The Westerbork SINGS survey

II Polarization, Faraday rotation, and magnetic fields

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ABSTRACT

A sample of large northern Spitzer Infrared Nearby Galaxies Survey (SINGS) galaxies has recently been observed with the Westerbork Synthesis Radio Telescope (WSRT). We present observations of the linearly polarized radio continuum emission in this WSRT-SINGS galaxy sample. Of the 28 galaxies treated in this paper, 21 are detected in polarized radio continuum at 18- and 22-cm wavelengths. We utilize the rotation measure synthesis (RM-Synthesis) method, as implemented by Brentjens & de Bruyn (2005, A&A, 441, 1217), to coherently detect polarized emission from a large fractional bandwidth, while simultaneously assessing the degree of Faraday rotation experienced by the radiation along each line-of-sight. This represents the first time that the polarized emission and its Faraday rotation have been systematically probed down to $\sim 10 \mu\text{Jy beam}^{-1}$ RMs for a large sample of galaxies. Non-zero Faraday rotation is found to be ubiquitous in all of the target fields, from both the Galactic foreground and the target galaxies themselves. In this paper, we present an overview of the polarized emission detected in each of the WSRT-SINGS galaxies. The most prominent trend is a systematic modulation of the polarized intensity with galactic azimuth, such that a global minimum in the polarized intensity is seen toward the kinematically receding major axis. The implied large-scale magnetic field geometry is discussed in a companion paper. A second novel result is the detection of multiple nuclear Faraday depth components that are offset to both positive and negative RM by $100\text{--}200 \text{ rad m}^{-2}$ in all targets that host polarized (circum-)nuclear emission.

Key words. ISM: magnetic fields – galaxies: magnetic fields – radio continuum: galaxies

1. Introduction

In the study of star formation properties and evolution of galaxies, an important ingredient is the magnetic field content of the ISM. Yet the precise role that magnetic fields play in regulating star formation, and the role of magnetic fields in the evolution of galaxy disks, is still far from well understood. One reason for this gap is that a systematic survey of magnetic field content in galaxies over a range of Hubble type and star formation properties had, until recently, not been performed.

Magnetic fields are expected to play an important role in several aspects of star formation and galaxy evolution. First, magnetic fields are a crucial consideration in the energy balance of the ISM (e.g., Beck 2007), and in particular are likely important in determining the conditions for gravitational instability that lead to the initial stages of star formation (McKee & Ostriker 2007). Magnetic fields are expected to be important agents in helping to shape galactic evolution on large scales (Boulares & Cox 1990), while the longevity of familiar morphological features such as spiral arm “spurs” may be dependent on the presence of ordered magnetic fields (Shetty & Ostriker 2006). Finally, magnetic fields may be an important piece of the puzzle in understanding how the disk-halo interaction proceeds (e.g., Tüllmann et al. 2000), and thus in determining how matter and energy are redistributed throughout a galactic disk and indeed within galaxy groups and clusters by feedback processes.

Clearly, magnetic fields should be a major consideration in the study of star formation and galaxy evolution. However,

observational measurements of the magnetic fields in nearby galaxies are relatively few. A review of the available observations is not warranted here, but some of the most recent studies, obtained with widely varying observational setups, include those of: NGC 6946 (Beck 2007); NGC 5194 (Berkhuijsen et al. 1997); NGC 4254 (Chyży et al. 2007); and the Large Magellanic Cloud (Gaensler et al. 2005). Taken together, all of the observations indicate a tendency for magnetic fields to be oriented in spiral patterns in disk galaxies, even in galaxies with no spiral structure visible in the gaseous or stellar morphology (e.g. NGC 4414; Soida et al. 2002). Where spiral arms are visible, the fields tend to be more ordered in the interarm regions. Halos seem to have large-scale magnetic fields; the ordered fields typically lie parallel to the disk in edge-on galaxies, and then turn to a more perpendicular orientation as distance from the midplane increases.

Information about the magnetic fields in galaxies is most efficiently obtained using two complementary techniques. The non-thermal synchrotron emission generated by relativistic electrons spiraling in a magnetic field oriented perpendicular to the line of sight (LOS) is linearly polarized. The electric field vector of the polarized radiation is oriented perpendicular to the magnetic field that accelerates the source electrons, and the radiation itself is beamed parallel to the trajectory of the ultra-relativistic electron. Thus, the plane of polarization of the observed synchrotron radiation is directly related to the component of the magnetic field perpendicular to the LOS ($B_{\perp}$) in the observed object. Moreover, the synchrotron emissivity is proportional to

Table 1. Summary of survey galaxies.

Galaxy ID	Hubble Type	D_{25} [arcmin]	Incl. [deg.]	$\psi'_{xy} \pm \text{err}$ [deg.]	Spiral sign	PA [deg.]	Ref ^a	Beam ellipse	σ_P [$\mu\text{Jy/bm}$]	$P \pm \text{err}$ [mJy]	$RM_{FG} \pm \text{err}$ [rad m ⁻²]	I [mJy]
Holmberg II	Im	7.9	56	...	–	168	4	1.06	11.8	<0.5	–10 ± 2	5.5
IC 2574	SABm	13.2	53	–	+1	56	1	1.08	12.5	<0.6	–18 ± 4	14.
NGC 628	SAC	10.5	7	15 ± 2	+1	25	5	3.68	13.5	23 ± 2	–34 ± 2	200.
NGC 925	SABd	10.5	66	25 ± 2	+1	287	1	1.81	13.0	<0.6	–10 ± 2	90.
NGC 2403	SABcd	21.9	63	21 ± 4	+1	124	1	1.10	9.0	28 ± 5	+11 ± 30	360
NGC 2841	SAB	8.1	74	–	–1	153	1	1.29	8.6	5.8 ± 0.5	–6 ± 3	100
NGC 2903	SABbc	11.5	65	13 ± 5	–1	204	1	2.73	12.6	14 ± 1	+3 ± 1	460
NGC 2976	SAC	5.9	65	–	–1	335	1	1.08	9.5	3.0 ± 0.6	–34 ± 2	68.
NGC 3184	SABcd	7.4	16	17 ± 3	+1	179	9	1.51	9.7	5 ± 1	+19 ± 2	80.
NGC 3198	SBc	8.5	72	–	–1	215	1	1.40	9.4	<0.5	+7 ± 2	49.
NGC 3627	SABb	9.1	62	–	–1	173	1	4.45	15.2	12.5 ± 1	+13 ± 1	500
NGC 3938	SAC	5.4	14	12 ± 3	+1	204	2,3	1.44	9.1	6.2 ± 0.5	+1 ± 2	80.
NGC 4125	E6p	5.8	–	–	–	83 ¹	6	1.10	6.7	<0.1	+19 ± 1	1.9
NGC 4236	SBdm	21.9	73	–	–1	161	7	1.07	9.1	<0.3	+15 ± 2	26.
NGC 4254	SAC	5.4	32	22 ± 4	+1	65	2,3	4.02	14.5	24 ± 2	–13 ± 3	510
NGC 4321	SABbc	7.4	30	15 ± 3	–1	159	2,3	3.67	13.1	16 ± 1	–17 ± 1	310
NGC 4450	SAab	5.2	48	10 ± 2	+1	352	2,3	3.40	13.5	<0.2	–8 ± 1	13.
NGC 4559	SABcd	10.7	65	–	–1	328	2,3	2.13	12.9	1.0 ± 0.2	–5 ± 2	110
NGC 4569	SABab	9.5	66	–	–1	23	2,3	4.39	13.3	12 ± 1	+18 ± 2	170
NGC 4631	SBd	15.5	85	–	–	86	2,3,8	1.86	12.6	40 ± 2	–4 ± 3	1290
NGC 4725	SABab	10.7	54	7 ± 1	+1	36	2,3	2.32	12.4	3.6 ± 0.5	–4 ± 4	100
NGC 4736	SAab	11.2	41	–	+1	296	1	1.52	17.3	11.5 ± 1	+1 ± 1	320
NGC 4826	SAab	10.0	65	7 ± 2	+1	121	1	2.71	13.5	0.7 ± 0.1	–8 ± 2	110
NGC 5033	SAC	10.7	66	19 ± 3	–1	352	2,3	1.68	10.5	3.5 ± 0.5	+9 ± 2	240
NGC 5055	SABc	12.6	59	11 ± 3	+1	102	1	1.49	10.6	17.5 ± 1	–8 ± 3	450
NGC 5194	SABbc	11.2	42	15 ± 2	–1	172	9	1.36	9.5	81 ± 5	+12 ± 2	1420
NGC 6946	SABcd	11.5	33	28 ± 4	+1	243	1	1.15	10.6	150 ± 10	+23 ± 2	1700
NGC 7331	SAB	10.5	76	14 ± 3	+1	168	1	1.77	11.4	14.5 ± 1	–177 ± 7	590

References: (1) de Blok et al. (2008); (2) Paturel et al. (2003); (3) Braun et al. (2007); (4) Bureau & Carignan (2002); (5) Kamphuis & Briggs (1992); (6) Jarrett et al. (2003); (7) Braun (1995); (8) de Vaucouleurs et al. (1991); (9) Tamburro et al. (2008).

the product of $B_{\perp}^{1+\alpha}$ and the relativistic electron density n_{CR} , where α is the spectral index (e.g., Longair 1994). This makes the observed polarized intensity itself a good tracer of $B_{\perp}$. This straightforward correspondence is complemented by the second technique for measuring magnetic fields: Faraday rotation. This effect is produced when polarized radiation passes through a magnetized plasma, which is birefringent (Gardner & Whiteoak 1963). The intrinsic linear polarization angles of the radiation are rotated by a different angle depending on the wavelength of the radiation. The effect is characterized by the Faraday “rotation measure”. The value of the rotation measure (RM) is dependent on the electron density n_e in the magnetized plasma, and the component of the magnetic field along the LOS ($B_{\parallel}$). The sign of RM is determined by whether $B_{\parallel}$ points toward or away from the observer. See Sect. 2.2 for an in-depth discussion.

The Spitzer Infrared Nearby Galaxies Survey (SINGS; Kennicutt et al. 2003) was conceived as a multi-wavelength Legacy program intended to address the question of how stars form in a wide range of galactic ISM environments. The strength of such a concerted survey campaign is that it draws together data over the widest possible range of observing bands to provide as much information as possible about the physical conditions in the galaxy ISM being investigated. Gaps in the coverage are generally covered by supplementary surveys such as The HI Nearby Galaxy Survey (THINGS; Walter et al. 2008).

One such supplementary survey is the Westerbork SINGS survey (WSRT-SINGS; Braun et al. 2007), which provides 18- and 22-cm radio continuum data, in all four Stokes parameters, for a subset of the SINGS galaxies (the survey selection criteria

are discussed below). Together with the SINGS survey itself, the data provided by the WSRT supplement enable, for example, investigation into the origin of the FIR-radio correlation (Murphy et al. 2006). In this paper and a companion work (Braun et al. 2009; hereafter Paper III), we utilize the linear polarization products of the WSRT-SINGS data to investigate the magnetic field content of the ISM in the subsample galaxies.

Of the galaxies that make up the SINGS sample, not all are observable with the WSRT. Because the individual antennas are arranged in a linear east-west array, the synthesized beam is significantly extended in the north-south direction when observing objects at low declination. At the frequencies observed in this survey, the synthesized beam would be $\geq 1'$ for sources at $\delta < 12.5^\circ$; we therefore exclude galaxies below this declination limit. Furthermore, in order to ensure that the galaxies themselves are large enough on the sky that they are spatially resolved, the additional criterion was adopted that the optical B band diameter at a surface brightness of 25 mag arcsec⁻², $D_{25} > 5'$. With the addition of four galaxies in the Starburst sample of Rieke, a total of 34 galaxies were observed in the WSRT-SINGS program. Twenty-eight of those galaxies are studied here; their properties are summarized in Table 1. The columns are: (1) Galaxy ID; (2) RC3 Hubble type; (3) D_{25} ; (4) Inclination; (5) Spiral pitch angle (from Kennicutt (1981)); (6) Spiral sense (+1 for counter-clockwise, –1 for clockwise); (7) Kinematic PA (measured east of north) of the receding major axis; (8) Reference for inclination and PA values; (9) Synthesized beam ellipticity (a/b , where the minor axis of the beam is in all cases $b = 15''$, and the beam position angle is 0°); (10) Noise levels in P ; (11) Integrated flux

in P with an estimated error; (12) Estimated foreground RM that applies to the target field; (13) Integrated 1365 MHz flux in I (from [Braun et al. 2007](#)).

This paper is organized as follows. We describe the observations and data reduction steps in Sect. 2, with a particular emphasis on describing the RM-Synthesis method (Sect. 2.2), which is a critical component of the analysis utilized in this work. An overview of the polarized emission detected in each of the survey galaxies is presented in Sect. 3. For those galaxies with detected polarized emission, a discussion of some derivable characteristics is given in Sect. 4. Properties of the global magnetic field geometries revealed by these observations are treated in detail in Paper III. A more detailed study of individual galaxies will form the basis of forthcoming work. We conclude the paper in Sect. 5 and provide an outlook for future investigations.

2. Observations and data reduction

2.1. Data collection and “standard” data reduction

The observational parameters of the WSRT-SINGS survey were presented in detail by [Braun et al. \(2007\)](#), and we list the most relevant points here. Each galaxy was observed for at least 12 h in two bands covering the ranges 1300–1432 and 1631–1763 MHz (22- and 18-cm, respectively). The observing band was switched every 5 mn during an individual synthesis. In each band, the correlator was set up to provide 512 channels separated by 312.5 kHz. Eight 20-MHz subbands (64 channels each) were used at each observing frequency, and the central subband frequencies were arranged to be separated by 16 MHz. This setup allows us to disregard frequency channels suffering from bandpass rolloff (which affects each of the individual subbands), and maximizes the continuity of the frequency coverage while still providing a large total bandwidth. Data were obtained in all four Stokes parameters.

The basic data reduction steps of each 20 MHz subband are also discussed by [Braun et al. \(2007\)](#); we repeat the most relevant details here. After careful editing of incidental radio frequency interference (RFI) the bandpass calibration in amplitude and phase was determined using the calibration sources 3C147, 3C286, CTD93 and 3C138 within the AIPS package ([Greisen 2003](#)). Relative broadband gains in the two perpendicular linear polarizations (X and Y) were then determined, after modifications to several key tasks (SETJY and CALIB) to enable the representation of source models, and the calculation of gain solutions, with arbitrary values of the Stokes parameters (I , Q , U , V). This was necessary to permit an equivalent representation of the measured linear polarization products (with an unchanging parallactic angle) within a software package that normally assumes right- and left-handed circular polarization products. Basic polarization calibration was then accomplished by determining the cross-polarization leakage from 3C147, under the assumption that this source is intrinsically unpolarized. The phase offset of the X and Y polarizations (which is assumed to remain constant during each 12 h track) was then determined using the linearly polarized emission properties of either 3C286 [e.g. (I , Q , U , V) = (14.65, 0.56, 1.26, 0.00) Jy near 1400 MHz] or 3C138. In cases where both 3C286 and 3C138 were observed bracketing the 12 h target track, it was possible to determine the consistency of the phase offset, which was found to be constant to better than 1–2 degrees. After a final check that the correct Stokes parameters were recovered for all calibration sources (both polarized and unpolarized), the calibrated data were exported from the AIPS package. Further refinement of the

polarization calibration was accomplished via self-calibration of each 20 MHz subband within the Miriad package ([Sault et al. 1995](#)) using the detected emission in each target field in Stokes I , Q and U . This step corrects for time-variable instrumental or ionospheric phase errors.

Following these reduction steps, the Q and U maps in each narrowband frequency channel (of 312.5 kHz) were imaged individually. They were CLEANed within mask regions derived from smoothed versions of the total Stokes I map in each subband. The same restoring beam size was used at all channel frequencies; see Table 1 for the effective resolution in each galaxy. Primary beam corrections were applied to each channel map individually. The primary beam correction was performed using the standard WSRT model [the primary beam response is approximated with the function $\cos^6(cvr)$, where $c = 68$ at L -band frequencies, v is the frequency in GHz, and r is the distance from the pointing center in radians]. An improved primary beam correction for the WSRT has been developed by [Popping & Braun \(2008\)](#) but is little different from the standard treatment at the small field angles which are considered here. After primary beam correction, the channel maps were arranged into cubes, and analyzed with the RM-Synthesis technique (described in Sect. 2.2). Individual channel maps are used as input to the RM-Synthesis software because the technique can be thought of as a technique for determining the Faraday rotation measure which maximizes the polarized signal-to-noise ratio across the full frequency band.

Stokes V images were generated, and the intensity histograms in those images are Gaussian, with an rms of about $20 \mu\text{Jy beam}^{-1}$. In some fields, very bright continuum sources far from the field center have instrumental circular polarization, at the $V/I \lesssim 0.5\%$ level.

2.2. RM synthesis

As discussed above, the effect of Faraday rotation is to change the intrinsic polarization angle of the radiation (χ_0) by an amount depending on the wavelength of the radiation. More specifically, the observed polarization angles after Faraday rotation are

$$\chi = \chi_0 + \phi \lambda^2, \quad (1)$$

where λ is the wavelength, and the rotation measure RM has been replaced by a more general quantity ϕ , the “Faraday depth”. The value of ϕ is related to the properties of the Faraday rotating plasma by the equation

$$\phi \propto \int_{\text{source}}^{\text{telescope}} n_e \mathbf{B} \cdot d\mathbf{l}, \quad (2)$$

where $\mathbf{B}$ is the magnetic field, $\mathbf{l}$ is the distance along the LOS, and n_e is the electron density. When $\mathbf{B}$ is expressed in μGauss , $\mathbf{l}$ in pc, and n_e in cm^{-3} , the proportionality constant is 0.81, and the units of ϕ are rad m^{-2} . From Eq. (2), it can be seen that the Faraday depth expresses the depth of Faraday rotating plasma between the source and the telescope. The dot product indicates that it is only the component of the magnetic field along the LOS ($B_{\parallel}$) that contributes to the integral. The sign of ϕ is taken to be positive for a magnetic field pointing toward the observer. The magnitude of ϕ is traditionally determined by fitting a linear relationship between χ and λ^2 (e.g., [Ruzmaikin & Sokoloff 1979](#)). However, this approach has well-documented problems such as $n\pi$ ambiguities. Sophisticated techniques have been developed to overcome these difficulties (e.g. [Pacerman, Dolag et al. 2005](#); [Vogt et al. 2005](#)), but these still suffer from the same fundamental

problem. Moreover, by fitting the change in the observed polarization angle with λ^2 , one is faced with the implicit constraint that the polarized signal must be bright enough at each observing frequency to allow a significant fit. For the faintest polarized emission this would not be possible. A different method for determining the effect on the polarized radiation produced by the magnetized plasmas along the LOS, first described by [Burn \(1966\)](#) and now called the RM-Synthesis method ([Brentjens & de Bruyn 2005](#)), can overcome the weaknesses in the traditional techniques for determining RM, and will be used in this paper.

Equation (1) is valid only in physical situations where all of the polarized emission is observed at a single Faraday depth ϕ . In more complicated circumstances (for instance, emission that arises both beyond and between two distinct Faraday rotating clouds along the LOS; for an in-depth discussion see [Sokoloff et al. 1998](#)), the simple relation is no longer valid. By expressing the polarization vector as an exponential ($P = p e^{2i\chi}$), using Eq. (1) for χ , and integrating over all Faraday depths, [Burn \(1966\)](#) shows that

$$P(\lambda^2) = \int_{-\infty}^{+\infty} F(\phi) e^{2i\phi\lambda^2} d\phi, \quad (3)$$

where $P(\lambda^2)$ is the (complex) observed polarization vector [$P(\lambda^2) = Q(\lambda^2) + iU(\lambda^2)$], and $F(\phi)$, the “Faraday dispersion function,” describes the *intrinsic* polarization vector at each Faraday depth.

Under the assumption that χ_0 is constant for all ϕ , the Fourier transform-like Eq. (3) can be inverted to give an expression for the Faraday dispersion function:

$$F(\phi) = \int_{-\infty}^{+\infty} P(\lambda^2) e^{-2i\phi\lambda^2} d\lambda^2. \quad (4)$$

Everything on the right-hand side of Eq. (4) is observable. However, we only measure discrete (*positive*) values of λ^2 . The form that is used in practice (e.g., [Brentjens & de Bruyn 2005](#)) is therefore expressed as a discrete sum,

$$F(\phi) \approx K \sum_{i=1}^N W_i P_i e^{-2i\phi(\lambda_i^2 - \lambda_0^2)}, \quad (5)$$

where W_i are weights which are allowed to differ from unity, and the normalization factor K is the inverse of the discrete sum over W_i . Note that the term λ_0^2 has been added to the exponential. [Brentjens & de Bruyn \(2005\)](#) demonstrate that when λ_0^2 is taken to be the weighted mean of the N individual observed λ_i^2 , a better behaved response function results. That response function, or rotation measure spread function (RMSF)², is formally given by

$$R(\phi) \approx K \sum_{i=1}^N W_i e^{-2i\phi(\lambda_i^2 - \lambda_0^2)} \quad (6)$$

and is conceptually equivalent to the dirty beam encountered when performing image synthesis with an array of radio telescopes. Just as a radio interferometer discretely samples uv -space, here we discretely sample λ^2 -space. Examples of the RMSF, specific to the observations presented in this paper, are shown in Fig. 1.

² This function was originally referred to as the rotation measure transfer function (RMTF) by [Brentjens & de Bruyn \(2005\)](#), but has since been relabeled to more accurately reflect its mathematical relationship to the Faraday dispersion function.

Fig. 1. RMSFs corresponding to the frequency coverage in the observations of NGC 628. RMSF values were calculated using the 22 cm band alone (untapered: **a**,**b**); tapered: **c**,**d**) and in the combination of the 18 cm and 22 cm bands (**e**,**f**). In each row, the left panel shows the value of the weight function $W(\lambda^2)$ for each of the sampled frequency channels, and the right panel shows the corresponding RMSF (real part: long dashed lines; imaginary part: dotted lines; absolute value: solid lines). Matching ranges of λ^2 are illustrated by diagonal lines between panels **c** and **e**, and matching ranges of ϕ between panels **d** and **f**.

Previous rotation measure experiments have had to rely on relatively few measurements in frequency space. But with modern correlator backends like the one at the WSRT, the technique of determining $F(\phi)$ as shown in Eq. (5) is made possible. The practical aspects of this technique have been developed by [Brentjens & de Bruyn \(2005\)](#). We use software developed by Brentjens to perform the inversion shown in Eq. (5) and obtain a reconstruction of $F(\phi)$. The software takes cubes of Stokes Q and U images in single frequency channels as input, along with a specification of the frequency at each plane of the cubes. As output, cubes of Stokes Q and U in planes of constant ϕ are obtained. Simply put, the inversion amounts to the computation of the implied values of Q and U for a whole series of trial values of the Faraday depth, ϕ . In this way, the coherent sensitivity of the entire observing band to polarized emission is retained, irrespective of possible Faraday rotation within the band, as long as such rotation is well resolved by the λ^2 sampling.

The polarization vectors described by the values of Q and U in each plane can be thought of as having been corrected for Faraday rotation – but note that the vectors have been derotated to a common non-zero value of λ^2 , namely to $\lambda^2 = \lambda_0^2$,

as shown in Eq. (5). Hence, to obtain the *intrinsic* polarization angle at each value of ϕ , multiplication of our reconstructed $F'(\phi) = Q(\phi) + iU(\phi)$ by $e^{-2i\phi\lambda_0^2}$ must be performed. Further explanation regarding this detail is provided in Appendix A.

The frequency sampling provided by the WSRT-SINGS survey gives sensitivity to polarized emission up to a maximum Faraday depth of $|\phi_{\max}| \approx \sqrt{3}/\delta\lambda^2 \approx 1.7 \times 10^5 \text{ rad m}^{-2}$ (see Brentjens & de Bruyn 2005), where $\delta\lambda^2$ refers to the channel separation. A search for large rotation measure emission was performed for each of the galaxy fields, by performing RM-Synthesis on the observed Q and U cubes in the range $|\phi| < 1.7 \times 10^5 \text{ rad m}^{-2}$ (albeit with coarse ϕ sampling). No emission at high values of Faraday depth was found in any of the target fields. Next, RM-Synthesis was performed on the 22 cm data alone, from -1500 rad m^{-2} to $+1500 \text{ rad m}^{-2}$ with fine sampling (50 rad m^{-2}). Given the λ^2 width of the 22 cm band, the ϕ resolution element ($FWHM$) is 450 rad m^{-2} . The first sidelobe of the RMSF is at 24% of the main lobe. The sidelobe level can be reduced, at the expense of lower ϕ resolution, by tapering in λ^2 space (by allowing W_i to deviate from unity in Eq. (5), and as illustrated in Fig. 1). After tapering with a Gaussian with $\sigma = \frac{1}{2}(\lambda_{\max}^2 - \lambda_{\min}^2)$, the width of the main lobe is 650 rad m^{-2} , and the first sidelobe is reduced to 2% of the RMSF peak. Increasing the denominator in the tapering function serves to further decrease the sidelobe level, while increasing the width of the main lobe. After testing a series of different tapers, this particular choice was selected as a reasonable tradeoff between sidelobe height and RMSF width. The cubes produced in this way can be used as a (very) low resolution verification of complicated $F(\phi)$ spectra.

RM-Synthesis was also performed on the combination of the 18 cm and 22 cm data. The results of this operation were used for most of the subsequent analysis. Together, the two bands provide a ϕ resolution of 144 rad m^{-2} . This is comparable to the maximum Faraday depth to which about 50% sensitivity to the polarized intensity is retained of about $\pi/\lambda_{\min}^2 = 110 \text{ rad m}^{-2}$. However, due to the large gap in frequency coverage between the two bands, the RMSF has large sidelobes, as shown in Fig. 1. The first sidelobes are at about the 78% level in P , which can potentially cause serious confusion, particularly in cases where polarized emission is detected at multiple ϕ along a single LOS. This difficulty can be alleviated by using a deconvolution technique similar to the Högbom CLEAN algorithm (Sect. 2.3).

2.3. Faraday dispersion function deconvolution

Once the RM-Synthesis was performed for each field, the $F(\phi)$ spectra were deconvolved using a variation of the Högbom CLEAN, as outlined by Brentjens (2007). The deconvolution is complex-valued and operates along the ϕ dimension, which is the third axis of the $Q(\phi)$ and $U(\phi)$ cubes produced by the RM-Synthesis technique. The steps of the procedure, called RM-CLEAN, are described in detail in Appendix A. Briefly, one iteratively subtracts scaled versions of the RMSF from the reconstructed Faraday dispersion function until the noise floor is reached, after which a smoothed representation of the “CLEAN model” is used as the approximate true Faraday dispersion function. In this paper, we take the RM-CLEAN cutoff to be equal to the noise in the individual $Q(\phi)$ and $U(\phi)$ maps, and the gain factor is 0.1 (see Appendix A for a more extensive description of these parameters).

Examples of the result of running RM-CLEAN on dirty $F(\phi)$ spectra are shown in Figs. 2 and 3. In Fig. 2, a single-valued

Fig. 2. Demonstration of the RM-CLEAN process for a relatively bright point source in the field of NGC 4125. *Top: P, middle: Q, bottom: U.* Gray lines are the dirty spectra; black lines are the cleaned spectra. A restoring RMSF with $FWHM$ 144 rad m^{-2} was used to produce the deconvolved spectra. The resulting $F(\phi)$ spectrum shows a single component at a central $\phi = +33 \text{ rad m}^{-2}$.

$F(\phi)$ spectrum has been RM-CLEANed. The only benefit is that the sidelobe structure has been significantly reduced. Note that the deconvolution routine is unable to improve the ϕ resolution, which is determined by the spread of sampled frequencies. In the right-hand panels, the data are compared to the λ^2 representation of the RM-CLEAN components found during the procedure. A solution equivalent to the best linear fit to χ^2 -vs- λ^2 has been determined. That this type of deconvolution is mathematically identical to a least-squares fit in the inverse Fourier domain has been shown by Schwarz (1978). In Fig. 3, a more complicated $F(\phi)$ is shown. Note that in cases such as this, where multiple structures are detected, the location of the peak of the fainter component is shifted relative to its true position because of confusion with sidelobes from the brighter component. Particularly in such cases, deconvolution is required to recover source parameters.

Final on-axis sensitivities in the deconvolved $F(\phi)$ cubes are listed in Table 1 for each galaxy. In view of the combined frequency coverage contributing to P (1300–1432 and 1631–1763 MHz), the effective center frequency is about 1530 MHz.

Fig. 3. Demonstration of the RM-CLEAN process for a relatively bright point source in the field of NGC 7331. *Top:* P , *middle:* Q , *bottom:* U . Gray lines are the dirty spectra; black lines are the cleaned spectra. A restoring RMSF with $FWHM$ 144 rad m^{-2} was used to produce the deconvolved spectra. The resulting $F(\phi)$ spectrum shows two components at central $\phi = -185, +170 \text{ rad m}^{-2}$.

2.4. Analysis of deconvolved Faraday depth cubes

The spatial distribution of polarized emission was determined by selecting the peak in each $P(\phi) \equiv \|F(\phi)\|$ spectrum. The grayscale maps of these images are shown in Fig. 4, with overlaid contours of the 22 cm Stokes- I maps for comparison. Since polarizing intensity has Ricean, rather than Gaussian statistics (see Wardle & Kronberg 1974), some care needs to be taken in determining the integrated value of P . In the absence of source signal, the noise has a Rayleigh distribution with a mean (the “Ricean bias”) and variance of

$$\langle P \rangle_n = \sigma_{Q,U} \sqrt{\frac{\pi}{2}} = 1.25 \cdot \sigma_{Q,U}, \quad (7)$$

and

$$\sigma_P = \sqrt{\frac{4 - \pi}{2}} \sigma_{Q,U} = 0.66 \cdot \sigma_{Q,U}, \quad (8)$$

for an rms noise in Q and U of $\sigma_{Q,U}$. In the case of high signal-to-noise, the noise statistics become Gaussian with the mean P in agreement with its noise-free value and $\sigma_P = \sigma_{Q,U}$.

We have carefully determined the noise level and Ricean bias in each target. To do this, we have determined the mean and variance in each image of peak P within a central, polygonal region (free of emission). The variances that we measure (and list in Table 1) are in good agreement with the expectation noted above, $\sigma_P = 0.66 \cdot \sigma_{Q,U}$, for a Rayleigh distribution. However, the bias values that we measure are in all cases enhanced by a factor of about two over the simple expectation, $\langle P \rangle_n = 1.25 \cdot \sigma_{Q,U}$. The cause of this high Ricean bias level is that the peak value of $P(\phi)$ has been extracted from a cube covering Faraday depths between -500 and $+500 \text{ rad m}^{-2}$ with an effective resolution of about 144 rad m^{-2} , and has thus been chosen from some 7 independent samples. The Rayleigh distribution function is given by

$$D(r) = 1 - \exp\left(\frac{-r^2}{2\sigma_{Q,U}^2}\right), \quad (9)$$

where r represents the flux in a given sample. In a Faraday dispersion function which contains only noise (no signal), the expectation value for the largest ($\hat{r}$) of N independent samples occurs for

$$\exp\left(\frac{-\hat{r}^2}{2\sigma_{Q,U}^2}\right) = \frac{1}{N}, \quad (10)$$

or

$$\hat{r} = \sigma_{Q,U} [2 \ln(N)]^{0.5}. \quad (11)$$

This should be a good estimator of the Ricean bias in our maps. Since we have $N = 7$, we obtain $\hat{r} = 2.0 \cdot \sigma_{Q,U}$, in good agreement with what is measured for the on-axis background level in all cases except NGC 6946 and NGC 7331, where patchy foreground emission from the Galaxy is apparent in the fields. The mean noise floor increases radially away from the field center due to the primary beam correction which has been applied to each original frequency channel during processing. For the purposes of display and the measurement of azimuthal trends, we have subtracted out a primary beam-corrected noise floor from the peak P images shown in Fig. 4.

For determination of the integrated P (or useful limits on P) for each target (as listed in Table 1), we have not carried out a spatial background subtraction of the noise floor, but instead have simply blanked the images at a level of $3\sigma_{Q,U} \sim 4.5\sigma_P$. At these brightnesses, the Ricean bias has already declined to below about 5% (Wardle & Kronberg 1974), so that no further bias correction of the integrated P was applied. The P emission was integrated within the smallest possible polygonal region which enclosed the region of significant target emission while excluding any apparent background sources. For comparison, we also list the integrated I of each target at 1365 MHz from Braun et al. (2007).

Polarized emission maps were also produced (using only the 22 cm data) for the purpose of determining the polarized fraction in these galaxies. The peak polarized intensity was extracted for each spatial pixel, and then divided by the corresponding 22 cm Stokes- I value. Clip levels were set at 4 times the noise level in both maps. Thus, polarization fraction estimates are not available for the faintest emission detected in the sample. The polarized fraction values are discussed in Sect. 3.2.

In order to determine the Faraday depth at the peak of the $P(\phi)$ spectra, we fit a parabola to the top three points in the over-sampled, RM-CLEANed $P(\phi)$ spectra. The result is called $\hat{\phi}$.

The polarization angle at the Faraday depth thus determined was obtained via

$$\chi_0 = \frac{1}{2} \arctan \left(\frac{U(\hat{\phi})}{Q(\hat{\phi})} \right). \quad (12)$$

We refer to this as the intrinsic polarization angle (χ_0) because the effect of Faraday rotation has already been corrected for, via the RM-Synthesis technique. The magnetic field orientation is obtained by simply rotating the polarization angle by 90° .

Errors associated with the magnetic field orientations were estimated by propagating errors through the mathematical operations required to calculate the quantity. Since

$$\chi_0 = \chi - \hat{\phi} \lambda_0^2, \quad (13)$$

error propagation yields the uncertainty in our determination of the intrinsic polarization angle,

$$\sigma_{\chi_0}^2 = \sigma_\chi^2 + \lambda_0^4 \sigma_{\hat{\phi}}^2. \quad (14)$$

The quantity σ_χ , the uncertainty in the observed (Faraday rotated) polarization angle can be shown to be given by (Brentjens 2007)

$$\sigma_\chi^2 = \frac{1}{4} \frac{\sigma^2}{|P|^2}, \quad (15)$$

where $\sigma = \sigma_Q \approx \sigma_U$ is the noise in the individual $Q(\lambda^2)$ and $U(\lambda^2)$ maps. The uncertainty in $\hat{\phi}$ can be estimated by propagating errors in the equation for fitting a parabola to the peak of the $P(\phi)$ profile, and is dominated by the RMSF resolution. We have calculated these uncertainties for all of the galaxies which have magnetic field vectors plotted in Fig. 4, and are typically $\leq 10^\circ$ in locations where the brightest P emission is detected.

Note that magnetic field orientations are easily interpreted only if the deconvolved $F(\phi)$ spectrum is single-valued. If there is more than one ϕ component, then the magnetic field orientations determined in this way only apply to the brightest component of polarized emission. The deconvolved Faraday depth cubes were analyzed to identify locations where multiple Faraday depths might be present (Sect. 4.3). These are noted throughout the paper, where appropriate.

3. Overview

Here, we summarize the main features of interest observed for each galaxy field based on a comparison of the polarized and total continuum brightness, together with the (Faraday rotation corrected) magnetic field orientation shown in Fig. 4, and the Faraday depth where peak polarized intensity is detected in Fig. 6.

3.1. Rotation measures of discrete background sources

In addition to the primary targets of our program, each observed field also contains a number of background sources with significant polarized brightness. While many of these sources are unresolved at the modest angular resolution of our study ($\geq 15''$), a significant number are also resolved into the classical edge-brightened double morphology associated with high luminosity radio galaxies (e.g. Miley 1980). Lobe separations of 1–2 arcmin are common, while a handful of objects with 5–10 arcmin angular size are detected. We have determined the Faraday depth and the associated error for the significantly detected polarized sources in the central $34' \times 34'$ of our fields,

making a particular note of the source morphology and classifying sources as unresolved, double, triple (double plus core), extended or complex. The individual lobes of double radio sources were measured separately where practical. The rotation measures listed in Table 2 were determined for each source from a plot of Faraday depth versus polarized brightness within a rectangular box that isolated the source (component). The listed RM is that of the peak in P while the error corresponds to the HWHM of the distribution. The columns are: (1) Galaxy field; (2) Discrete source position; (3) Morphology; (4) Rotation measure with estimated error. Morphologies are classified as unresolved: UNR, double: DBL, triple: TRPL, complex: CMPLX and extended: EXT. For DBL and TRPL sources, the individual lobes (N, S, E or W) are measured where possible, always beginning with the brightest one (in Stokes P). The weaker lobe is prefaced by its flux ratio with respect to the brighter. When the source is (possibly) affected by the target galaxy disk the morphology is further flagged as FG(?).

From the values in Table 2 it is apparent that when multiple, double-lobed sources are detected in an individual galaxy field then they generally have RMs that are in good agreement with one another. Unresolved sources in the field have RMs which are sometimes consistent, but seem to have a larger intrinsic scatter. Furthermore, when the lobes of double-lobed sources are within a factor of two in brightness they generally have better RM agreement, often as good as $1\text{--}2 \text{ rad m}^{-2}$. For more extreme lobe brightness ratios, this consistency declines. To the extent that a single Galactic foreground RM contribution is appropriate in a particular field, the scatter in the measured RMs of the background sources is likely caused by variations in the intrinsic RMs of the sources themselves.

Since the likely red-shift of the luminous edge-brightened double sources we detect is greater than about $z = 0.8$ (Condon et al. 1998), the associated physical sizes are likely in the range 0.5–5 Mpc. The large physical separation of such radio lobes from the host galaxy makes it unlikely that high densities of thermal electrons will be mixed with the emitting regions. A relevant phenomenon which has been documented is the tendency for enhanced Faraday depolarization and RM fluctuations to be seen toward the fainter lobe of a pair (in both Stokes I and particularly P) (Laing 1988; Garrington et al. 1988; Laing et al. 2006). This phenomenon is consistent with the fainter lobe being the more distant one and its radiation suffering additional propagation effects while passing through the magneto-ionic halo of the host galaxy. A prediction of this interpretation is that edge-brightened doubles with equal brightness lobes are least likely to have differences in their associated Faraday depth, as we confirm. In any case, it is likely that well-separated lobes of luminous radio galaxies can provide a good estimate of the line-of-sight rotation measure with a minimal intrinsic contribution, in contrast to unresolved and possibly core-dominated AGN, for which a local host contribution to the Faraday depth is more likely.

A plausible method of estimating the Galactic foreground contribution to the RM in each field seems to be a weighted median value whereby double-lobed sources, particularly those of similar lobe brightness, are given a very high weight. Some discussion of these considerations is given below for each target field in turn, with the result listed in Table 1. While the majority of our target galaxies are well-removed from the Galactic plane ($|b| > 25^\circ$), where it is plausible that a single foreground RM may be expected to apply to a region of $34' \times 34'$, the two exceptions are the fields containing NGC 7331 ($b = -21^\circ$) and NGC 6946 ($b = +12^\circ$). Diffuse, patchy polarized emission from

Fig. 4. Images of sample galaxies. Contour levels (*white*) in Stokes I run from $0.1 \text{ mJy beam}^{-1}$ in powers of two. The color range of the peak polarized intensity in each $F(\phi)$ spectrum is displayed in the colorbar at the top of each panel, in units of Jy beam^{-1} . The galaxy ID is indicated in the upper left of each panel. In targets with sufficient polarized emission, the magnetic field orientations are displayed with blue vectors. The cyan ellipse indicates D_{25} .

Fig. 4. continued.

Fig. 4. continued.

Fig. 4. continued.

Fig. 4. continued.

the Galaxy is apparent in these fields, accentuating the likelihood that foreground RM fluctuations may also be present. We stress that we have in no case made use of polarized emission from the target galaxy itself to estimate the Galactic foreground RM, since this would bias the outcome by artificially imposing a zero mean RM on the target galaxy. For those targets in the direction of the Virgo cluster, or more generally along the Super-galactic plane, there is also the possibility that a non-zero contribution to the RM seen toward the distant background radio galaxies of Table 2 arises within these media. Detection of such a contribution would require a much more extensive sampling of the RM sky, such as envisioned for the Square Kilometre Array and its Pathfinders (e.g. Johnston et al. 2008).

3.2. Notes on individual galaxies

Here, we discuss the polarized features detected in each of the target fields. For much of the analysis, we utilize the 18 + 22 cm

(deconvolved) Faraday cubes, and the associated peak P and $\hat{\phi}$ maps shown in Figs. 4 and 6. Comparisons with optical images are shown in Fig. 5. We occasionally refer to the Faraday cubes produced using the 22 cm data alone. Trends in the azimuthal and radial variations in polarized flux and Faraday RM lead to a generic, consistent picture of the global magnetic field geometry in the spiral galaxies included in our sample (see Sect. 4.2). These trends and the global magnetic field geometry are discussed in detail in Paper III. Most galaxies with extended polarized flux show signs of broadened Faraday dispersion functions in small localized regions; see Sect. 4.3 for details. All galaxies with compact (circum-)nuclear polarized emission show signs of significant Faraday structure in their nuclei. This is discussed in Sect. 4.4.

Holmberg II: There is no convincingly detected polarized emission from Holmberg II. There is possibly very faint (at/below about the 4σ level) emission at the location of the higher brightness features in the eastern part of the galaxy which,

Table 2. Discrete source rotation measures.

Galaxy field	(RA, Dec) _{J2000}	Morphology	RM	Galaxy field	(RA, Dec) _{J2000}	Morphology	RM	Galaxy field	(RA, Dec) _{J2000}	Morphology	RM
Holmberg II	08:16:06, 70:47:00	UNR	-18 ± 2	NGC 3627	11:19:28, 13:02:50	TRPL W	+13 ± 1	NGC 4725	12:49:17, 25:33:10	UNR	+15 ± 2
	08:17:24, 70:38:03	DBL S	-13 ± 2			0.15 E	+23 ± 3		12:50:40, 25:28:05	DBL E	+4 ± 4
		0.95 N	-8 ± 5		11:20:41, 13:05:20	UNR	+3 ± 2		12:50:49, 25:35:10	UNR	+4 ± 3
	08:19:18, 70:55:00	EXT	+27 ± 5		11:21:21, 12:51:50	UNR	+23 ± 3		12:51:18, 25:31:05	UNR	+2 ± 2
	08:20:16, 70:52:15	EXT	-8 ± 2		11:52:13, 44:09:05	DBL N	+1 ± 2		12:50:55, 41:23:00	DBL W	+1 ± 1
IC 2574	08:20:25, 70:53:10	TRPL S	-8 ± 4	NGC 3938		0.6 S	+7 ± 2	NGC 4736	12:51:17, 40:57:30	DBL N	-8 ± 10
	10:26:28, 68:19:10	UNR	-12 ± 3		11:52:28, 44:21:50	CMPLX	+6 ± 2		12:51:50, 41:02:10	DBL W	-8 ± 5
	10:26:54, 68:24:35	UNR	-24 ± 3		11:53:10, 44:14:25	UNR (D?)	+2 ± 2		12:56:09, 21:43:34	DBL E	-8 ± 2
	10:29:17, 68:13:20	UNR	-17 ± 2		12:07:33, 65:24:35	DBL S	+20 ± 2			0.15 W	-1 ± 3
	01:35:42, 15:37:10	DBL W	-36 ± 3	NGC 4125	12:07:03, 65:18:10	UNR	+31 ± 3		12:56:19, 21:42:25	UNR	-13 ± 4
NGC 628	01:36:16, 15:41:40	DBL N	-28 ± 3		12:07:37, 65:15:35	UNR	0 ± 2	NGC 4826	12:56:59, 21:52:35	UNR	+8 ± 3
	01:36:58, 15:44:20	UNR FG?	-39 ± 3		12:07:51, 65:21:20	DBL E	+16 ± 2		12:57:26, 21:47:30	UNR	+4 ± 4
	01:37:43, 15:42:35	DBL E	-38 ± 4		12:08:02, 65:10:10	DBL S	+20 ± 2		13:12:05, 36:23:20	UNR	+3 ± 1
		0.5 W	-23 ± 3		12:08:10, 65:00:30	UNR	+32 ± 2		13:12:25, 36:40:50	UNR	+13 ± 1
	02:28:23, 33:18:45	DBL W	-8 ± 3	NGC 4236	12:15:30, 69:31:50	DBL W	+16 ± 1		13:13:16, 36:24:50	EXT	+9 ± 2
NGC 925	02:28:25, 33:26:15	UNR	-18 ± 3			0.2 E	+20 ± 5		13:13:39, 36:50:20	UNR	+16 ± 2
	02:28:26, 33:21:10	UNR	-12 ± 3		12:16:35, 69:28:15	DBL S FG	-3 ± 2		13:14:18, 36:49:15	UNR	-3 ± 2
	07:34:18, 65:28:05	UNR	+13 ± 3		12:16:36, 69:33:40	UNR	+23 ± 2		13:14:44, 36:39:00	UNR	-29 ± 1
	07:38:00, 65:49:05	UNR	-22 ± 3		12:18:50, 69:34:35	DBL S	+13 ± 2	NGC 5055	13:15:18, 41:49:25	DBL N/S	-5 ± 2
NGC 2403	07:38:45, 65:37:45	UNR	+42 ± 2			0.4 N	+17 ± 5		13:15:33, 41:56:15	EXT	-18 ± 3
	09:20:56, 51:13:50	UNR	-6 ± 3	NGC 4254	12:18:10, 14:15:40	DBL E	-13 ± 3		13:16:25, 41:51:30	DBL S	-13 ± 2
	09:21:18, 51:02:45	UNR	-28 ± 2			0.7 W	0 ± 5			0.5 N	+1 ± 4
	09:21:25, 50:46:15	DBL S	-12 ± 3		12:19:13, 14:40:10	UNR	-11 ± 3		13:16:36, 42:08:55	UNR	-10 ± 2
	09:22:27, 50:53:50	DBL E	-25 ± 2	NGC 4321	12:21:50, 15:36:10	UNR	-12 ± 2		13:29:34, 46:58:50	DBL E	+14 ± 1
NGC 2841	09:23:47, 51:02:40	DBL E	-5 ± 3		12:23:04, 15:36:50	UNR	-8 ± 2		13:29:41, 47:17:35	UNR FG?	+20 ± 1
		0.6 W	-6 ± 4		12:23:15, 15:41:40	DBL W	-7 ± 1		13:30:16, 47:10:25	EXT FG	+28 ± 4
	09:31:00, 21:35:30	DBL W	+20 ± 2			0.75 E	-7 ± 2		13:30:45, 47:03:10	EXT	+17 ± 2
	09:31:13, 21:28:00	DBL W	+4 ± 2	NGC 4450	12:27:35, 17:07:00	DBL E	-8 ± 5		13:31:25, 47:13:10	DBL W	+9 ± 1
		0.6 E	+2 ± 2		12:28:15, 17:05:00	TRPL SE	-10 ± 5	NGC 6946	20:33:09, 60:00:30	1.0 E	+3 ± 1
NGC 2903	09:31:37, 21:34:20	UNR	+8 ± 2			SW	-15 ± 5			DBL E	-14 ± 2
	09:32:23, 21:36:20	UNR	-8 ± 2		12:35:48, 28:05:50	0.4 N	+12 ± 2		20:35:19, 60:02:05	DBL FG?	+67 ± 5
	09:46:18, 67:49:25	UNR	-44 ± 4		12:35:58, 27:43:15	UNR	+4 ± 1		20:36:09, 59:53:20	EXT	+23 ± 2
	09:46:37, 67:46:30	UNR	-37 ± 8	NGC 4559		DBL E	-6 ± 3		20:36:15, 60:07:30	UNR FG?	+14 ± 2
NGC 2976	09:48:12, 67:44:15	UNR	-26 ± 3			1.0 W	-4 ± 3		22:35:51, 34:30:10	UNR	+56 ± 3
	09:48:35, 67:53:10	DBL E	-34 ± 2		12:36:21, 27:57:30	UNR	+6 ± 2	NGC 7331	22:35:55, 34:14:25	DBL N	-143 ± 3
	09:48:41, 68:04:15	UNR	+24 ± 6		12:37:05, 27:55:05	UNR	+8 ± 2			0.7 S	-153 ± 2
	10:17:05, 41:15:10	DBL W	+19 ± 2		12:37:12, 27:44:30	UNR	+5 ± 2		22:35:55, 34:18:40	UNR	-10 ± 4
	10:17:23, 41:30:50	UNR	+29 ± 2	NGC 4569	12:36:38, 12:58:55	DBL W	+18 ± 2		22:36:53, 34:20:45	DBL N	-184 ± 2
NGC 3184	10:18:19, 41:09:40	UNR	+12 ± 3			0.2 E	+12 ± 2		22:36:58, 34:16:55	0.2 S	-176 ± 3
	10:19:01, 41:27:35	UNR	+11 ± 3		12:36:52, 13:01:05	UNR	+13 ± 2		22:38:08, 34:17:50	UNR	-178 ± 3
	10:19:09, 41:41:25	UNR	+25 ± 3		12:41:10, 32:45:10	DBL S	-4 ± 3			UNR	-161 ± 3
	10:19:17, 45:28:40	UNR	+7 ± 2		12:41:33, 32:46:30	CMPLX	-2 ± 3	NGC 3198			
	10:19:32, 45:37:35	DBL N	+8 ± 2		12:41:53, 32:27:15	DBL W FG?	-38 ± 2				
NGC 3198		0.8 S	+8 ± 2			0.6 E FG?	-28 ± 3				
	10:21:06, 45:23:30	CMPLX	+3 ± 3		12:43:25, 32:25:40	UNR	+4 ± 1

Fig. 5. Optical images of sample galaxies with extended polarized flux. The background images are red plates from the DSS-2, and are presented with a square-root color transfer to bring out the faint structures. Contour levels (*white*) of polarized intensity run from $50 \mu\text{Jy beam}^{-1}$ in powers of 2. The galaxy ID is indicated in the upper left of each panel. The magnetic field orientations are displayed with red vectors.

Fig. 5. continued.

as discussed by [Braun et al. \(2007\)](#), are associated with $H\alpha$ -emitting regions. This possible emission is not seen in the map produced using only the 22 cm data. However, to the southwest (visible in Fig. 4) is a classic double-lobed radio source which is strongly polarized. The source is catalogued as 6C B081222.3+704711. The morphology of the polarized emission mostly fills the region of continuum emission, but with strong depolarization channels in the northern lobe. The southern lobe is somewhat brighter in both polarized and unpolarized emission. The polarized fraction is about 3–4% in the core, and about 10–20% along the jet axis. There are localized regions of higher polarized fraction, at about the 40% level, and even reaching as high as 50%. The magnetic field orientation is parallel to the northern and southern lobes on their western edges, but on the eastern edges is perpendicular to the lobes, where the total continuum morphology also suggests a smooth decline toward the east. Despite the fact that the two lobes have nearly equal integrated brightness in P , they display RMs which follow the pattern noted above in Sect. 3.1 for a larger degree of RM fluctuations to be seen toward the fainter, northern lobe. Given the obvious depolarization channels, this difference is perhaps not too surprising. In view of the 1.5 arcmin angular separation of the depolarization channels in the northern lobe from the nuclear position, it would require either a very extended dispersive halo of the host galaxy, a localized source of significant rotation, or internal depolarization to account for both the RM fluctuations and depolarization. Unfortunately no red-shift information is available for this source, although the nucleus appears to be coincident with a moderately bright, but uncatalogued Digital Sky Survey source. The most likely Galactic foreground RM for this field seems to be about $-10 \pm 2 \text{ rad m}^{-2}$.

IC 2574: IC 2574 does not show evidence for significant polarized emission in either the 22 cm map or the 18 + 22 cm map. Since only unresolved polarized background sources are detected in this field, the Galactic foreground RM remains quite uncertain at about $-18 \pm 4 \text{ rad m}^{-2}$.

NGC 628 (M74): This relatively face-on spiral galaxy shows substantial polarized emission in the form of an incomplete ring near the edge of the optical disk which is brightest at PA $\sim 80^\circ - 340^\circ$ (Position Angles measured east of north). The minimum in polarized intensity occurs at the PA of the receding major axis (PA = 25° , as tabulated in Table 1). The brightest emission is associated with two inter-arm regions in the outer galaxy; one extending from PA $\sim 80^\circ$ to 210° and the other from PA $\sim 200^\circ$ to 340° . These seem to be continuations into the outer disk of the inner disk interarm regions. The polarized fraction at 22 cm in these regions is approximately 10–20% at small radii; increasing to 40–50% at the largest radii, indicating an exceptionally well-ordered magnetic field. The magnetic field vectors are closely aligned with the features themselves. The Faraday depth distribution shows some systematic variation with PA which we will discuss in Paper III. Based on the brighter lobes of the three polarized double sources detected in this field, the likely Galactic foreground RM is about $-34 \pm 2 \text{ rad m}^{-2}$.

NGC 925: There is no polarized emission detected in this galaxy. However, several faint background sources are seen toward the edges of the field. Excluding the unresolved polarized source most discrepant from the single double source lobe, we

obtain an estimate of the Galactic foreground RM with a value of about $-10 \pm 2 \text{ rad m}^{-2}$.

NGC 2403: There is a faint polarized component which is predominantly diffuse, but is too faint to characterize well with the current observations. Smoothing to a beam size of $45'' \times 45''$ enhances the signal to noise ratio of some of the polarized emission, which is concentrated in the western half of the galaxy, with some localized enhancements at the eastern and western edges of the optical disk. But even after application of smoothing, it is still extremely faint (typical surface brightness $\sim 30\text{--}50 \mu\text{Jy/beam}$, reaching as high as $\sim 100 \mu\text{Jy/beam}$). The lowest brightness of polarized emission occurs on the receding major axis (PA = 125° , as tabulated in Table 1). Deeper observations would be required to further constrain the magnetic field properties in this target. The three unresolved polarized sources which are detected in the field do not permit a good estimation of the Galactic foreground RM in view of their large scatter.

NGC 2841: In Stokes I , [Braun et al. \(2007\)](#) note a diffuse “hourglass” structure, with the long axis of the hourglass oriented perpendicular to the disk major axis. In the polarized emission, the highest brightnesses are seen along the minor axis trailing away slowly to the northwest and more rapidly to the southeast. The lowest brightness of polarized emission occurs near the receding major axis (PA = 153° , as tabulated in Table 1). The directions of the magnetic field vectors are primarily aligned along the polarized arcs. The three polarized background doubles in this field display substantial differences in their RMs. The greatest consistency is seen between the two lobes of one of the doubles, at $-6 \pm 3 \text{ rad m}^{-2}$. There may be significant structure of the foreground RM in this field.

NGC 2903: In this galaxy, one of the Starburst supplement to the basic SINGS sample, bright polarized arcs are detected along both sides of the minor axis trailing away in brightness slowly to the northeast and more rapidly to the southwest. The lowest brightness of polarized emission occurs on the receding major axis (PA = 204° , as tabulated in Table 1). The polarized fraction increases from about 1% in the inner parts to about 5–15% at intermediate radii, to as high as 40%. The magnetic field vectors are roughly parallel to optical spiral arm structures for the minor axis features, although generally with a slightly larger radial component. Field lines run almost perpendicular to the linear major axis feature. The Faraday depth distribution shows a small systematic variation with PA in the minor axis features which we will comment on in Paper III, together with a large systematic offset of these (by 60 rad m^{-2}) relative to the major axis feature. Very good consistency is found for the RMs toward both lobes of a double source in the field, suggesting a value of $+3 \pm 1 \text{ rad m}^{-2}$ for the Galaxy in this direction.

NGC 2976: There is very faint diffuse polarized emission associated with this galaxy, together with a modest enhancement along the southwestern edge of the optical disk. Only a single lobe of one double source is detected in this field, yielding a Galactic foreground RM of $-34 \pm 2 \text{ rad m}^{-2}$. The unresolved sources in the field show significant scatter about this value.

NGC 3184: In this galaxy, faint polarized emission is apparent over much of the northern half of the disk. The lowest

brightness of polarized emission occurs near the receding major axis (PA = 179°, as tabulated in Table 1). Interarm regions may be enhanced relative to the spiral arms, but deeper observations would be required for a definitive analysis. Only a single lobe of one double source is detected in this field, yielding a Galactic foreground RM of $+19 \pm 2 \text{ rad m}^{-2}$. The unresolved sources in the field show significant scatter about this value.

NGC 3198: No significant polarized emission is detected in this target, apart from a possible detection of the nucleus. An equal brightness double source in the field allows a very consistent assessment of the Galactic foreground RM of $+7 \pm 2 \text{ rad m}^{-2}$.

NGC 3627 (M66): Bright polarized emission is detected in this galaxy, with a conspicuous north-south gradient of the fractional polarization. It originates in both optical spiral arm and in inter-arm regions. The polarized fraction at 22 cm is less than 1% in the bright optical bar and inner disk of the galaxy, and increases in the regions outside of the spiral arms to as much as 15% on the eastern minor axis. The lowest brightness of polarized emission occurs near the receding major axis (PA = 173°, as tabulated in Table 1). The magnetic field orientation closely follows the optical spiral structure, except at the largest radii where it generally becomes more radial. Some possible systematic variation in the Faraday depth can be discerned which we will comment on in Paper III. Note that [Soida et al. \(2001\)](#) have published VLA and Effelsberg observations of this galaxy at 4.8 and 8.5 GHz which detect many of the same trends, although not detecting the same northern extent. The brighter lobe of a background triple source permits assessment of the Galactic foreground RM of $+13 \pm 1 \text{ rad m}^{-2}$. Other field sources are scattered around this value.

NGC 3938: Moderately faint polarized emission is detected in this almost face-on spiral. The polarized emission is concentrated to the outer disk and is enhanced in inter-arm regions. In contrast to other galaxies in our sample, the lowest brightness of polarized emission seem to occur near the *approaching* rather than the receding major axis (i.e., opposite to PA = 204°, as tabulated in Table 1). However, as apparent in the Stokes *I* imaging ([Braun et al. 2007](#)), there is also a minimum in the total intensity on the approaching major axis, so that this object does not represent a counter-example to the trend we see in the azimuthal modulation of *P*. The polarized fraction (where detected) is about 10–25%. In the few regions where there is enough signal to determine the magnetic field orientation, the field lines run parallel to the spiral arms. The brighter lobe of a double source in the field permits assessment of the Galactic foreground RM of $+1 \pm 2 \text{ rad m}^{-2}$. Other field sources display only a small scatter around this value.

NGC 4125: In this elliptical galaxy, [Braun et al. \(2007\)](#) report a continuum source at the nucleus, which we find is not polarized. They also report a double radio galaxy just to the southwest, the southern component of which is polarized at about the 5% level. The three double sources in this field provide a very consistent measurement of the Galactic foreground RM of $+19 \pm 1 \text{ rad m}^{-2}$.

NGC 4236: In this galaxy, [Braun et al. \(2007\)](#) report detecting continuum emission from the bright knots in the disk. There is no polarized counterpart associated with these features. The

double background radio source behind the disk of NGC 4236 is detected in polarization, at about the 7% polarized fraction level with an RM of $-3 \pm 2 \text{ rad m}^{-2}$. The two unconfused background double sources in the field provide a consistent estimate of the Galactic foreground RM of $+15 \pm 2 \text{ rad m}^{-2}$. The difference may well be due to the magneto-ionic ISM of NGC 4236.

NGC 4254 (M99): Bright polarized emission is detected from an incomplete ring extending from PA ~ 90 – 330° . The peak of the polarized continuum is to the south of the southern spiral arm. The Stokes *I* peak is also slightly offset to the south from the nucleus of the galaxy, though not as far as the peak of the polarized emission. The lowest brightness of polarized emission occurs near the receding major axis (PA = 65°, as tabulated in Table 1). Both the interior and exterior of the unusual western spiral arm display bright polarized emission that subsequently extends far to the north of the optical disk. The polarized fraction is only moderate in the vicinity of the southern peak; 4% at the peak and 1–10% elsewhere in that region. Polarized fractions are also low in the inner spiral arm region; below one percent ranging up to a few percent. Along the outer western edge and in the northern polarized extension, the polarized fraction is generally in the range 10–15%, but in some areas as high as 20–25%. The magnetic field lines follow the spiral arm structure very well, especially in the southern region where the polarized emission is brightest. To the north, at the location of the radio continuum extension, the magnetic fields continue to follow the direction defined by the optical spiral arm structure, even though the optical arm is no longer detected. The apparent departure from this simple pattern in the southwest is due to a polarized background source. The Faraday depth distribution shows some interesting systematic variation: the Faraday depth tends to be negative on the outside of the spiral arms, and positive on the inside. Within the bright radio continuum disk there may be evidence for some azimuthal variation, while the western and northern polarized extensions do not participate in this pattern. This galaxy has recently been studied by [Chyży et al. \(2007\)](#) and [Chyży \(2008\)](#), who report on VLA and Effelsberg polarimetric observations at 1.4, 4.8 and 8.5 GHz. A single double source in the field allows reasonable assessment of the Galactic foreground RM (from the brighter lobe) of $-13 \pm 3 \text{ rad m}^{-2}$.

NGC 4321 (M100): In this spiral galaxy, polarized emission is clearly detected throughout most of the disk. In the northwest, bright polarized emission is present throughout the interarm regions. But in the southeast the polarized surface brightness declines dramatically. The lowest brightness of polarized emission occurs near the receding major axis (PA = 159°, as tabulated in Table 1). The polarized fraction in this disk is generally rather low, ranging from less than or about 2% in the inner regions to about 5–10% in the interarm regions, with the polarized fraction tending to be higher outside of the arm than inside the arm. At the edges, the polarized fraction is higher at about the 15% level, and localized spots where the fraction reaches 30%. The appearance of the magnetic field lines is highly ordered, and follows the orientations of the optical spiral arms. An almost equal double in the field allows consistent assessment of the Galactic foreground RM of $-17 \pm 1 \text{ rad m}^{-2}$.

NGC 4450: No significant polarized emission is detected in this galaxy. The almost equal double and brighter lobe of a triple in

the field allow consistent assessment of the Galactic foreground RM of $-8 \pm 1 \text{ rad m}^{-2}$.

NGC 4559: In this spiral galaxy, diffuse continuum emission is detected, but the polarized component is extremely faint and only detected in a small region in the southeast portion of the disk. This asymmetry is again consistent with the lowest polarized intensity to be seen on the receding major axis. Deeper observations would be needed to better characterize the polarized emission. The equal double in the southern part of the field provides a consistent estimate of the Galactic foreground RM of $-5 \pm 2 \text{ rad m}^{-2}$, while the remaining four unresolved sources in the north and east of the field are all tightly clustered around an RM of $+6 \pm 2 \text{ rad m}^{-2}$. This systematic difference of the RM by of $\sim 10 \text{ rad m}^{-2}$ over $\sim 15'$ in a field so near the Galactic pole ($b = 86^\circ$) is surprising.

NGC 4569 (M90): In this moderately inclined spiral galaxy, polarized emission is detected in the central disk region on either side of the minor axis. Polarized intensity declines more slowly to the southwest and more rapidly to the northeast (where the receding major axis is located ($\text{PA} = 23^\circ$, as tabulated in Table 1). Moreover, the spectacular double lobe extension which is oriented roughly along the minor axis is also detected in polarization, particularly along its edges. Even more interesting is the continuum bridge connecting the galaxy to its small companion, IC 3583 (located about 6 arcmin to the northwest, and visible in both Figs. 4 and 5), which also has a polarized counterpart. The large-scale structures in our map have already been observed at lower spatial resolution and analyzed by Chyży et al. (2006), who observed this system with the Effelsberg telescope. The polarized bridge and the lobe extensions have rather high polarized fractions. The bridge is polarized at the 20–30% level, the lobes at the 10–20% level, with localized hot-spots of higher polarized fraction, of about 40%. The disk itself has polarized fractions of only about 1–2%. As for the magnetic field orientations, the situation is confused in the disk due to the modest angular resolution, but there seems to be a slight tendency for field lines to follow the optical spiral arms. In the radio lobes, the field lines appear to trace the edges of apparent cavities. Finally, in the extension toward IC 3583, the magnetic field lines run roughly along the direction of the extension. The brighter lobe of a background double source provides an estimate of the Galactic foreground RM in this direction of $+18 \pm 2 \text{ rad m}^{-2}$.

NGC 4631: In this edge-on interacting spiral, the polarized emission is found in a roughly X-shaped morphology, and comes mainly from the extraplanar regions. The disk itself seems to be largely depolarized. Polarized emission is detected in the central region and in each of the four extraplanar galaxy quadrants. The north side is brighter in polarization than the south side. The brightest polarized intensity is from the northeast quadrant, which is the region where the dramatic HI extension studied by Rand (1994) is located. The polarized structure runs roughly parallel with the HI extension, but fills the region between the disk and the HI filament. The polarized fraction in this galaxy is less than one percent in the central regions and increases with height above the midplane. At the largest z -heights, the polarized fraction reaches as high as 30–40% in some places. The magnetic field lines run along the X-shaped polarized morphology. In the northeast quadrant, they run almost parallel to the HI extension, but these seem to be unrelated. The polarized structures reported

here have been observed previously by Hummel et al. (1991) and Golla & Hummel (1994). The best estimate of the Galactic foreground RM in this direction comes from the unconfused double source in the field with an RM of $-4 \pm 3 \text{ rad m}^{-2}$; consistent with several other sources in the field. The double background source lying just south of NGC 4631 is likely to be strongly affected by the halo of that galaxy, the brighter lobe of which displays an RM of $-38 \pm 2 \text{ rad m}^{-2}$.

NGC 4725: Extremely faint polarized emission is detected in this moderately inclined barred spiral galaxy, with the polarized emission originating at both ends of the minor axis. The polarized emission avoids the bar, which is at a position angle of about 45 degrees, and is mostly found on the outer periphery of the ring-like structure. The polarized emission is too faint to allow investigation of its detailed properties; deeper observations would be required. It is not possible to say anything about the magnetic field orientation, as too little signal is available. The foreground RM from the Galaxy in this direction can be estimated from the double radio source in the field at $+4 \pm 4 \text{ rad m}^{-2}$; a value consistent with several other unresolved sources in the field.

NGC 4736 (M94): The polarized emission in this galaxy is seen from both the inner star-forming disk and also concentrated along the minor axis, particularly in the form of a possible polarized lobe directed toward the southwest. Within the central disk, the polarized intensity declines to a minimum in the direction of the receding major axis ($\text{PA} = 296^\circ$, as tabulated in Table 1). The central source is polarized at about the 2% level. The inner ring is polarized on the south side, at about the same fraction. The polarized fraction increases at large radii up to about 40%. Magnetic field lines in the possible lobe structure are aligned radially away from the nucleus. Since the near-side of the stellar disk in this system (as determined from optical dust lanes) is in the northeast, the location of the southwestern lobe is consistent with it being the closer of a pair of symmetric nuclear outflows, in which the more distant lobe suffers greater depolarization from the intervening disk. This, together with the lack of a conspicuously distinct feature in the Stokes I map at the same location, points to the lobe structure being intrinsic to NGC 4736 (as opposed to an extended, polarized, background source). Galactic foreground RM in the field can be estimated from several double sources which are detected in polarization. Two of these are rather faint and have large uncertainty, while the high signal-to-noise detection yields a value of $+1 \pm 1 \text{ rad m}^{-2}$. A very extended (6 arcmin) background double radio galaxy is also seen in the southwest portion of the field. Although both lobes have similar brightness in both I and P , the polarized surface brightness is so faint that an accurate RM determination is not practical.

NGC 4826 (M64): There is a low level of polarized emission detected in the southern quadrant of this system that nowhere exceeds 4σ . The best estimate of the Galactic foreground RM in this field comes from the brighter lobe of a double radio source yielding $-8 \pm 2 \text{ rad m}^{-2}$.

NGC 5033: The polarized emission in this galaxy is associated with the bright inner continuum disk reported by Braun et al. (2007). It has a roughly X-shaped appearance, which may be

indicative of minor axis outflows, as seen elsewhere in our sample. The polarized brightness declines to a minimum in the direction of the receding major axis ($PA = 352^\circ$, as tabulated in Table 1). In the central parts the polarized fraction is of the order of $\lesssim 1\%$. At larger radii the polarized fraction increases to about 5–7%. Although there are no well resolved double radio sources in the field, at least one source is observed to be somewhat extended with an RM of $+9 \pm 2 \text{ rad m}^{-2}$. The various other unresolved sources in the field show scatter about this value.

NGC 5055 (M63): Diffuse polarized emission is detected from the disk of this inclined galaxy on both sides of the minor axis. The highest brightnesses are associated with the zone of strong warping of the gaseous disk in the southwest at the edge of the star-forming disk. A fainter counterpart is seen in the northeast. The minimum in polarized intensity occurs at the PA of the receding major axis ($PA = 102^\circ$, as tabulated in Table 1). The polarized fraction of the brightest feature is mainly in the range of 5–10%, but at the southernmost end (where the contribution from the bright inner disk is significantly fainter) the fraction increases to 15–25%. The magnetic field lines closely follow the spiral arm structure observed in the optical image. Two background double sources yield an estimate of the background RM in this field of about $-8 \pm 3 \text{ rad m}^{-2}$.

NGC 5194 (M51): In M51, the polarized emission is clearly detected throughout the disk, though there are large variations in the polarized fraction. The bright polarized emission traces out a spiral pattern that runs parallel to the optical arms. The minimum in polarized intensity occurs at the PA of the receding major axis ($PA = 172^\circ$, as tabulated in Table 1). The companion, NGC 5195, is not detected in polarization. The polarization fraction at 22 cm in M51 is variable, remaining lower than 5% within most of the optical disk, and increasing at large radii, beyond the outer spiral arms, to as much as 25–30%. The orientation of the magnetic field lines closely tracks both the large-scale spiral pattern (as also seen by Horellou et al. 1992, see their Fig. 10), as well as small-scale features that often have dust-lane counterparts in the optical imagery. In two locations on the eastern side of the disk, the polarized emission crosses from the inside of the optical arm to the outside; at the crossing point, the magnetic field vectors turn from running parallel to the spiral to follow the polarized emission across the arm. These features occur near $(\alpha_{J2000}, \delta_{J2000}) = (13:30:1.5, 47:12:15)$ and $(13:30:5.4, 47:10:30)$. Systematic variation in the Faraday depth is seen as function of azimuth, which will be discussed in Paper III. Two background double radio sources are detected with very high signal-to-noise, including one with comparable integrated P from each lobe. In Stokes I , the brightness ratio of the two lobes in that source is actually 0.75, with the western lobe being the brighter. The best estimate of the Galactic foreground RM for this field is $+12 \pm 2 \text{ rad m}^{-2}$.

NGC 6946: The polarized emission is strongly detected from the northeast half of this galaxy, tapering away toward the southwest. The minimum in polarized intensity occurs at the PA of the receding major axis ($PA = 243^\circ$, as tabulated in Table 1). The polarized fraction (in the northeast) is quite low in the inner parts at less than 10%, moderate at intermediate radii at about 20–30%, and very high in the outer parts, reaching up to (and perhaps above) 40–50%. The magnetic field lines are closely related to the large-scale spiral morphology traced by massive star

formation and dust lanes, running largely parallel to the optical arms. As has been pointed out by Beck (2007), the peaks in polarized emission originate in the interarm regions. The Faraday depth distribution shows a very clear systematic variation with azimuth, and will be discussed in Paper III. Beck (2007) have recently reported VLA and Effelsberg observations of this galaxy at 1.4, 2.6, 4.8, 8.5 and 10.6 GHz. They demonstrate that there is substantial depolarization at 20 cm in the southwest quadrant relative to higher frequencies. The large-scale features that he discusses are very similar to this work.

Unfortunately only a single well-resolved double background source is detected in this field (about $10'$ southwest of NGC 6946), and this source is quite asymmetric. The brighter lobe has a well-defined RM of $-14 \pm 2 \text{ rad m}^{-2}$. Several other sources in the field are possibly influenced by RM contributions from the disk of NGC 6946 itself; including the extended background source at $(\alpha 20:35:19, \delta +60:02:05)$ just $2'$ south of the NGC 6946 disk that appears to be a barely resolved ($30''$) double with a well-defined RM of $+23 \pm 2 \text{ rad m}^{-2}$. As previously noted, the low Galactic latitude of this field ($b = +12^\circ$, decreasing to the southeast) enhances the likelihood of fluctuations in the foreground RM. We suggest that the most likely value of the foreground affecting NGC 6946 is an RM of $+23 \pm 2 \text{ rad m}^{-2}$, but stress that there is a substantial systematic uncertainty in this value. Ehle & Beck (1993) and Beck (2007) have previously determined a value of $\approx +40 \text{ rad m}^{-2}$ in this field, which is consistent with the mean Faraday depth that we have observed in the disk of NGC 6946 (see Fig. 6). We note that their foreground RM value is derived using the diffuse emission of NGC 6946 itself, while our derivation was performed using only background sources in the field. We postulate that the difference may be due to a non-zero contribution to the rotation measures in NGC 6946 from a vertical component of the magnetic field in the halo of that galaxy. We return to this possibility in Paper III.

NGC 7331: The bright inner disk of this highly inclined spiral disk is highly polarized, and polarization is also detected in the outer disk on both sides of the minor axis, extending well out into the low surface brightness outer disk. The polarized fraction is quite low in the inner parts, at about 1–3%, but it increases rapidly toward the outer parts up to about 20–40%. This is a galaxy in which multiple Faraday depth components are encountered along some lines-of-sight, implying large-scale interspersal of emitting and rotating media. Magnetic field orientations of the single brightest polarized component along each line-of-sight show some tendency to be aligned with the star-forming disk at small radii, but become increasingly radial in the minor axis extensions. The peak Faraday depth distribution is bi-modal, with two dominant ranges occurring, one near $\phi = 0 \text{ rad m}^{-2}$ in the inner disk and the other near -150 rad m^{-2} associated with the minor axis structures. The Galactic foreground RM in this general direction is known to be quite extreme (cf. Broten et al. 1988; Han & Qiao 1994), even at tens of degrees from the Galactic plane. The brighter lobes of two resolved double sources in the field suggest a value of about $-177 \pm 7 \text{ rad m}^{-2}$. As was the case for NGC 6946, the relatively low Galactic latitude ($b = -21^\circ$) increases the likelihood of fluctuations in the foreground RM. This is reflected in the larger scatter of RM values of even the most reliable of probes.

Fig. 6. Images of peak ϕ in some of the survey galaxies. The colorbar on the right edge shows the range of ϕ [rad m^{-2}] displayed with the colormap. Galaxy ID is indicated in the upper left of each panel.

Fig. 6. continued.

4. Discussion

4.1. Circular polarization

In cases of extreme Faraday rotation, linearly polarized emission can be *Faraday converted* into circular polarization (e.g., Jones & O'Dell 1977). Stokes V images (created as part of the pipeline described in Sect. 2.1) were examined for signs of any circularly polarized emission associated with the target galaxies. No detections were made.

4.2. Magnetic field distributions

In Sect. 3.2, a few general trends can be discerned in the sample spiral galaxies. The most obvious of these is that the polarized intensity is minimized along the receding major axis. This points to a common global magnetic field geometry which is tied not only to the morphology of the galaxy, but also to the dynamics of the galaxy. In Paper III, we discuss a quite general and simple model which may be at the origin of the observed patterns.

4.3. Extended Faraday depth profiles

The frequency coverage obtained in the WSRT-SINGS survey is sufficient for excellent recovery of polarized emission at a single Faraday depth or multiple well-separated Faraday depths. Well-separated regions of synchrotron emission and Faraday rotation lead to “Faraday thin” emission, which appears as one or more unresolved features in the Faraday dispersion function. The WSRT-SINGS frequency coverage is however insufficient for recovery of polarized emission at a continuous range of Faraday depth. Such circumstances occur in regions referred to as “Faraday thick”. In Faraday thick regions, emitting and rotating plasmas with regular magnetic fields may be uniformly collocated along the LOS, such that synchrotron emission from the far side of the volume suffers more Faraday rotation than the synchrotron emission from the near side. In the simplest such case, a constant level of polarized flux will be detected at a continuous range of Faraday depth. Faraday thickness can also originate in volumes in which the Faraday rotation is generated by turbulent magnetic fields. This will also lead to polarized flux being distributed over a range of Faraday depth (Burn 1966). Berkuijsen et al. (1997) describes how this latter mechanism can cause depolarization of the synchrotron emission within the disk at 18- and 20-cm wavelengths in the particular case of NGC 5194. In this picture, the intervening halo is transparent to polarized emission, and acts as a “Faraday screen”.

Recall that the resolution in Faraday depth space, $\Delta\phi$, is inversely proportional to the width of the sampling in λ^2 space, $\Delta\lambda^2$. The offset of the λ^2 sampling from $\lambda^2 = 0$ does not affect the resolution. However, the ability to detect polarization in the presence of internal Faraday depolarization (either caused by regular or turbulent fields, as described above) is determined by the actual values of λ^2 . As shown by Burn (1966), when observing a Faraday thick region with regular magnetic fields, the $\|P(\lambda^2)\|$ distribution is a sinc function. Differential Faraday rotation within the emitting and rotating region depolarizes the emission to some degree at all non-zero wavelengths, and the effect is generally stronger at larger λ^2 . The depolarization takes place within the volume and not at the telescope. It is thus independent of the channel width used in performing the observation, but it is dependent on the frequency band itself. The fractional recovery of the polarized flux by RM-Synthesis is determined by the sampled values of λ^2 . A smaller value of $\lambda_{\min}^2$ means sampling $\|P(\lambda^2)\|$ closer to its peak, and thus recovering more of the intrinsic

polarized flux. With observations made at $\lambda^2 \gg 0$, neither the RM-Synthesis technique nor a subsequent RM-CLEAN operation will completely recover the intrinsic degree of polarization (i.e., $P(\lambda^2 = 0)$) if internal depolarization has been present. There is no substitute for obtaining the required full sampling of λ^2 .

The reconstruction of the intrinsic polarized flux in Faraday thick regions is incomplete because of the Fourier transform at the heart of RM-Synthesis. Large-scale structures in $P(\phi)$ are recovered by observations at small λ^2 . Thus the consequence of $\lambda_{\min}^2 \gg 0$ in a given observation is that only the high-frequency structures in $P(\phi)$ are sampled. The front and back “skins” of a Faraday thick region will be detected in polarization, each with a depth in ϕ of about $\pi/\lambda_{\min}^2$ (the largest scale that we are able to recover with our frequency sampling). For the current observations with $\lambda_{\min} = 17$ cm, this corresponds to a skin depth of about 108 rad m^{-2} , while our resolution is about $\Delta\phi \approx 144 \text{ rad m}^{-2}$. If we imagine a uniform slab with a Faraday depth exceeding $2\pi/\lambda_{\min}^2$, we might begin to resolve the front and back skins of such a structure, albeit with the inevitable reduction of polarized intensity from its intrinsic value.

Although we are unable to reconstruct the intrinsic degree of polarization for arbitrary Faraday thick structures with the present frequency coverage, we can look for indications that Faraday thick regions are present. The most obvious of these would be the detection of ϕ -broadening, or even resolved ϕ -splitting in Faraday depth. The amount of broadening or splitting would begin to constrain the likely degree of depolarization that affects the current observations. A systematic decrease of polarized emission, such as seen toward the southwest half of NGC 6946, would be a more ambiguous indicator. This form of differential depolarization would require a systematic increase in the Faraday depth of some regions relative to others. In the case of NGC 6946 this seems rather unlikely to be due to the distribution of electron density, as also concluded by Beck (2007), but may instead be due to a large-scale pattern in the field geometry which might lead to both a systematic increase of the Faraday depth as well as a decrease in the intrinsic degree of polarization (given their orthogonal dependence on the field orientation). We return to this discussion in Paper III.

To assess the presence of broadened and/or split Faraday dispersion function profiles, we adapt the so-called “velocity coherence” technique described by, e.g., Braun et al. (2009). The RM-CLEANed $P(\phi)$ cubes were smoothed along the ϕ axis with a boxcar kernel, of width 143 rad m^{-2} , which is similar to the $FWHM$ of the Faraday resolution. After this smoothing operation, an unresolved Faraday dispersion function will peak at about 81% of its original amplitude. Broadened profiles will have a higher relative peak amplitude. Images of the Faraday depth coherence, $\phi_C \equiv P(\hat{\phi}_{bc})/P(\hat{\phi})$, were produced for each galaxy, where $P(\hat{\phi}_{bc})$ is the peak polarized flux in each pixel of the boxcar-smoothed P cube, and $P(\hat{\phi})$ is the same quantity in the original cube. Inspection of these images did not reveal any global systematic patterns, but some small-scale localized features are of note.

In galaxies with distributed polarized flux, small localized Faraday thick regions tend to appear in interarm regions. In NGC 4254, the region between the nucleus and the large north-western spiral arm is significantly Faraday thick compared to the rest of the disk. In NGC 4631, the average ϕ_C is somewhat higher than in the other sample galaxies. This is not unexpected, since its edge-on orientation may cause a significant amount of Faraday depolarization. The largest values of ϕ_C (corresponding to the broadest $P(\phi)$ profiles) appear along the southern edge of the polarized extension in the northeast quadrant of the galaxy.

In other targets, there does not appear to be a recognizable structure in ϕ_C which can be associated with morphological features.

4.4. Nuclear Faraday dispersion functions

In all of the galaxies with compact, (circum-)nuclear polarized emission, the nucleus is detected at two distinct Faraday depths (and perhaps three in the case of NGC 6946) which are offset to both positive and negative values from the estimated Galactic foreground RM by about 100 rad m^{-2} . Recall that this splitting corresponds almost exactly with the condition noted above for resolving the two skins of an intrinsically Faraday deep distribution with our observing setup, of $2\pi/\lambda_{\text{min}}^2 \sim 200 \text{ rad m}^{-2}$. A possible exception is NGC 4569, for which the polarized emission appears to be associated with the nucleus, but shows only a hint of a broadened feature in the Faraday dispersion function. Table 3 lists the characteristics of the polarized nuclear emission in the targets with polarized emission at multiple Faraday depths. The columns are (1) Galaxy ID; (2,3) RA (J2000.0) and Dec (J2000.0) from which the Faraday dispersion functions were extracted; (4) Nucleus classification from Ho et al. (1997), where H indicates HII nucleus, S indicates Seyfert nucleus, L indicates LINER nucleus, T indicates transition nucleus, and numbers indicate subclasses; (5) RM feature number; (6) ϕ value at the location of the RM feature; (7) Total polarized flux at that RM; (8,9) Stokes Q and U values at that RM; (10) Polarization angle derived from Q and U . The deconvolved Faraday dispersion functions are plotted in Fig. 7. Note that in Fig. 4, only the polarized flux (and polarization angle) of the brightest of these components is plotted.

What is the origin of the split Faraday dispersion functions? Given the λ^2 coverage of the observations, there are two possibilities. Either polarized emission with two distinct rotation measures originates within the spatial beam of our observations, or we are detecting Faraday thick emission. In the latter case (as noted in Sect. 4.3), our observational setup is unable to recover extended features in the Faraday depth domain. We would recover emission only from the edges of such a structure, giving the appearance of two distinct features. In either case, the physical origin must be a characteristic geometry of the nuclear magnetic field and ionized gas distribution common to all galactic nuclei with such Faraday dispersion functions. Understanding these nuclear Faraday dispersion functions may therefore illuminate the physics in the central regions of these galaxies. The rather general detection of both positive and negative net Faraday depths is already indicative of both positive and negative signs of $B_{\parallel}$. Such a sign change of the LOS field, seen from galaxies inclined between 30 and 85 degrees, might be understood with a radially directed (outward or inward) field geometry in either or both of the galaxy mid-plane or parallel to the rotation axis. We note that somewhat higher resolution observations of NGC 6946 (Beck 2007, see his Fig. 11) show a continuation of the spiral pattern all the way into the nuclear regions, but perhaps with a greater radial component than at larger radii. Since, in the nuclear Faraday dispersion functions, comparable levels of polarized intensity are seen from both the negative and positive RM components, it seems plausible that the synchrotron emitting region has a significant radial extent that is relatively symmetric about the origin of the sign change of $B_{\parallel}$, which presumably corresponds to the galaxy nucleus. It is worth mentioning that a global magnetic field geometry which is everywhere inward- or outward-directed would, in the spatially unresolved central region, show at least a double-peaked Faraday dispersion function. However, the magnitude of the ϕ values that we

Fig. 7. RM spectra extracted from the central regions of the indicated galaxies (coordinates are listed in Table 3). Features with tabulated characteristics are indicated with solid lines; the polarization angle at that value of RM is indicated. The Galactic foreground contribution (from Table 1) is indicated with dotted lines.

observe in the nuclear regions are much larger than the typical ϕ values elsewhere in the disks, suggesting either that an additional magnetic field component is present in the nuclei, or that enhanced magnetic field strengths and/or electron densities are present in the nuclear regions.

In the case of NGC 4631, the split Faraday dispersion function may be influenced by the almost edge-on aspect of the galaxy. The orientation could lead to a large Faraday depth toward the nucleus, which might also be responsible for the prominent areas of likely depolarization throughout the disk plane. A connection of Faraday depth with the outer disk orientation is not as obvious for the more face-on targets. In fact, the largest observed splitting between the two detected components is seen in NGC 6946, for which the disk inclination is only 33° . For a circum-nuclear dipole field, a sign reversal would not occur in the vertical component, but would only be expected to occur in the radial component. This would be most apparent in an edge-on viewing geometry. For a quadrupole field a sign reversal would be expected to occur in both the radial and vertical directions, and thus might be seen independent of the viewing angle. Although neither edge-on nor face-on viewing geometries of the outer disk are strongly preferred for witnessing this phenomenon, our sample size is not large enough to draw general conclusions on a preferred circum-nuclear field configuration. There is also no immediately apparent trend with the type of nucleus. Nuclei with optical (Ho et al. 1997) and MIR

Table 3. Characteristics of split RM profiles in galaxy cores.

Galaxy ID	RA J2000	Dec J2000	Nucleus type	Feature no.	ϕ [rad m ⁻²]	$P(\phi)$ [μ Jy]	$Q(\phi)$ [μ Jy]	$U(\phi)$ [μ Jy]	$\chi(\phi)$ [deg]
NGC 2903	09 32 09.8	21 30 00	H	1	-93	143.0	-102.4	18.3	84.9
NGC 2903				2	+70	276.0	141.3	-245.6	-30.0
NGC 3627	11 20 15.8	12 59 26	T2/S2	1	-133	144.0	111.7	-39.5	-9.7
NGC 3627				2	+55	153.0	146.8	44.1	8.4
NGC 4321	12 22 54.9	15 49 21	T2	1	-103	191.0	-149.6	-40.6	-82.4
NGC 4321				2	+150	135.0	9.6	-136.6	-43.0
NGC 4631	12 42 07.7	32 32 26	H	1	-108	88.0	-57.5	-60.1	-66.9
NGC 4631				2	+73	87.0	33.1	-74.9	-33.1
NGC 4736	12 50 53.1	41 07 14	L2	1	-128	178.0	268.3	-63.1	-6.6
NGC 4736				2	+135	184.0	164.6	-66.5	-11.0
NGC 5194	13 29 52.7	47 11 47	S2	1	-28	91.0	12.7	-4.1	-8.9
NGC 5194				2	+128	97.0	73.7	9.3	3.6
NGC 6946	20 34 52.3	60 09 22	H	1	-208	122.0	-53.1	-45.4	-69.7
NGC 6946				2	+15	74.0	26.2	50.9	31.4
NGC 6946				3	+233	110.0	68.3	-30.4	-12.0

(Dale et al. 2006) emission consistent with an AGN are just as likely to show split profiles (4/11) when compared to nuclei which are classified as non-AGN (3/10). Similar analysis, using the RM-Synthesis technique, of a larger number of galaxies would help to clarify the situation.

Based on our sample, a sufficient condition for the existence of a multiply peaked nuclear Faraday dispersion function is simply the presence of a compact, polarized nuclear source. There are two apparent exceptions to this pattern which deserve further comment. NGC 7331 has split profiles but no compact nuclear source. This particular galaxy exhibits split Faraday dispersion functions throughout the inner disk, so the splitting noted here does not apply to a nucleus. Moreover, only one of the RM components in NGC 7331 (the inner disk) is displaced significantly from the Galactic foreground value, rather than both as seen toward polarized nuclear sources. On the other hand, NGC 4569 has what appears to be a compact, polarized nuclear source, but the nuclear Faraday dispersion function is not obviously split. In this case there is some indication for broadening of the profile toward the nucleus in the Faraday depth coherence image described in Sect. 4.3; it may be that there is splitting which is only barely resolved with our RM resolution (~ 144 rad m⁻²). Further work to investigate nuclear polarization should be performed at higher frequency, where the effects of internal Faraday depolarization are less important, and Faraday thick regions can be unambiguously distinguished from regions with multiple distinct Faraday depths. At higher frequencies, the width of the RMSF will likely be broader than we have obtained here. Judicious combinations of observations at low and high frequency can lead to the recovery of Faraday thick polarized flux. As pointed out by Brentjens & de Bruyn (2005), the condition for recovering such flux is $\lambda_{\min}^2 < \Delta\lambda^2$.

5. Conclusions and outlook

We have presented linear polarization data measured in two broad frequency bands near 1400 and 1700 MHz in the WSRT-SINGS survey. The RM-Synthesis method was used to reconstruct the intrinsic properties of the polarized emission, obtaining and correcting for the Faraday depth contributions from both the Milky Way and the target galaxies themselves. The reconstructed Faraday dispersion functions were deconvolved using a technique similar to the CLEAN algorithm commonly utilized

in synthesis imaging. The deconvolution was particularly important with the present observations, because the gap in frequency coverage between our two frequency bands causes the RM spread function (RMSF) to exhibit sidelobes at nearly the 80% level.

The results of these processing steps were used to derive maps of the linearly polarized flux in each of the target galaxies, and, in cases where sufficient flux was measured, to analyze the spatial distributions of Faraday rotation measures, which probe the component of the magnetic field along the line of sight, and polarization vectors, which probe the component of the magnetic field perpendicular to the line of sight. The Faraday rotation corrected polarization angles were used to generate maps of the magnetic fields perpendicular to the line of sight.

Linearly polarized emission was detected in 21 of the 28 galaxies considered in this investigation. The detected galaxies all have Hubble type between Sab and Sd; only three galaxies (out of 24) in this range of classification were undetected in polarized flux. All of the (albeit few) sample galaxies with Hubble type later than Sd or earlier than Sa were all undetected. We have not detected any circularly polarized emission from any of the galaxies.

The most prominent trend which has emerged through this analysis is that in all galaxies with spatially extended polarized emission, the azimuthally-binned polarized flux is consistently lowest along the receding major axis. For such a trend to appear in such a large and diverse sample of spiral galaxies implies that a common magnetic field geometry has been revealed. In Paper III, we attempt to model the observed azimuthal variations in both rotation measure and polarized flux, using toy models of axi- and bi-symmetric magnetic field configurations, with the additional possibility of a non-zero vertical component to the field. We find that such a magnetic field geometry can explain the azimuthal variation in polarized flux, its dependence on inclination, as well as the azimuthal variation in the rotation measures attributed to the target galaxies.

Another interesting feature was discovered in the galaxies with prominent nuclear emission in both total power and linearly polarized flux. The Faraday dispersion functions in those galaxies' cores show indications of significant broadening and/or splitting, indicating the presence either of spatially collocated synchrotron-emitting and Faraday-rotating plasma, or distinct Faraday thin emitting regions within the resolution element. At the wavelengths observed in this survey, we are rather

insensitive to significantly broadened Faraday dispersion functions – these would appear (at best) as double-peaked profiles. It is possible that all of these galaxies host *Faraday thick* regions in their cores, but we are unable to make this distinction. Observations at higher radio frequencies, where depolarization issues are less significant, would clarify the situation. What is clear, from the occurrence of both positive and negative net RMs (after accounting for the Galactic foreground contribution), is that the polarized emission arises on either side of a reversal of the LOS field, presumably reflecting a radially directed field (either inward or outward) centered on the nucleus. Whether the LOS magnetic field simply changes sign near the nucleus, or polarized flux is present at an extended range of Faraday depth (centered near $\phi = 0 \text{ rad m}^{-2}$), is not clear with the present observations.

The techniques used here can be extended to observations performed at other radio telescopes. In particular, the new class of telescopes which are being built now and into the era of the SKA, will all provide polarization data at excellent frequency resolution covering wide bandwidth. These telescopes will provide data which is excellently suited for use with the RM-Synthesis method, and will enable the study of a larger sample of galaxies at greater sensitivity, and improved resolution in the Faraday domain. Of particular interest is the LOw Frequency ARray (LOFAR; Falcke et al. 2007) array which is presently being built, and will operate at frequency ranges between 30–80 and 120–240 MHz. At these low frequencies, we will have RM resolutions of order 1 rad m^{-2} and better (cf. the WSRT-SINGS RM resolution $\approx 144 \text{ rad m}^{-2}$), yielding sensitivity to far weaker magnetic field structures in nearby galaxies (Beck 2008).

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Appendix A: Deconvolution of the Faraday dispersion function

The Faraday dispersion function recovered using RM-Synthesis has undesirable features resulting from the incomplete sampling in the λ^2 domain. These effects can be reduced using a deconvolution procedure, similar to what is done in the synthesis imaging case. Here, we outline and justify our procedure in greater detail than was provided in Sect. 2.3.

There are two salient features of the RMSF: the width of the main lobe ($\Delta\phi$), and the sidelobe structure. In the WSRT-SINGS survey, the sampling function (see Fig. 1, panel e) can be described as two windows. The form of our RMSF can be likened to the interference pattern in a double-slit experiment. If the windows (slits) were infinitely narrow, the sidelobes would have unit amplitude and the spacing would be inversely related to the distance in λ^2 between the windows. In fact, the locations on the ϕ -axis of the sidelobes would be identical to the $n\pi$ ambiguity which would result from a standard rotation measure determination using the two λ^2 frequency samples alone. In actuality, the windows are made up of many individual frequency measurements, and therefore each effectively have a

finite width. This provides a taper to damp down the sidelobes. But the windows are still relatively narrow compared to the distance between them, so the sidelobes remain rather high. It is therefore desirable to remove these sidelobes from the recovered Faraday dispersion function, particularly in cases which may potentially contain multiple distinct sources or broadening along the ϕ axis. Before deconvolution, the sidelobe structure of a brighter component contaminates the response to fainter components, and may shift the location of peaks relative to their true position.

The mechanism for performing this deconvolution is quite similar to the CLEAN algorithm which is already well known from the synthesis imaging case. We first describe the algorithm. Then we move on to justifying our choice of working in a domain in which $\lambda_0^2 \neq 0$ (see Eq. (5)). Here we demonstrate that deconvolution in that space is equivalent to deconvolution in the “true” measurement space. Next we describe how a restoring RMSF was selected, and conclude with some general remarks about the routine.

A.1. The deconvolution procedure

The algorithm, also described by Brentjens (2007), consists of the following steps:

1. in each spatial pixel, the complex $(Q(\phi), U(\phi))$ spectrum is cross-correlated with the complex RMSF. The location of the peak absolute value of the cross-correlation, ϕ_m , is noted;
2. if $P(\phi_m)$ is greater than a user-defined cutoff, a shifted and scaled version of the complex RMSF is subtracted from the complex $(Q(\phi), U(\phi))$ spectrum. The scaled RMSF is $gP(\phi_m)R(\phi - \phi_m)$, where g is a (real) gain factor.
3. the value $gP(\phi_m)$ is stored as a “clean component”;
4. steps 1–3 are repeated until the value of $P(\phi_m)$ is no longer higher than the cutoff, or a maximum number of iterations have been performed;
5. finally, the clean components are convolved with a restoring Gaussian beam with a *FWHM* equal to $2\sqrt{3}/\Delta\lambda^2$ (see A.3), and added to the residual $F(\phi)$. The result is the deconvolved $F(\phi)$ spectrum.

The reason for using a cross-correlation in step (1), rather than simply searching for the peak $P(\phi)$ (in analogy to imaging deconvolution), is the hope that incorrect component localization due to possible sidelobe confusion will be eliminated. In practice, the two techniques were found to yield the same results in our data.

A.2. Deconvolution in the “shifted” domain

We begin with the definitions of the dirty Faraday dispersion function in its unshifted (pure) form:

$$\tilde{F}(\phi) = F(\phi) * R(\phi) = K \int_{-\infty}^{+\infty} \tilde{P}(\lambda^2) e^{-2i\phi\lambda^2} d\lambda^2 \quad (\text{A.1})$$

and its shifted form:

$$\tilde{F}'(\phi) = K \int_{-\infty}^{+\infty} \tilde{P}(\lambda^2) e^{-2i\phi(\lambda^2 - \lambda_0^2)} d\lambda^2 \quad (\text{A.2})$$

$$\tilde{F}'(\phi) = K \int_{-\infty}^{+\infty} \tilde{P}(\lambda^2) e^{-2i\phi\lambda^2} e^{+2i\phi\lambda_0^2} d\lambda^2 \quad (\text{A.3})$$

Noting that the factor $e^{2i\phi\lambda_0^2}$ is constant in λ^2 , we can pull it out of the integral as a constant factor.

$$\tilde{F}'(\phi) = K e^{2i\phi\lambda_0^2} \int_{-\infty}^{+\infty} \tilde{P}(\lambda^2) e^{-2i\phi\lambda^2} d\lambda^2, \quad (\text{A.4})$$

which is seen to be equivalent to:

$$\tilde{F}'(\phi) = e^{2i\phi\lambda_0^2} \tilde{F}(\phi). \quad (\text{A.5})$$

In exactly the same way, it can be shown that the same relation holds for the RMSF:

$$R'(\phi) = e^{2i\phi\lambda_0^2} R(\phi). \quad (\text{A.6})$$

We also must define

$$F'(\phi) \equiv e^{2i\phi\lambda_0^2} F(\phi), \quad (\text{A.7})$$

which is just the *actual* Faraday dispersion function multiplied by the “shift” factor.

Again beginning with the shifted, dirty Faraday dispersion function,

$$\tilde{F}'(\phi) = e^{2i\phi\lambda_0^2} \tilde{F}(\phi) = e^{2i\phi\lambda_0^2} \times [F(\phi) * R(\phi)] \quad (\text{A.8})$$

and incorporating the definition of a convolution,

$$\tilde{F}'(\phi) = e^{2i\phi\lambda_0^2} \int_{-\infty}^{+\infty} F(\phi - u) R(u) du. \quad (\text{A.9})$$

We can now move the exponential inside the integral, and introduce two exponentials whose product is unity:

$$\tilde{F}'(\phi) = \int_{-\infty}^{+\infty} \left(e^{2iu\lambda_0^2} e^{-2iu\lambda_0^2} \right) e^{2i\phi\lambda_0^2} F(\phi - u) R(u) du. \quad (\text{A.10})$$

Rearranging,

$$\tilde{F}'(\phi) = \int_{-\infty}^{+\infty} \left(F(\phi - u) e^{2i(\phi-u)\lambda_0^2} \right) \left(R(u) e^{2iu\lambda_0^2} \right) du \quad (\text{A.11})$$

$$\tilde{F}'(\phi) = \int_{-\infty}^{+\infty} F'(\phi - u) R'(u) du \quad (\text{A.12})$$

which is just

$$\tilde{F}'(\phi) = F'(\phi) * R'(\phi). \quad (\text{A.13})$$

This means that the shifted, dirty Faraday dispersion function is the convolution of the shifted RMSF $R'(\phi)$ with the “rolled-up” Faraday dispersion function $F'(\phi)$. After deconvolution, then, we will have determined $F'(\phi)$. Recovery of the actual goal, $F(\phi)$, can be realized by multiplying by the “inverse shift factor”, $e^{-2i\phi\lambda_0^2}$.

A.3. Selection of a restoring beam

The width of the main lobe of the RMSF, $\Delta\phi$, reflects the fact that we have only limited precision in our determination of the Faraday depth of a polarized source. This is fundamentally related to the sampling function. Thus, once we have extracted point source components during the deconvolution routine, they must be replaced at a resolution appropriate to the measured frequency domain. In other words the point source model is convolved with a “restoring beam”. How does one choose the form of this restoring function?

By derotating to $\lambda_0^2 \neq 0$, [Brentjens & de Bruyn \(2005\)](#) show that the variation in the imaginary part of the RMSF is minimized. In a sense, we have selected a frame which rotates as a function of λ^2 in (Q, U) space such that the polarization vector stays along the Q axis as much as possible. We would like to choose a restoring function which is equivalent to zeroing out the residual U response in this rotating frame: in other words, asserting that we have in fact determined the true rotation measure of the polarized source. (Recall, this is equivalent to eliminating the sidelobes of the RMSF). Thus, we set the imaginary part of the restoring function to zero, and the real part to a Gaussian similar to the central lobe of the real part of the RMSF, *in the rotating frame* $\lambda^2 - \lambda_0^2$. Formally, we choose

$$R(\phi) = e^{-\phi^2/2\sigma^2}, \quad (\text{A.14})$$

a real-valued function, where σ is selected to match the width of the real part of the shifted RMSF. As in the case of image plane deconvolution, it has proven to be useful to retain a main lobe width that is matched to the “dirty” image. While a narrower restoring RMSF might be selected, this would result in a mismatched resolution when compared to the deconvolution residuals. After the restoring function in Eq. (A.14) is used to smooth the point source model to the appropriate resolution, it is put back into the measurement domain by multiplying with the inverse shift factor.

A.4. Practical considerations

Formally, this technique is straightforward. In the presence of noise, however, one must take care to properly treat the residuals and the CLEAN components which are returned by the deconvolution algorithm. In practice, the residuals are multiplied by the inverse shift factor (described above) separately. Then, the model is convolved with the restoring beam selected above, multiplied by the inverse shift factor, and added to the residuals. The final result is our deconvolved Faraday dispersion function, as used in this paper.

A final consideration is that the cubes should be reordered prior to performing the deconvolution routine. This is because the routine works not on individual image slices, but rather on spectra along the ϕ axis. Therefore it is considerably more efficient for the routine to be able to read out spectra sequentially, instead of having to read through the full cube to construct each spectrum.

This RM-CLEAN algorithm has been implemented by us as a MIRIAD task and has been made publically available³. The task typically takes less than 20 mn to operate on a pair of $(Q(\phi), U(\phi))$ cubes with dimensions $(512 \times 512 \times 401)$ on a dual 1.8 GHz Opteron system, to the cutoff level described in Sect. 2.3.

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³ The RM-CLEAN procedure is available for download from <http://www.astron.nl/~heald/software>

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