AGN relics in the radio sky
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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2015

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):

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Chapter 5

Age mapping of the AGN relic
B2 0924+30: the LOFAR perspective

The first principle is that you must not fool yourself, and you are the easiest person to fool.

– Richard Feynman
Abstract

We have observed the steep spectrum radio source B2 0924+30 using the LOw Frequency ARray (LOFAR) telescope. Hosted by a $z=0.026$ elliptical galaxy, its extent of $30'$ allows us to make detailed studies of its structure and map its spectral index and age distribution.

We construct low frequency spectral index maps and use synchrotron aging models to derive source ages. We find that the derived integrated spectral index is consistent with results of earlier studies. Furthermore, our detailed spectral index mapping, while agreeing with earlier lower resolution studies, shows flattening of the spectral index towards the outer edges of the lobes. The spectral index of the lobes is $\alpha_{609} \sim -1$ and gradually steepens to $\alpha_{140} \sim -1.8$ moving towards the inner edges of the lobes.

Using radiative aging model fitting we show that the AGN activity has ceased around 100 Myr ago. We note that the inner regions of the lobes are younger (having ages around 20 Myr) which may be interpreted as signs of relic hotspots.

The spectral index properties as well as the derived ages of B2 0924+30 are consistent with it being an FRII AGN radio relic. LOFAR data are proving to be instrumental in extending our studies to the lowest radio frequencies and enabling analyses of the oldest source regions.

We also elaborate on the discovery of a double-double radio galaxy with relic outer lobes in the field (several other interesting sources), as well as the lowest frequency detection of a radio halo connected to the galaxy cluster Abell 781.

A. Shulevski, R. Morganti, P. D. Barthel et al.
to be submitted to Astronomy & Astrophysics
5.1 Introduction

Radio relics are the only observable tracer of a past accretion episode of an Active Galactic Nucleus (AGN). Once the accretion of matter onto its super massive black hole (SMBH) stops, the AGN ceases to emit jets of plasma that feed the regions around its host galaxy emitting the radio radiation. These radio relic regions then slowly fade away as time passes. Searches have uncovered relics with various spatial scales, from small \cite{Stanghellini:2005, Dwarakanath:2009} to large and in particular in galaxy clusters \cite{Murgia:2011}. However, the question remains why there are so few AGN radio relics detected (a few dozen in total) relative to the number of active radio galaxies. Further, most of the radio relics observed so far are hosted by cluster galaxies. Questions arise whether the paucity of relics (especially in the field) is due to the fact that they fade out in a short time after the AGN ceases its activity. Does the cluster environment help preserve relics by confining the radio plasma and prolonging the relic lifetimes?

Here we study the B2 0924+30 relic radio source. Its host galaxy, IC 2476, belongs to a group of 8 galaxies \cite{Jamrozy:2004} located at a redshift of $z = 0.026141$. Its Sloan Digital Sky Survey (SDSS; \cite{Aihara:2011}) spectrum does not show emission lines indicative of an optical AGN. The radio morphology (Figure 5.3) of B2 0924+30 suggests that it is an (FRII) radio relic. It has lobes reminiscent of those of active FRII radio galaxies which have maximum brightness regions at positions where hotspots would be located if this was an active source. It lacks a discernible radio core or jets. Spectral index studies \cite{Cordey:1987, Jamrozy:2004} show that the spectral index steepens going from the lobes to the inner regions, and the overall spectral index distribution is steeper ($\alpha \sim -1$) than what is observed in active FRII radio galaxies. All of these features point towards the conclusion that it is a radio relic of a shutdown FRII source.

Spectral index studies \cite{Cordey:1987, Jamrozy:2004} with the highest spatial resolution to date, enabling us to characterize in detail the spectral properties of the relic lobes. Also, we derive radiative ages across the source extent.

We expand on previous research efforts by extending the spectral index studies to the lowest frequencies so far, using the LOw Frequency ARray (LOFAR, \cite{vanHaarlem:2013}) with the highest spatial resolution to date, enabling us to characterize in detail the spectral properties of the relic lobes. Also, we derive radiative ages across the source extent.

The organization of this chapter is as follows. Section 5.2 describes the data used in this study and outlines the data reduction procedure. Section 5.3 outlines our results; in Section 5.3.1 we give the spectral analysis results and source ages. We discuss the implications of our study in Section 5.4.

5.2 Observations and data reduction

The target was observed with LOFAR in the night of March 13, 2014 for a total on source time with the high band antennas (HBA) of 7.5 hours. The HBA observation was done in interleaved mode, using the HBA_DUAL_INNER configuration. 3C 196 was observed as a flux calibrator source for two minutes, followed by a scan of the target of 30 minutes duration with a one minute gap between calibrator and target scans allowing for beam forming and target re-acquisition. 325 sub-bands (SBs) were recorded covering 64 MHz

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1 The adopted cosmology in this work is: $H_0 = 73 \text{ km s}^{-1} \text{Mpc}^{-1}$, $\Omega_{\text{matter}} = 0.27$, $\Omega_{\text{vacuum}} = 0.73$. At the redshift of B2 0924+30, $1'' = 0.505 \text{ kpc}$; its luminosity distance is 109.6 Mpc \cite{Wright:2006}.
Table 5.1: LOFAR HBA data properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central Frequency</td>
<td>150 MHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>64 MHz</td>
</tr>
<tr>
<td>Integration time</td>
<td>2 s</td>
</tr>
<tr>
<td>Observation duration</td>
<td>7.5 h</td>
</tr>
<tr>
<td>Polarization</td>
<td>Full Stokes</td>
</tr>
<tr>
<td>UV coverage</td>
<td>0.1kλ – 20kλ</td>
</tr>
</tbody>
</table>

of bandwidth between 116 MHz and 180 MHz. Each SB has 64 frequency channels and a bandwidth of 200 kHz. The integration time was set to 2 seconds for both calibrator and target. Four polarizations were recorded. The HBA station field of view (FoV, primary beam) covers around 5 degrees full width at half maximum (FWHM) at 140 MHz. The station beams are complex valued, time, frequency and direction dependent, and are not the same for all of the stations.

The data were pre-processed by the observatory pipeline (Heald et al. 2010) as follows. Each SB was automatically flagged for RFI using the AOFlagger (Offringa et al. 2012), and then averaged in time to 10 seconds per sample and in frequency by a factor of 16, making the frequency resolution of the output data 4 channels / SB. The calibrator data were used to derive amplitude solutions for each (NL) station using the Black Board Self calibration - BBS (Pandey et al. 2009) tool which takes into account the time and frequency varying LOFAR station beams. The flux density scale of Scaife & Heald (2012) was used in the calibration model for 3C 196 ($S_{150} = 83$ Jy).

The amplitudes of the target visibilities were corrected using the derived solutions. The target visibilities were then phase (self)calibrated incrementally, using progressively longer baselines to get to the final resolution (Vilchez et al. in preparation). The initial phase calibration model was derived from the VLSR catalog covering the FoV out to the first null of the station, containing spectral index information for each source in the model. Before initializing the calibration, we have concatenated the data into 4 MHz (20 SB) groups previously averaging each SB to 1 frequency channel to reduce the data size. We have chosen this setup to maximize the S/N while maintaining frequency dependent ionospheric phase rotation to a manageable level. We have not performed any directional solving and did not perform further corrections to mitigate ionospheric effects.

The imaging was done using the LOFAR imager (Tasse et al. 2013), which incorporates the LOFAR beam and uses the A-projection (Chandra et al. 2004) algorithm to image the entire FoV. We have used Briggs (Briggs 1995) weights with the robustness parameter set to 0, and have imaged the field selecting baselines larger than 0.1 kλ. Ten self-calibration steps were performed, each using a sky model generated in the previous cycle and each subsequent one using larger baseline lengths. Once the imaging was completed, we obtained 10 images for each averaged SB group of 4 MHz. Out of these images, we have selected two sub-groups of images, a low resolution and a high resolution one. The low resolution images were chosen such as to ensure that we have the highest sensitivity to the diffuse emission of the target comparable to the integrated flux density measured in previous studies. The higher resolution images were chosen so that we have enough sensitivity to diffuse emission while being able to resolve finer details. Both sets

2 VLSS is the VLA Low frequency Sky Survey carried out at 74 MHz (Cohen et al. 2007)
of images exclude the longest baselines which in general had poorer calibration solutions due in part to ionospheric phase errors. Finally, we have constructed our two final data sets by taking into account only the images from these two sub-groups with the lowest image noise and smallest source distortions. At the end of the selection, we were left with seven high resolution and seven low resolution LOFAR images.

Table 5.2: Image properties

<table>
<thead>
<tr>
<th>ID</th>
<th>$\nu$ [MHz]</th>
<th>$\sigma$ (low res.</th>
<th>high res.)</th>
<th>[mJy beam$^{-1}$]</th>
<th>Beam size (low res.</th>
<th>high res.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOFAR$^a$</td>
<td>113</td>
<td>8.3</td>
<td>4.5</td>
<td>56.6$''$ × 40.9$''$</td>
<td>20.2$''$ × 14.1$''$</td>
<td></td>
</tr>
<tr>
<td>LOFAR$^a$</td>
<td>124</td>
<td>6.3</td>
<td>3.6</td>
<td>47.7$''$ × 38.1$''$</td>
<td>19.3$''$ × 15.7$''$</td>
<td></td>
</tr>
<tr>
<td>LOFAR$^a$</td>
<td>132</td>
<td>4.3</td>
<td>3.1</td>
<td>48$''$ × 35.4$''$</td>
<td>22$''$ × 16.7$''$</td>
<td></td>
</tr>
<tr>
<td>LOFAR$^a$</td>
<td>136</td>
<td>4.3</td>
<td>3</td>
<td>46.9$''$ × 34.3$''$</td>
<td>21.7$''$ × 17.1$''$</td>
<td></td>
</tr>
<tr>
<td>LOFAR$^a$</td>
<td>160</td>
<td>2.3</td>
<td>1.9</td>
<td>51.9$''$ × 37.6$''$</td>
<td>20$''$ × 17.9$''$</td>
<td></td>
</tr>
<tr>
<td>LOFAR$^a$</td>
<td>163</td>
<td>2</td>
<td>1.8</td>
<td>56.6$''$ × 38.2$''$</td>
<td>20.2$''$ × 17.8$''$</td>
<td></td>
</tr>
<tr>
<td>LOFAR$^a$</td>
<td>167</td>
<td>1.8</td>
<td>1.7</td>
<td>51.1$''$ × 37.5$''$</td>
<td>20.5$''$ × 17.5$''$</td>
<td></td>
</tr>
<tr>
<td>LOFAR$^{ae}$</td>
<td>140</td>
<td>2.5</td>
<td>1.2</td>
<td>60$''$ × 43.5$''$</td>
<td>22$''$</td>
<td></td>
</tr>
<tr>
<td>WENSS$^b$</td>
<td>325</td>
<td>3.6</td>
<td></td>
<td>54$''$ × 108$''$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WSRT$^c$</td>
<td>609</td>
<td>0.77</td>
<td></td>
<td>29$''$ × 56$''$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NVSS$^d$</td>
<td>1400</td>
<td>0.45</td>
<td></td>
<td>45$''$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ This work  
$^b$ WENSS  
$^c$ [Jamrozy et al. 2004].  
$^d$ NVSS  
$^e$ Averaged images.

We have smoothed the high and low resolution LOFAR images to an identical restoring beam size and have averaged them to obtain two final images, each having a bandwidth of 28 MHz. We have used these images for studies of the target source, as well as investigating potential undiscovered relics in the LOFAR HBA FoV. The smoothed, non-averaged, images were used in our aging analysis. Table 5.2 lists the image properties for the LOFAR image set, as well as survey (WENSS$^3$ and NVSS$^4$) images used in our subsequent analysis.

To check whether the station beam correction applied by the AW imager resulted in correct flux density scaling across the FoV, we have used PyBDSM [Ramanujam 2007] to extract sources from our averaged images and measure their flux densities. Then, we have matched the extracted sources with survey catalogs (VLSS, WENSS and NVSS using a 30$''$ match radius) and determined the catalog flux density for each source by interpolating the flux densities from the catalog entries to the LOFAR frequency. Finally, we have divided the obtained catalog flux density at 140 MHz with the measured flux density from the LOFAR image. Assuming power law spectra, the ratio should be 1 if the station beam correction produces correct fluxes over the FoV. The results are given in Figure 5.1. We can see that for both of the HBA images the points cluster around 1, which shows that the flux correction over the FoV applied by the AW imager gives  

$^3$ WENSS is the Westerbork Northern Sky Survey carried out at 325 MHz [Rengelink et al. 1997]  
$^4$ NVSS stands for the NRAO VLA Sky Survey carried out at a frequency of 1.4 GHz [Condon et al. 1998]
reasonable flux density values. The scatter is around 20%. Most of the data points belong to point sources.

![Graph](image)

**Figure 5.1:** Ratio of measured and catalog extrapolated fluxes for our high and low resolution averaged LOFAR images. The red dashed line denotes the median flux ratio, while the green dash dot lines give the 1σ limits.

### 5.3 Results

Figure 5.2 shows the averaged low resolution $5^\circ \times 5^\circ$ LOFAR image. It has a resolution of $60'' \times 43.5''$ and an r.m.s. noise level of $2.5\text{ mJy beam}^{-1}$.

Figure 5.3 shows the LOFAR view of the target in the high resolution averaged image (see Table 5.2). We can see that the extended lobes have the highest surface brightness, and that there is an enhancement of brightness at the position of the host elliptical galaxy UGC 5043 (IC 2476). There is no noticeable radio core. The source is enveloped in a low surface brightness radio cocoon. It is interesting to note that there are several localized increases in the surface brightness of the radio lobes. Two of them in the eastern lobe can be identified with background galaxies, possibly signifying that the enhancements are produced by radio emission connected to background galaxies. The highest surface brightness regions in the lobes are probably aged remnants of hotspots. There is an optical source at the highest radio surface brightness point in the western lobe, but this is probably a chance alignment. The cocoon has extensions at the lobe edges, causing the source to have an overall shape reminiscent of the letter Z. There is a bright point source off the edge of the western lobe which has been identified with a quasar (Ekers et al. 1981).

### 5.3.1 Spectral analysis

The morphology of B2 0924+30 and previous studies point to it being an AGN radio relic which is fading away after the AGN which has created it has shut down (i.e. a fader). Here, we elaborate on its spectral properties. The spectral shape encodes the
Figure 5.2: LOFAR FoV, averaged low resolution image (28 MHz bandwidth). Beam size: $60'' \times 43.5''$, $\sigma = 2.5\text{mJy beam}^{-1}$. 
activity history of a fading radio source and can be a powerful tool in understanding the exact nature of the observed radio emission.

Integrated spectrum

Jamrozy et al. (2004) have fitted a synchrotron aging model to the data collected from the literature as well as their own observations. We have repeated the fitting procedure adding integrated flux densities measured from our LOFAR maps (all except the first two of the LOFAR images listed in Table 5.2; we have discarded them due to flux scaling issues; the measurements had systematically higher values). An overview of the measurements is given in Table 5.3.

We have performed the fit using a value for the magnetic field strength derived by assuming an equipartition between the energy contained in the magnetic field and in relativistic particles according to Miley (1980). In our calculations, we have used a central frequency of 609 MHz, with a spectral index of $\alpha = -1.2$ (average over the source) and lobe extent of 4.8’. We have computed the magnetic field value for each lobe separately and then averaged the result. Our estimate gives a value of $1.35\mu G$.

A Jaffe-Perola (JP, Jaffe & Perola 1973) model was fitted to the data, assuming an instantaneous particle injection phase (which is a reasonable assumption taking into account the nature of the target), and found best fit values for the overall source age (time elapsed since the particle injection has ceased) and injection index of $t_{off} = 60\pm8$ Myr and $\alpha_{inj} = -0.92 \pm 0.06$ respectively. The $\chi^2$ value threshold for accepting the fit at a probability level of 5% was 14.1, and we had a value of $\chi^2 = 5.2$. Our best fit values are consistent with those reported by Jamrozy et al. (2004) within their error bars ($54^{+12}_{-11}$ Myr). The best fit model is shown in Figure 5.4.

We notice the overall curvature of the integrated spectrum, an indication of the nature
Table 5.3: B2 0924+30 Flux density

<table>
<thead>
<tr>
<th>$\nu$ [MHz]</th>
<th>$S_\nu$ [mJy]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>132</td>
<td>6774 ± 1356</td>
<td>This work</td>
</tr>
<tr>
<td>136</td>
<td>6738 ± 1348</td>
<td>This work</td>
</tr>
<tr>
<td>151</td>
<td>4600 ± 360</td>
<td><strong>Cordey (1987)</strong></td>
</tr>
<tr>
<td>160</td>
<td>5214 ± 1043</td>
<td>This work</td>
</tr>
<tr>
<td>163</td>
<td>4751 ± 950</td>
<td>This work</td>
</tr>
<tr>
<td>167</td>
<td>4702 ± 940</td>
<td>This work</td>
</tr>
<tr>
<td>325</td>
<td>2425 ± 124</td>
<td>This work (WENSS)</td>
</tr>
<tr>
<td>609</td>
<td>1094 ± 56</td>
<td>This work \cite{Jamrozy2004}</td>
</tr>
<tr>
<td>1400</td>
<td>420 ± 43</td>
<td>This work (NVSS)</td>
</tr>
<tr>
<td>4750</td>
<td>60 ± 7</td>
<td>\cite{Jamrozy2004}</td>
</tr>
<tr>
<td>10550</td>
<td>10 ± 4</td>
<td>\cite{Gregorini1992}</td>
</tr>
</tbody>
</table>

Figure 5.4: Best fit JP model to the integrated flux density measurements. LOFAR data are represented with red symbols.
of the target - a fader.

**Spectral and curvature maps**

To disentangle the plasma properties in the relic lobes, we have derived the highest resolution low frequency spectral index map of B2 0924+30 to date, using an average of our LOFAR observations and the 609 MHz WSRT image (kindly contributed by M. Jamrozy). The input images were matched in UV coverage and smoothed to a resolution of 60″. The spectral index map was derived by fitting a first order polynomial to the flux density values for each pixel above a 5σ level in the input images. We have also derived a spectral curvature map ($SPC = \alpha_{140}^{609} - \alpha_{609}^{140}$). The resulting maps are shown in Figure 5.5.

![Spectral index and spectral curvature maps for pixels with surface brightness greater than 5σ.](image)

**Figure 5.5:** Spectral index and spectral curvature maps for pixels with surface brightness greater than 5σ. We have used the averaged low resolution LOFAR image (Table 5.2). Overlaid are LOFAR contours with levels: $(-10, 10, 20, 30, 40, 50, 60)\cdot\sigma$, with $\sigma = 4$ mJy beam$^{-1}$. The black cross marks the position of the host galaxy.

In figure 5.5a we can see that the lobes show a relatively steep low frequency spectral index of $\alpha \sim -1$, in agreement with previous studies, and the derived injection spectral index we have obtained previously. The spectrum of the south-west lobe seems to be overall flatter compared to the north-eastern lobe ($\Delta \alpha \sim 0.1$), consistent with what was reported by Jamrozy et al. (2004).

Interestingly, this spectral index difference between the two lobes is exactly the same as the values reported by Liu & Pooley (1991); Garrington & Conway (1991); Garrington et al. (1991). They propose that in radio galaxies which have a one sided jet (possibly enhanced in brightness by doppler beaming), the jet side is closer to us than the counter-jet side and find that the counter-jet side is depolarized more w.r.t to the jet side (Laing-Garrington effect). Garrington & Conway (1991) find a correlation between the depolarization and the spectral index of the lobes; the lobe on the jet side has a flatter spectral index than the counter-jet lobe. In our case, this suggests that the south eastern lobe of B2 0924+30 is closer to us. Garrington & Conway (1991) suggest that in active sources the spectral index difference between the hotspots may be explained
by beaming effects, but that spectral index differences in the lobes are more difficult to explain. We do not observe jets in B2 0924+30, and the difference in spectral index between the lobes may be explained by different physical conditions of the lobes.

As was already mentioned, there is an alignment between the highest surface brightness region in the LOFAR image in this lobe and a background galaxy, which, if it is radio active may contribute to the surface brightness of that region of the lobe thus causing the spectral flattening.

Theoretical considerations (e.g. Komissarov & Gubanov 1994) indicate that what we observe are spectral index values typical for radio plasma not being replenished by AGN activity. Indeed, the observed low frequency spectral index is steeper than spectral indices in lobes and hotspots of active AGN, or acceleration regions (typical values are \(-0.8 < \alpha < -0.6\)); we observe at lower frequencies and expect to trace the injection spectral index. If so, we determine that the injection spectral index values are steeper than 0.8. Harwood et al. (2013) have also reported steeper injection spectral indices in lobes of active radio galaxies, in line with our observations.

Indeed, comparing our low frequency spectral index map with previous spectral index studies done at higher frequencies, we can see that LOFAR detects spectral index flattening in particular lobe regions which may signify that we detect the lowest energy particles which have energies comparable to the injection level values. This is prominent at the outer edges of the lobes.

The highest surface brightness regions are similar to hotspots which are no longer clearly outlined (since they are no longer replenished by the AGN), but we do not detect any structure in our spectral index maps which is on roughly the same spatial scale as the features in the intensity map. Consequently, we can not claim that we see spectral signatures of aged hotspots. We observe that the lobes have spectral index values of around \(-0.9\) with spectral flattening on the outermost lobe edges, especially the north-eastern lobe. The spectral index steepens as we approach the host galaxy, consistent with what is typical of FRII sources.

In line with our previous discussion, the curvature map shown in Figure 5.5b is also very interesting. We observe a lot more structure in the relic lobes, with some areas showing large curvature up to \(SPC = 1\). This suggests that different regions have spectral breaks at different frequencies, indicating different radiative ages.

Taken together, the spectral index map and the spectral curvature map of the relic core region suggest that it is the oldest part of the source. Its spectrum is the steepest at low frequencies and it steepens even more at higher frequencies. The appearance of the core regions with their steepest spectral index further support the claim that we are seeing a fading FRII source.

Radiative ages

To gain a better insight into the history of the radio source over its extent, we have taken five of our lower resolution LOFAR images (listed in Table 5.3) together with the 609 MHz WSRT image and an NVSS map and fitted a JP synchrotron aging model to the flux densities for measurement regions spanning the source. The JP model was chosen since B2 0924+30 is a relic source, with no signs of ongoing activity, thus a model with an infinitesimal duration of the injection phase of activity is more suitable. The injection index was not fitted for; its value was fixed to the one found during the integrated
chapter 5: Age mapping of the AGN relic B2 0924+30 using LOFAR spectrum modeling in Section 5.4.

The results of the age analysis are shown in Figure 5.6. We note that the derived ages for the core and lobes follow a pattern which is in line with a fading FRII radio galaxy. The youngest ages (of around 20 Myr) are found towards the outer edges of the lobes, and the oldest are the regions towards the host galaxy. We have more limited spectral coverage (up to around 1400 MHz) than the integrated spectral index fit which we have presented earlier, but even so, the overall ages tend to average around the value arrived at during the integrated spectrum model fitting.

Our resulting ages show that (as expected) the age derived from a model fit to an integrated spectrum is only the average. Age mapping gives us more information; for example, we can see that the latest particle acceleration in the lobes ceased around 20 Myr ago, and that the AGN activity stopped at least 100 Myr before that (looking at the core regions). The ages derived for the core regions of B2 0924+30 are comparable to the oldest sources in e.g. the sample of Murgia et al. (2011).

Spectral shifts

Katz-Stone et al. (1993) have outlined a powerful tool for determining the energetic conditions in radio galaxies. A data set of imaging spread over at least three frequencies is needed to construct a "color-color" diagram of regions of interest.

Shifting the measured flux densities for each source region in the $\log(S) - \log(\nu)$ plane, we scale the spectrum of each region to a common break frequency. The amount of shift needed in the flux-frequency plane and the correlation between these shifts can point to the injection spectral index and give us a hint about the dominant energy loss mechanism. The technique has been implemented in a number of cases (van Weeren et al. 2012a, also see Chapter 4 of this thesis).

We have plotted our measurement regions in a color-color diagram and derived the corresponding shift diagrams for B2 0924+30. The results are given in Figure 5.7.
5.4: Discussion

B2 0924+30 is an AGN radio relic, a leftover from the time when it was an active FRII radio galaxy. The relic radio lobes are very well outlined, which might may indicate confinement by the IGM (which is unusual, since it is not located in a dense environment). The lobes are younger roughly at the position where we observe an enhancement of the surface brightness in the LOFAR maps. Regions closer to the host galaxy are progressively older, and the diffuse radio emission at the position of the host galaxy (noticeable in the LOFAR image) is the oldest region of the source. There is no sign of a restarted AGN activity, which suggests that the AGN has been inactive for around $10^8$ yrs.

In Section 5.3.1 we have argued that the dominant energy loss mechanism is synchrotron radiation. Jamrozy et al. (2004) mention a ROSAT detection identified with B2 0924+30 indicating the possibility that a hot gas halo is present around the source. Comparing the plasma ages that we have derived with those found by Murgia et al. (2011) for a sample of AGN relics located in galaxy clusters, we see that the overall age of B2 0924+30 corresponds to the total ages for 4 out of 7 sources in their sample. The ages derived for the lobes of B2 0924+30 are lower than the lowest total age for all of the sources in the sample of Murgia et al. (2011), while the ages of the central regions are comparable to the oldest sources found in their sample.

These arguments, and the fact that the relic lobes of B2 0924+30 are very well outlined seem to suggest that the radio emitting regions are sufficiently confined; at least comparable to radio sources found in some clusters of galaxies. A larger sample of AGN radio relics hosted by field galaxies is needed to infer whether B2 0924+30 is an outlier.

![Color-color plot](image1.png)  ![Shift diagram](image2.png)  ![Total set of shifted data](image3.png)

**Figure 5.7:** Color-color plot and shift analysis results for the B2 0924+30 source regions.

The color-color plot (Figure 5.7a) of the source regions shows that the spectral shape for most of them is best fit by synchrotron radiation from an aged plasma.

There is a correlation between the shift in frequency and in flux (Figure 5.7b), meaning that the dominant energy loss are radiative synchrotron losses. Moreover, the fit to the shift data has a slope ($-1.2 \pm 0.06$) which has similar value as the injection spectral index we have found earlier from the integrated flux density fit.
5.5 Conclusions

We have used LOFAR to obtain images of B2 0924+39 at low frequencies with the highest resolution to date. This has enabled us to produce detailed spectral index maps and derive radiative ages over the extent of the source. We have confirmed previous inferences consistent with this source being a FRII relic. We have also shown that there is a continuum of ages increasing from the outer lobes (around 20 Myr) to the regions at the position of the host galaxy (around 100 Myr, the time elapsed since the AGN has shut down). Further studies on relics of the same type (when discovered) will be necessary to answer the question whether the derived timescales are typical for relics hosted by field galaxies.

Appendix 5.A Spectra of some field sources

There are two sources in the immediate vicinity of B2 0924+30 which show interesting spectral behavior (see Figure 5.A1).

The source to the north-east of the northern lobe has a steep low frequency spectrum ($\alpha_{609} \sim -1.2$), and surprisingly, shows signs of spectral flattening (SPC < 0) at higher frequencies. It is unresolved, and this might indicate that we are observing a restarted AGN where the active core dominates the emission at higher frequencies, with a flatter spectral index.

Another source, further to the north-east, shows a spectral index associated with active radio AGN ($\alpha_{609} \sim -0.6$) at low frequencies, but it also has a pronounced spectral curvature (SPC $\sim 1$). It is suggestive of a source which we are observing very soon after its AGN has stopped being active.

These examples demonstrate the utility of wide field, low frequency observations and how we can use integrated spectral index properties to make preliminary inferences about the AGN activity history of multiple sources.

Appendix 5.B LOFAR Double-Double radio galaxy discovery

Most of the extended sources in our LOFAR image are radio galaxies. Based on their appearance (double lobes, sometimes with a visible radio core located in between them), most of them seem to be FRIIs. There are several others which resemble FRIs and some of irregular morphology. One of the former, J092743.8+293232, is a double-double source (DDRG; Schoenmakers et al. 2000), as can be noticed when we compare our LOFAR map with a FIRST image (Figure 5.B2). We can not resolve the inner pair of lobes, but the outer pair is noticeably fainter when looked at in an NVSS image. This fact points to the conclusion that the outer lobes are relic lobes. Indeed, their spectral index (Figure 5.B3) supports this conclusion.
Another notable extended radio source in the LOFAR FoV is shown in Figure 5.C4; an extended radio emission connected to the galaxy cluster Abell 781. It has been studied in detail by Venturi et al. (2011) and Govoni et al. (2011), and classified to be a galaxy cluster radio halo. Our image is its lowest frequency detection so far. We also detect other sources in the vicinity which do not have a counterpart the NVSS survey maps, but appear in the higher sensitivity maps of Venturi et al. (2011) (labeled S3 and S5 with spectral indices $\alpha_{140}^{325} = -1.1$ and $\alpha_{140}^{325} = -0.3$ respectively). They may be components related to the galaxy cluster halo which is hosted by Abell 781.
Figure 5.B2: LOFAR contours (red) superposed on a FIRST survey grayscale image of J092743.8+293232. Contour levels: $(-3, 3, 6, 9, 12)\sigma$. $\sigma = 2$ mJy beam$^{-1}$. 
Figure 5.B3: $\alpha_{1400}^{1400}$ spectral index map (made using our LOFAR image and an NVSS survey image) of the field double-double radio galaxy showing its steep spectrum relic outer lobes (left) compared to the active source 7C 0923+2947 (right).
Figure 5.C4: LOFAR high resolution image contours (red) superposed on an NVSS survey grayscale image of Abell 781. Note that LOFAR detects the extended galaxy cluster halo, and that there are two LOFAR detections not having an NVSS counterpart. Contour levels: \((-3, 6, 9, 12) \sigma\). \(\sigma = 2\) mJy beam\(^{-1}\).