Spectropolarimetry with the Giant Metrewave Radio Telescope at 610 MHz: a case study of two Southern Compact Group fields

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ABSTRACT

We present 610 MHz spectropolarimetric images from the Giant Metrewave Radio Telescope (GMRT). We discuss the properties of the GMRT’s full-polarisation mode in detail and provide a technical characterisation of the instrument’s polarisation performance. We show that the telescope can be used for wide-field spectropolarimetry. The application of Rotation Measure Synthesis results in a sensitivity at the level of tens of \(\mu\)Jy in Faraday space. As a demonstration of the instrument’s capabilities, we present observations of two Southern Compact Groups – the Grus Quartet and USCG S063. The observations are compared with other radio and infra-red data to constrain the group members’ spectral index, polarisation fraction, and Faraday depth. Radio continuum emission is detected from all four galaxies in the Grus Quartet and one galaxy in USCG S063. Linear polarisation is detected from a circumnuclear starburst ring in NGC 7552, the active nucleus of NGC 7582, and three extended radio galaxies in the background of the Grus Quartet field. These background sources allow for the classification of an FR-I and an X-shaped radio galaxy. No evidence is found for interaction with the intragroup medium in either galaxy group.

Key words: techniques: polarimetric – techniques: interferometers – radio continuum: galaxies – galaxies: individual: USCG S063, NGC 7552, NGC 7582

1 INTRODUCTION

Polarised radio emission is fundamentally related to the presence of magnetic fields, and observations of polarisation are the best way of directly studying quasi-regular fields (e.g. Beck et al. 2013). A key issue for polarimetry of astrophysical sources is removal of effects that alter the properties of the radiation as it propagates across the Universe and through the various components of a radio telescope (e.g. Hamaker et al. 1996). The ‘full-polarisation’ mode of the Giant Metrewave Radio Telescope (GMRT) – which provides observations of all four cross-correlation products i.e. \(RR, LL, RL, LR\) – has recently become available at 610 MHz.

The properties of faint polarised sources at frequencies \(\leq 1.0\) GHz are relatively poorly constrained by observations, despite this being the region where Faraday depolarisation effects are expected to dominate (e.g. Burn 1960). Measurements of polarised emission require a combination of high sensitivity to probe the weak polarised signals at these frequencies, together with consideration of the numerous systematics that can affect wide-field and low-frequency polarised observations.

There are a number of facilities designed for spectropolarimetry at other frequencies: ASKAP will observe at frequencies between \(700\) MHz to \(1.8\) GHz (e.g. Johnston et al. 2008), ATCA at \(\geq 1.1\) GHz (e.g. Wilson et al. 2011), GALFACTS between 1.2 to 1.5 GHz (e.g. Taylor et al. 2010), the JVLA at >1.2 GHz (e.g. Perley et al. 2009), and LOFAR at \(<230\) MHz (e.g. Anderson et al. 2012). The GMRT itself is currently undergoing an upgrade that will further improve upon its science capabilities (Gupta 2011). When the upgrade is complete, the intended nearly-seamless frequency coverage from 150 MHz to 1.5 GHz, with instantaneous bandwidths of 400 MHz, will be centred within a frequency range with limited complementary observational data. Wide-field polarimetric surveys with the GMRT therefore have the potential to fill a crucial gap in our understanding of cosmic magnetic fields (e.g. Beck et al. 2012).

As a demonstration of the instrument’s capabilities, we here present wide-field spectropolarimetric observations of two Southern Compact Groups (SCGs) made at 610 MHz with the GMRT. Galaxy groups are some of the smallest and most dense associations of galaxies. These groups are gravitationally bound structures in various stages of dynamical evolution, from young and spiral-dominated to almost completely merged. They are amongst the best natural laboratories for investigating the evolution of the intragroup medium (IGM). It is known that mergers and less powerful interactions can be a significant contributor to heating of the IGM via both supernova explosions and the triggering of active galactic nuclei (AGN) (Pompei, Dahlem & Iovino 2007). These data show that it is possible to
make wide-field spectropolarimetric observations with the GMRT at 610 MHz. Note that Joshi & Chengalur (2010) present 610 MHz polarisation results from the GMRT using the bandwidth-averaged Stokes $Q/U$ observations. Also, Farnes et al. (2013) present other 610 MHz GMRT spectropolarimetric observations of the nearby galaxy M51, which is depolarised below the sensitivity limit.

Sections 2 and 3 represent, respectively, background information related to the technique of Rotation Measure synthesis, and details of the GMRT polarisation observations, data reduction procedures, and a technical characterisation of the instrument’s polarisation performance. The results for the case study observations of the two SCGs are presented and discussed in Section 4 and for other sources in the fields in Section 5 with conclusions presented in Section 6. Throughout this paper a LCDM cosmology has been assumed with $\Omega_m = 0.27$, $\Omega_{\Lambda} = 0.73$, and $H_0 = 71 \, \text{km \, s}^{-1} \, \text{Mpc}^{-1}$. The spectral index, $\alpha$, is defined such that $S \propto \nu^{-\alpha}$. All stated Faraday depths are the observed values – a rest-frame correction of $(1+z)^2$ has not been applied. Unless otherwise specified, all coordinates are equatorial J2000.

2 ROTATION MEASURE SYNTHESIS

A key issue for polarimetry of astrophysical sources is removal of effects that alter the properties of the radiation as it propagates across the Universe and through the various components of a radio telescope (e.g. Hamaker et al. 1999). One such effect, Faraday rotation, occurs as linearly polarised radiation travelling through a magnetised plasma undergoes birefringence. The linear polarisation can be considered as two counter-rotating circularly polarised components which experience different refractive indices. Upon exiting the plasma, Faraday rotation will have caused the electric vector of the incoming linearly polarised wave to rotate.

Consider a simple model with just one source along the line of sight with no internal Faraday rotation, and only a single slab of plasma existing between us and the source. In this case, the electric vector polarisation angle (EVPA) will be rotated by an amount proportional to the squared wavelength of the radiation as described by

$$\Phi_{\text{EVPA}} = \Phi_0 + \text{RM} \cdot \lambda^2,$$

where $\Phi_{\text{EVPA}}$ is the observed EVPA, $\Phi_0$ is the intrinsic EVPA at the source, and $\lambda$ is the wavelength of the radiation. The factor of proportionality is known as the rotation measure (RM).

The measurement of RM allows magnetic fields oriented along the line of sight to be probed. The interpretation of RM measurements is complicated as Faraday rotation occurs both within a source and in the intervening magnetised plasmas between us and the source. For example, Faraday rotation from the interstellar medium of our own Galaxy (the ‘Galactic foreground’) corrupts the measurement of weak magnetic fields in extragalactic sources. In addition, Faraday rotation in the Earth’s ionosphere further modifies polarised signals and inhibits polarisation calibration.

The relationship between EVPA and $\lambda^2$ can be far more complicated than the simplified linear-dependence that equation 1 suggests. Many astronomical sources contain both non-thermal and thermal electron populations – leading to internal Faraday rotation. Furthermore, multiple Faraday rotating regions may exist along the line of sight between us and a source. This can lead to a non-linear dependence between $\Phi_{\text{EVPA}}$ and $\lambda^2$, with the RM effectively becoming a function of wavelength. The separation of the differing wavelength-dependent contributions to the RM (which exist at different Faraday depths) is essential to understand cosmic magnetism. The capabilities of modern correlators allow for a single observation to output a large number of frequency channels. In combination with the technique of RM Synthesis (Brentjens & de Bruyn 2005), it is possible to separate these differing contributions to the RM, eliminate ambiguities, and maximise the sensitivity to polarised emission.

The RM is defined as

$$\text{RM} = \frac{d\Phi_{\text{EVPA}}(\lambda^2)}{d\lambda^2},$$

and now equation 1 can be redefined with a factor of proportionality equal to the Faraday depth, $\phi$, so that

$$\phi(s) = \frac{e^2}{2\pi\epsilon_0 m_e c^3} \int_0^d n_e B_\parallel ds,$$

where $n_e$ is generally the electron number density of the plasma and $B_\parallel$ is the strength of the component of the magnetic field parallel to the line of sight. The constants $e$, $m_e$, and $c$ are the electronic charge, the mass of the electron, and the speed of electromagnetic radiation in a vacuum respectively. The integral from 0 to $d$ represents the distance along the line of sight between the observer and the source.

Now the RM is simply the slope of a $\Phi_{\text{EVPA}}$ versus $\lambda^2$ plot, and $\phi$ is defined so that it can vary along the line of sight and such that a positive value implies a magnetic field pointing towards the observer. Sources of radiation may now exist at different Faraday depths along a line of sight. Note that the Faraday depth does not have a simple relation to physical depth.

To obtain the Faraday depth from our observations, we perform RM Synthesis and obtain the peak in the deconvolved ‘Faraday dispersion function’ which describes the intrinsic polarisation at each Faraday depth (Burn 1966). In essence, the mathematical derivation of the RM Synthesis technique allows for polarisation vectors that are close together in $\lambda^2$-space to be Fourier inverted into ‘Faraday space’ i.e. $\phi$-space. The polarisation vectors are summed coherently at a number of trial Faraday depths, with the sensitivity being maximised to polarised emission at that Faraday depth. For a full description of the technique, see Brentjens & de Bruyn (2005).

As RM Synthesis requires a Fourier inversion of a windowed function, the Faraday dispersion function, $F(\phi)$, is convolved with a point-spread function in Faraday space. This point-spread function is known as the Rotation Measure Spread Function (RMSF), and has a FWHM given by

$$\delta \phi \approx \frac{2 \sqrt{3}}{\Delta \lambda^2} \cdot$$

where $\Delta \lambda^2$ is the width of the $\lambda^2$ distribution i.e. the range in $\lambda^2$ of the observing bandwidth. However, the precision in a measurement of the peak Faraday depth is a function of the FWHM of the RMSF divided by twice the signal–to–noise ratio (s/n) (Brentjens & de Bruyn 2005). In principle, the RMSF can be deconvolved from $F(\phi)$ using a one-dimensional clean that is analytically identical to that used during aperture synthesis imaging (Heald et al. 2009). There are clearly many analogies between RM Synthesis and aperture synthesis, with the concepts of $\lambda^2$-coverage and $uv$-coverage, and of an RMSF and a synthesised beam (see Brentjens & de Bruyn 2005 for more detail). RM Synthesis therefore provides a useful tool with which to probe magnetic fields in the Universe.

3 GMRT OBSERVATIONS AND DATA REDUCTION

The GMRT observations are summarised in Table 1. Both observations used the flux calibrators 3C138 and 3C48. Observation
17,060,1 used the phase calibrator J0240–231, while 17,060,2 used J2314–449. The derived fluxes were found to be 5.23 ± 0.06 Jy and 3.05 ± 0.04 Jy respectively. Data reduction and calibration were carried out using standard tasks in the 31DEC10 AIPS package.

All GMRT observations were taken in spectral-line mode, which assists with excising narrow-band interference. Radio-frequency interference (RFI), pointing errors, and problems with position control (i.e. the servo system) result in anomalous data being recorded by an interferometer. These bad data need to be removed (‘flagged’) from the observation. Full-polarisation data taken with the GMRT require particularly extensive flagging, as the data were first flagged in the Jones matrices. The response of antenna atmosphere and the electronics, and channel was checked in RRLL and RLRR. Indications that RFI remains in the data were time-averaged before calibration into 2 minute intervals (Δt). Varying the time-averaging between 1–10 minutes was found to have a negligible effect on the polarisation calibration. As the linearised model loses accuracy for large leakages, the quality of calibration was limited for several antennas in the array with high leakage amplitudes. Consequently, all antennas with leakages ≥15% were flagged from the data. This removed 7 antennas from each observation. There is an associated loss in sensitivity, and occasionally outer arm antennas had to be flagged – leaving relatively large gaps in the uv-coverage. An appropriate selection of uv-range and/or uv-taper was used during the imaging stage to accommodate for these gaps. Extended polarisation emission remains well-sampled by the over-density of antennas in the GMRT’s central square. The minimum baseline length of ~ 100 m means the data is sensitive to polarisation emission on scales up to ~ 17 arcmin. Checks on the calibrators 3C48 and 3C138 show that the residual instrumental polarisation is ≤ 0.25%, providing a check on both an unpolarised and polarised source at these frequencies [Perley & Butler 2013].

### 3.1 Instrumental Leakage

Following Hamaker et al. (1996), the response of an interferometer can be described by antenna-based response matrices, known as Jones matrices. The response of antenna j with orthogonal circularly polarised feeds (R and L) can be expressed in terms of a Jones matrix that operates on the column vector \((R, L)\)’. The multiplication order is the inverted sequence of effects that take place as the signal propagates from the source to the antenna. The Jones matrix is then given by

\[
J_j = G_j D_j P_j,
\]

where \(G_j\) is the gain, with the matrix representing the effects of the atmosphere and the electronics, and \(P_j\) describes the effects of the rotation of an altitude–azimuth (alt–az) mounted antenna as seen by a tracked source. The ‘D-term’ is given by

\[
D_j = \begin{pmatrix}
1 & d_{jR} \\
-d_{jL} & 1
\end{pmatrix},
\]

which models the deviations of the feed’s polarisation response from that of an idealised system. The complex leakage terms \(d_{jR}, d_{jL}\) represent the fraction of the orthogonally polarised signal ‘leaking’ into a given feed. In practice, antenna feeds are never perfectly circularly polarised. This leads to detectors sensitive to \(R\) also detecting a certain percentage of \(L\) and vice-versa. These imperfections can be modelled by a ‘polarisation leakage’. This leakage, or ‘instrumental polarisation’, was found to be highly frequency-dependent at the GMRT (also see Taylor 2009). The typical leakage amplitude is \(\approx 5–10\%\), with a few antennas having leakages of up to ~ 40%, as shown in Fig. 1. The instrumental polarisation must therefore be calculated for each individual spectral channel. Separation of instrumental and source contributions was achieved through repeated observation of the phase calibrators (listed at the start of this section) over a large range in parallactic angle, \(\chi\). Such a technique is advantageous in that the source can be polarised or unpolarised, for further details see e.g. Roberts et al. (1994). This was done with the AIPS task PCAL using a linearised model of the feeds (SOLTYPE=’APPR’). The data were time-averaged before calibration into 2 minute intervals (SOLINT=2). Varying the time-averaging between 1–10 minutes was found to have a negligible effect on the polarisation calibration.

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### 3.2 Ionospheric Faraday rotation

Prior to instrumental polarisation calibration, small corrections for the effect of ionospheric Faraday rotation were made using the task TECOR. These corrections were enacted together with an ionospheric model produced by the Jet Propulsion Laboratory, that is freely available from the CDDSIS data archive. The maps were used to correct for ionospheric Faraday rotation at the reference antenna, with differences between the antennas being removed by self-calibration. The
GPS measurements of the vertical total electron content (TEC) are spatially interpolated and temporally smoothed, and updated every 15 minutes. The nearest GPS receivers to the GMRT are located in Bangalore and Hyderabad. There is currently no widely available model to correct for differences in the observing geometry or the ionosphere’s magnetic field strength. Nevertheless, the magnetic field is only weakly variable over the duration of a typical observation, while the TEC can be highly variable (Cotton 1993). Maps of the TEC are therefore an important first-order correction, and were found to reduce the variance of the $RLLR$ phase in the GMRT data from $18^\circ$ to $15^\circ$, and typically by $\approx 1^\circ - 3^\circ$. The maximum Faraday rotation due to the ionosphere was estimated by the model to be $\leq 2$ rad m$^{-2}$ over the duration of each observation.

3.3 Time-Stability of the Leaksages

Due to s/n constraints, it is generally only possible to calculate a single leakage for each antenna in a full-synthesis observation. However, each observation actually takes place over many hours. In order to calibrate the data, we must therefore make the critical assumption that the antenna’s on-axis response is sufficiently stable that it can be parameterised by a single complex leakage for the entirety of an observation.

Time-dependent leakages would result in uncorrected ‘residual’ instrumental polarisation. This residual polarisation would cause emission in Stokes $I$ to leak into and corrupt $Q$ and $U$.

The short-term time-stability of the leakages was investigated by initially solving for the instrumental and source polarisation simultaneously – using the phase calibrator over the full range in parallactic angle. The source polarisation determined via this process was then used as an input model for future calculations of the instrumental polarisation. This allowed for the instrumental polarisation to be calculated in a manner similar to when a source of known polarisation is used.

This method allowed the leakages to be calculated for each individual ~ 5 minute scan of the phase calibrator throughout four consecutive observations, two of which were 17,060,1 and 17,060,2. This yielded 49 calculations of the instrumental leakage in each spectral channel during the two day observing period. The RMS variation in these leakages will be a consequence of two effects: a contribution due to thermal noise, and an additional component due to time-variability of the leakages. An analysis of the time-variability is therefore reliant on the ability to separate out these two contributions. As the observations use four separate phase calibrators, the data also allow for any significant elevation-dependence to be identified.

The methodology used by Sault et al. (2010) was adopted, and they find that the uncertainty due to system noise is approximately given by

$$\sigma_D^2 = \frac{1}{N} \frac{\sigma_C^2}{I^2},$$

where $\sigma_C^2$ is the variance of the real or imaginary parts of the leakages, $\sigma_n^2$ is the variance of the correlation data, and $N$ is the number of antennas. $\sigma_C^2/I^2$ can be estimated from the RMS of the closure phase, which is expected to be equal to $3\sigma_n^2/I^2$. To calculate $\sigma_D^2$, the RMS of the closure phase was extracted from the data using the AIPS task SHOUV, and was found to be approximately constant across the band. Equation (7) is derived using the approximation that the error in each leakage term is independent. This is incorrect as the leakages are derived per antenna and not per baseline, but this only affects the results by a factor of order $1/N$. We find $\sigma_D \approx 0.0135$. A plot showing the RMS leakage variability across the band is shown in Fig. 2.

The variation between the best, median, and 80th percentile antennas is approximately twice that of the RMS variability expected due to thermal noise. This range is not large, it is only $2.2\sigma$. However, there are a number of anomalous antennas which seem to have significant time-dependent leakage. Across the entire band, the worst antenna was C09 – with an RMS leakage variability $\approx 8$ times larger than that expected due to thermal noise. Antennas C06 and E02 also possibly had statistically significant time-dependent leakage.

![Figure 1](image-url) The amplitude of the leakage terms $d_R$, $d_L$ (see Section 3.1 for further details) for observation 17,060,2, in both $R$ (left) and $L$ (right). The $x$-axis shows the antenna number, the $y$-axis shows the channel number across the observing bandwidth, and the colour-scale shows the leakage amplitude. Antennas coloured black across the entire band are flagged.
Figure 2. The short-term time-variability of instrumental polarisation across the GMRT band at 610 MHz. The ‘RMS leakage variability’ has been calculated about the mean of the derived solutions. The best, median, 80th percentile, 2nd worst, and worst antenna, in terms of their RMS variability are shown. Both $R$ and $L$ are plotted. A line showing the sensitivity limit of the four observations (i.e. $\sigma_D$) is also displayed and shows the expected RMS variation due to thermal noise; this was found to be approximately constant across the band.

After polarisation calibration, the matrix of $RL$ and $LR$ phases displayed by RLDIF showed that the mean phase of antennas C09 and E02 was offset from the matrix average. The offset was present in all four of the observations used for the analysis. While C09 has the highest leakage of all antennas during these observations, E02 has leakage below the mean level. The data appear consistent with the effects of residual time-dependent instrumental polarisation. The cause of this time-dependent instrumental polarisation at 610 MHz is unknown. Both antennas were flagged – with the $RL$ and $LR$ visibilities being removed from every observation. Both antennas are physically located within or near to the central square, which fortunately minimises the size of the gaps in the uv-coverage that results from antenna removal. The issue with these antennas was provided to the team at the observatory. Following maintenance, this offset was not present for either antenna in follow-up observations taken in 2011 January.

Taking into account the sensitivity limit of these observations,
the instrumental polarisation of the median antenna is essentially independent of time. Leakages vary by $<2\%$ over a timescale of a few days, and $\leq 0.5\%$ over the length of a typical observation.

### 3.4 Polarisation angle calibration

When solving for the instrumental leakage, the absolute value of the phase offset between $R$ and $L$ is left as an unconstrained degree of freedom. A change in this $R - L$ phase difference is equivalent to a change of parallactic angle, therefore causing a rotation of $Q \pm iU$ – which is also equivalent to a change in the electric vector polarisation angle (EVPA) (e.g. [Hamaker et al. 1996]).

Following leakage calculation at the GMRT, the variation in the EVPA across the band conspires such that every source has an ‘instrumental RM’ with a typical magnitude of several hundred rad m$^{-2}$. For 3C138 in observation 17$_{060}$2, the instrumental RM is $-678 \pm 5$ rad m$^{-2}$. This instrumental RM was corrected for each spectral channel using 3C138, which was taken to have an RM of 4.0 rad m$^{-2}$ ([Farnes 2012]).

The typical method of using the average phase from the matrix of the $RL/\overline{LR}$ correlations was found to be noisy and to provide inconsistent results. We instead calibrated the EVPA using the integrated flux of 3C138 as determined from the Stokes $Q$ and $U$ images, with the appropriate correction factor being applied to the $uv$-data. No significant emission was found in Stokes $V$.

### 3.5 Direction-dependent instrumental polarisation

The response of an interferometer varies across the primary beam, and wide-field polarimetry requires calibration of these ‘direction-dependent’ or ‘off-axis’ instrumental effects. Similar to the case of on-axis calibration, the ‘polarisation beam’ manifests itself with flux in total intensity leaking into the polarisation images. These polarimetric aberrations result in an increase in the observed fractional polarisation and also alter the absolute EVPA of sources – polarimetric aberrations result in an increase in the observed fractional polarisation and also alter the absolute EVPA of sources – polarimetric aberrations result in an increase in the observed fractional polarisation and also alter the absolute EVPA of sources – polarimetric aberrations result in an increase in the observed fractional polarisation and also alter the absolute EVPA of sources – polarimetric aberrations result in an increase in the observed fractional polarisation and also alter the absolute EVPA of sources.

Beam squash tends to produce a ‘four-lobed’ pattern, in which two regions on opposite sides of the beam centre have a positive sign and two lobes rotated by $90^\circ$ have a negative sign. This quadrupolar pattern tends to give rise to instrumental linear polarisation that is oriented radially with respect to the phase-centre.

We measured the GMRT polarisation beam by taking complementary observations in modified holography mode. Two reference antennas remained fixed on an unpolarised calibrator (3C147) while the remaining antennas were slewed in azimuth and/or elevation to a co-ordinate such that the calibrator source was observed offset from the phase-centre. In all cases, the two reference antennas were excluded from the data analysis so that only the offset antennas were used – allowing the power pattern to be directly retrieved, rather than the voltage pattern.

A number of offsets were used, such that a grid of ‘raster scans’ were observed. The grid used for observing these off-axis raster scans is shown in Fig. 3. An EVPA calibration was applied to obtain the $Q$ and $U$ beam in the calibrated antenna frame. This correction to the holography data was made by assuming that the EVPA of the azimuth axis was oriented radially outwards from the phase-centre.

By outputting the average amplitude and phase of all visibilities for each holography raster in all four cross-correlations, it is possible to parameterise the direction-dependent response in terms of the response of the average antenna. Variations between antennas have not been considered here. For an ideal, calibrated interferometer with circular feeds, the cross-correlations are complex quantities defined as

$$RR = \mathcal{A}(RR)e^{i\psi_{RR}} = I + V,$$

$$LL = \mathcal{A}(LL)e^{i\psi_{LL}} = I - V,$$

$$RL = \mathcal{A}(RL)e^{i\psi_{RL}} = Q + iU,$$

$$LR = \mathcal{A}(LR)e^{i\psi_{LR}} = Q - iU,$$

where $\mathcal{A}(jk)$ and $\psi_{jk}$ are the amplitude and phase respectively. For a calibrated point-source, $\psi_{RR} = \psi_{LL} = 0$, so the phase terms of equations (8) and (9) can be neglected. However, the terms $\psi_{RL}$ and $\psi_{LR}$ cause mixing of $Q$ and $U$ and cannot be ignored.

By applying Euler’s formula to equations (10) and (11) and substituting into $RL = LR^*$, the solutions can be used to obtain the fractional polarimetric beam response at a given raster. This was done for every raster in each of the individual 220 channels across the band. The holography source was taken to be unpolarised, so no correction for source polarisation was required.

![Figure 3](image-url)
Spectropolarimetry with the GMRT at 610 MHz: A case study of two SCG fields

Figure 4. The main lobe of the instantaneous GMRT primary beam at 610 MHz. Contours show the Stokes I response with contour levels at 10, 20, 30...90%. Polarisation vectors are proportional to the linearly polarised intensity and indicate the orientation of the linearly polarised response. At the 50% Stokes I contour, the polarisation vectors show a typical leakage of ~10%. The pseudocolour scale shows the instrumental circular polarisation from −10% to +10%. There are artefacts at the outer periphery of the beam that result from interpolating over a greater tangential distance at large radii.

Figure 5. The Stokes Q (left) and U (right) instantaneous fractional instrumental polarisation beams of the main lobe of the GMRT at 610 MHz. Contour levels are at ±1, 2, 5, 10, 20, 30...70%.
The instrumental polarisation and effects of parallactic angle ($\chi$) rotation have only been corrected at the phase-centre. These effects are actually direction-dependent and due to the GMRT’s alt–az mount, any residual instrumental polarisation will display an E\textsuperscript{V}PA that rotates with $\chi$. All off-axis holographic raster scans had to be corrected for the effects of this $\chi$-dependent mixing of $Q$ and $U$, so that

$$ (Q' + iU') = (Q + iU)e^{-2i\chi}. \quad (12) $$

The derotated $Q'$ and $U'$ can then be used to form a beam profile in full-Stokes for each channel across the band. The beam was found to be independent of frequency across the observing bandwidth. The mean response across the band was obtained for each holography raster, so that the beam was described by a single datum per raster – creating a set of nine data per beam axis. Each axis was then fitted with a 5th order polynomial in Stokes $I$, $Q$, $U$, and $V$ using an ordinary least-squares fit. The polynomial fits were then used to create a two-dimensional map of the GMRT beam at 610 MHz by tangentially interpolating and gridding the beam response around the phase-centre at a given radius. This was carried out using cubic spline interpolation in order to smoothly interpolate the sparsely sampled data over the large tangential distances.

The polarisation beam response along the diagonal axes suggested a significant problem with the Elevation-X axis. The direction-dependent response along this axis was observed to be oriented in the same direction as the Azimuth-X axis – in contradiction to the expected, previously measured quadrupolar response \cite{Pen et al. 2009, Farnes et al. 2013}. Further investigation of our data showed that an observational bug led to the re-observation of the Azimuth-X axis instead of independently measuring the Elevation-X axis. We therefore lack data from the true Elevation-X axis. The orientation of polarisation vectors along the observed Elevation-X axis were therefore rotated so that they were oriented radially – this rotation was equivalent to a change of sign for both $Q$ and $U$. The resulting maps therefore use the Azimuth-X axis twice, under the assumption that the true Elevation-X axis is similar to the Azimuth-X, but maintains a radial orientation. This assumption is justified as the resulting maps are consistent with the response of the GMRT inferred using both RM Synthesis \cite{Farnes et al. 2013}, and from antenna theory \cite{Pen et al. 2009}. The final two-dimensional beam at 610 MHz is shown in Fig. 4 and 5. It is possible to correct for the effects of wide-field instrumental polarisation by calibrating the $uv$-data using the beam model for each ‘time-chunk’ of approximately constant parallactic angle \cite[e.g.][]{Farnes 2012}. Nevertheless, the process is highly computationally expensive. These observations have therefore not been corrected for these wide-field instrumental effects. However, our constraints on the polarisation beam – particularly the radial orientation of the polarisation vectors, which averages down the instrumental effect in our full-track observations – allow us to be confident in our polarisation detections across the field of view. Where appropriate, we have provided an estimate of the residual instrumental effects alongside each of our off-axis polarisation measurements.

### 3.6 Imaging and RM Synthesis

Following calibration, each channel was imaged in Stokes $QIU/V$ individually using multi-facet imaging – breaking the sky up into 31 facets across the field of view (FOV). The resulting Stokes $Q$ and $U$ maps were combined into images of polarised intensity, $P = \sqrt{Q^2 + U^2}$, and the resulting 220 images of $P$ were averaged together into a final image of the band-averaged polarised intensity. As the images of $P$ are averaged, rather than averaging $Q/U$, the images are not subject to bandwidth depolarisation – and therefore provide a useful diagnostic of the polarisation across the FOV. Nevertheless, full RM Synthesis is needed to retrieve the properties of the polarised emission.

The Stokes $Q$ and $U$ images were therefore used to form a three-dimensional datacube, so that the technique of RM Synthesis could be applied \cite[Brentjens & de Bruyn 2005]{}, using a code developed in Python. This code also implemented a form of RM-clean \cite{Heald et al. 2009} to deconvolve the Faraday dispersion function (FDF) from the Rotation Measure Spread Function (RMSF). The version of RM-clean used here considers the effects of the residuals, and uses complex cross-correlation in order to locate the peak in Faraday space \cite{Heald et al. 2009}. There is currently some question over the capability of RM-clean to fully reconstruct the Faraday dispersion function along the line of sight \cite{Frick et al. 2010, Farnsworth et al. 2011}, and it is possible that modelling of $Q(\phi)$ and $U(\phi)$ is advantageous under many circumstances \cite{O'Sullivan et al. 2012}. These issues are not the limiting factor for our data, due to the 16 MHz bandwidth and the corresponding FWHM of the RMSF = 321 rad m$^{-2}$. The RMSF is shown in Fig. 6. RM-cleaning was performed down to a 2$\sigma$ limit. The cleaned Faraday spectrum was convolved with a FWHM equal to that of the RMSF. Unless otherwise specified, the polarisation was summed up coherently across the band for trial Faraday depths ranging from $-2000$ rad m$^{-2}$ to +2000 rad m$^{-2}$. The ‘RM-cubes’ generated by RM Synthesis were always oversampled – sampling of $\Delta\phi = 1$ rad m$^{-2}$ was often used. The RM Synthesis observational setup, which uses a 16 MHz bandwidth, with 62.5 kHz channel spacing at 610 MHz, has a maximum Faraday depth to which one is sensitive of $|\phi_{\text{max}}| \sim 35000$ rad m$^{-2}$, and a FWHM of the RMSF of 321 rad m$^{-2}$. No attempt was made to distinguish multiple Faraday components along a single line of sight. Bandwidth depolarisation will affect these data for a [RM] $\gtrsim 20000$ rad m$^{-2}$. The maximum scale in Faraday space to which the data are sensitive is 14 rad m$^{-2}$, consequently the data are not sensitive to Faraday thick emission. Faraday depths (FDs) were retrieved using a least-squares Gaussian fit to the peak of the deconvolved FDF.

### 3.7 Spectral Indices

The GMRT data were compared with VLA data from the 1.425 GHz atlas of the IRAS Bright Galaxy Sample \cite{Condon et al. 1996} in order to retrieve the peak brightness and spectral index of sources. When the source was not available in the atlas, and when the s/n...
allowed, the GMRT data were instead combined with images from the SUMSS (Bock et al. 1999) at 843 MHz. For comparison with the 1.425 GHz atlas data, the GMRT images were convolved to a resolution of 60 arcsec. For SUMSS data, GMRT images were reconvolved to 45 × 45 csc |δ| arcsec2, where δ is the declination of each observation (Mauch et al. 2003). The higher frequency images were then regridded to the same geometry as the GMRT images. The 1.425 GHz data had an r.m.s. noise of 0.2 mJy beam−1, and the 843 MHz data had an r.m.s. noise of 2.2 mJy beam−1 in the field of USCG S063, and 1.8 mJy beam−1 in the field of the Grus Quartet. All compact sources in the images appear aligned to ± 1′.2.

Note that errors in the derived spectral indices are otherwise dominated by flux calibration errors, which are assumed to be 5% and 3% for the GMRT/VLA and SUMSS data respectively. These systematic errors originating from the accuracy of the beam model at the GMRT. All images were corrected for the effects of primary beam attenuation using PBCOR in AIPS and the coefficients that have been determined at the observatory."}

Notes:

a) The co-moving distance, assuming a flat cosmology with $\Omega_M = 0.27, \Omega_{\Lambda} = 0.73$, and $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$.

b) Calculated using $v = cz$ with $z$ taken from the NASA/IPAC Extragalactic Database (NED) (http://ned.ipac.caltech.edu/).

c) Pompei, Dahlem & Iovino (2007); Dahlem (2005). Note that NGC 7552 is listed as a HII Liner galaxy with a giant nuclear H region (Forbes, Kotilainen & Moorwood 1994; Forbes & Norris 1998). Similarly, NGC 7582 has also been classified as Sy1 by other authors (e.g. Ricci et al. 2010).

### 4 GROUP GALAXIES

The SCG catalogue consists of 121 groups over ~ 25% of the southern sky (Iovino 2002). The automated algorithm used to select the SCG sample followed criteria that was similar to that used for the Hickson’s Compact Groups (HCGs), which consists of many groups that are physically bound and in different stages of evolution (Hickson 1982). The SCG catalogue avoids one of the biases of the HCG catalogue – as fainter galaxy members with a magnitude close to the cut-off limit were discarded by the eyeball search used for the identification of HCGs. The selection criteria for the SCGs are based on richness, isolation, and compactness in order to identify groups in the blue plates of the COSMOS survey (Iovino 2002).

The groups observed in this paper, the Grus Quartet and USCG S063 (also known as SCG 2315–4241 and SCG 0141–3429 respectively), are both in ‘phase 2’ of their evolution, i.e. with extended tidal tails and a perturbed gas distribution (Dahlem 2005; Pompei, Dahlem & Iovino 2007). They are observed with the GMRT at 610 MHz and used alongside Sydney University Molonglo Sky Survey data at 843 MHz, VLA data at 1.425 GHz, and near-infrared data from the DSS-2 survey. These data allow for constraints on the group members’ spectral index, polarisation fraction, and Faraday depth. They also allow for identification of counterpart sources at other wavelengths, and act as a probe of tidal interactions or ram pressure from the IGM compressing the magnetic field of the galaxies.

Tidal interactions and/or ram pressure stripping have been shown to occur frequently in compact groups, with ~ 50% of the galaxies showing signs of morphological disturbances. In a simple case, tidal interactions would lead to bridges and tails, ram pressure stripping would lead to a smooth swept-up morphology and displaced gas disks, while turbulent viscous stripping would lead

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![Figure 7. The near-IR DSS-2 image of the four group galaxies in the Grus Quartet. The labels are defined in Table 2. The pseudocolour scale uses the cubehelix colour scheme (Green 2011).](http://ncra.tifr.res.in:8081/~ngk/primarybeam/beam.html)
to effects on the entire gas disk (Cayatte et al. 1994). It is likely that these hydrodynamical interactions play a substantial role in the evolution of group galaxies and their morphological type (e.g. Pompei, Dahlem & Iovino 2007). Several groups of galaxies have shown evidence for ram pressure like events shaping their morphology, with many member galaxies showing an H I deficiency, alongside the presence of massive H I structures in the IGM (e.g. Verdes-Montenegro et al. 2001; Kantharia et al. 2005; Rasmussen et al. 2006; Kilborn et al. 2009; Kilborn et al. 2012; Mishra et al. 2012). The presence and role played by the IGM in the evolution of groups of galaxies therefore continues to be of interest (e.g. Mulchaey et al. 1996; Verdes-Montenegro et al. 2001). X-ray emission has been detected from the IGM of several groups (e.g. Mulchaey et al. 2003), with the detection rate being higher in the evolved elliptical dominated groups as compared to spiral-rich groups. However, as shown by Kantharia et al. (2005), the member galaxies of the poor group Holmberg 124 seem to show signatures attributable to ram pressure like events being experienced by the galactic interstellar medium. Furthermore, cold H I gas has been detected between the member galaxies in several Hickson’s groups (Verdes-Montenegro et al. 2001), which could enhance the density of the IGM and lead to ram pressure like events playing a more significant role. Nevertheless, due to observational difficulties and faint signatures, it has been difficult to rigorously determine the effect of the IGM on the galaxies in groups.

Another way to address this is to study the linearly polarised emission from the group members. Polarised emission is, in principle, an ideal tracer of such interactions, and directly reveals regular magnetic fields that result from field compression due to interaction with the IGM (Harnett et al. 2004). Previous attempts to understand these processes have been made both observationally (e.g. Węgowiec et al. 2012; Vollmer et al. 2013) and through three-dimensional magnetohydrodynamical simulations (Pfrommer et al. 2010). Such a study has been done for spiral members of the Virgo cluster (Vollmer et al. 2007, 2013), with all the studied galaxies showing an asymmetric polarised intensity distribution along ridges in the outer part of each galaxy which differs from what is typically observed in field spiral galaxies. Vollmer et al. (2007) attributed the observed behaviour of these galaxies to interactions with the intra-cluster medium that are mediated by ram pressure. While Vollmer et al. (2013) found that tidal interactions and accreting gas envelopes can lead to compression and shear motions which enhance the po-

Figure 8. The Stokes I GMRT image of the field surrounding the Grus quartet at full-resolution of $9.5 \times 4.6$ with a position angle of $16^\circ$. 

J. S. Farnes, et al.
larised radio continuum emission. Observing a large sample of galaxy groups in linear polarisation will therefore assist in further understanding the signatures of various processes that influence the radio emission.

Various properties of the galaxies in the target groups are summarised in Table 2. The individual groups are discussed in further detail in Sections 4.1 and 4.2.

4.1 The Grus Quartet

The Grus Quartet at a luminosity distance of 18.3 Mpc and a velocity of 1571 km s\(^{-1}\) contains four galaxies, all of which are spirals as shown in Fig. 7. X-ray emission has previously been detected from three of the galaxies – NGC 7552, NGC 7582, and NGC 7590 (Ward et al. 1978; Maccacaro et al. 1981).

The four members of the Quartet have been observed in \(\text{H} \alpha\) by Dahlem (2005) who found an extended tidal tail with an \(\text{H} \alpha\) mass of \(1.34 \times 10^9 \ M_\odot\) emerging from NGC 7582 and also a large \(\text{H} \alpha\) cloud of mass \(7.7 \times 10^8 \ M_\odot\) removed from the galaxy and now a part of the IGM. The group is evolving with 11% of its \(\text{H} \alpha\) in the IGM (Dahlem 2005), making it an important case study of how the enhanced densities in the IGM might be affecting the other properties of the galaxy.

The 610 MHz data from observation 17,060,2 achieved \(\sigma = 85 \ \mu\text{Jy beam}^{-1}\) near the phase-centre in Stokes \(I\) at full-resolution of \(9.5' \times 4.6'\) with a position angle of 16°, and a noise level in the band-averaged \(Q/U\) of \(\sim 36 \ \mu\text{Jy beam}^{-1}\) at a resolution of 24 arcsec. The low resolution for the polarisation images were chosen in order to maximise the s/n within each beam. The removal of antennas with leakages > 15%, some of which were located in the GMRT’s outer arms, meant that the data had to be tapered in the \(\phi\)-plane in order to avoid large gaps in the \(\phi\)-coverage. The cleaned \(\phi\)-cubes had \(\sigma = 54 \ \mu\text{Jy beam}^{-1}\) rms\(^{-1}\). The Stokes \(I\) FOV is shown in Fig. 8.

At 610 MHz, all four group galaxies were detected in Stokes \(I\). The galaxies NGC 7552, NGC 7582, NGC 7590, and NGC 7599 were found to have a peak brightness of 377, 379, 75, and 53 mJy beam\(^{-1}\) respectively. The Stokes \(I\), near-IR data, and polarised intensity at 610 MHz are shown for NGC 7552 in Fig. 9 and for NGC 7582 in Fig. 10. The emission from NGC 7590 and NGC 7599 is shown in Fig. 11.

The brightest emission emanates from the nuclei of NGC 7552 and NGC 7582. Extended emission is detected at 610 MHz along the bar of NGC 7552. There is clear radio structure along the bar of NGC 7582 through to the outer northern and southern edges of the galaxy. These knots of emission are also visible in \(\text{H} \alpha\) (Hameed & Devereux 1999). Diffuse emission is detected across most of the disk of NGC 7590, with very little structure in the emission. The emission from NGC 7599 is faint, and only the peaks in emission are detected. The peak brightness in NGC 7599 is located towards the west of the outer disk, and arises from a region associated with the spiral arm which emerges in the south and then turns towards the north.

There was insufficient resolution to investigate spatial spectral index variations across these galaxies. For the brightest emission, \(\phi_{610}\) was found to be \(0.62 \pm 0.05\) in NGC 7552, \(0.62 \pm 0.05\) in NGC 7582, \(0.71 \pm 0.24\) in NGC 7590, and \(0.97 \pm 0.35\) in NGC 7599. This emission comes from the cores of NGC 7552 and NGC 7582, and is integrated across the disk in both NGC 7590 and NGC 7599. The knot of emission in the bar to the north of NGC 7582 (and correlated with \(\text{H} \alpha\)) is just resolved, and has \(\sigma = 0.8 \pm 0.3\).

NGC 7590 and NGC 7599 were undetected in polarisation to 3\(\sigma\) upper limits of < 0.9% and < 1.4% respectively. Bright polarisation was detected from the nucleus of both NGC 7552 and NGC 7582. It is important to compare this polarised emission to that expected due to direction-dependent instrumental effects – especially for these two ‘polarised’ galaxies which are both displaced from the phase-centre. This comparison is complicated by a number of factors, especially since the amount of spurious polarisation is reliant on both the position of the source within the primary beam and the precise values of source and instrumental polarisation at this location. It is important to note that for observations with a long track in parallactic angle, the direction-dependent instrumental polarisation averages down substantially, as shown in Fig. 12. This averaging is limited for these observations due to the low declination. USCQ S063 was observed with parallactic angles ranging from \(-32°\) to \(+51°\), while the Grus Quartet was observed with parallactic angles ranging from \(-29°\) to \(+31°\). Some averaging down of the off-
Figure 10. Top: Stokes $I$ contours at 610 MHz overlaid on the near-IR DSS-2 image of NGC 7582 in the field of the Grus Quartet. The contours are at $(-2, -1, 1, 2, 3, 4, 5, 10, 20, 40, 80, 160) \times \sigma$ level, where $\sigma$ is 185 $\mu$Jy beam$^{-1}$. The 610 MHz image is at full resolution of 9\,''5 × 4\,''6 with a PA of 16\,°. Bottom: Stokes $I$ contours at 610 MHz overlaid on the $P$ image of NGC 7582 at a Faraday depth of $-10$ rad m$^{-2}$. The $P$ image has a resolution of 24 arcsec, and has not been corrected for the effects of the primary beam or for Rician bias. The synthesised beams are shown in the bottom left.

Figure 11. Stokes $I$ contours at 610 MHz overlaid on the near-IR DSS-2 image of NGC 7590 and NGC 7599 in the field of the Grus Quartet. NGC 7590 is further to the west. The contours are at $(-2, -1, 1, 2, 3) \times \sigma$ level, where $\sigma$ is 205 $\mu$Jy beam$^{-1}$. The 610 MHz image is at full resolution of 9\,''5 × 4\,''6 with a PA of 16\,°. The synthesised beam is shown in the bottom left.

Figure 12. The fractional polarisation, $\Pi$, of sources surrounding the nearby galaxy M51 as a function of distance from the phase-centre for a full-track observation with considerable averaging down over the large range in parallactic angle. Sources detected above an $8\sigma$ limit following RM Synthesis are shown with error bars. Sources undetected in polarisation within the sensitivity limit ($P < 8\sigma$) are shown as an upper limit. The half-power and 10% points of the $I$ beam are indicated by the solid vertical lines (Farnes et al. 2013).

axis response is therefore expected, particularly as measurements of the polarisation beam indicate that it is oriented radially outwards.

The polarised peak brightness and Faraday depth were measured by fitting a Gaussian to the points surrounding the peak of the Faraday spectrum. Only pixels with a peak in $\phi$-space greater than 8$\sigma$ were analysed, where $\sigma$ is the noise in the cleaned $\phi$-cubes. The polarised intensity measurements were corrected for the effects of Rician bias using an alternative estimator, $P_0 = \sqrt{P^2 - 2.3\sigma^2_{QU}}$, which is a more effective estimator of the true polarised intensity in $\phi$-cubes (George, Stil & Keller 2012), where $P$ is the linearly polarised intensity, and $P_0$ is the corrected quantity.

The corrected values were then used to calculate the fractional polarisation, $\Pi = P_0/I$. The fractional polarisations are 0.87 ± 0.02% and 0.70 ± 0.01% for NGC 7552 and NGC 7582 respectively. Note that the quoted 1$\sigma$ uncertainties are our measurement errors – there are likely further contributions due to systematics in the calibration of the instrument. We estimate the maximum residual instrumental polarisation at the phase-centre to be $\leq 0.25\%$. The Stokes $I$, near-IR data, and polarised intensity at 610 MHz are shown for NGC 7552 in Fig. 9 and for NGC 7582 in Fig. 10.

NGC 7552 and NGC 7582 are located 20.1 and 7.6 from the phase-centre, yielding an approximate upper limit for the direction-dependent instrumental polarisation of 2.0% (NGC 7552) and 0.3%
Spectropolarimetry with the GMRT at 610 MHz: A case study of two SCG fields

The estimated upper limit at the location of NGC 7552 is large enough to account for the polarisation detection as an instrumental effect, although the effects of parallactic angle averaging cannot be trivially taken into account. As the frequency-dependence of the instrumental polarisation has been removed from the data (see Section 3.3) and the polarisation beam has been found to be essentially independent of frequency across the GMRT band (see Section 3.5), instrumental effects will tend to accumulate at Faraday depths (FDs) of 0 rad m$^{-2}$ (see e.g. Brentjens & de Bruyn 2005 for further details). RM Synthesis was therefore applied in order to diagnose the nature of the emission. The peak in the Faraday Dispersion Function is at a FD of 7.71 ± 0.29 rad m$^{-2}$ – a plot of the Faraday spectrum is shown in Fig. 13. Surrounding pixels have varying FDs from ~4–14 rad m$^{-2}$. The Faraday depth (FD) of the pixel of peak polarisation was found to be 7.8 ± 0.5 rad m$^{-2}$. The polarisation to the west of the nucleus has a ‘smudged’ appearance and does not coincide with a distinct feature of the galaxy in Stokes I. It is likely that errors in the determination of the leakage phase arising from the use of a linear model have led to this spurious polarisation to the west of the nucleus. As the FD is non-zero, it implies that the polarisation detection does not result from the effects of instrumental polarisation.

Following RM Synthesis of the brightest polarised pixel in NGC 7582, the peak in Faraday space occurs at a FD of $-1.83 \pm 0.22$ rad m$^{-2}$ – a plot of the Faraday spectrum is shown in Fig. 13. FDs in the immediately surrounding bright pixels are all negative, varying between $-9$ rad m$^{-2}$ to $-1$ rad m$^{-2}$. The consistently negative, and non-zero, FDs are again indicative of the detection not resulting from instrumental polarisation.

In an attempt to constrain the presence of beam depolarisation, the data were over-resolved using uniform weighting. This provided a beam with a FWHM of $7.5 \times 3.4$ and a position angle of 9.5°. A cellsize of 0.8 was used to ensure the synthesised beam was well-sampled. The core of NGC 7582 remained unresolved in both total intensity and linear polarisation. However, the core of NGC 7552 reveals a structure that is just-resolved on these scales (with $\sim 2$ beams across the source). The polarisation structure, overlaid with total intensity contours, is shown in Fig. 14. Note that no polarisation was detected in the arms of the galaxy, as has been previously observed at higher frequencies (Beck 2002; Ehle et al. 2002). The presence of a circumnuclear starburst ring in this galaxy has been previously well-documented (Forbes, Kotilainen & Moorwood 1994; Forbes & Norris 1998). Circumnuclear starburst rings can exhibit relatively large magnetic field strengths in comparison to the rest of a galaxy – for example, the ring in NGC 1097 has a field strength of 60 µG (Beck et al. 2005). While no AGN has been confirmed in NGC 7552, if there was one then material could be transported from the ring to the central black hole by magnetic braking as believed to be the case in NGC 1097 (Beck et al. 1999).

The polarisation image reveals two hotspots, one located to the east (at $23^h16^m10^{s}.9$, $-42^\circ35^\prime4^\prime.7$) and another to the northwest (at $23^h16^m10^{s}.6$, $-42^\circ35^\prime3.1$) both of which are coincident with the regions ‘A’ and ‘D’ respectively as found and defined by Forbes, Kotilainen & Moorwood (1994). The locations of peak polarised intensity are offset to the peaks in total intensity. The fractional polarisation increases at high-resolution relative to the 24 arcsec resolution images – consistent with the polarisation structure changing on scales less than the original beam size. The uniform-weighted data provide a lower limit on the fractional polarisation of $2.60 \pm 0.24\%$ in the eastern edge of the ring, and $2.09 \pm 0.23\%$ to the northwest. The percentage polarisation is similar to that reported at higher frequencies (e.g. Beck et al. 1999). The peak FD in these regions were found to be $57.7 \pm 0.7$ rad m$^{-2}$ to the east, and $-3.3 \pm 0.6$ rad m$^{-2}$ to the northwest – demonstrating a change in the heading (i.e. a change of direction along the line of sight) of the magnetic field on either side of the ring. Follow-up VLBI observations would reveal further information on the magnetic field structure.

4.2 USCG S063

The group USCG S063 contains five galaxies, all of which are either lenticular or spiral as shown in Fig. 15. The 610 MHz data from observation 17_060_1 achieved a noise-level of $\sigma = 270$ µJy beam$^{-1}$ near the phase-centre in Stokes I at full-resolution of $9.7 \times 5.6$ with a position angle of 37°. The field was strongly affected by residual phase errors from an off-axis source located 8.5 from the phase-centre with a peak brightness of 213 mJy beam$^{-1}$ at full-resolution. The algorithm PEELR can help to remove such phase errors. Standard self-calibration only provides a single gain solution per antenna, but this gain is only accurate in the direction towards the calibration source from which the solution was derived. Nevertheless, the signal from sources at different positions in the FOV pass through different regions of the ionosphere. This is an increasingly significant problem at lower observing frequencies, as both the effects of the ionosphere and the size of the FOV increase. It is therefore necessary to find solutions for the direction-dependent gains, which can be done through iterative ‘peeling’ of the phase solutions at each position. Application of PEELR led to a mild improvement in the residual...
FOV is shown in Fig. 16. of <3 polarisation was detected from ESO 0353–G036 to a range in the surrounding region. The cleaned phase errors, but the off-axis source limits the obtainable dynamic phase of IRAS F01415–3433 and ESO 0353–G039 (towards east). The offset emission is also extended by two synthesised beams directed towards IRAS F01415–3433 and ESO 0353–G036. At 610 MHz, galaxies IC 1724, IC 1722, IRAS F01415–3433, and ESO 0353–G039 were all undetected in Stokes I to a 5σ upper limit of < 1.35 mJy. The galaxy ESO 0353–G036 was detected and found to have a peak brightness of 15.4 mJy beam$^{-1}$ (as shown in Fig. 17). The peak of radio emission from ESO 0353–G036 appears to be offset from the emission in the near-IR, with the offset directed towards IRAS F01415–3433 and ESO 0353–G036 (towards the east). The offset emission is also extended by two synthesised beams towards the east, and reaches beyond the extent of the disk that is visible at near-IR wavelengths. Further higher resolution observations will be required to identify the cause of this emission.

None of the group galaxies were detected in polarisation. No polarisation was detected from ESO 0353–G036 to a 3σ upper limit of < 0.4%.

\[\text{Radio Emission} \times 10^{-24} \text{W m}^{-2} \text{Hz}^{-1} \text{Hz}^{-1}\]

\[\text{Stokes I} \times 10^{-24} \text{W m}^{-2} \text{Hz}^{-1} \text{Hz}^{-1}\]

\[\text{Stokes I} \times 10^{-24} \text{W m}^{-2} \text{Hz}^{-1} \text{Hz}^{-1}\]

\[\text{Stokes I} \times 10^{-24} \text{W m}^{-2} \text{Hz}^{-1} \text{Hz}^{-1}\]

\[\text{Stokes I} \times 10^{-24} \text{W m}^{-2} \text{Hz}^{-1} \text{Hz}^{-1}\]

\[\text{Stokes I} \times 10^{-24} \text{W m}^{-2} \text{Hz}^{-1} \text{Hz}^{-1}\]

5 OTHER EXTENDED SOURCES

Three spatially extended sources were detected in the field of the Grus quartet that are unrelated to the group galaxies themselves. These three radio sources J2317.9–4213, MCG–07–47–031, and PKS 2316–429 have all been previously detected but are largely unstudied (Ewald & Hjellming 1980). In this section, these individual sources are described in further detail. As we shall show, J2317.9–4213 resembles an FR-I radio source, MCG–07–47–031 is classified as a blazar, and PKS 2316–429 is likely an FR-II X-shaped radio source. This allows a glimpse into the polarisation properties of these different types of sources at 610 MHz.

5.1 J2317.9–4213

The complex radio galaxy J2317.9–4213 is located ~ 1 arcmin to the west of NGC 7590 at 23°17′55″, –42°13′29″. It has possibly been detected as an X-ray source, indicating the presence of an AGN (Ewald & Hjellming 1980). It is well-resolved, with the two jets/lobes projecting along an axis that is approximately aligned east–west, as shown in Fig. 15 and 16. The spectrum, $\alpha_{1425}$, was found to be 0.43 ± 0.15 at the location of the AGN, and 0.84 ± 0.26 and 0.56 ± 0.12 in the brightest emission from the east and west jet respectively. The jet to the east curves away to the north relative to the approximate east–west axis as seen in projection. Such distortions are commonplace in FR-I sources (e.g. Leahy & Parma 1992; Dennett-Thorpe et al. 2002; Cheung 2007). This suggests interaction between the surrounding environment to the east and the expanding jet – resulting from either ram pressure or a denser ambient medium (e.g. Begelman et al. 1984; Burns et al. 1986; Best et al. 1998).

In the near-IR DSS images is an apparent counterpart source coincident with the brightest 610 MHz Stokes I emission. This counterpart is shown in Fig. 18. The counterpart has $z = 0.056$ and is therefore in the background of the galaxy group, with the emission from the lobes extending across 43 kpc. The general morphology, in combination with the presence of low brightness regions towards the periphery is indicative of the FR-I class. The 610 MHz polarisation is brighter in the western jet and the contrasting lack of polarised emission to the east is likely a consequence of the Laing–Garrington effect (e.g. Garrington et al. 1988). This suggests the eastern jet is located more distantly along the line-of-sight and therefore subject to stronger Faraday depolarisation.

No polarisation was detected from the AGN, to a 3σ upper limit of < 0.2%. However, there are two pairs of polarised hotspots located on both the east and west side of the nucleus, as shown in Fig. 19. These hotspots are approximately equidistant from each other and the associated AGN. The hotspots to the east have fractional polarisations of 5.2 ± 0.4% and 4.0 ± 0.3%, and the hotspots to the west are polarised to 3.2 ± 0.3% and 2.2 ± 0.2%. The lesser of each of these values is associated with the hotspot that is in closer proximity to the AGN. These values also show that the polarisation is ~ 2% higher on the east side of the nucleus.

Moving from the hotspot furthest to the east, through to the west, the FDs extracted from the datacubes are 15.9 ± 1.3 rad m$^{-2}$, 12.7 ± 0.5 rad m$^{-2}$, 22.1 ± 0.6 rad m$^{-2}$, and 27.4 ± 1.1 rad m$^{-2}$. The FDs are clearly higher on the western side. Relative to the outer polarised hotspots, the pair nearest to the AGN have lower FDs. The polarised hotspots are associated with regions that also show an increase in total intensity, and may originate from strong shocks along the boundary of the jet outflow. A strong shock would compress...
Figure 16. The Stokes I GMRT image of the field surrounding USCG S063 at full-resolution of $9.7' \times 5.6'$ with a position angle of $37^\circ$.

Figure 17. Left: Stokes I contours at 610 MHz overlaid on the near-IR DSS-2 image of the region near ESO 0353–G036 in the field of USCG S063. The galaxies IC 1722 and IC 1724, which are not detected at 610 MHz, are visible to the northwest and south respectively. The contours are at $(-2, -1, 1, 2, 4, 8, 16) \times$ the off-source $4\sigma$ level, where $\sigma$ is $270 \mu$Jy beam$^{-1}$. The 610 MHz image is at full resolution of $9.7' \times 5.6'$ with a PA of $37^\circ$. Right: The image is the same as to the left, but zoomed in towards ESO 0353–G036. The synthesised beam is shown in the bottom left.
Figure 18. Top: Stokes \( I \) contours at 610 MHz overlaid on the near-IR DSS-2 image of the FR-I source J2317.9−4213 in the field of the Grus Quartet. The contours are at \((-2,-1,1,2,3,\ldots,10,12,\ldots,28)\times\) the off-source 3\( \sigma \) level, where \( \sigma \) is 185 \( \mu \)Jy beam\(^{-1} \). The 610 MHz image is at full resolution of 9\(.5 \times 4^\prime.6 \) with a PA of 16\(^{\circ} \). The synthesised beam is shown in the bottom left. Bottom: Similar to the top image, but zoomed in towards the centre of J2317.9−4213 and with the synthesised beam shown in the top left.

Figure 19. Stokes \( I \) contours at 610 MHz overlaid on the \( P \) image at a Faraday depth of 10 rad m\(^{-2} \) for the FR-I source J2317.9−4213 in the field of the Grus Quartet. The grayscale is in units of mJy beam\(^{-1} \). The contours are at \((-2,-1,1,2,3,4,5,10,14,18,22,28)\times\) the off-source 3\( \sigma \) level, where \( \sigma \) is 185 \( \mu \)Jy beam\(^{-1} \). The Stokes \( I \) contours are at full resolution of 9\(.5 \times 4^\prime.6 \) with a PA of 16\(^{\circ} \). The \( P \) image has a resolution of 24 arcsec, and has not been corrected for the effects of the primary beam or for Rician bias. The synthesised beams are shown in the bottom left.
and order the magnetic field, leading to an increase in the linear polarisation fraction. If this is the case, the polarisation fractions would mildly suggest a denser ambient medium to the east in near proximity to the AGN. The combination of the observed polarisation fractions and Faraday depths of these hotspots support two scenarios near to the AGN, that are not mutually exclusive: either the magnetic field strength is weaker, or alternatively there is a combination of increased turbulence, that increases the random component of the magnetic field, together with lower electron density.

The western jet can be approximately split into four regions of polarised emission, as indicated in Fig. 19. The FD of these four regions of extended polarisation in the western jet are (moving from east to west): $-11.7 \pm 2.4$ rad m$^{-2}$, $-2.0 \pm 1.1$ rad m$^{-2}$, $-10.9 \pm 1.1$ rad m$^{-2}$, and $+4.7 \pm 1.4$ rad m$^{-2}$. There appears to be a large scale change of heading of the magnetic field along the line of sight (as shown by the predominantly negative FD) relative to that near to the nucleus (which has positive FD). The polarised region (number 4) furthest to the northwest, and at the outer periphery of jet, again has a positive FD. This suggests another change in the heading of the magnetic field along the line of sight relative to the rest of the western jet. The morphology of this region is indicative of shocked material causing an increase in the ordering of the magnetic field, with the polarised emission laying along the western edge.

5.2 MCG−07−47−031

The blazar or BL Lac, MCG−07−47−031, is located ~ 10 arcmin to the north of galaxy NGC 7599 at $23^{19}09^58.4 -42^0649^9$. This bright AGN appears to have a near-IR counterpart in the DSS images, which is located at $z = 0.055$, or 228 Mpc away. The identified counterpart in J2317.9−4213 is located at $z = 0.056$. The similar redshifts of these two sources may indicate that they are part of the same background cluster. The Stokes $I$, near-IR data, and polarised intensity at 610 MHz are shown in Fig. 20.

Near the core in Stokes $I$, there are at least three other point-like regions of emission that appear associated with the blazar – although foreground/background sources cannot be ruled out. At the faintest levels in the images, there is a $3\sigma$ detection of two jet-like features leading from the AGN – one directly north, and another to the east. There is also some indication of a bridge of emission connecting the two jets.

The nucleus was found to have a flat spectrum typical of a blazar of $\alpha_{500} = 0.29 \pm 0.25$, and is detected in linear polarisation at this epoch with a fraction of 7.03 ± 0.11%. A point-like source to the east of the nucleus is also polarised to 1.88 ± 0.05%, although instrumental effects are anticipated to be on the order of at most ~ 2.5% at 23/7 from the phase-centre. Nevertheless, this polarised emission is likely real – with the peak in polarised intensity having a non-zero FD of 2.5 ± 0.6 rad m$^{-2}$. The nucleus itself has a FD of 6.5 ± 0.1 rad m$^{-2}$. No polarisation was detected from the jets to a 3$\sigma$ upper limit of < 0.7%.

5.3 PKS 2316−429

This previously unclassified radio source is located ~ 25 arcmin south of galaxy NGC 7599 at $23^{19}09^58.4 -42^337^53^9$. The radio morphology has a central unresolved core, with two bright hotspots to the northwest and southeast periphery. Diffuse emission extending along the east–west is also detected, giving the source an X-shaped morphology. The Stokes $I$, near-IR data, and polarised intensity at 610 MHz are shown in Fig. 21.

Two near-IR sources enclosed within the Stokes $I$ emission are feasibly in the background and unrelated to the radio source, as their location bears no strong relevance to the radio structure. Nevertheless, one of these sources is near to the approximate intersection of the X-shaped structure, and could be an associated AGN – although no redshift data was available. Note that the identified counterpart in J2317.9−4213 is located at $z = 0.056$, and the counterpart in MCG−07−47−031 is located at $z = 0.055$. The similar redshifts of these two sources, when also considered together with PKS 2316−429 and the similar angular size of all three radio sources, may indicate that they are all part of the same background cluster. Nevertheless, this is not clear without redshift information for PKS 2316−429.

The PKS 2316−429 radio source is also detected in the SUMSS, and comparison with the 610 MHz data shows the source to have a non-thermal spectrum with $\alpha_{600} = 0.57 \pm 0.13$. There are two peaks in linear polarisation that are offset from the two total intensity hotspots. The polarisation fraction determined from the FDF at the position of the peak polarised emission is 3.86 ± 0.07% and 6.7 ± 0.3% to the northwest and southeast respectively. Directional...
dependent effects are estimated to be at most ~ 2.0%. The FD is similar for both polarisation peaks, being 15.39 ± 0.15 rad m⁻² and 16.56 ± 0.19 rad m⁻² to the northwest and southeast. No polarisation was detected from the core to a 3σ upper limit of < 0.6%.

The non-thermal spectrum, polarisation properties, and radio morphology – particularly the bright outer hotspots – is typical of an FR-II type, X-shaped radio galaxy with both a set of active lobes and wings. The GMRT has previously been used to study such objects (Lal & Rao 2007; Lal et al. 2008). Only ~100 candidate sources at most have been identified to date, and even this is likely an overestimated sample that includes Z- and S-shaped distortions that are common in FR-I sources (e.g. Leahy & Parma 1992; Dennett-Thorpe et al. 2002; Cheung 2007). A frequent explanation for the unusual morphology is that the central supermassive black hole underwent a recent realignment (e.g. Merritt & Ekers 2002).

The complementary SUMSS data does not have sufficient resolution to measure any spatial spectral index variations in this X-shaped galaxy. Future observations could allow for the spectral index of the active and the winged lobes to be measured – the active lobes typically have α ≈ 0.7 and the wings α ≈ 1.2, and the aged electron population can reveal which of the jets is from the more recent period of AGN activity (Dennett-Thorpe et al. 2002). Nevertheless, the bright hotspots and coincident polarisation are typical of termination shocks as the jet fluid encounters approximately stationary lobe material – indicating that these are the active lobes.

6 DISCUSSION AND CONCLUSIONS

We have shown that it is possible to calibrate the GMRT’s full-polarisation mode for the use of spectropolarimetry, in order to investigate some aspects of cosmic magnetism. In addition, our characterisation of the wide-field polarisation beam allows us to be confident of polarisation measurements within an appropriate portion of the FOV. The application of RM Synthesis to GMRT data requires consideration of a large number of systematics, including the instrumental polarisation, instrumental time-stability, quality of υ-data calibration, ionospheric Faraday rotation, polarisation angle corrections across the observing bandwidth, and the wide-field response. However, we have shown that all of these calibration issues can be addressed, resulting in a sensitivity of a few tens of μJy in Faraday-space at 610 MHz.

Nevertheless, there are a number of limitations for GMRT polarisation data that restrict the instrument’s current use for high-dynamic range polarimetric observations. The on-axis instrumental polarisation is both large and highly frequency-dependent at 610 MHz. The rapid wrapping of phase with frequency limits the quality of polarisation calibration. Furthermore, the fact that some antennas have high leakage requires the use of a non-linear model in order to separate the source and instrumental polarisation. Nevertheless, a full non-linearised model is not currently available in commonly used data reduction packages, (see Farnes 2012, for further detail). It has been possible to make progress with GMRT polarimetry by removing antennas with instrumental polarisation ≥ 15%, thereby eliminating antennas for which a small-leakage approximation breaks down. The loss of antennas that are located in the outer arms of the array frequently leaves significant gaps in the υ-coverage. This requires tapering of the data in the υ-plane, which reduces the highest resolution that is available. Nevertheless, the major upgrade that is currently underway will essentially revolutionise GMRT polarimetry, as the better quality receivers that are currently being installed will likely have completely different polarisation properties.

The GMRT has been used for both deep surveys at 610 MHz (e.g. Garn et al. 2007, 2008a,b, 2009, 2010) and large-area surveys such as the TIFR GMRT Sky Survey (TGSS) at 150 MHz. The TGSS is planned to detect up to two million sources in total intensity at 150 MHz. The resolution and sensitivity of the GMRT at low radio frequencies means that polarimetric radio surveys have the potential to be complementary to planned surveys with facilities such as ASKAP that explore a similar parameter space at higher frequencies and more Southern declinations (e.g. Johnston et al. 2008).

Future observations with the polarisation mode of the GMRT could make useful predictions of the number density of polarised sources observable with the SKA and its pathfinders, and opens

![Figure 21](http://tgss.ncra.tifr.res.in/)
up the possibility to model magnetic fields and their evolution in populations of faint radio sources (e.g. Stil et al. 2007, Taylor 2009). Furthermore, it has been argued by Beck et al. (2012) that a combination of GMRT, LOFAR, and JVLA data will allow for magnetic structures at intermediate scales to be recognised – comparable to the range of recognisable scales in Faraday space for SKA data. This would allow for much stronger constraints to be placed on the prevailing depolarisation mechanisms at low frequencies, allow for improved estimates of polarised source counts at low frequencies, and demonstrate the feasibility of using next-generation facilities, such as the SKA, for observing the RM-grids that will be essential for understanding cosmic magnetism (Gaensler, Beck & Feretti 2004).

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