Radio Continuum Imaging of High Redshift Radio Galaxies

C.L. Carilli$^{1,2}$, H.J.A. Röttgering$^2$, R. van Ojik$^2$, G.K. Miley$^2$

W.J.M. van Breugel$^3$

$^1$National Radio Astronomy Observatory, PO Box O, Socorro, NM 87801

$^2$Leiden Observatory, Postbus 9513, 2300 RA, Leiden, The Netherlands

$^3$Lawrence Livermore National Laboratories, L-413 PO Box 808, 7000 East Ave., Livermore, CA, 94550

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ABSTRACT

We present sensitive radio continuum images at high resolution of 37 radio galaxies at z > 2. The observations were made with the Very Large Array (VLA) at 4.7 GHz and 8.2 GHz, with typical resolutions of 0.45″ and 0.25″, respectively. Images of total and polarized intensity, and spectral index, are presented. Values for total and polarized intensity, and values of rotation measures, are tabulated for the hot spots in each source. The positions of the radio nuclei are tabulated, along with a variety of other source parameters.

Analysis of the polarization data reveals large rotation measures (RMs) towards six sources. We argue that the RMs are due to magnetized, ionized gas local to the radio sources. The magnitude of the RMs are in excess of 1000 rad m$^{-2}$ (rest frame) for these sources. Drawing an analogy to a class of lower redshift radio galaxies with extreme RMs, we speculate that these sources may be at the centers of dense, X-ray emitting cluster atmospheres.
1. Introduction

Prior to 1989 only a single radio galaxy had been identified beyond \( z = 2 \). Since then there have been over 60 galaxies identified beyond \( z = 2 \) (cf. McCarthy 1993), including eight beyond \( z = 3 \), and one beyond \( z = 4 \) (Lacy et al. 1994). Standard cosmologies dictate that the universe at \( z = 2 \) is only 20\% its present age. During this epoch the space density of luminous active galaxies was a few hundred times larger than today (Dunlop and Peacock 1990). High redshift radio galaxies are extremely luminous, and spatially extended, in many wavebands. Hence, the study of high redshift radio galaxies continues to play an important role in our understanding of the cosmic environment at large redshift.

The most effective method for finding high redshift radio galaxies is by selecting for steep spectrum radio sources with faint optical counterparts (cf. Chambers, Miley, and van Breugel 1990, Miley and Chambers 1989, McCarthy et al. 1990, Röttgering 1993, van Ojik 1995). Although such sources are targeted on the basis of their radio continuum properties, subsequent study has focused almost exclusively on optical and near-infrared observations. Radio continuum studies of these sources have remained cursory. Sensitive, high resolution, polarimetric radio imaging provides important information on these sources and their environments in many ways, including: (i) identification of the location of the active nucleus, (ii) study of the cosmological evolution of radio source structure (cf. Barthel and Miley 1988), (iii) tests of quasar-radio galaxy unification schemes as a function of redshift (cf. Antonucci 1993), (iv) searching for extreme rotation measures and ultra-steep spectrum regions (Carilli, Owen, and Harris 1994, Carilli 1995, Tribble 1993), (v) determination of the projected magnetic field morphology, and (vi) detection of radio jets, and study of correlations between jet sided-ness and depolarization, or spectral index, asymmetries (cf. Garrington et al. 1989, 1991, Laing 1988a). All of these parameters probe radio source physics, as well as the physical environments of the sources. High resolution images of a large sample of sources can also be used to search for small scale gravitational lensing events (scales \(< 0.5''\)) towards the extended structures in the radio sources - thereby constraining the space density of small galaxies \((\leq 0.1 \, L_*)\) at intermediate redshifts (Carilli et al. 1994, Carilli 1995, Kochanek and Lawrence

\footnote{We use \( q_o = 0.5, \text{ and } h \equiv H_o/(100 \, \text{km sec}^{-1} \, \text{Mpc}^{-1}). \)}
The discovery of the radio-optical ‘alignment effect’ for high redshift radio galaxies (Chambers, Miley, and van Breugel 1987, McCarthy et al. 1987), establishes a clear relationship between the radio and optical emission from such galaxies. Detailed comparative studies in the different spectral regimes are essential for understanding the various processes involved in this phenomenon. High resolution radio images provide a unique data-set for comparison with high resolution optical images in order to study the radio-optical alignment effect on sub-kpc scales (cf. Miley et al. 1992, Carilli, Owen, and Harris 1994, Best, Longair, and Röttgering 1996, Chambers et al. 1996). Such small scale alignments provide important constraints on shocks, scattering, and/or jet-induced star formation as possible causes for this enigmatic phenomenon (McCarthy 1993).

This paper presents multifrequency images of the total and polarized radio continuum emission from 37 radio galaxies at $z > 2$. Section 2 describes the sample, and section 3 describes the observations and data reduction. The images and basic source parameters are presented in Section 4. In section 5 we present preliminary physical analysis of a few basic parameters, such as core properties, and the origin of large rotation measures.

2. The Sample

The Leiden observatory has, for some years, been performing a systematic search for radio galaxies at high redshift under the direction of G. Miley (Röttgering et al. 1996, Röttgering et al. 1995, van Ojik 1995, Röttgering et al. 1994, Röttgering 1993, Chambers et al. 1990, Chambers et al. 1987, Chambers 1988, Chambers et al. 1996). One of the primary goals of this search is to increase the number of known sources at high redshift in order to study the redshift evolution of radio source properties. We have selected a sub-sample of sources from the Leiden sample of high redshift radio galaxies, supplemented with sources taken from the literature, for follow-up high resolution polarimetric imaging with the Very Large Array. The sample was originally defined as an optical magnitude limited sample for an imaging program with the Hubble Space Telescope, with the criteria of: $z \geq 2$ and optical magnitude $R \leq 23.5$.

The sources are listed in Table 1. The source name and redshift are listed in Columns 1 and 2. The
catalog in which the radio source was first identified is listed in column 3. References to these catalogs are given in the notes to the table. Columns 4, 5, 6, 7, and 8 list the source R magnitude, the maximum extent of the radio source, and integrated flux densities at 1.5 GHz, 4.7 GHz, and 8.2 GHz, respectively. Column 9 lists the reference for the optical identification and redshift determination.

The nomenclature ‘radio galaxy’ for these sources (as opposed to ‘radio quasar’) is based on the observation of relatively narrow emission lines from these sources, typically \( \approx 1000 \text{ km sec}^{-1} \), and in many cases on the fact that the optical emission is spatially extended, although this latter conclusion is unclear for some of the optically fainter sources in the sample. It should be emphasized that to date no direct evidence exists indicating that the optical continuum emission from these sources is stellar in origin.

3. Observations and Data Reduction

Observations were made using the Very Large Array (Napier, Thompson, and Elsner 1983) in its A (27 km) configuration on March 18 and 19, 1994. We employed two frequencies in the 5 GHz band of the VLA (4535 MHz and 4885 MHz), and two frequencies in the 8 GHz band (8085 MHz and 8335 MHz). Bandwidths at all frequencies were 50 MHz. Each source was observed for 20 min at 8 GHz and 10 min at 5 GHz. The theoretical noise is 25 \( \mu \text{Jy} \) at 8 GHz, and 40 \( \mu \text{Jy} \) at 5 GHz. In most cases this noise level is achieved on the final image.

All data were processed using the Astronomical Image Processing System (AIPS). Standard gain calibration was done using 3C 286, and checked with scans of 3C 48. We estimate the uncertainty in absolute fluxes to be \( \leq 2\% \). An important limitation for large angular scale sources is the lack of the shortest spacings in the data. The A array short spacing limit implies a maximum size on which we have information of about 10" at 5 GHz and 6" at 8 GHz. This limitation will have a negligible effect when considering spectra of bright, small components, such as the hot spots and cores of the radio sources, but will have a large effect when considering extended structures in big sources.

The on-axis antenna polarization response terms were determined using multiple scans of the calibrator 0746+483 over a large range in parallactic angle. Absolute linear polarization position angles
were measured using two scans of 3C 286 separated in time by 6 hours. From the difference in solutions between the two scans on 3C 286 we estimate an uncertainty in the observed position angles due to calibration (i.e. in addition to those dictated by signal-to-noise) of about 2° at all frequencies. This minimum error sets a minimum RM magnitude which can be measured between 5 GHz and 8 GHz of about 25 rad m\(^{-2}\). Below we adopt a 4σ limit to RM magnitude of 100 rad m\(^{-2}\) as a reliable RM detection.

The calibrated data were then edited and self-calibrated using standard procedures (Perley 1988) to improve image dynamic range. For the faintest sources the first self-calibration iteration at 8 GHz involved phase self-calibration using a model derived from the 5 GHz data. Natural weighting of the gridded visibilities was employed in the final imaging stage in order to maximize sensitivity. Images were deconvolved using the CLEAN algorithm as implemented in the AIPS task MX. The FWHM of the Gaussian restoring beams are listed in Table 2. Images of the three Stokes polarization parameters, I, Q, and U were synthesized, and all images were CLEANed down to the level of 2.5 times the theoretical RMS on the image.

For total intensity analysis the data from the two frequencies per band were combined, and we adopt the mean frequency in each band (8210 MHz and 4710 MHz). Spectral index images were generated by convolving the 8 GHz image with the Gaussian restoring beam of the 5 GHz image, then checking for small astrometry differences possibly introduced in the phase boot-strap procedure, or during self-calibration, by looking at the positions of the hot spots and core. Spectral index, \(\alpha\), is defined as a function of surface brightness, \(I_\nu\), at frequency, \(\nu\), as: \(I_\nu \propto \nu^\alpha\). Astrometric differences between images at the two frequencies were typically \(< 0.1''\), and always \(< 0.2''\). Spectral index values were calculated only for regions with surface brightnesses \(> 4\sigma\) at each frequency, where \(\sigma\) is the measured off-source RMS on an image.

Rotation measures were derived using position angles for the polarized intensity from three frequencies: 4535 MHz, 4885 MHZ, and 8200 MHz. Rotation measures were derived for the polarized emission from the hot spots in each lobe, as listed in Table 3, by fitting a quadratic function in wavelength to the observed position angles at the three frequencies. Fitting was done only for hot spots with polarized
intensities > 4σ. The maximum rotation measure that can be measured is set by assuming less than π/2 rad rotation between the two frequencies in the 5 GHz band, implying a limit of: \( \text{RM} < 5200 \text{ rad m}^{-2} \). The RM values quoted in Table 3 were derived using the observed frequencies. If the Faraday ‘screens’ are local to the source, then a factor of \((1+z)^2\) is required in the calculation of RM. We return to this point in Section 5.

4. Images and Observed Parameters

Images of total intensity at 4.7 GHz and 8.2 GHz are shown in Figure 1, along with images of spectral index between 4.7 GHz and 8.2 GHz. Also shown are images of polarized intensity at 5 GHz, along with position angles for the electric field vectors of the polarized emission.

The sources have been observed in either J2000 or B1950 coordinates, as dictated by the original identification work. We have chosen to preserve the position equinox from the original identification work in our current observations in order to facilitate comparison between these images and existing data at other bands. The position equinox is noted on each image.

One important question that can be addressed with these data are the positions of the active nuclei. We identify the nuclei as unresolved components located between the outer-most components, and having spectral indices which are as flat as, or flatter than, any other source component. In Table 2 we list the position of the nucleus in each source in which a nucleus was detected. Column 1 lists the source name, and column two lists the nuclear position. Again, we have preserved positional equinox from the original optical identification work for ease of comparison with previous work at optical and other wavebands. The equinox of the position is indicated in each case. Columns 3 and 4 list the flux densities of the nuclei at 8.2 GHz and the spectral index between 4.7 and 8.2 GHz, respectively. Column 5 lists the core fraction, as defined by the ratio of the core flux density to the total flux density at a rest frame frequency of 20 GHz, as derived by extrapolating the integrated source spectrum and the core spectrum to a rest frame frequency of 20 GHz for each source. In many cases the nuclear identification is clear. In some cases there is no nucleus detected, or the detection is unclear. In particular, there are a number of sources which show central unresolved components which have steep spectra (spectral indices ≤ -1), and/or two
compact central components with comparable spectral indices. In these cases a ‘U’ is placed before the core flux in Table 2 to denote uncertainty in identification.

Source parameters pertaining principally to the hot spots in each source are listed in Table 3. The table is organized such that parameters for the southern-most hot spot in each source are in columns 2 - 5, while those for the northern-most hot spot are in columns 6 - 10. Columns 2 - 5 give the southern hot spot peak surface brightness at 4.7 GHz, the spectral index between 4.7 GHz and 8.2 GHz, the hot spot fractional polarization at 4.7 GHz and 8.2 GHz (matched resolutions), and the observed rotation measure at the hot spot position, respectively. Columns 6 - 10 give the corresponding numbers for the northern hot spots.

5. Analysis

5.1 Morphological Classifications, Hot Spots, and Cores

We should emphasize that the observations presented herein are at a high frequency when redshifted into the rest frame of the sources (15 GHz to 30 GHz), and at high spatial resolution. Hence these data are well suited for studying the higher surface brightness, flatter spectrum regions of the sources, such as hot spots and cores, but less so for studying the extended structures in the sources, i.e. the radio lobes.

Most of the sources in the sample have typical edge-brightened ‘Fanaroff-Riley Class II’ morphologies (Fanaroff and Riley 1974), either having obvious hot spots at the extremities of the radio source, or appearing as simple doubles. About 57% of the sources show multiple hot spots on at least one side. Of the multiple hot spot sources, about half the sources show double hot spots (0140-257, 0406-244, 0508+606, 0748+134, 1232+397, 1545-234, 1744+183, 1901+480, 2025-218, 2105+236, 2139-292, 2202+128), while in the others the hot spot regions are more complex (0015-229, 0156-252, 0448+091, 0828+193, 1113-178, 1138-262, 1410-001, 1436+157, 1809+407). The parameters listed in Table 3 pertain to the brightest hot spot in each lobe for each source. Multiple hot spots are a common phenomenon in FRII sources (cf. Laing 1988b, Black et al 1992). A likely physical interpretation of multiple radio hot spots is that the jet has changed direction by a small amount on a timescale << the source lifetime, either due to a change in the ejection axis from the central engine, or from a jet-cloud interaction along the course of the jet.
Making the standard minimum energy assumptions (Miley 1980) we derive typical minimum pressures in the hot spots in these high redshift sources ranging from $1.0 \times 10^{-9}$ dyne cm$^{-2}$ to $10.0 \times 10^{-9}$ dyne cm$^{-2}$, with corresponding magnetic fields ranging from 200 $\mu$G to 600 $\mu$G. For comparison, the magnetic fields in the hot spots of the closest ultra-luminous radio galaxy Cygnus A (3C 405) are about 200 $\mu$G, as determined using both the minimum energy assumption, and through observation of synchrotron self-Compton X-ray emission from the hot spots (Harris, Carilli, and Perley 1994).

Five of the sources are small (14% of the full sample), and can be considered compact steep spectrum (CSS) sources with sizes $\leq 10$ h$^{-1}$ kpc (cf. Fanti et al. 1990, O’dea et al. 1992). Of the five CSS sources, three appear as small FRII’s (1345+245, 1324-262, and 0744+464), one is unresolved (0030-219), and the fifth is a core dominated source with very bent, stubby ‘arms’ (2251-089). For comparison, the sample of steep spectrum radio loud quasars at $z \geq 1.5$ observed by Lonsdale, Barthel, and Miley (1993) showed a larger fraction (27%) of CSS sources.

The most unusual looking sources in the sample are 0015-229 and 1138-262. These sources appear as a string of knots, or `Beads-on-a-String’. In both cases the spectral index distribution does not conform to the standard FRII character of having the flattest spectrum regions (besides the nucleus itself) associated with the hot spots at the lobe extremities. The spectra of the knots in these sources steepen with distance from the center. These sources might be ‘frustrated jets’ propagating through a dense, clumpy medium. Such a model has been hypothesized for some CSS sources (see Fanti et al. 1990). The important difference for 1138-262 and 0015-229 is that the dense medium must exist on a scale of 60 h$^{-1}$ kpc, about an order of magnitude larger than for CSS sources. In the case of 1138-262 a possible indication of a dense environment is the extreme rotation measure values observed. This source has the largest RM in the sample ($46250$ rad m$^{-2}$ in the rest frame). Detailed investigation of 1138-262, including deep optical broad and narrow band imaging and spectroscopy, is in progress (Pentericci et al in preparation).

Most of the sources have radio core identifications (Table 2). The median core-fraction for these sources at a rest frame frequency of 20 GHz is 2%. For comparison, the two most luminous radio galaxies
below $z \leq 0.5$ are Cygnus A (3C 405) and 3C 295. These two sources have total radio luminosities similar to the high redshift sources published herein. For these two sources the core fractions at a rest frame frequency of 20 GHz are: 1.5% and 0.5%, respectively (Carilli et al. 1991, Perley and Taylor 1991).

About one third of the nuclei listed in Table 2 have a spectral index $\leq -1$. Lonsdale, Barthel, and Miley (1993) also found that many of the high redshift quasars in their study have steep spectrum cores, although the fraction of sources with steep spectrum cores in their sample is not discussed. Lonsdale et al. (1993) and Ramana et al. (1996) present a model for steep spectrum cores in high redshift radio sources which is based on the substantial radio K-corrections involved: observations at 5 GHz and 8 GHz are sampling the core spectra at rest frame frequencies of 20 GHz to 30 GHz. They propose that the dominant component in the core-jet may not be synchrotron self-absorbed at these high frequencies, thereby setting a lower limit of about 1 mas to the typical size of the dominant core component. This model can be tested by multifrequency VLBI imaging of these sources.

5.2 Rotation Measures

An important parameter from this study is that of the rotation measure of the polarized emission from the radio source. Extensive observation of lower redshift radio galaxies has shown a correlation between large rotation measures and cluster environment: all sources located at the centers of dense, X-ray emitting cluster atmospheres show large amounts of Faraday rotation (Taylor, Barton, and Ge 1994). Indeed, Taylor et al. find a clear correlation between cluster core thermal electron density derived from X-ray observations, and magnitude of Faraday rotation derived from radio observations. An important point is that this correlation is independent of radio source luminosity and morphological class, and hence is a probe of cluster properties, and not radio source properties. The implication is that the hot cluster gas must be substantially magnetized, with field strengths of order a few $\mu$G.

An important question to address for the sources in the current study is whether the observed rotation measures are Galactic in origin, or are caused by a magneto-ionic medium local to the source itself (cf. Pedelty et al. 1989). Besides the obviously different physical conclusions that would be reached in the two cases, there is the additional factor of $(1+z)^2$ which must be included in determining the
RM magnitude in the case of a screen local to the source. We believe that for most sources with detected rotation measures the Faraday ‘screen’ local to the source, for the following reasons. First and foremost, for most sources with detected rotation measures we find significant changes in the RM values for hot spots separated by typically $\leq 10''$. Changes larger than $100 \text{ rad m}^{-2}$ on scales less than a few arcseconds are observed. Such large gradients on small scales are difficult to model via a Galactic screen (Leahy 1987). Second, the data presented herein are only sensitive to fairly large observed-frame rotation measures ($100 \text{ rad m}^{-2}$), which in themselves are atypical of all but very low latitude Galactic lines-of-sight (Simard-Normandin, Kronberg, and Button 1981). And third, there are a number of sources which show significant depolarization between 8.2 GHz and 4.7 GHz at matched resolutions, indicative of local gradients in Faraday rotation across the sources.

Are high rotation measures common in high redshift radio sources? To be more secure in the detection of large intrinsic RMs, we adopt the strict standards of: polarized intensity $\geq 5\sigma$ and fractional polarization $\geq 1.5\%$ at all frequencies, and an observed RM lower limit of $100 \text{ rad m}^{-2}$. Of the 37 sources in the sample, 6 meet these criteria: 0406-244, 1138-262, 1324-262, 1436+157, 1809+407, 2105+236, and 2202+128. Hence, the implied rest-frame rotation measures are $\geq 1000 \text{ rad m}^{-2}$ for 19% of the sources.

We consider this a lower limit to the fraction of large RM sources in the sample for the following reasons. First, for the sources with no polarized emission, it is possible that the lack of polarized emission is due to depolarization by gradients in a Faraday screen, and hence that RM values are in fact very large. And second, for sources with polarized flux and low observed RM values it could be that the high surface brightness regions studied herein do not sample the large RM regions.

Overall, we can only set a lower limit of about 19% to the fraction of sources with intrinsic rotation measures $\geq 1000 \text{ rad m}^{-2}$ in the sample. Drawing the analogy to lower redshift sources with extreme RMs, the simplest interpretation is that the large RMs in the high redshift sources result from a dense, ‘cooling-flow’ cluster-type environment for the sources. Of course, we cannot rule-out the possibility that the large RMs are produced by different physical phenomena for the high redshift sources than the low redshift sources. An important observations would be to obtain deep X-ray images of the extreme RM
radio galaxies at high redshift to search for the (hypothetical) cluster thermal emission. Such observations are at the limit of current instrumentation (cf. Crawford and Fabian 1993, Worrall et al. 1994). Such observations would be particularly significant in the light of recent debate over the redshift evolution of the luminosity function for X-ray clusters (cf. Edge et al. 1990, Gioia et al. 1990, Luppino and Gioia 1995, Ebeling et al. 1995), and could also test the hypothesis that cooling flow cluster atmospheres play a fundamental role in the formation of giant elliptical galaxies at high redshift (Nulsen and Fabian 1995).

A interesting alternative is to hypothesize that in some cases the large RM screens are neither Galactic nor associated with the source, but cosmologically intervening material (Wolfe, Lanzetta, and Oren 1992, Oren and Wolfe 1995). A possible test of this idea would be to search for faint, gas rich objects in the vicinity of the radio galaxy that have substantially lower redshifts than the radio galaxy.

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FIGURE CAPTIONS

Figures 1 to 39: Images of total and polarized intensity for the sample of high redshift radio galaxies in Table 1. For each source there is one page of four images: total intensity at 4.7 GHz (upper left) and 8.2 GHz (upper right) at full resolution, plus spectral index between these two frequencies at the resolution of the 4.7 GHz image (lower right) and polarized intensity at 4.7 GHz (lower left). The intensity contour levels are a geometric progression in $2^{1/2}$, which implies a factor 2 change in surface brightness every two contours (negative contours included). The surface brightness of the first contour level is indicated in the caption to each image, as are values for the FWHM of the Gaussian restoring beams. In all cases the major axis of the restoring beam is oriented north-south. The peak surface brightness in each image is also given in the caption. The polarized intensity images also show line-segments indicating the observed position angles for the electric field vectors. The contour levels for the spectral index images are: -3.0, -2.8, -2.6, -2.4, -2.2, -2.0, -1.8, -1.6, -1.4, -1.2, -1.0, -0.8, -0.6, -0.4, -0.2, and 0. The spectral index greyscale ranges from -3 to 0.

Figure 1: Radio images of 0015-229. At 4710 MHz the FWHM of the restoring beam is $0.85'' \times 0.44''$, while at 8210 MHz the beam is $0.47'' \times 0.26''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 17.9 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 1.07 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 7.83 mJy beam$^{-1}$.

Figure 2: Radio images of 0030-219. At 4710 MHz the FWHM of the restoring beam is $0.84'' \times 0.44''$, while at 8210 MHz the beam is $0.50'' \times 0.26''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 80.7 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 0.21 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 41.7 mJy beam$^{-1}$.
Figure 3: Radio images of 0140-257. At 4710 MHz the FWHM of the restoring beam is $0.88'' \times 0.44''$, while at 8210 MHz the beam is $0.48'' \times 0.27''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 24.7 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 1.36 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 10.9 mJy beam$^{-1}$.

Figure 4: Radio images of 0156-252. At 4710 MHz the FWHM of the restoring beam is $0.90'' \times 0.44''$, while at 8210 MHz the beam is $0.49'' \times 0.25''$. At 4710 MHz the first contour level in the total intensity image is 0.175 mJy beam$^{-1}$ and the peak surface brightness is 59.5 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 3.70 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 25.5 mJy beam$^{-1}$.

Figure 5: Radio images of 0200+015. At 4710 MHz the FWHM of the restoring beam is $0.54'' \times 0.45''$, while at 8210 MHz the beam is $0.31'' \times 0.25''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 21.4 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 4.04 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 7.0 mJy beam$^{-1}$.

Figure 6: Radio images of 0211-122. At 4710 MHz the FWHM of the restoring beam is $0.68'' \times 0.44''$, while at 8210 MHz the beam is $0.39'' \times 0.26''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 18.8 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 2.28 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 7.7 mJy beam$^{-1}$.  

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Figure 7: Radio images of 0214+183. At 4710 MHz the FWHM of the restoring beam is $0.48'' \times 0.46''$, while at 8210 MHz the beam is $0.28'' \times 0.26''$. At 4710 MHz the first contour level in the total intensity image is 0.150 mJy beam$^{-1}$ and the peak surface brightness is 58.4 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 4.99 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.090 mJy beam$^{-1}$ and the peak surface brightness is 25.7 mJy beam$^{-1}$.

Figure 8: Radio images of 0316-257. At 4710 MHz the FWHM of the restoring beam is $0.90'' \times 0.44''$, while at 8210 MHz the beam is $0.48'' \times 0.25''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 53.7 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 0.65 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 20.9 mJy beam$^{-1}$.

Figure 9: Radio images of 0406-244. At 4710 MHz the FWHM of the restoring beam is $0.87'' \times 0.44''$, while at 8210 MHz the beam is $0.51'' \times 0.25''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 55.2 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 4.05 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 22.7 mJy beam$^{-1}$.

Figure 10: Radio images of 0417-181. At 4710 MHz the FWHM of the restoring beam is $0.72'' \times 0.44''$, while at 8210 MHz the beam is $0.42'' \times 0.25''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 46.5 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 0.38 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 24.5 mJy beam$^{-1}$. 
Figure 11: Radio images of 0448+091. At 4710 MHz the FWHM of the restoring beam is 0.51" ×0.45", while at 8210 MHz the beam is 0.30" ×0.29". At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam\(^{-1}\) and the peak surface brightness is 3.62 mJy beam\(^{-1}\). The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam\(^{-1}\) and 0.29 mJy beam\(^{-1}\). At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam\(^{-1}\) and the peak surface brightness is 0.94 mJy beam\(^{-1}\).

Figure 12: Radio images of 0508+606. At 4710 MHz the FWHM of the restoring beam is 0.48" ×0.44", while at 8210 MHz the beam is 0.29" ×0.26". At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam\(^{-1}\) and the peak surface brightness is 12.5 mJy beam\(^{-1}\). The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam\(^{-1}\) and 0.86 mJy beam\(^{-1}\). At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam\(^{-1}\) and the peak surface brightness is 4.5 mJy beam\(^{-1}\).

Figure 13: Radio images of 0731+438. At 4710 MHz the FWHM of the restoring beam is 0.46" ×0.43", while at 8210 MHz the beam is 0.28" ×0.25". At 4710 MHz the first contour level in the total intensity image is 0.150 mJy beam\(^{-1}\) and the peak surface brightness is 62.9 mJy beam\(^{-1}\). The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam\(^{-1}\) and 3.62 mJy beam\(^{-1}\). At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam\(^{-1}\) and the peak surface brightness is 25.7 mJy beam\(^{-1}\).

Figure 14: Radio images of 0744+464. At 4710 MHz the FWHM of the restoring beam is 0.49" ×0.44", while at 8210 MHz the beam is 0.28" ×0.25". At 4710 MHz the first contour level in the total intensity image is 0.150 mJy beam\(^{-1}\) and the peak surface brightness is 120.0 mJy beam\(^{-1}\). The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam\(^{-1}\) and 1.26 mJy beam\(^{-1}\). At 8210 MHz the first contour level in the total intensity image is 0.100 mJy beam\(^{-1}\) and the peak surface brightness is 58.0 mJy beam\(^{-1}\).
Figure 15: Radio images of 0748+134. At 4710 MHz the FWHM of the restoring beam is 0.51'' × 0.45'', while at 8210 MHz the beam is 0.29'' × 0.25''. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam⁻¹ and the peak surface brightness is 3.15 mJy beam⁻¹. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam⁻¹ and 0.52 mJy beam⁻¹. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam⁻¹ and the peak surface brightness is 0.99 mJy beam⁻¹.

Figure 16: Radio images of 0828+193. At 4710 MHz the FWHM of the restoring beam is 0.51'' × 0.46'', while at 8210 MHz the beam is 0.28'' × 0.25''. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam⁻¹ and the peak surface brightness is 6.22 mJy beam⁻¹. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam⁻¹ and 0.46 mJy beam⁻¹. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam⁻¹ and the peak surface brightness is 2.56 mJy beam⁻¹.

Figure 17: Radio images of 0943-242. At 4710 MHz the FWHM of the restoring beam is 0.90'' × 0.44'', while at 8210 MHz the beam is 0.52'' × 0.25''. At 4710 MHz the first contour level in the total intensity image is 0.150 mJy beam⁻¹ and the peak surface brightness is 40.3 mJy beam⁻¹. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam⁻¹ and 0.27 mJy beam⁻¹. At 8210 MHz the first contour level in the total intensity image is 0.090 mJy beam⁻¹ and the peak surface brightness is 13.5 mJy beam⁻¹.

Figure 18: Radio images of 1106-258. At 4710 MHz the FWHM of the restoring beam is 0.77'' × 0.44'', while at 8210 MHz the beam is 0.42'' × 0.26''. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam⁻¹ and the peak surface brightness is 28.9 mJy beam⁻¹. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam⁻¹ and 2.02 mJy beam⁻¹. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam⁻¹ and the peak surface brightness is 11.9 mJy beam⁻¹.

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Figure 19: Radio images of 1113-178. At 4710 MHz the FWHM of the restoring beam is $0.77'' \times 0.44''$, while at 8210 MHz the beam is $0.42'' \times 0.26''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 20.3 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 3.14 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 6.45 mJy beam$^{-1}$.

Figure 20: Radio images of 1138-262. At 4710 MHz the FWHM of the restoring beam is $0.96'' \times 0.44''$, while at 8210 MHz the beam is $0.54'' \times 0.25''$. At 4710 MHz the first contour level in the total intensity image is 0.150 mJy beam$^{-1}$ and the peak surface brightness is 32.2 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 1.38 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.090 mJy beam$^{-1}$ and the peak surface brightness is 7.39 mJy beam$^{-1}$.

Figure 21: Radio images of 1232+397. At 4710 MHz the FWHM of the restoring beam is $0.48'' \times 0.44''$, while at 8210 MHz the beam is $0.28'' \times 0.25''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 12.7 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 1.86 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 4.7 mJy beam$^{-1}$.

Figure 22: Radio images of 1324-262. At 4710 MHz the FWHM of the restoring beam is $0.80'' \times 0.44''$, while at 8210 MHz the beam is $0.49'' \times 0.25''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 54.1 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 4.46 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 25.2 mJy beam$^{-1}$.
Figure 23: Radio images of 1345+245. At 4710 MHz the FWHM of the restoring beam is $0.50'' \times 0.49''$, while at 8210 MHz the beam is $0.27'' \times 0.27''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 71.1 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 4.11 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 29.6 mJy beam$^{-1}$.

Figure 24: Radio images of 1410-001. At 4710 MHz the FWHM of the restoring beam is $0.56'' \times 0.45''$, while at 8210 MHz the beam is $0.33'' \times 0.25''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 16.1 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 1.60 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 6.1 mJy beam$^{-1}$.

Figure 25: An expanded view of the hot spot region in the northwest lobe of 1410-001. The upper image is at 4710 MHz and the lower image is at 8210 MHz. The beams and contour levels are the same as Figure 24.

Figure 26: Radio images of 1435+633. At 4710 MHz the FWHM of the restoring beam is $0.51'' \times 0.44''$, while at 8210 MHz the beam is $0.29'' \times 0.25''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 48.6 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 0.24 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 15.2 mJy beam$^{-1}$.

Figure 27: Radio images of 1436+157. At 4710 MHz the FWHM of the restoring beam is $0.49'' \times 0.46''$, while at 8210 MHz the beam is $0.28'' \times 0.26''$. At 4710 MHz the first contour level in the total intensity image is 0.180 mJy beam$^{-1}$ and the peak surface brightness is 22.7 mJy beam$^{-1}$. The corresponding
numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 2.17 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.100 mJy beam$^{-1}$ and the peak surface brightness is 12.0 mJy beam$^{-1}$.

Figure 28: Radio images of 1545-234. At 4710 MHz the FWHM of the restoring beam is $0.76'' \times 0.44''$, while at 8210 MHz the beam is $0.47'' \times 0.26''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 16.2 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 0.73 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 3.91 mJy beam$^{-1}$.

Figure 29: Radio images of 1744+183. At 4710 MHz the FWHM of the restoring beam is $0.49'' \times 0.44''$, while at 8210 MHz the beam is $0.28'' \times 0.25''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 161 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 16.0 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 79.1 mJy beam$^{-1}$.

Figure 30: Radio images of 1809+407. At 4710 MHz the FWHM of the restoring beam is $0.48'' \times 0.44''$, while at 8210 MHz the beam is $0.27'' \times 0.26''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 37.2 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 1.09 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 12.1 mJy beam$^{-1}$.

Figure 31: Radio images of 1931+480. At 4710 MHz the FWHM of the restoring beam is $0.49'' \times 0.44''$, while at 8210 MHz the beam is $0.28'' \times 0.26''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 43.0 mJy beam$^{-1}$. The corresponding
numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 3.03 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 14.1 mJy beam$^{-1}$.

Figure 32: Radio images of 2025-218. At 4710 MHz the FWHM of the restoring beam is $0.75'' \times 0.44''$, while at 8210 MHz the beam is $0.40'' \times 0.25''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 24.1 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 2.97 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 8.39 mJy beam$^{-1}$.

Figure 33: Radio images of 2036-254. At 4710 MHz the FWHM of the restoring beam is $0.80'' \times 0.44''$, while at 8210 MHz the beam is $0.47'' \times 0.25''$. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam$^{-1}$ and the peak surface brightness is 48.9 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 9.35 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam$^{-1}$ and the peak surface brightness is 26.0 mJy beam$^{-1}$.

Figure 34: Radio images of 2105+236. At 4710 MHz the FWHM of the restoring beam is $0.48'' \times 0.44''$, while at 8210 MHz the beam is $0.29'' \times 0.27''$. At 4710 MHz the first contour level in the total intensity image is 0.160 mJy beam$^{-1}$ and the peak surface brightness is 15.6 mJy beam$^{-1}$. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam$^{-1}$ and 1.64 mJy beam$^{-1}$. At 8210 MHz the first contour level in the total intensity image is 0.100 mJy beam$^{-1}$ and the peak surface brightness is 6.52 mJy beam$^{-1}$.

Figure 35: An expanded view of the two hot spot regions in 2105+236. The upper images are at 4710 MHz and the lower images are at 8210 MHz. The beams are the same as in Figure 34, and the first contour level is 0.180 mJy beam$^{-1}$ at 4710 MHz and 0.120 mJy beam$^{-1}$ at 8210 MHz.
Figure 36: Radio images of 2139-292. At 4710 MHz the FWHM of the restoring beam is 0.84′′ ×0.44′′, while at 8210 MHz the beam is 0.44′′ ×0.25′′. At 4710 MHz the first contour level in the total intensity image is 0.120 mJy beam⁻¹ and the peak surface brightness is 43.5 mJy beam⁻¹. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam⁻¹ and 7.19 mJy beam⁻¹. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam⁻¹ and the peak surface brightness is 16.6 mJy beam⁻¹.

Figure 37: Radio images of 2141+192. At 4710 MHz the FWHM of the restoring beam is 0.49′′ ×0.44′′, while at 8210 MHz the beam is 0.28′′ ×0.25′′. At 4710 MHz the first contour level in the total intensity image is 0.125 mJy beam⁻¹ and the peak surface brightness is 34.5 mJy beam⁻¹. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam⁻¹ and 0.21 mJy beam⁻¹. At 8210 MHz the first contour level in the total intensity image is 0.075 mJy beam⁻¹ and the peak surface brightness is 14.1 mJy beam⁻¹.

Figure 38: Radio images of 2202+128. At 4710 MHz the FWHM of the restoring beam is 0.51′′ ×0.44′′, while at 8210 MHz the beam is 0.32′′ ×0.25′′. At 4710 MHz the first contour level in the total intensity image is 0.150 mJy beam⁻¹ and the peak surface brightness is 19.1 mJy beam⁻¹. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam⁻¹ and 1.47 mJy beam⁻¹. At 8210 MHz the first contour level in the total intensity image is 0.090 mJy beam⁻¹ and the peak surface brightness is 7.47 mJy beam⁻¹.

Figure 39: Radio images of 2251-089. At 4710 MHz the FWHM of the restoring beam is 0.65′′ ×0.44′′, while at 8210 MHz the beam is 0.36′′ ×0.25′′. At 4710 MHz the first contour level in the total intensity image is 0.180 mJy beam⁻¹ and the peak surface brightness is 45.9 mJy beam⁻¹. The corresponding numbers for the 4710 MHz polarized intensity image are 0.12 mJy beam⁻¹ and 5.98 mJy beam⁻¹. At 8210 MHz the first contour level in the total intensity image is 0.090 mJy beam⁻¹ and the peak surface brightness is 20.0 mJy beam⁻¹.