)|^2 \rangle,$$

where $\delta \theta$ is the angular separation between two lines of sight and $\langle \ldots \rangle$ stands for ensemble average. The formulae above can be further expanded to

$$\text{SF}_p(\delta \theta) = 2\langle p^2 \rangle - 2\langle p(\theta)p(\theta + \delta \theta) \rangle$$

or

$$\text{SF}_P(\delta \theta) = 2\langle \psi^2 \rangle - 2\langle |\psi(\theta)\psi(\theta + \delta \theta)| \rangle - 2\langle \psi(\theta)\psi(\theta + \delta \theta) \rangle.$$
make linear fits to all the structure functions in logarithmic scales, and the results are shown in Fig. 9.

If the observed polarisation is intrinsic, there will be no correlation between polarised intensity and polarisation angle. We can rewrite the structure function of complex polarised intensity by separating the averages in the 2nd term in Equation (5) as

\[
SF_p(\delta \theta) = 2 \langle p^2 \rangle \\
-2 \langle p(\theta)p(\theta + \delta \theta) \rangle \langle \cos \{2 [\psi(\theta) - \psi(\theta + \delta \theta)] \} \rangle \\
= 2 \langle p^2 \rangle - 2 \langle p(\theta)p(\theta + \delta \theta) \rangle \times \\
\left(1 - 2 \sin^2 [\psi(\theta) - \psi(\theta + \delta \theta)] \right) \\
\approx 2 \langle p^2 \rangle - 2 \langle p(\theta)p(\theta + \delta \theta) \rangle \times \\
\left(1 - 2 [\psi(\theta) - \psi(\theta + \delta \theta)]^2 \right) \\
= SF_p(\delta \theta) + 4 \langle p(\theta)p(\theta + \delta \theta) \rangle \times SF_\psi(\delta \theta).
\]

Here SF_\psi(\delta \theta) is the structure function for polarisation angles and it is assumed that \(|\psi(\theta) - \psi(\theta + \delta \theta)|\) is small. The assumption is reasonable because we only focus on coherent structures over angular scales of \(30' < \delta \theta < 200'\). We then substitute \(\langle p(\theta)p(\theta + \delta \theta) \rangle\) according to Equation (4) and derive the following

\[
SF_p(\delta \theta) = SF_p(\delta \theta) + (4\langle p^2 \rangle - 2 SF_p(\delta \theta)) \times SF_\psi(\delta \theta).
\]

Generally it is expected that SF_p and SF_\psi should have the same slopes and it is obvious that \(2\langle p^2 \rangle > SF_p\), therefore we conclude that SF_p should have a similar slope as SF_p but a much larger amplitude than SF_p.

On the contrary, if the observed polarisation structures are caused by Faraday screens with beam depolarisation, polarised intensity will be anti-correlated with variation of polarisation angles as they are both related to RM fluctuations of the Faraday screens. In this case, the average term in SF_p in Equation (4) cannot be separated. We shall expect larger amplitude but flatter slope for SF_p than for SF_p as most of the intrinsic structures are smeared out by Faraday screens.

From Fig. 9 we can see at 4.8 GHz SF_p and SF_p have similar slopes, while at 2.3 GHz SF_p has much shallower slope than SF_p. This means that polarisation from the Urumqi 4.8 GHz data is intrinsic and polarisation from the Parkes 2.3 GHz data is caused by Faraday screens, which supports the discussion in Sect. 3.1. We also note that SF_p at both frequencies have similar slopes. This is because polarised intensities at these two frequencies differ only by the depolarisation factor.

3.4.2 Gradient

The spatial gradient of complex polarised intensity was first proposed and applied to SGPS data by Gaensler et al. (2011) revealing many filamentary structures corresponding to cusps or jumps in the turbulent interstellar medium. Following Gaensler et al. (2011), we calculated the gradient maps for the Parkes 2.3 GHz and Urumqi 4.8 GHz data as

\[
\nabla P = \sqrt{\left( \frac{\partial U}{\partial x} \right)^2 + \left( \frac{\partial U}{\partial y} \right)^2 + \left( \frac{\partial Q}{\partial x} \right)^2 + \left( \frac{\partial Q}{\partial y} \right)^2}.
\]

The results are shown in Fig. 10.

In the gradient maps, all the bright structures except for discrete sources near \(|b| = 0^\circ\) caused by instrumental polarisation are at latitudes \(|b| > 2^\circ\) for the Parkes 2.3 GHz data. On the contrary, the prominent structures are mainly

Figure 8. Longitude profiles for U and Q taken from the Parkes 2.3 GHz data (gray) and the Effelsberg 2.7 GHz data (red).
Absolutely calibrated radio polarimetry of the inner Galaxy at 2.3 GHz and 4.8 GHz

Figure 10. Gradient maps ($|\nabla P|$) calculated from the Parkes 2.3 GHz data (top panel) and the Urumqi 4.8 GHz data (bottom panel) according to Equation (8).

The structures in the gradient maps basically follow the distribution of polarised intensity (Fig. 2). Unlike the gradient map from the SGPS survey (Gaensler et al. 2011), the contrast between the bright and weak features is much larger for the gradient maps from the Parkes 2.3 GHz and Urumqi 4.8 GHz data.

Burkhart et al. (2012) has proposed many statistical methods to infer turbulence properties based on the gradient maps. One of the probes is the probability distribution function (PDF) which seems to be a good indicator of sonic Mach number of the interstellar turbulence. Following Burkhart et al. (2012) we first shifted and normalised the gradients from both the Urumqi 4.8 GHz and Parkes 2.3 GHz data as $\frac{|\nabla P| - <|\nabla P|>}{\sigma_{|\nabla P|}}$ and then derived their PDFs. The results are shown in Fig. 11. For reference we also plot the result from simulated data with only random noise. The PDFs from these two observation data are very similar with a skewness of 1.7 and a kurtosis of 3.7 for the Urumqi 4.8 GHz data and a skewness of 1.9 and a kurtosis of 5.6 for the Parkes 2.3 GHz data, and both are significantly skewed in comparison with the PDF from the random noise.

Figure 11. Probability distribution functions for normalised $|\nabla P|$ calculated from the Urumqi 4.8 GHz data, the Parkes 2.3 GHz data, and a simulation containing only random noise.

Although the PDFs of the gradients from the Parkes 2.3 GHz and the Urumqi 4.8 GHz data are similar, their physical meanings are totally different. The analysis by Gaensler et al. (2011) and Burkhart et al. (2012) has presumed that the observed polarised structures are caused by Faraday screens. For the data they considered, the gradi-
ents were able to trace the jumps and cusps in the foreground Faraday screens caused by MHD turbulence. If the polarised structures are intrinsic, the gradient analysis cannot be applied. The PDF of the gradients from the Parkes 2.3 GHz data indicate that the turbulence in the foreground Faraday screens are trans-sonic type by comparing Fig. 11 with Fig. 6 of Burkhart et al. (2012) and referring to Fig. 7 of Burkhart et al. (2012). However, it is not clear what the PDF of the gradients from the Urumqi 4.8 GHz data mean, as the polarised structures are intrinsic.

4 CONCLUSIONS

By comparing polarised images covering $10^6 < \ell < 34^\circ$ and $|b| < 5^\circ$ at 2.3 GHz from S-PASS and at 4.8 GHz from the Sino-German $\lambda 6$ cm polarisation survey, we obtain the following results:

- Polarised structures seen at 4.8 GHz are intrinsic, and are caused by random magnetic fields. Most of the polarised emission originates from the Scutum arm at a distance of 3–4 kpc.
- Polarised structures at 2.3 GHz are caused by foreground Faraday screens consisting of warm ionised gas at a distance of 2–3 kpc. These screens have an RM fluctuation of about 65 rad m$^{-2}$ over scales smaller than 6–9 pc, so that they cause nearly complete beam depolarisation.
- The low-latitude branch extending from the North Polar Spur is at a distance more than 2–3 kpc. If the branch and the NPS are physically associated, the NPS cannot be local but likely associated with the Galactic bulge, possibly tracing a shock front formed in the Galactic centre.
- Structure functions of complex polarised intensity and polarised intensity are capable of indicating whether observed polarised structures are intrinsic or are caused by foreground Faraday screens.
- Gradients of the 2.3 GHz data indicate that turbulence in the warm ionised medium is transonic. Gradients cannot be used to interpret the 4.8 GHz data in this way because the polarised structures seen at this higher frequency are intrinsic.

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