The Galactic foreground in the direction of A2255

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Abstract

**Aims.** The goal of this work is to understand the very complex linear polarization of the Galactic foreground in the direction of the cluster A2255. **Methods.** We use RM-synthesis to unravel the patterns of polarized emission caused by structures in our Galaxy and describe a simple cartoon model to interpret the results. **Results.** Polarized emission has been detected over a very wide range of Faraday depths, from about −4 to +44 rad m⁻². At least three distinct patterns have been identified at Faraday depths of approximately +2, +12, and +28 rad m⁻². The third pattern, however, shows a large gradient across the field of view with values from +12 to +44 rad m⁻². Based on the observed patterns, we suggest that the polarization emitting medium has both sheet, cloud, as well as filamentary morphological structures. A simple physical model is proposed with multiple regions of synchrotron emission, where the polarized signals are built up, separated by Faraday rotating regions (screens) that create the imprint at specific Faraday depths. Discrete background sources have a RM close to the highest Faraday depths where diffuse Galactic emission has been detected. **Conclusions.** From the similarity between the Faraday depth of the filamentary diffuse Galactic emission and the RM of distant discrete background sources we conclude that the filamentary region at high Faraday depths (ϕ ≈ +28 rad m⁻²) is the most distant structure, and that we have reached the edge of the Galaxy in both Faraday depth and in polarized synchrotron emission. The sheet-like pattern at Faraday depth +2 rad m⁻² is the nearest structure. From the sign of the Faraday depth of the various structures we deduce that the magnetic field in this direction (l = 94°, b = +35°) is directed towards us. This is opposite to the
magnetic field direction within the Galactic plane in this direction. We note a close spatial correspondence between the filamentary pattern and Loop III, a spur in the Galactic foreground synchrotron emission. If the distance of Loop III, believed to be an old SNR, is only 150 pc, then a significant fraction of the observed polarization is produced within a few hundred pc from the Sun. Understanding the Faraday-depth structure of the Galactic foreground polarization is crucial for a proper interpretation of low-frequency polarization emitted by diffuse extragalactic radio sources such as clusters, extended radio galaxies, and the cosmic web.

5.1 Introduction

In Chapter 4 of this thesis we have described the linear polarization structures observed in the field containing the cluster A2255. We have done this analysis using so called RM-cubes produced by RM synthesis (Brentjens & de Bruyn 2005). An RM-cube contains the 2-dimensional spatial distribution of polarized emission in a serious of planes, or frames, with the third dimension being Faraday depth. Faraday depth can only be mapped into physical depth if we have independent information on the properties of the magneto-ionic medium, and in particular the sign of the magnetic field along the line of sight.

In our study of A2255 we have synthesized RM-cubes in three distinct wavelength regimes. Henceforth we will refer to them as the 21 cm RM-cube, the 85 cm RM-cube and the 2 m RM-cube. The 21 cm RM-cube is dominated by polarized emission from discrete and diffuse radio sources in the cluster; it only shows some faint traces of Galactic foreground polarized emission. This is largely due to the relatively poor surface brightness sensitivity at 21 cm. The 85 cm RM-cube, on the other hand, is filled with intense and widespread Galactic foreground emission, covering the whole primary beam. However, at the location of several radio sources of A2255, polarized emission at restricted Faraday depths has been detected. In the 2 m RM-cube no polarized emission could be convincingly detected from the cluster nor from the Galactic foreground.

As discussed in Chapter 4, it has been far from trivial to separate the weak polarized signals originating in the cluster from the strong Galactic foreground polarization in the 85 cm RM-cube. That this was possible at all is only because of their separation in 'Faraday-space'.

In this Chapter we analyze the Galactic foreground polarization signals in more detail. This analysis, although highly interesting in its own right, belongs in this thesis on the radio emission from clusters of galaxies. This is because Galactic polarization will continue to be a serious contaminant in many future high sensitivity studies of the polarized extragalactic sky at low frequencies, with LOFAR, e-VLA, WSRT, GMRT, or the SKA. It is also a serious contaminant for study of the polarized component of the CMB (e.g. Page et al. 2007).

The best opportunity to study the polarization from the outer parts of clusters, including emission from LSS-shocks and the cosmic web, is when their Faraday depth is distinctly different from that of the bulk of the polarized emission from our Galaxy.
We return to this question in the discussion.

The analysis and discussion of the data still has a preliminary nature and has not yet been fully concluded at the time that the thesis went to press. However, we have already been able to reach some interesting conclusions. The completed analysis will appear in the near future (de Bruyn & Pizzo 2010).

This Chapter is organized as follows. In Sect. 5.2 we present the 85 cm RM-cube and we discuss the instrumental and astronomical signal in it. In Sect. 5.3 we present a simple physical model of the structure of our Galaxy towards A2255. We introduce synchrotron emitting regions as well as Faraday rotating screens along the line of sight, arguing for their relative and absolute distance from the Sun. We summarize and conclude our work in Sect. 5.4.

5.2 The 85 cm RM-cube: structure in Faraday space

The 85 cm RM-cube towards A2255 is the deepest low-frequency RM-cube ever made. For a description of the data, their calibration, and the production of the RM-cube, we refer to Pizzo et al. (2009a, Chapter 4). The angular resolution of the images is $54'' \times 64''$. The resolution in Faraday space, the Rotation Measure Spread Function or RMSF, is $12.5 \text{ rad m}^{-2}$ at half-power width. However, significant changes already occur at one-third this resolution as shown in Fig. 5.1, where we display three panels of the full field images of the polarized intensity (PI) in steps of $4 \text{ rad m}^{-2}$, going from $-8 \text{ rad m}^{-2}$ to $+52 \text{ rad m}^{-2}$. Significant signals were detected at Faraday depths from $-4$ to $+44 \text{ rad m}^{-2}$. The images at $-8$, $+48$, and $+52 \text{ rad m}^{-2}$ are included to give an idea of the noise levels and instrumental artifacts when no celestial signals are present. The noise in the Stokes Q and U images is about $43 \mu\text{Jy beam}^{-1} \text{ RMSF}^{-1}$. In PI we find a mean noise value of about $60 \mu\text{Jy beam}^{-1} \text{ RMSF}^{-1}$, which is the expected polarization bias (Wardle & Kronberg 1974) for very low signal-to-noise polarization images. We have not corrected the images for this bias. The rms noise deviation on this Ricean-bias in PI is about $35 \mu\text{Jy beam}^{-1} \text{ RMSF}^{-1}$.

Because polarized radiation is a vector quantity, the intensity only contains part of the astrophysical information. The polarization images, however, have generally low signal-to-noise ratio per resolution element. It is therefore not useful to display the images of polarization angle because, especially at the higher Faraday depths, they mostly show chaotic patterns in which it is difficult to distinguish noise from signal. Instead, we show the corresponding images of one of the two Stokes parameters. Fig. 5.2 shows the same 16 frames as shown in Fig.5.1 for Stokes Q; we could also have shown Stokes U, but they basically convey the same morphological information. Because of the large number of resolution elements in these images, we also show an enlarged version of the Stokes Q frames in Fig. 5.3. Scanning and comparing the 16 polarized intensity and Stokes Q frames reveals several remarkable properties. This is best done in an animated display\(^1\).

Before we discuss the more interesting astrophysical properties in detail, we will guide the reader through some basic features and facts exhibited in the various pa-

\(^1\)The PI, Q, and U cubes are available at the URL: www.astro.rug.nl/~pizzo/movies/A2255_85CM_NOCUT_PI.gif, .._Q.gif, and .._U.gif.
Figure 5.1: Panel of full field of view frames from the 85 cm RM-cube. Shown is the polarized intensity, in units of mJy beam\(^{-1}\) RMSF\(^{-1}\), at Faraday depths from –8 to +12 rad m\(^{-2}\). The intensity scale is shown on the right. The noise fluctuations in the PI images, away from calibration artifacts, and after correction for polarization bias, is about 35 μJy beam\(^{-1}\) RMSF\(^{-1}\).
Figure 5.1: Continued: Polarized intensity for Faraday depths from +16 to +36 rad m$^{-2}$. 
nels. The first thing to notice in the individual frames is that the signal intensity rapidly falls beyond a radius of about 1.5° from the (pointing) center of the image. This, of course, is the tell-tale signal that they are coming from the sky. The decrease in intensity towards the edges of the field are due to the attenuation by the WSRT primary beam, which measures about 2.5° at half-power (at 350 MHz). An immediate corollary is that a much larger area of the sky probably displays similar polarization signals. Secondly, we note that there is no detectable total intensity emission associated with any of the observed polarization signals. We refer to Pizzo & de Bruyn (2009, Chapter 4) for the total intensity 85 cm image. This lack of corresponding features in total intensity is common to all WSRT 350 MHz Galactic foreground polarization images (Wieringa et al. 1993; Haerkanorn et al. 2003; de Bruyn et al. 2006; Schnitzeler et al. 2007b) and is attributed to the fact that the total intensity does not contain significant power on angular scales probed by the WSRT base-
Figure 5.2: Panel of full field of view frames from the 85 cm RM-cube. Shown is Stokes $Q$, in units of mJy beam$^{-1}$ RMSF$^{-1}$, at Faraday depths from $\phi = -8$ to $+12$ rad m$^{-2}$. The intensity scale is shown to the right of each frame. The noise level in most images, away from calibration artifacts, is about 43 $\mu$Jy beam$^{-1}$ RMSF$^{-1}$.
Figure 5.2: Continued: Intensity of Stokes $Q$ from $\phi = +16$ to $+36$ rad m$^{-2}$.
Figure 5.2: Continued: Intensity of Stokes $Q$ from $\phi = +40$ to $+52$ rad m$^{-2}$.

The polarization however does show structure, due to the fact that (an) intervening Faraday screen(s) create structure on spatial frequencies that can be detected by the interferometer. A third noteworthy, albeit distracting, property of the images are the ring-like artifacts around many of the brighter compact sources, especially those at the edge of the field. These rings are of instrumental origin and are due to position-dependent polarization leakage, exacerbated by small differences between the leakages of the 14 telescopes of the WSRT. The beam-pattern of the WSRT has strong instrumental off-axis polarization (e.g. de Bruyn & Brentjens 2005; Popping & Braun 2008), which changes strongly with frequency with a dominant 17 MHz pattern. The error patterns are of a multiplicative nature, and are therefore only visible around sources with significant total intensity (at least hundred times the noise level). Hence they have no significant effect on the ubiquitous diffuse polarized signals which, as discussed above, have no counterpart in Stokes I. The proper cal-
Figure 5.3: Zoom view of Stokes Q frames at Faraday depths from −8 to +12 rad m$^{-2}$. The intensity scale is shown on the right of each frame.
Figure 5.3: Zoom view of Stokes Q frames at Faraday depths from +16 to +36 \text{ rad m}^{-2}.
Figure 5.3: Continued: Intensity of Stokes Q from $\phi = +40$ to $+52 \text{ rad m}^{-2}$.
separately discuss, three distinct patterns. The first convincing emission, taking into account the sidelobes of the RMSF, probably starts at slightly negative Faraday depth with some significant emission at about \(-4 \text{ rad m}^{-2}\). In the frames from \(-4\) to \(+8 \text{ rad m}^{-2}\) the dominant pattern has a 'sheet-like' morphology. Its polarized intensity is rather uniform and there are only very small spatial changes in polarization angle (see also Fig. 5.15). These sheets have sharp, almost unresolved edges, and can be coherent in polarization angle on scales up to 1°. One of these unresolved edges, oriented vertically at RA = 17° 16' and Dec = +64° 30' shows all the characteristics of a depolarization canal (Haverkorn et al. 2004b). A second structural pattern is present at Faraday depths from about \(+8 \text{ rad m}^{-2}\) to \(+16 \text{ rad m}^{-2}\). It is present mostly on the Eastern side of the image, starting at the sharp 'canal-like' discontinuity in Stokes Q (at RA > 17° 16'). This emission has significant wavy polarization angle structure on scales of about 10'. The third, and arguably the most interesting pattern, starts at a Faraday depth of about \(+12 \text{ rad m}^{-2}\) on the Western side of the image. It is strongly anisotropic in polarized intensity with stripes in a direction of about 120° (N-through-E). In the images from \(+12\) to \(+48 \text{ rad m}^{-2}\) the stripy pattern appears to move slowly from North-West to South-East, with an estimated gradient of about 10–20 rad m\(^{-2}\) per angular degree. Although this may be fortuitous, we note that this large-scale gradient is approximately along the direction of the stripy pattern. This third pattern is most conspicuous in the morphology of the polarization angle (see Fig. 5.3). It shows a mottled pattern, with arcminute scale variations in the sign of Stokes Q; similar structure is observed in the Stokes U images at those Faraday depths. The stripy polarized intensity pattern at the higher Faraday depths is therefore accompanied by rapid spatial changes in polarization angle. The emission in this third, filamentary, pattern also covers the broadest range in Faraday depth and significant emission is probably present up to a Faraday depth of \(+44 \text{ rad m}^{-2}\) in the South-East corner of the image.

To emphasize the remarkable change in morphology of the total polarized intensity as a function of Faraday depth, we have integrated the emission in the frames from \(-4\) to \(+4 \text{ rad m}^{-2}\) and from \(+20\) to \(+36 \text{ rad m}^{-2}\). We used a cutoff level of 100 μJy beam\(^{-1}\) RMSF\(^{-1}\) for including a pixel in the summed image. These integrated images are shown in Fig. 5.4 and Fig. 5.5.

Close inspection of the polarized intensity RM-cube reveals several faint discrete sources with significant polarization at a Faraday depth similar to the diffuse emission near their position. Two examples of such coincidences are presented in Fig. 5.6 and Fig. 5.7. The RM of these two discrete sources are also representative of the 30 background radio sources observed around A2255 which cluster between \(+20\) to \(+40 \text{ rad m}^{-2}\) (see Chapter 4). The small RM dispersion in this sample confirms previous studies (Simonetti & Cordes 1986; Leahy 1987) that the intrinsic RM of most extragalactic radio sources is rather small. The close agreement between the highest Faraday depth of the diffuse polarized emission from our Galaxy and the RM of these discrete distant extragalactic sources therefore suggests that we have detected diffuse polarized emission from our Galaxy all the way out to the edge of the magneto-ionic Faraday rotating medium. We return to this in the next section when we discuss the relative and absolute distances of the various screens and emission regions.
Figure 5.4: Polarized emission integrated over Faraday depths from $\phi = -4$ to $+4$ rad m$^{-2}$. Note that at this very small Faraday depth the instrumental polarization around most off-axis sources is very prominent.

We now would like to draw attention to a property of the RM cubes that may not be immediately apparent. When one compares the two integrated polarized intensity images it is obvious that the intensity patterns overlap spatially, i.e. at a given location there are multiple emission regions in Faraday space. Such double-peaked spectra could already be discerned in the top parts of Fig. 5.6 and Fig. 5.7. A further example of very bright diffuse emission with multiple peaks is shown in Fig. 5.8. The polarized emission, at any given location, generally does not cover the full range of Faraday depths from $-4$ to $+44$ rad m$^{-2}$ but is concentrated around one or two specific values. The emission from most peaks appears slightly resolved by the RMSF. In those cases where the signal-to-noise ratio appears good enough to permit a deconvolution we derive a width of typically 4–6 rad m$^{-2}$. However, a deeper
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Figure 5.5: Polarized emission integrated over Faraday depths from $\phi = +20$ to $+36$ rad m$^{-2}$.

analysis of the Faraday spectra should be done to confirm this (see also Schnitzeler et al. 2007b).

The intrinsic spread in Faraday space of the polarized emission at any given location is important when we come to discuss a specific model for the structure along the line of sight. In this connection we want to point out an important caveat in interpreting Faraday spectra. The observations used to make the 85 cm RM-cube have only limited coverage in $\lambda^2$-space, with $\lambda^2$ lying in the range $0.63-0.93$ m$^2$. This makes our observations progressively less sensitive to polarized emission from layers that become Faraday thick, i.e. that are extended over Faraday depths such that $(\lambda_{\min})^2 \Delta \phi > 1$. This is shown graphically in Fig. 5.10 where we plot the instrumental response of top-hat slabs in Faraday space, also called Burn-slabs, as a function of $\lambda^2$ for various thicknesses $\Delta \phi$. These graphs show that in our broadband 85 cm WSRT observations we have lost a significant fraction of the intrinsic polarized signal if the
Faraday width of the emission region is significantly larger than 2 rad m$^{-2}$. This may in fact be the case, if we take the deconvolved widths given above at face value. Of course Burn-slabs are an idealization, and we do not have super resolution, so if the diffuse polarized emission has significant structure on scales of 2 rad m$^{-2}$ within the RMSF a significant amount of emission may in fact still be recovered. We refer to Brentjens & de Bruyn (2005, their appendix B) for further discussion of the effects of the frequency coverage to (combinations of multiple) slabs in Faraday space. The lack of sensitivity to emission from layers that are Faraday-thick was also discussed in Pizzo et al. (2009a, Chapter 4), when we talked about Burn-slabs in connection with polarized emission originating in the cluster A2255.

The polarized emission integrated over all Faraday depths varies from about 0.5–
Figure 5.7: Bottom: Faraday spectrum at the location of a polarized discrete source at position: RA = 17° 22′ 58.2″, Dec = +64° 18′ 44″. The peak at $\phi = 0$ rad m$^{-2}$ is due to instrumental polarization, while the peak at $\phi = +44$ rad m$^{-2}$ is due to intrinsically polarized emission from the source which is 25 mJy strong. Top: averaged Faraday spectrum for a region of 10′ × 10′ about 20′ west of the discrete source. Note the different intensity scale and the much lower noise level in the spatially averaged diffuse emission as compared to the single pixel spectrum.

1 mJy beam$^{-1}$ across the field of view (after correcting for the primary beam attenuation). This flux density corresponds to a polarization brightness temperature of about 2–4 K. This should be compared to the total Galactic foreground intensity of about 30 K at 350 MHz as deduced from the Haslam et al. (1982) 408 MHz image, after correction for the 2.7 K CMB and discrete extragalactic source contributions and correcting for a temperature spectral index of −2.55. Hence the maximum observed polarization at 350 MHz is only about 6–13%. Most of the synchrotron emission of our Galaxy therefore does not lead to observable polarized emission at frequencies around 300–400 MHz. At much higher frequencies the percentages are much larger (Brouw & Spoelstra 1976; Page et al. 2007). This suggests that depolariza-
The main mechanism responsible for lowering the observed polarization percentages are the spatial effects, rather than non-uniform magnetic fields in the emitting regions. The trend of reduced polarization when going towards lower frequencies continues when going to the 2 m RM-cube. As noted by Pizzo et al. (2009a, Chapter 4), we have not yet detected any believable polarization at frequencies from 120–160 MHz. The 2 m RM-cube does, however, show some tantalizing hints of faint narrow, essentially unresolved, features in Faraday space with polarized intensities of about 2–3 mJy beam$^{-1}$ RMSF$^{-1}$. An example is shown in Fig. 5.13. At this point it is good to recall the very different coverage in wavelength available in the 85 cm and 2 m data. These are shown in Fig. 5.9. The RMSF’s synthesized from these data are shown in Fig. 5.11 and in Fig. 5.12. The 85 cm RMSF has a halfwidth of 12.5 rad m$^{-2}$ while the 2 m RMSF has a halfwidth of only 1.1 rad m$^{-2}$.

If the 2 m band emission can be confirmed in subsequent analysis, the polarized emission at 2 m is present at brightness temperature levels of about 10 K. For Faraday thin emission between wavelengths of 85 cm and 2 m the observed values of about 2 K at 85 cm, for the sheet-like features at $\phi \approx +2$ rad m$^{-2}$, should have increased to about 20 K for a temperature spectral index of $-2.55$. We definitely do not see such levels and therefore we conclude that, in general, depolarization due to a finite Faraday depth must play an important role in quenching the 2 m band polarization.

The very different morphology in polarized intensity and polarization angle strongly suggests that the different spatial patterns originate in distinct regions along the line-of-sight. In the next section we discuss a simple model from which we draw some first order conclusions about the physical conditions that might give rise to these patterns. We also suggest a possible configuration along the line of sight.

### 5.3 Discussion

#### 5.3.1 Properties of the Galactic foreground polarization

The field towards the cluster A2255 covers the range in Galactic coordinates from $l = 93^\circ \div 96^\circ$ and $b = +33^\circ \div +36^\circ$, in the region between the Sagittarius and Perseus spiral arms, and above the local spiral arm. Assuming that the bulk of the Galactic synchrotron emission is emitted from a disk with a width of about 1–2 kpc (Beuermann et al. 1985), the observed emission therefore represents the integral of contributions along a path that may be up to several kpc deep. The interpretation of the very complex spatial and Faraday depth structure of the polarized emission as presented above requires knowledge of the magneto-ionic component of the interstellar medium and the distribution of relativistic electrons responsible for the synchrotron emission. This is a vast field of research, with many open questions, and we will limit ourselves to a very brief summary. We start with a brief introduction into the field of polarimetry of the Galactic foreground (note that with our new cosmological perspective the terminology has changed from Galactic background to Galactic foreground).

The first successful Galactic polarization studies were done with the Dwingeloo 25 m radio telescope in 1960 (Westerhout et al. 1962) followed by studies with the
Figure 5.8: An example of very bright emission at two very different Faraday depths along the line of sight, averaged over a 5'×5' region centered at RA = 17h15m49.9s, Dec = +64°30'41".

Figure 5.9: The coverage in wavelength squared of the 85 cm and 2 m band data.
Figure 5.10: The expected polarization fraction as a function of $\lambda^2$ for Burn-slabs, top-hats in Faraday space, of various widths. The WSRT wavelength coverage in the 85 cm band is indicated by the shaded bar.

Parkes and Jodrell Bank telescopes. A review of the early polarization work was given by Gardner & Whiteoak (1966). For a review and analysis of the 1960-ies Dwingeloo multi-frequency datasets we refer to Brouw & Spoelstra (1976) and Spoelstra (1984). All Galactic polarization studies up to the late 1980-ies were done with the low resolution of single dishes, typically 1–2°, depending on frequency. The discovery of very bright polarization structure fine structure on angular scales as small as 1' by Wieringa et al. (1993) with the WSRT therefore came as an enormous surprise and led to renewed interest in the study of the Galactic foreground. The fine structure is due to the action of a highly structured magneto-ionic foreground Faraday screen on the apparently highly polarized signals coming from the region around the Sun, the more distant disk and possibly the halo of our Galaxy. The surprisingly high polarization brightness temperatures observed with an interferometer, when compared to the single dish values, could be attributed to beam depolarization. The WSRT 325 MHz observations were followed by many detailed studies of various areas in the Galaxy, ranging from very low to very high latitude (Haverkorn et al. 2003; de Bruyn et al. 2006; Schnitzeler et al. 2007a, b, 2009). These studies made clear
Figure 5.11: The Rotation Measure Spread Function (RMSF) synthesized from the wavelength coverage in the 85 cm band.

Figure 5.12: The Rotation Measure Spread Function (RMSF) synthesized from the wavelength coverage in the 2m band.

Figure 5.13: An example of faint polarized emission in the 2 m band. The spectrum refers to an area at RA = 17h11m, Dec = +64°30’, where the polarization angle at 85 cm is very uniform. A weak unresolved feature may have been detected at a Faraday depth of about 4 rad m⁻².
that, despite the rapid increase of depolarizing effects at low frequency, there is still a large amount of polarization left at frequencies around 325 MHz, wherever we look. At higher frequencies, 1400 and 2700 MHz, the Effelsberg 100 m telescope was used by Uyaniker et al. (1998, 1999) to image the polarized emission in large regions of the Galaxy, especially at low latitudes. A beautiful all-sky single-dish image of the polarized emission at 1400 MHz was presented by Wolleben et al. (2006). At the same frequency the Australia Telescope Compact Array (Gaensler et al. 2001) and the Canadian Galactic Plane Survey with the Penticton array have revealed a wealth of fine structure at low Galactic latitudes with lots of evidence for depolarizing effects (Taylor et al. 2003; Uyaniker et al. 2003). At the much higher frequency of 22 GHz, where Faraday rotation is unlikely to play any role, WMAP has imaged the linear polarization of the whole sky (Page et al. 2007; Hinshaw et al. 2009).

Although the total intensity of Galactic synchrotron emission decreases steeply towards higher Galactic latitudes (Haslam et al. 1982; Beuermann et al. 1985; de Oliveira-Costa et al. 2008), this rapid falloff is not shared by the polarized intensity. In several studies, up to Galactic latitudes of 70° (e.g. de Bruyn et al. 2006), a polarization brightness temperature of typically 5 K at 350 MHz has been detected. The reduced polarization levels at low latitude are thought to be due to the depolarizing action of the much higher density plasma close to the Galactic plane which creates a complicated Faraday structure with much higher Faraday depth. This is also seen in the systematic increase of the (absolute value of the) RM of polarized extragalactic radio sources (Simard-Normandin et al. 1981; Brown et al. 2007; Taylor et al. 2009) when going to very low Galactic latitude.

5.3.2 A simple physical model

The images in Faraday space, derived from the WSRT 85 cm polarization data show a bewildering range of complexity. A physical interpretation is hampered by our poor understanding of the detailed structure of the magneto-ionic ISM, especially at high Galactic latitudes and at large distances above the plane.

The generally very smooth distribution of the total synchrotron emission, implied by the lack of detection in interferometric data (see the new low-resolution grey-scale images from the 325 MHz WENSS survey at http://www.astron.nl/wow) is consistent with a large filling factor of the relativistic electron population. We also know that the Galactic magnetic field contains both random and uniform components (e.g. Beck 2001; Han 2009). The distribution of the thermal plasma, on the other hand, is known to be extremely inhomogeneous with a very small filling factor for the Warm Ionized Medium (WIM) (e.g. Reynolds 1991a,b), that is responsible for the Faraday rotation. The large-scale electron density distribution in our Galaxy has been described by the NE2001 model (Cordes & Lazio 2002) but is already known to be a poor representation when one looks in detail. For a recent observational review of the electron density distributions of the gas in the solar neighborhood and for the vertical component of this distribution, we refer to Berkhuijsen & Müller (2008) and Gaensler et al. (2008).

Sokoloff et al. (1998) were the first to discuss the depolarization and Faraday effects in the disks of spiral galaxies. Their main emphasis was on the polarization
distribution observed from external galaxies as obtained using data at only a few frequencies (i.e. without the benefit of RM-synthesis). Modeling the fine-scale component in our Galaxy was first attempted by Haverkorn et al. (2004a). They analyzed possible geometric configurations and distributions of the random and uniform component of the magnetic field and magneto-ionic medium. The amount of information in the data available to them, however, did not allow a detailed confrontation with the data. Here we make a new attempt. To help visualize the complexity of the radiative transfer problem of the polarized signals detected in our RM-cube we have constructed a simple physical model that we believe contains the essential ingredients of any model that attempts to explain the data. A cartoon of this model is shown in Fig. 5.14.

The cartoon shows a viewing cone at moderate Galactic latitude at the transition from the 1st to the 2d Galactic quadrant. In the cartoon the intensity of the synchrotron emission is indicated by the smooth background. Following Beuermann et al. (1985), we assume the half-width of the thick disk emission to be about 1-2 kpc, although the authors note that in this inter-arm direction the model is very poorly
constrained. Indeed, looking at external galaxies (e.g. NGC6946, Beck 2007; see also Heald et al. 2009) the intensity of the synchrotron emission between major spiral arms is often considerably reduced.

Moving outwards along the cone, we introduce four Faraday screens designated by Roman numerals I, II, III, and IV. We will call them screens but of course they do not necessarily have to be physically thin structures; they could also be deep columns of electrons. The screens are separated by polarization emitting synchrotron structures, designated by the letters S, C, and F. The motivation for introducing several distinct emission regions along the line of sight is suggested by the different morphological patterns that we see at distant locations in Faraday space.

To gain insight into the complicated radiative transfer issues we will begin the discussion with a qualitative description on how we believe the signals are built up. We will do this in two ways: first we move away from the Sun to the edge of the Galaxy, after which we retrace our path.

When we move away from the Sun, to a physical distance $L$, we build up Faraday depth $\phi$ as given by the following equation:

$$\phi \ [\text{rad m}^{-2}] = 0.812 \int_0^{d_{\text{pc}}} \frac{n_e \ [\text{cm}^{-3}] B \ [\mu\text{G}] \cdot d\ell}{BP_0 / BM_{810} / CI_L [\text{pc}] 0 / ne^{3} B / CZ / AM_{G} / A_{1} d / BN_{1} (5.1)}$$

The observed complex polarized signal (as a function of frequency) in a given direction is the line of sight integral of the Faraday dispersion function (Burn 1966; Brentjens & de Bruyn 2005), which describes the distribution of polarized emission as a function of Faraday depth. Faraday depth should not be confused with physical depth or with optical depth. To simplify our description we assume that the magnetic field does not change direction along the line of sight and is directed towards us. This is consistent with the generally positive values of Faraday depths in our field, although this certainly will not be the case in general. At various physical distances we probably come across regions of enhanced electron density that contribute significantly to the accumulated Faraday depth. When we arrive at the edge of the Galaxy we reach a Faraday depth that varies from about +20 to +40 rad m$^{-2}$, depending on the direction within our field of view. We do not know whether we see polarized emission all the way to the edge of the Galaxy. That is, there might still be Faraday rotating magneto-ionic medium beyond the last region of diffuse polarized emission that we detect. However, as we argued earlier, the close similarity between the RM of discrete background sources and the Faraday depths out to which we see diffuse polarized emission suggests that this contribution is not significant in terms of Faraday depth. Hence region IV in the cartoon may be empty. We note that a Faraday depth of +20 to +40 rad m$^{-2}$ can be obtained with a typical large-scale magnetic field of 1 $\mu$G (with no sign reversals), an average electron density of 0.01–0.02 cm$^{-3}$ and a path length of 2 kpc. Gaensler et al. (2008) give a typical mid-plane filling factor of 0.04, and mid-plane electron density of 0.014 cm$^{-3}$ for the Warm Intercloud Medium (WIM). This would obviously be insufficient to accumulate the Faraday depth we need at the latitude where we observe. Obviously, a couple of denser screens or clouds along the line of sight could produce the remaining Faraday depth and the small filling factor of the ionized medium argues that this is likely to be what is happening (Reynolds 1991a,b; Gaensler et al. 2008). The WHAM data in this direction
(Haffner et al. 2003), however, do not reveal any obvious bright Hα-structures which we could relate to our Faraday space emission patterns.

Now let us retrace our path. Starting at the edge of the Galaxy we build up a polarized signal from those regions along the line of sight that have a significant uniform magnetic field component (in order to create a net polarized signal) and are sufficiently Faraday thin to not fully quench the signal. Each of the polarized emission contributions will be observed at the Faraday depth contributed by the remainder of the physical path towards the Sun. The spatial structure that we observe at a given location in Faraday space will, in our simplistic model, depend on the spatial structure in the polarized radiation field incident at that particular Faraday depth. The medium has to be inhomogeneous in both the Faraday rotating and in the polarization emitting regions. Between the various Faraday rotating screens additional polarized signal must be emitted, because if this were not the case the structures could not be distinguished as separate features in Faraday space. The three Faraday patterns described above appear to be essentially unresolved by the RMSF, at any given location. This conclusion is based on the lack of any significant change in the Stokes Q (or Stokes U) RM-cube when we scan the range covered by the S-region ($\phi = -4$ to $+12$ rad m$^{-2}$) and the range covered by the F-region (Faraday depths from $+12$ to $+44$ rad m$^{-2}$). The S, C, and F-regions may therefore all be Faraday-thin, i.e. have a Faraday thickness $\phi$ such that $\lambda^2 \Delta \phi \leq 1$. This may seem to be inconsistent with the deconvolved sizes derived earlier. This should be investigated further.

5.3.3 Distances of the Faraday space emission patterns

Having introduced a qualitative model for the various components along the line of sight, the next obvious question concerns their relative distances. The cartoon obviously suggests a relative disposition; we will now underpin this choice.

If the large-scale uniform magnetic field in this direction does not reverse direction then obviously the S-region (at $\phi \approx +2$ rad m$^{-2}$) must be nearer than the C-region (at $\phi \approx +12$ rad $^{-2}$), which must again be nearer than the F-region (at an average $\phi \approx +28$ rad $^{-2}$). But is there any hard evidence from which we can deduce that this is actually the case? We believe there is. In the previous section we concluded that the F-region is located at the edge of our Galaxy as deduced from the close similarity between the RM of distant background sources and the highest Faraday depth of the diffuse Galactic emission. But the data may contain additional independent information about which region is closest to the Sun. For example, if the F-region would be in front of the S-region we require an additional Faraday screen with opposite magnetic field polarity beyond the F-region in order to end up at the S-region with a fairly uniform Faraday depth of about $+2$ rad m$^{-2}$. In addition, this screen should have the opposite spatial gradient as that observed in the screen in front of the F-region. We would consider this as extremely unlikely. The information contained in the spatial patterns will be addressed in a future paper where we will search for correlations between the various spatial gradients and polarization angle fine structure patterns observed at the various Faraday depths. It might help break the fundamental uncertainty between Faraday depth and physical depth inherent in RM synthesis (Brentjens & de Bruyn 2005).
Can we say anything about the absolute distances of the media giving rise to the three morphological patterns? A2255 lies near the upper part of Loop III, a spur protruding from the Galactic plane around longitude $l \sim 90^\circ$ (Spoelstra 1972). We also note that Loop III appears to be associated with a region of generally positive RM, within a sea of generally negative RM, in the large-sky NVSS image of RMs of extragalactic sources (Taylor et al. 2009). Where Loop III emerges from the Galactic plane there is also excess polarization in the WMAP image at 22 GHz (Page et al. 2007; Hinshaw et al. 2009). Loop III is significantly polarized at 21 cm wavelength and was modeled by Spoelstra (1972) as a local SNR with an angular diameter of $90^\circ$ at a distance of only 150 pc. The association of the material in the F-region with Loop III is supported by the fact that the position angle of the stripy pattern is, within the errors, tangential to the shell of the SNR as presented in Spoelstra (1972). The F-region may therefore be due to compressed gas, with an associated enhanced and more uniform magnetic field, at the expanding boundary of an old SNR.

An important consequence of such a small distance for the F-region is that the S-region and C-region are even closer. If Loop III is only 150 pc distant, then we
would have to conclude that most polarized emission in this direction would be coming from a path of only a few hundred pc deep, and reaching out to only about 100 pc from the Galactic plane. Similarly, most of the Faraday depth in this direction would be produced very close to the Galactic plane. This would be a somewhat surprising conclusion given the expectation that the higher regions of the Galactic non-thermal disk are probably located in more tenuous low filling factor ionized regions and could therefore be expected to contribute significantly to the polarized emission. Alternative explanations for the origin of Loop III should therefore be investigated. For example, Loop III could be associated with synchrotron emitting loops caused by large-scale halo magnetic fields of our Galaxy (e.g. Sun et al. 2008). In that case the distance could be much larger, relaxing the distance to the S-region and C-region. Further discussion of this possibility is beyond the scope of this paper.

5.4 Conclusions

We have discussed the morphology of the polarized radio emission at 85 cm in the direction of the cluster A2255. Polarized emission has been detected over a very wide range of Faraday depths, from about −4 to +44 rad m$^{-2}$. At least three distinct patterns have been identified at Faraday depths of approximately +2, +12, and +28 rad m$^{-2}$, with the latter one being rather broad and showing a spatial gradient. Based on the observed patterns we suggest that there are three emitting regions with sheet, cloud, and filamentary emission. A simple physical model is proposed with both synchrotron emitting regions, where part of the polarized signal is built up, separated by Faraday screens responsible for the imprint at specific Faraday depth. We presented arguments that the filamentary region at high Faraday depth is the most distant component and that no further contributions to either Faraday depth or polarized emission are produced at larger distances. We also conclude that the magnetic field direction towards longitude $l = 94^\circ$ at a latitude of $b = +35^\circ$ is directed towards us, opposite to that within the plane at this Galactic longitude.

We suggest that the filamentary region is related to the outer edge of Loop III, a Galactic spur believed to be due to old nearby SNR. However, if the distance of this structure is indeed only 150 pc (Spoelstra 1972), then most of the observed polarized signal would be produced within a few hundred pc from the Sun. We propose to explore alternative explanations for Loop III.

The analysis of the complex Faraday structure in this fairly high Galactic latitude direction underscores the potential of RM-synthesis to allow tomography of media with significant Faraday depth, especially if they are composed of many Faraday-thin layers. It is also clear that the study of diffuse polarized emission from extragalactic sources, like clusters and the cosmic web, is seriously complicated by emission from the Galactic foreground. The best situation may occur when the outer part of our Galaxy contributes a significant component to the extragalactic RM without contributing itself to the polarized emission. How often such a fortunate situation exists, however, is not clear.

Alternatively, if the intergalactic medium would contribute a significant RM itself, the contributions would be separated. The fact that we have seen a close agree-
ment between the RM of background sources surrounding the A2255 cluster and the diffuse emission from the outer part of our Galaxy, is used to argue that at least in this direction we have no significant RM contribution from the IGM.

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