AGN relics in the radio sky
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LOFAR first look at the giant radio galaxies NGC 6251 and 3C 236

Curving back within myself, I create again and again.

– the Bhagavad Gita
Abstract

We have examined the giant Mpc-class radio galaxies NGC 6251 and 3C 236 using LOFAR at 144 MHz. This represents the lowest frequency study of these objects to date at angular resolution comparable with observations done at higher frequencies. Our studies hence produced the highest resolution spectral index maps to date at low frequencies of these objects.

As for NGC 6251, we observe that the extent of the north-western lobe is larger at lower frequencies, and also find flatter spectral indices at low frequencies in its resolved jet and hotspots. We trace spectral index variations in the lobes. We also detect a counter-jet connecting the core to the south-eastern lobe. The jet/counter-jet brightness ratio is 60:1 at a distance of 240″ from the core and 27:1 at a distance of 340″ from the core.

The spectral index maps of 3C 236 show that the spectral steepening at the inner edges of the northern lobe is prominent at low frequencies. Our low frequency, high resolution spectral index map shows that the inner north-western lobe is broken up in multiple components, and that there is a pronounced spectral curvature of the lobe regions closer to the core, which is indicative of spectral aging.

A. Shulevski, P. D. Barthel, R. Morganti
7.1 Introduction

Giant radio galaxies (GRGs) are radio galaxies whose radio emitting regions (jets, lobes) extend over projected distances $\geq 1$ Mpc (Willis et al. 1974; Schoenmakers et al. 1999, 2001; Machalski et al. 2008; Saripalli et al. 2012). Their morphology can be classified as belonging to either the FRI or FRII type, and there is no evidence to point to them being particularly more energetic than the general population of radio galaxies. The surrounding environment may be an important factor allowing their large sizes when compared to other radio sources. Mack et al. (1998) have indeed found that the surrounding medium for their sample of GRGs is an order of magnitude less dense than that around smaller radio sources. This may be the reason for their large sizes; they can expand freely, which in turn may imply that expansion losses are the dominant energy loss mechanism for the relativistic particle populations in their lobes.

Apart from their size, GRGs are not fundamentally different from other radio galaxies, and we expect them to be subject to the same processes that are present in smaller radio galaxies. The AGN that power them probably go through a cycle of active and inactive periods (e.g. Barthel et al. 1985). Consequently, we also expect to see morphological and spectral signatures of radiative aging in GRGs.

Images at lower frequencies trace the oldest particle populations, and using the LOw Frequency ARray (LOFAR; van Haarlem et al. 2013) telescope allows us to trace the oldest emission regions in radio galaxies. Its unprecedented resolution at low frequencies enables us to produce spectral index maps with the highest resolution at these frequencies and map the energetics of the jets and radio lobes.

We have observed two giant radio galaxies, NGC 6251 (e.g. Willis et al. 1978) and 3C 236 (e.g. Willis et al. 1974) as part of the studies of nearby AGN in the framework of the LOFAR Surveys Key Science Project (KSP). Our goal is to study the radio morphology of the jets and lobes at the lowest frequencies and derive the highest resolution low frequency spectral index maps of these sources to date.

The radio emission associated with the galaxy NGC 6251 ($z = 0.0247$) was discovered by Waggett et al. (1977) who describe it as a giant RG with an exceptionally outlined long jet. Readhead et al. (1978) discovered an inner radio jet and have shown that it is aligned to the larger scale one over spatial scales of six orders of magnitude.

For many years after its discovery in the late 1950s, 3C 236 was an unresolved source. It was cataloged as such in the first 3C catalog and kept its status up to and including the study of Pooley & Henbest (1974). However, using the Westerbork Synthesis Radio Telescope (WSRT), Willis et al. (1974) have discovered low surface brightness active radio lobes emanating from it and extending for 4 Mpc ($z = 0.1005$). For decades, it was the largest known radio galaxy (see Machalski et al. 2008). Hence, 3C 236 is listed as a GRG in radio survey catalogs. Strom et al. (1981) studied the spectral index variations across the lobes and found that the spectral index steepens going from the outward edges of the lobes towards the host galaxy, consistent with what is observed in FRII radio galaxies.

The Infrared Astronomy Satellite (IRAS) observations by Golombek et al. (1988) detected warm dust in the host galaxy probably connected to ongoing star formation (Hes et al. 1995). Barthel et al. (1985) performed investigations of the radio morphology at a variety of scales; the north-west lobe was shown to have a possible sign of an additional activity episode, with a middle lobe/ridge embedded in the larger scale emission. The compact core is a Compact Steep Spectrum (CSS) source showing structure down to pc
scales. The lobes show a ridge of emission along their axes which is observed to wiggle, independent of brightness contributions coming from background sources visible through the lobes. The ridge has flatter spectral index ($\alpha \sim 0.5$).

Hubble Space Telescope (HST) imaging (Martel et al. 1999, O’Dea et al. 2001, Tremblay et al. 2010) has revealed repeated bursts of star formation in the host galaxy and the possibility that the youngest starburst may be connected to the AGN reactivation which produced the currently active CSS radio source. Thus, 3C 236 may be a good example of a radio galaxy showing signs of multiple epochs (possibly three) of restarted radio activity.

The large scale lobes of 3C 236 are intriguing in the sense that the north-western one is shorter than the south-eastern one, and this relationship is inverse for the small scale emission of the CSS core; there the north-western extension is longer than the south-eastern as seen by Schilizzi et al. (2001). They also note that the dust lane imaged by the Hubble Space Telescope (HST) close to the core may be part of the material which shapes the radio emission. The south-eastern jet seems uninterrupted throughout its extent, while the appearance of the north-western lobe might indicate that the jet on that side is weaker or interrupted (this side is thought to be approaching us). The maps of the large scale emission lack sufficient resolution, so it is possible that short period disturbances may have gone unnoticed.

The organization of this chapter is as follows. Section 7.2 describes the data and the reduction procedure. In Section 7.3 we outline our results, we discuss them in Section 7.4 and conclude with Section 7.5.

7.2 Data

Both targets were observed with the LOFAR HBA antennas, using an interleaved approach, with 11 minutes of dwell time on the target and 2 minute scan of a calibrator (total on-source time of 4.4 hours). NGC 6251 was observed in the night of August 22, 2013, while 3C 236 was observed in the night of March 14, 2013. Details of the observation are given in Table 7.1.

<table>
<thead>
<tr>
<th>Central Frequency [MHz]</th>
<th>144</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth [MHz]</td>
<td>64</td>
</tr>
<tr>
<td>Integration time</td>
<td>2 seconds</td>
</tr>
<tr>
<td>Observation duration</td>
<td>6 hours</td>
</tr>
<tr>
<td>Polarization</td>
<td>Full Stokes</td>
</tr>
<tr>
<td>UV range</td>
<td>$\leq 20k\lambda$</td>
</tr>
</tbody>
</table>

The data were initially calibrated by the observatory pipeline (Heald et al. 2010). The station gains were determined using the calibrator pointings and set to the (Scaife & Heald 2012) flux scale. The target data were corrected using the derived gains and then incrementally phase (self) calibrated with the LOFAR imaging pipeline (Vilchez et al. in prep.) using increasing baseline lengths for each calibration step. The imaging was performed using the LOFAR imager correcting for the station beam. Directional effects were not considered. For the starting model of the phase calibration, we have
used models extracted from a VLSS\footnote{VLSS \cite{Cohen2007} is the VLA Low frequency Sky Survey carried out at a frequency of 74 MHz} image using a spectral index of $\alpha = -0.8$ for the model components.

In the case of NGC 6251, we have imaged the entire LOFAR HBA band; each image having a bandwidth of 4 MHz. After rejecting the edges of the band, and images which we judged to suffer from excessive artifacts, we were left with nine images which we have averaged to produce the final image (with 36 MHz total bandwidth) of the target and the surrounding field.

For 3C 236, the reduction procedure was the same, but we have imaged 12 MHz total bandwidth due to time constraints; the full-bandwidth images eventually will yield higher S/N.

K. H. Mack has kindly provided us with WSRT images of NGC 6251 at 325 MHz and 3C 236 at 609 MHz which we have used in our analysis. The image properties are summarized in Table 7.2.

### Table 7.2: Image properties.

<table>
<thead>
<tr>
<th>Target</th>
<th>Instrument</th>
<th>$\nu$ [MHz]</th>
<th>$\Delta \nu$ [MHz]</th>
<th>$\sigma$ [mJy beam$^{-1}$]</th>
<th>Beam size</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 6251</td>
<td>LOFAR</td>
<td>144</td>
<td>36</td>
<td>4</td>
<td>55$''$</td>
</tr>
<tr>
<td></td>
<td>WSRT\textsuperscript{a}</td>
<td>325</td>
<td>15</td>
<td>2.3</td>
<td>55$''$</td>
</tr>
<tr>
<td>3C 236</td>
<td>LOFAR</td>
<td>144</td>
<td>12</td>
<td>7</td>
<td>50$''$ $\times$ 38.8$''$</td>
</tr>
<tr>
<td></td>
<td>WSRT\textsuperscript{a}</td>
<td>609</td>
<td>-</td>
<td>0.7</td>
<td>50$''$ $\times$ 40$''$</td>
</tr>
<tr>
<td></td>
<td>WSRT\textsuperscript{b}</td>
<td>1400</td>
<td>-</td>
<td>0.4</td>
<td>45$''$</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Image provided by K. H. Mack

\textsuperscript{b} NVSS image (NVSS stands for the NRAO VLA Sky Survey carried out at a frequency of 1.4 GHz \cite{Condon1998})

### 7.3 Results

#### 7.3.1 NGC 6251

We present the image of the complete LOFAR HBA $5^\circ \times 5^\circ$ field of view (FoV) in Figure 7.1. There are no noticeable variations in the background noise levels and the remaining artifacts around brighter sources can be attributed to uncorrected phase errors over the FoV, most likely of ionospheric origin.

A detailed LOFAR view of NGC 6251 with a WSRT contour overlay is given in Figure 7.2. We have marked the significant regions with letters, in agreement with the labels used in the work of Willis et al. (1982). Background sources are visible through the lobes (one in the north-western lobe and another to the south of the region labeled B). Our image reveals interesting new features of the radio emission of NGC 6251. We detect an extension of the counter-jet (marked E in our image) which connects the core region (at the base of the prominent jet in the north-west lobe) to the south-east lobe. Taken together with the jet emission and the two lobes, it supports the FRI classification of NGC 6251 (its radio luminosity is $L_{1480} = 2.2 \times 10^{24}$ WHz$^{-1}$ \cite{Perley1984}. We also note that the extension of the north-western lobe goes on further to the west in
Figure 7.1: The HBA $5^\circ \times 5^\circ$ FoV with NGC 6251 in the center. Image properties are listed in Table 7.2.
Figure 7.2: Grayscale LOFAR map of NGC 6251 at 140 MHz. Grey contours: \((-3, 2, 3, 6, 9, 18, 27)\)σ. Shown in red is the 2σ contour level of the WSRT 325 MHz map. Map properties as listed in Table 7.2. The WSRT map is rotated around the phase center which induces increasing offset in the source positions as one moves away from it. Our conclusions are not significantly affected by the offset. The white cross indicates the position of the host galaxy.
Figure 7.3: NGC 6251 $\alpha_{144}^{325}$ spectral index map.

the LOFAR image compared to the WSRT map (G). These are regions containing the lowest energy particles which radiate at lower frequencies and mark the oldest particle population in the lobes.

Connecting the hotspot in the north-western lobe (A) with the jet (F) and continuing through the core, the counter-jet (E), the brightness enhancement at the inner edge of the south-eastern lobe (B) and ending up at its hotspot (C), we trace a structure that resembles the stretched out letter 'W'. If we add the edges of the lobes (D and G) to it, we can think of the entire source as having a helical morphology, with the helix being smaller near the core, and the largest at the edges of the lobes. This is reminiscent of a structure created by jet precession, suggesting that the diffuse edges of both lobes may be farther away and in the background of the hotspots.

We show the $\alpha_{144}^{325}$ spectral index map in Figure 7.3. The spectral index map was made by fitting a first order polynomial to the flux density values vs. frequency in log-log space for each pixel of both the LOFAR and WSRT images. Only pixels with values above 3$\sigma$ in the corresponding maps were taken into account. The spectral index map shows the
jet and hotspots to have the flattest spectrum; there is a gap between the jet and hotspot in the north-western lobe, which might indicate a flicker in the AGN activity. The lobes show a steep spectrum with small scale variations, indicative of localized differences in the energy of the particles, probably combined with magnetic field strength variations.

### 7.3.2 3C 236

The LOFAR image of 3C 236 suffers from overall higher noise levels when compared to the NGC 6251 image due in part to the fact that we have imaged a smaller bandwidth. Looking at the LOFAR image in Figure 7.4, we note the bright (restarted) CSS core. We can see ripple artifacts superposed over the lobes (most probably leftover sidelobes after the deconvolution caused by the very bright core). We also note that in our LOFAR maps we trace less lobe emission than what is seen in the literature; due to the limited bandwidth we have imaged we miss the fainter lobe regions towards the core.

Notably, we can see that the inner region of the north-western lobe is fragmented, meaning that we detect the middle lobe, a possible sign of a flicker in the past activity of the AGN [Barthel et al. 1985].

The low frequency spectral index map (Figure 7.5) shows that the mid regions of the lobes have a spectral index which is characteristic of a young particle population, identical to the spectral index of the recently restarted CSS core [Schilizzi et al. 2001]. This might indicate that the lobes are still being replenished with plasma ejected by the AGN at the end of the previous active epoch, or that the particles are being re-accelerated in the lobes. We also can detect the middle lobe (fragmentation of the inner region of the north-western lobe). If the fragmentation is due to an interruption in AGN activity, the episode must have been very short.

We observe lobe edges having steep spectral index, with a sharp transition. Comparing with point sources in the field which show similar features, we note that the steep spectrum regions in the case of the target are slightly wider. At those positions there is enough source flux in both of the maps we use (above $5\sigma$). We may be tracing the very low energetic particles outlining a radio cocoon enveloping the lobes.

Mack et al. [1998] estimate the age of 3C 236 to around 100 Myr, based on spectral aging arguments. There is a possibility that the lobe replenishment via the jets may have been interrupted on timescales of a few Myr due to jet collapse or encounter with intervening clumps of matter closer to the core. While not detected in the large scale maps, the intermittency might be causing the fragmentation which we see in the north-western lobe and spectral index maps.

### 7.4 Discussion

#### 7.4.1 NGC 6251

Very Large Array (VLA) observations of the radio galaxy were performed by Perley et al. [1984] at frequencies ranging from 1370 MHz to 4885 MHz. They have discovered a 130″ counter-jet. The jet/counter-jet brightness ratio ranges from 40:1 at 100″ from the core (measured at 610 MHz) to more than 250:1 at 240″ from the core (also at 610 MHz). In our LOFAR image we detect an extension to the already known inner counter-jet (also detected in lower resolution maps as an extension of the southern lobe by Waggett et al.
Figure 7.4: Grayscale LOFAR map of 3C 236 at 140 MHz. Gray contours: $(-3, 2, 3, 6, 9)\sigma$. Shown in red is the $2\sigma$ contour level of the WSRT 609 MHz map.
Figure 7.5: $\alpha_{144}^{609}$ spectral index map. Overlaid in gray are LOFAR contours with levels: $(-3, 3, 6, 9, 15) \sigma$

... but not seen by Mack et al. (1998) which connects the south-eastern lobe to the core.

We compute the flux density ratio for the jet to the counter-jet at 144 MHz to be 60:1 at a distance of 240″ from the core and 27:1 at a distance of 340″ from the core.

Given its large (projected) size, the radio axis of NGC 6251 is likely to be close to the sky plane. Consequently, beaming and orientation effects are less important and there must be intrinsic differences between the east and west side of the source, possibly having to do with different radiative efficiencies between the jet/counter-jet.

The flux densities of the hotspots (A, C) and jet (F) at 140 MHz are: 1.3, 0.7 and 6.3 Jy respectively.

Comparing our spectral index map with ones made by Mack et al. (1998) at higher frequencies, we can see that our study is in agreement on the spectral index trends for the outermost edges of the lobes where spectral index values of $\alpha = -1.4$ are prevalent. Their coarser resolution prevents them from resolving the jet clearly, and they report different high frequency spectral index of the hotspots ($\alpha \sim -0.8$ for the north-western one and $\alpha \sim -1.2$ for the south-eastern one), while we see the jet and hotspots having a spectral index of about $\alpha \sim -0.6$ at low frequencies, a clear sign that we see older particle population, indicating that there are signs of spectral aging in the jet / hotspots.
Minor jet misalignment was reported by Cohen & Readhead (1979), and a wiggle in the jet at a distance of 85 kpc from the core was discovered by Saunders et al. (1981). There may be a connection between it and the large scale morphology that we see. The spatial resolution of our map is too poor to directly compare the jet in our image with the deviations of the jet reported by Perley et al. (1984). We detect a noticeable bending of the counter-jet at a distance of around 240″ (150 kpc) from the core.

### 7.4.2 3C 236

Our low frequency spectral index studies match the conclusions drawn by Mack et al. (1998) from their higher frequency spectral index maps. We observe that the spectral index steepens from $\alpha = -0.5$ to $\alpha = -0.8$ going from the outer lobe edges towards the core, especially evident in the north-western lobe. We also note that the inner mid lobe regions have flatter spectral index and are fragmented (possible spectral index signature
Figure 7.7: $\alpha_{1400}$ spectral index map of 3C 236. The contours are the same as shown in Figure 7.5.

of the middle lobe/ridge reported by [Barth et al. (1985); Figure 7.6]. [Mack et al. (1998)] report that that lobe has an overall steeper spectral index compared to the south-eastern one. Our higher resolution spectral index mapping (Figure 7.5) shows that this may be due to beam effects averaging the spectral index in lower resolution maps.

A ridge of emission in the south-eastern lobe, mentioned previously, is observed in our spectral index maps (ex. Figure 7.5) and we see signs of the reported wiggle of the ridge.

Spectral index mapping at higher frequencies at the same spatial resolution (Figure 7.7) confirms these trends. The flatter spectral index regions in the north-western lobe is clearly outlined. The spectral curvature map shown in Figure 7.8 shows a spectral break at the inner edge of the north-western lobe, suggesting that it is a region of aged plasma. The northern edge of the south-eastern lobe shows no curvature, and steep low frequency spectrum, suggesting that it may be composed by the oldest particle population observed in 3C 236.

[O’Dea et al. (2001)] suggest (based on their HST studies of star formation in the nucleus of the host galaxy) an age of the large scale lobes in the range of $10^8$ to $10^9$ years and an off timescale of around $10^7$ years. Assuming a total age (for the outer lobes) of $t_s = t_{ON} + t_{OFF} = 110$ Myr and a magnetic field strength in the lobes of $4\mu$G, using the
relations between the break frequency in the lobe spectrum and the age of the plasma given in Murgia et al. (2011), we estimate the break frequency to be $\nu_b = 1900$ MHz. From the spectral curvature map shown in Figure 7.8, we can see that the lobes show little curvature up to 1400 MHz, in line with the ages estimated in O’Dea et al. (2001). An exception to this argument is the inner north-western lobe which shows spectral curvature in the frequency range below 1400 MHz, pointing to its age being greater than 120 Myr under the above assumptions.

### 7.5 Conclusion

We have presented our LOFAR observations of two GRGs: NGC 6251 and 3C 236. We study these sources for the first time at a resolution of 50$''$ at such low frequencies. We elaborate the extent of low energy particle population in the lobes of NGC 6251, and describe a counter-jet cocoon. We confirm earlier work on the spectral properties of the lobes of 3C 236, and spatially resolve different particle populations.

The low frequency spectral index maps we have derived show previously undetected small scale variations (see Mack et al. 1998 for reference) in the surface brightness in the
lobes of NGC 6251 and a possible detection of a cocoon of low intensity radio emission enveloping the lobes of 3C 236. These results represent a first look and can be improved upon by utilizing the full LOFAR bandwidth, especially in the case of 3C 236.

LOFAR represents a very valuable instrument for these kind of studies. As we have demonstrated in this chapter, its sensitivity combined with its potential for high resolution imaging at low frequencies offers an unprecedented detailed view at the oldest diffuse emission regions. Using LOFAR will prove instrumental in the future in revealing new features in known objects as well as enabling new discoveries.