Properties of Polarized Radio Sources in the Wide Chandra Deep Field South from 2 to 4 GHz

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ABSTRACT

In this paper we discuss our results regarding the linear polarization properties of radio sources in the Wide-Chandra Deep Field South observed from 2 to 4 GHz. The main properties we looked at were the source counts, polarization angles and fractional polarization. The biggest contributor of Faraday Rotation the sources experience came from the Milky Way’s magnetic field. For sources with a total intensity above 10 mJy the mean fractional polarization value was 5% with some correlation between fractional polarization and redshift. We also provided an estimate for the limit on the fractional polarization level for sources with a total intensity below 1 mJy.

Keywords: polarization — extragalactic survey

1. INTRODUCTION

1.1. Polarization

Natural light is often non polarized. It is once the light goes through a process such as reflection or scattering that the redirected light inhabits a specific orientation, known as polarization. There are two types of polarization: linear and circular. When light is linearly polarized, the electromagnetic wave, when viewed on a plane, appears to be moving in one direction. Circular polarization involves two waves propagating perpendicularly to one another with a 90 degree phase shift in between and from a planar view the electric vector of each wave appears to rotate in a circle. The technique to measure polarization is known as Polarimetry and it is done through the use of Stokes parameters: $I$, $U$, $Q$, and $V$. $I$ represents the total intensity, while $V$ is circular polarization, and $U$ and $Q$ together are linear polarization. Equation 1 expresses a relationship between the Stokes parameters, which supports the realistic notion that light is never 100% polarized.

\[ I^2 \geq U^2 + Q^2 + V^2 \] (1)

Synchrotron emission, produced by relativistic electrons in magnetic fields and the main source of radio emission from Active Galactic Nuclei (AGN) and star-forming galaxies, is a natural source of linearly polarized light. The polarization arises from the relativistic beaming of emission as the electron orbits magnetic field lines. This paper will discuss two properties: fractional polarization and polarization angles. The former is simply the percentage of the total intensity that is polarized. As for the latter, when light passes through a magnetized plasma, its axis changes by an angle that is proportional to the rotation measure ($RM$) through the plasma and the wavelength squared. This is referred to as Faraday Rotation. The $RM$ is specific to every magnetic field and it can be determined from looking at the polarization angle of a source along many wavelengths.

1.2. The Wide Chandra Deep Field South

Medium-depth surveys over $\sim 10 \text{deg}^2$ fields provide a useful insight into the high redshift universe, whilst at the same time spanning a range of environments from isolated galaxies to moderately-rich clusters (Krefting et al. 2020). The Legacy Survey of Space and Time (LSST) has pre-defined four such fields as “Deep drilling fields” (DDFs) which will be repeated with a shorter cadence than the main survey, and will result in a deeper co-added dataset to $r \approx 27$. The radio data in these fields will mostly be contributed at $\approx 1 \text{GHz}$ by the MeerKAT MIGHTEE survey (Heywood et al. 2022) and the ASKAP EMU survey (Norris et al. 2021), but only EMU will cover the full LSST fields of view.
At 3 GHz a MeerKAT survey is planned, but only over the central regions (Jarvis et al. 2016). This motivated us to image the entire 10 deg$^2$ of one of the DDFs, namely that in the Wide-Chandra Deep Field South (W-CDFS), with the Karl G. Jansky Very Large Array (VLA) in S-band at 2-4 GHz as the beginning of a campaign to image the full extent of all the DDFs in S-band. In particular, we were interested in polarization properties, which have to date not been investigated for large numbers of faint, high redshift radio sources at frequencies above 2 GHz. This survey also provides validation data for the VLA Sky Survey (Lacy et al. 2020).

2. METHODS

2.1. Observations

The 10 deg$^2$ of the LSST DDF in CDFS were observed on the VLA in C-configuration in S-band (2–4 GHz) as program 21A-017 between 2021-07-24 and 2021-09-09. The observations were split into 13 scheduling blocks each of duration $\approx 2$hr that each observed a strip $\approx 200$-arcmin in R.A. by 15-arcmin in Declination. The observations were made on a grid of 513 pointings (two pointings [03:29:12.7 -26:41:21 and 03:36:00.8 -26:41:21] accidentally had their coordinates missed in one of the scheduling blocks and the subsequent pointings duplicated, resulting in a small area of uneven coverage). The program was observed in filler time, with an intended coverage of three executions, however, the program was not completed, so only one complete coverage was obtained. Each field was observed for approximately 110s. The phase calibrator was J0402-3147. Flux density and bandpass calibration was performed using 3C 138 (J0521+1638) and the very low polarization object 3C 84 (J0319+4130) was used as the polarization leakage calibrator.

2.2. Calibrating and Imaging the data

Flux density, amplitude and phase calibration were performed by the VLA pipeline version 2020.0.36 running under CASA version 6.1.2.7. The pipeline does not yet perform polarization calibration, so this was carried out using the procedure outlined in the polarization calibration CASA guide. Cross-hand delays were solved per spectral window ("single-band" delays), the leakage terms then derived assuming 3C 84 is unpolarized ("Df" mode) and the $R - L$ phase calibrated using 3C 138. Imaging was performed in CASA version 6.4.4.31. Each execution block was first imaged individually using uniform weighting, cleaned to 2mJy using a mask derived from the VLASS survey data and self-calibrated with a single iteration in phase only and a solution interval of 1020s (the time interval between observations of the phase calibrators). The final imaging was then carried out on the combined set of 13 execution blocks. The final Stokes $I$ multifrequency synthesis mosaic image was made with three Taylor terms and Briggs weighting with a robust=0.5. For speed, we used the mosaic gridder and cleaned down to 0.5 mJy. The RMS in source-free regions of the final image is $\approx 50$ $\mu$Jy. For the polarization images, we divided the 2 GHz bandwidth into four equal channels, imaging in Stokes $IQUV$ using a Högbom clean. The noise on each channel is $\approx 100$ $\mu$Jy. In total there were 1924 sources detected in the Stokes $I$ image.

2.3. Obtaining and Graphing Linear Polarization Counts

Since our sample consists of only extragalactic sources, we focused on linear polarized properties as extragalactic radio sources have very low (<1%) circular polarization. Through the `immath` command in CASA version 6.5.0.15, the linear polarization intensity was obtained for each channel and then averaged together to create one polarized image. The PYBDSF script (Mohan & Rafferty 2015) detected 276 polarized sources in the polarized image, providing information on their total polarized flux values and positions. To gain a better understanding of the sample’s flux range, the data was grouped into bins with a logarithmic scaling in TOPCAT (Taylor 2011).

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2. https://science.nrao.edu/facilities/vla/docs/manuals/obsguide/modes/pol#section-4
To display the information, a python script was written to plot both the total intensity and the linear polarization source counts. As a guide we used Hales et al. (2014), which focused on the polarization properties of radio sources at 1.4 GHz. It’s sample was observed at the same depth and includes roughly the same number of sources as ours, covering the CDFS as well. There were some expected differences between our results and theirs as our observation was done at a higher frequency, causing more depolarization from Faraday Rotation. Additionally, a few sources were excluded due to the dispersion of source counts throughout the bins.

Figure 1. Plotted is the flux density of the linear polarization and the total intensity. Additionally we plot a line that represents the convolution of the total intensity curve at 1.4 GHz from Hales et al. (2014) with a fractional polarization distribution as described in that paper.

2.4. Polarization of the Brightest Sources in the Sample

To analyze the polarization properties, a focus was put on the sources with a total intensity greater than 10 mJy because of their good signal to noise ratio. These are all active galactic nuclei and 109 sources in our sample fit the requirement.

2.4.1. Polarization Angles

The polarization angels were acquired through extracting Stokes Q and U values from their respective cubes and using Equation 2 to obtain the position angle of the polarization, \(\chi\),in units of degrees. This was done in python, where the Astropy package was beneficial in gaining access to the cube data.

\[
\chi = \frac{1}{2} \arctan\left(\frac{U}{Q}\right) \times \frac{180}{\pi}
\]  

(2)

For 37 of the sources, the plot of \(\chi\) versus \(\lambda^2\) did not show a simple linear trend. In most cases this was traced to low signal-to-noise resulting in noisy estimates of \(\chi\) in each channel, but in some cases the rotation measure was high and the solution for \(\chi\) changed domains in the \(Q, U\) plane. An adjustment of 180 degrees was applied to some channels of the latter group, resolving the wrapping problem. For non-wrapped sources, their change in angles as wavelength increased was calculated in order to estimate the Rotation Measure (RM), given by \(RM = (\chi - \chi_0)/\lambda^2\), where \(\chi_0\) is the original polarization position angle in the absence of Faraday Rotation. These results were plotted two different ways. The first being according to their positions as in Figure 2 and then as a histogram in Figure 3, where the peak number of sources around 35 - 40 degrees is from Faraday Rotation caused by the magnetic field of the Milky Way.
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Figure 2. The rotation measure of the brightest sources. The negative values are due to the line-of-sight magnetic field being in the opposite direction.

Figure 3. The distribution of rotation measure for the brightest sources

2.4.2. Fractional Polarization

The $Q$ and $U$ cube data was used again, but this time to calculate the fractional polarization. For each of the four channels a polarization intensity image was calculated, then the four polarization images were averaged to obtain a mean polarization image. For each of the bright sources, the fractional polarization was then calculated using Equation 3. The mean value was about 5% for this subgroup, which is close to the 4% median value from Hales et al. (2014). Using the fractional polarization we can infer if the sources experienced depolarization which could be a result of Faraday Rotation occurring within the synchrotron-emitting region, averaging of spatially-varying polarization within the VLA beam, and/or significant Faraday rotation within a channel width.

$$f = \frac{P}{I} = \frac{\sqrt{Q^2 + U^2}}{I} \tag{3}$$

To take this a step further, we compared the fractional polarization values to the redshifts of the corresponding host galaxies. There were 28 matches found in the optical/infrared catalog of Nyland et al. 2022 (in preparation), using a 2 arcsec match radius. Our prediction was that as the redshift value increase the fractional polarization would decrease primarily due to denser local environments around radio sources. Based on Figure 4 it appears as if this prediction holds some truth as a slight descending slope is depicted and there was 20% chance that the slope was non-zero. If our sample was larger, this correlation may be more significant.
Another subset of sources we looked at were those with a total intensity below 1 mJy, which would put the sources’ flux output just above the noise level. At these flux densities, the population becomes dominated by starburst galaxies, and we might expect a difference in the polarization properties of these compared to the AGN population that dominates at high flux densities. There were 1053 sources that met this requirement. As these objects were close to the catalog limit in total intensity, we did not expect to be able to detect individual objects in polarized flux density. We then stacked the sources in order to reduce the noise and obtain a limit on the fractional polarization of these objects. This was done through taking 60 x 60 polarized sub-images centered around each source and stacking them to create mean and median polarization images. The process was then repeated for a central position shifted 20 pixels from the source. The difference between the shifted and non-shifted mean and median images was taken to calculate the limit of fractional polarization and the fractional polarization values for the faint sample. The limit was found from taking the standard deviation of the difference image and substituting into Equation 4. As for the actual fractional polarization value, it was calculated using the max of the difference image as P in Equation 3. The fractional polarization median value and the median limit both came out to be about 1%, but the mean values had a greater difference with the limit being about 2% and the fractional polarization value being 0.6%. To check for any bias, we repeated the process with the bright sources, obtaining a fractional polarization value of about 5% which aligns with what was calculated previously.
\[ \text{limit} = \sigma_\text{I} \times 3 > f \quad (4) \]

Figure 6. The difference polarized images for the faint sources.

Figure 7. The difference polarized images for the bright sources.

3. CONCLUSION

In this paper, we provided our results on the linear polarization properties of sources in the W-CDFS observed from 2 - 4 GHz. Out of the 1924 sources in our initial sample, 276 of them had linearly polarization detections. We find that the polarized source counts at 3 GHz are in-line with those expected from the 1.4 GHz study of Hales et al. (2014), consistent with a similar mean polarization \( \approx 5\% \). We also compared the polarization properties of bright and faint sources in the sample, by breaking the sample into two sub-groups based on their flux density. The first group contained 109 sources that had a total intensity above 10 mJy. From this group it was determined that the main source of Faraday Rotation came from the Milky Way, which has a RM of about 35-40 degrees. These bright sources also had a mean 5\% fractional polarization value that when plotted against redshift, showed a slight descending slope. We predict that with a larger sample the correlation would be more significant. The other subset focused on sources with a total intensity below 1 mJy, which we expect to contain a high fraction of star-forming galaxies. The fractional polarization and its limit for this group was about 1\%. 
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**Software:** astropy (Astropy Collaboration et al. 2013, 2018),

REFERENCES


