Multi-frequency radio continuum mapping of giant radio galaxies

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Abstract. The giant radio galaxies NGC 315, DA 240, 3C 236, 3C 326, and NGC 6251 have been observed at 92 cm and 49 cm wavelengths with the Westerbork Synthesis Radio Telescope (WSRT) and at $\lambda\lambda$ 11 cm, 6.3 cm, and 2.8 cm using the Effelsberg 100-m telescope. These objects all exhibit strong polarized radio emission across the entire radio frequency domain. Their spectral index distributions are very complex, with significant variations across individual objects.

Key words: galaxies: individual: NGC 315; DA 240; 3C 326; 3C 236; NGC 6251; radio continuum: galaxies

1. Introduction

Giant radio galaxies (GRGs) form an extreme class of extragalactic radio sources. They can be studied in detail because of their large angular size. Their huge intrinsic sizes must be due either to very powerful AGNs or to a surrounding medium of very low density. These large sizes imply long evolution times which can be investigated by multi-frequency observations. This type of source also allows us to study characteristics of the intergalactic medium as the source expands into the host galaxy's surrounding environment.

Numerous studies of GRGs have been performed especially in the low-frequency regime (e.g. Willis & Strom 1978; Willis et al. 1978; 1981; Bridle et al. 1979; Strom & Willis 1980; Barthel et al. 1985; Jägers 1986; 1987a,b). At higher frequencies there have been measurements with the Effelsberg 100-m telescope at $\lambda\lambda$ 11 cm and 6 cm by Baker et al. (1974), Stoffel & Wielebinski (1978),

Strom et al. (1981), Klein et al. (1994), and Saripalli et al. (1996).

Since particle aging first affects higher electron energies, low-frequency observations mainly show the unevolved stage of the sources. Knowledge of the low-frequency spectral indices is essential to fit spectral aging models, which will be reported in forthcoming papers.

High-frequency observations as reported by Klein et al. (1994) and Saripalli et al. (1996) are essentially free of Faraday effects and thus enable us to directly “map” the intrinsic (projected) magnetic field. A comparison of these observations with the low-frequency measurements allows us to determine the degree of disorder and (de-)polarization characteristics. The very high degree of polarization which is a general characteristic of the sources chosen in this study provide significant polarization information even at 326 MHz.

Here we report observations of the GRGs NGC 315, DA 240, 3C 236, 3C 326, and NGC 6251 at $\lambda\lambda$ 92 cm and 49 cm, carried out with the Westerbork Synthesis Radio Telescope (WSRT) and $\lambda\lambda$ 11 cm, 6.3 cm, and 2.8 cm using the Effelsberg 100-m telescope. The WSRT observations and results had previously been presented in brief by Willis & O'Dea (1990). The 10.6-GHz data had been published by Klein et al. (1994), but the maps had not yet been cleaned with the antenna pattern, which has been performed in the meantime.

In Sect. 2 we describe the observations and the data analysis. In Sect. 3 the maps of total intensity and linear polarization are presented, along with a brief description of their most striking characteristics. In Sect. 4 we have compiled the integrated flux densities of the sources and source components to derive their integrated spectra. More detailed studies will be presented in forthcoming papers.

Throughout this paper we use $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 1$.

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Table 1. Map parameters of the WSRT maps

Source	Phase centre		Beam size				rms noise			
	α_{50}	δ_{50}	(326 MHz)		(609 MHz)		[mJy/b.a.]			
	[^h : ^m : ^s]	[[°] : ['] : ^{''}]	[α ["] $\times$ δ ["]]		[α ["] $\times$ δ ["]]		σ_I^{92}	σ_{Ip}^{92}	σ_I^{49}	σ_{Ip}^{49}
NGC 315	00 57 48.0	30 20 59.9	55	110	28	55	1.7	0.8	0.6	0.5
DA 240	07 49 01.9	55 50 28.9	55	67	28	34	2.0	1.2	0.6	0.5
3C 236	10 06 56.1	34 45 20.5	55	96	28	48	1.8	0.8	0.5	0.4
3C 326	15 51 49.0	20 05 04.2	55	161	28	81	2.7	3.1	1.0	0.6
NGC 6251	16 34 36.8	82 29 06.3	55	55	28	28	1.5	1.1	0.4	0.3

Table 2. Map parameters of the Effelsberg maps

Source	map centre (2.7, 4.8 GHz)		map centre (10.6 GHz)		rms noise					
	α_{50}	δ_{50}	α_{50}	δ_{50}	[mJy/b.a.]					
	[^h : ^m : ^s]	[[°] : ['] : ^{''}]	[^h : ^m : ^s]	[[°] : ['] : ^{''}]	σ_I^{11}	σ_{Ip}^{11}	$\sigma_I^{6.3}$	$\sigma_{Ip}^{6.3}$	$\sigma_I^{2.8}$	$\sigma_{Ip}^{2.8}$
NGC 315	00 55 46.4	30 01 42	00 55 45.0	30 00 00	4.9	2.1	2.4	1.2	1.4	0.4
DA 240	07 44 19.2	55 56 32	07 44 34.0	55 56 47	4.8	2.6	1.8	1.9	1.2	0.5
3C 236	10 03 02.3	35 08 57	10 03 06.0	35 08 46	4.1	1.7	2.2	1.2	1.2	0.4
3C 326	15 49 37.3	20 14 37	15 49 41.5	20 13 49	4.2	1.8	2.1	0.9	1.0	0.5
NGC 6251	16 40 01.8	82 30 16	16 42 59.0	82 32 57	3.4	2.2	3.4	1.3	1.1	0.4

2. Observations and data reduction

2.1. WSRT data

All galaxies were observed by the WSRT in full redundancy mode; the correlator sampled both parallel and crossed dipole configurations. The parallel dipole data (WSRT channels XX and YY) were used to produce high dynamic range total intensity maps with the aid of the NRAO AIPS package as follows; the WSRT data were loaded into AIPS and first processed with the special AIPS task REDUN. REDUN is a translation into AIPS of the corresponding Dwingeloo DWARF program. It computes telescope dependent amplitude and phase errors by analyzing the observed amplitudes and phases of the many redundant baselines in the Westerbork array. After this initial operation has been done, WSRT observations can be further processed into high dynamic range images using the AIPS programs MX and ASCAL as has been described by Perley (1986). The signals in the crossed dipole channels XY and YX may be combined with the difference in signal between XX and YY channels to yield maps of the Stokes polarization parameters Q and U . At 326 MHz electric vector position angles can be rotated from their intrinsic position angles by many tens of degrees (more than 100 degrees is not uncommon) because of Faraday rotation within the ionosphere. Therefore all observations were first corrected for ionospheric Faraday rotation using the method developed at Dwingeloo by Spoelstra (1981). The flux calibration scale is that of Baars et al. (1977). In Table 1 we have compiled relevant observational parameters for the WSRT maps.

2.2. Effelsberg data

The high-frequency observations have been carried out with the Effelsberg 100-m telescope using the 2.7-GHz 1-horn, 3-channel receiver, the 4.8-GHz 2-horn, 3-channel, and the 10.6-GHz 4-horn, 8-channel receiver system, all installed in the secondary focus of the telescope. The observations with the 10.6-GHz system have been described in detail by Klein et al. (1994). At 2.7 GHz and 4.8 GHz we had to use the single-beam mode (owing to limited observing time allocation), which is more strongly affected by bad weather conditions and terrestrial interference. The maps were large enough to cover the source plus some emission-free areas used for determination of zero levels and noise. Contrary to the multi-beam technique, which requires scanning in the horizontal system, the 2.7-GHz and 4.8-GHz maps have been obtained by scanning alternately along, and perpendicular to, the position angle of the source. The drive rates were 2°/min at 2.7 GHz and 1°/min at 4.8 GHz, the scan interval 2' and 1', respectively. The individual maps were edited to diminish the influence of weather or terrestrial interference before they were averaged to yield final maps of Stokes I , Q , and U , employing the Fourier filter technique of Emerson & Gräve (1988). The 10.6-GHz maps shown by Klein et al. (1994) have been CLEANed, applying the algorithm described by Klein & Mack (1995). The 4.8-GHz maps have also been CLEANed, but the algorithm is more complicated in the case of maps not observed in the horizontal system so that some residual artifacts introduced by the antenna pattern may be left.

Table 2 summarizes the relevant map parameters for each source. The data have been calibrated applying the scale of Baars et al. (1978). Because of the relatively large number of maps, where parts of them had to be blanked because of weather or interference effects, the noise level may vary significantly across the final maps. This is of special importance for the calculation of the polarized intensity maps. These have been produced as suggested by Wardle & Kronberg (1974). Since the polarization information represents a pseudovector where neither the amplitude nor the phase has a Gaussian probability distribution one has to apply a correction term, especially in the case of polarized low-brightness regions that we are concerned with. The best estimate of the true polarized intensity can be calculated as

$$I_P = \sqrt{Q^2 + U^2 - (1.2\sigma_{QU})^2}$$

where Q , U is the intensity in the Stokes Q - and U -map, respectively, and σ_{QU} is the mean value of the noise in the Q - and U -maps. The factor 1.2 has been found empirically to be best suited to shift the peak of the (positive) noise distribution function to zero.

In view of this correction it is clear that the determination of the proper noise value is very important to obtain the true polarized intensity. Therefore we have developed a routine which calculates the noise at each map pixel as a function of the number of individual maps (i.e. integration time) to be averaged at this pixel. The polarized intensity is thus calculated by accounting for the inhomogeneous distribution of the noise level.

3. The maps

In the following we present the radio continuum maps of the GRGs. The results for each source are discussed individually. We show two maps per source and frequency, one displaying the total intensity, with vectors proportional to the polarized intensity, the other giving the polarized intensity as contours, with vectors proportional to the percentage polarization. The angle of the vectors is the direction of the electric field. For magnetic field maps we refer to Klein et al. (1994). Detailed studies of spectral indices, rotation, and depolarization measures will be presented in forthcoming papers. We have also compiled a number of point sources observed in the galaxies' fields which probably do not have any physical connection to the GRGs. Their coordinates and flux densities at 609 MHz can be found in Table 3-6.

3.1. NGC 315

The first detailed study of this source was performed by Bridle et al. (1976) using the Arecibo telescope at 0.43 GHz, 1.41 GHz, and 2.38 GHz. Stoffel & Wielebinski (1978) made first measurements with the Effelsberg telescope at 2.7 GHz. Concentrating on the jet,

Bridle et al. (1979) observed NGC 315 at 609 MHz, 1.4 GHz, and 4.9 GHz with the WSRT and the VLA. The most extensive study including the polarization data was performed by Willis et al. (1981). A new map at 609 MHz was obtained by Jägers (1987a) using the up-graded WSRT.

Table 3. Point sources found in the NGC 315 field (at 609 MHz)

No.	coordinates		S_{609} [mJy]	comments
	α_{50} [^h : ^m : ^s]	δ_{50} [[°] : ['] : ^{''}]		
1	00 53 45.3	29 52 08.0	50.4 ± 2.8	extended
2	00 53 49.0	30 19 51.8	7.0 ± 2.1	
3	00 53 52.6	30 01 52.4	6.8 ± 2.3	
4	00 54 08.9	29 42 56.9	32.8 ± 2.2	
5	00 54 19.7	30 13 09.4	20.7 ± 4.3	confused
6	00 54 25.5	30 02 23.2	5.7 ± 2.3	
7	00 54 25.8	29 38 51.3	9.5 ± 2.0	
8	00 54 41.9	30 16 31.7	27.6 ± 2.4	
9	00 55 20.3	29 38 49.7	20.8 ± 2.2	
10	00 55 34.4	29 54 49.6	5.0 ± 2.2	
11	00 55 44.5	29 58 53.6	32.3 ± 2.3	
12	00 55 47.8	29 40 34.6	29.5 ± 2.4	extended
13	00 55 50.4	29 40 24.1	7.1 ± 2.1	extended
14	00 55 51.7	30 06 42.5	4.0 ± 2.2	
15	00 55 54.0	30 20 49.0	62.4 ± 2.3	extended
16	00 55 51.7	30 20 12.8	38.2 ± 2.3	extended
17	00 55 57.7	29 46 55.2	6.4 ± 2.4	extended
18	00 56 15.9	30 06 57.8	11.9 ± 2.7	extended
19	00 56 31.2	29 49 04.5	19.6 ± 2.4	extended
20	00 56 31.3	30 00 16.2	9.0 ± 2.2	
21	00 56 37.6	29 56 10.1	17.6 ± 2.2	
22	00 56 44.9	30 08 22.6	5.9 ± 2.1	
23	00 56 59.3	29 38 02.9	39.4 ± 2.2	
24	00 57 03.5	29 39 48.3	22.1 ± 2.1	
25	00 57 14.7	30 11 49.7	21.7 ± 2.2	
26	00 57 15.1	30 06 08.2	6.0 ± 2.0	
27	00 57 39.2	30 03 50.7	159.1 ± 2.6	extended
28	00 57 45.6	30 18 59.0	23.7 ± 2.4	
29	00 57 54.8	30 02 55.1	7.0 ± 2.1	
30	00 58 00.7	30 02 36.6	13.5 ± 2.2	

“Extended” means sources with a deconvolved axis in $\alpha \geq 30''$ or in $\delta \geq 58''$ of the fitted ellipse.

The overall structure of NGC 315 suggests precessing beams, although the two lobes are anything but symmetric. The south-eastern lobe is broad, with its northern extension having a steep spectrum: it is not visible at 10.6 GHz. In contrast, the north-western lobe is narrow, with its “back-flowing” extension having a remarkably flat spectrum as suggested by the high-frequency maps, in which it is still easily visible. This peculiar behaviour was already pointed out by Klein et al. (1994), and suggests that a simple precession model is not able to

explain the overall morphology and spectral characteristics. While the jet feeding the north-western lobe is bright and permanently visible over the whole frequency range, the counter-jet is only visible intermittently. As will be shown in Sect. 4.1, the spectrum of NGC 315 and its individual components is difficult to determine reliably. In any case, the strong asymmetry of the source, both, in its lobe structure as well as in its jet/counter-jet lengths, strongly suggests different densities/pressures of the intergalactic medium on either side of the host galaxy, rather than an intrinsic cause.

3.2. DA 240

Willis et al. (1974) presented the first high-resolution observations of this source at 609 MHz. Baker et al. (1974) showed a λ 11 cm map, obtained with the Effelsberg telescope. Spectral index studies have been performed by Strom et al. (1981) who compared maps at $\lambda\lambda$ 49 cm and 6 cm. Tsien (1982) obtained 0.15 and 1.4-GHz maps of the entire source and high-frequency observations of the famous hot spot. New 609-MHz observations were obtained by Jägers (1987b) with the 3-km WSRT.

Table 4. Point sources found in the DA 240 field (at 609 MHz)

No.	coordinates		S_{609} [mJy]	comments
	α_{50} [^h : ^m : ^s]	δ_{50} [[°] : ['] : ^{''}]		
1	07 43 32.5	55 48 59.8	38.6 ± 0.4	confused
2	07 44 01.4	56 08 36.6	6.6 ± 0.2	
3	07 44 13.0	55 44 00.6	11.6 ± 0.2	
4	07 44 12.9	56 04 38.5	55.8 ± 0.2	
5	07 44 23.2	56 15 18.0	17.9 ± 0.2	
6	07 44 37.1	56 08 04.0	4.5 ± 0.2	
7	07 45 22.8	56 05 50.4		confused
8	07 45 56.9	56 02 59.9		confused
9	07 46 34.5	55 42 59.4	11.9 ± 0.3	extended
10	07 46 49.6	55 52 54.3	22.5 ± 0.2	

“Extended” means sources with a deconvolved axis in $\alpha \geq 30''$ or in $\delta \geq 36''$ of the fitted ellipse.

At low frequencies DA 240 is the archetype of a fat double radio galaxy with almost circularly extended lobes, the western lobe having an additional protrusion in the south-western direction. At higher frequencies the lobes shrink to a small straight channel marking the active zone of the source. The hot spot in the eastern lobe, 4C 56.16, is the most salient feature at high frequencies.

3.3. 3C 236

The first high-resolution study was presented by Willis et al. (1974) using WSRT observations at 609 MHz.

Strom & Willis (1980) studied the spectral index distribution between 609 MHz, 1.4 GHz, and 4.8 GHz. The large and small scale structure of 3C 236 was the subject of a paper by Barthel et al. (1985) who included both, 1.4-GHz WSRT and VLBI observations for their study. Jägers (1987b) obtained a 609-MHz map with the 3-km WSRT.

At 326 MHz the bridge between the outer lobe areas and the central core is almost closed. The source is very narrow. While most sources of this species reveal low-brightness protrusions in a lateral direction at low frequencies, 3C 236 maintains its straight direction without showing any large-scale curves, wiggles or bends. The observed polarization of the core is an instrumental artifact. The north-western lobe looks more complex in polarized intensity than does the south-eastern one. This is even more evident if one compares the orientations of the electric field vectors.

Table 5. Point sources found in the 3C 236 field (at 609 MHz)

No.	coordinates		S_{609} [mJy]	comments
	α_{50} [^h : ^m : ^s]	δ_{50} [[°] : ['] : ^{''}]		
1	10 01 43.6	35 04 00.2	60.5 ± 0.7	
2	10 01 49.3	35 04 29.0	32.1 ± 0.7	
3	10 02 21.1	35 16 48.7		confused
4	10 02 43.5	35 05 40.6	24.4 ± 0.7	
5	10 02 46.6	34 50 35.7	114.4 ± 0.7	
6	10 02 49.7	34 54 46.8	9.9 ± 0.7	
7	10 02 51.3	35 16 51.8	164.1 ± 0.7	
8	10 03 02.7	35 04 27.4	13.3 ± 0.7	
9	10 03 09.4	35 03 50.1	27.7 ± 0.7	
10	10 03 16.5	34 56 42.7	422.1 ± 0.7	
11	10 03 36.6	35 11 24.9	9.1 ± 1.0	
12	10 04 00.4	35 09 22.7	19.3 ± 1.0	
13	10 04 07.2	34 52 32.0	5.4 ± 0.7	
14	10 04 17.5	35 09 34.9	8.4 ± 0.8	
15	10 04 17.7	34 52 33.3	8.9 ± 0.8	
16	10 04 21.0	34 59 35.9		confused
17	10 04 28.7	34 59 12.3		confused
18	10 04 46.2	34 53 29.7	154.6 ± 0.9	
19	10 04 50.6	35 17 47.8	10.0 ± 0.8	
20	10 04 54.1	35 16 43.6	23.5 ± 0.8	
21	10 04 53.8	34 56 36.8	17.7 ± 0.7	

“Extended” means sources with a deconvolved axis in $\alpha \geq 30''$ or in $\delta \geq 51''$ of the fitted ellipse.

The overall morphology is characterized by the narrow extent of the lobes perpendicular to the source axis. Comparing the two lobes, however, the north-western one appears broader, a fact which becomes especially evident in the polarized intensity map. The bridge emission between the core and the outer lobes becomes fainter with increasing frequency, which results in a steepening of the

spectrum and is indicative of aged particles, a typical behaviour in FR II-radio galaxies.

3.4. 3C 326

The first maps of 3C 326 were presented by Mackay (1969) at 408 and 1407 MHz. Bridle et al. (1972) and Baker (1974) published single-dish observations at 1.4 GHz. The most detailed analysis of this source has been performed by Willis & Strom (1978) who presented maps at frequencies of 609 MHz, 1.4 and 5 GHz.

Table 6. Point sources found in the NGC 6251 field (at 609 MHz)

No.	coordinates		S_{609} [mJy]	comments
	α_{50} [^h : ^m : ^s]	δ_{50} [[°] : ['] : ^{''}]		
1	16 22 53.7	82 48 07.0	23.2 ± 0.1	
2	16 23 02.0	82 34 00.9	11.5 ± 0.1	
3	16 25 05.2	82 55 31.3	35.8 ± 0.1	
4	16 26 07.1	82 50 04.6	7.7 ± 0.1	
5	16 26 43.0	82 37 54.2	6.8 ± 0.1	
6	16 27 02.3	82 38 12.8	4.8 ± 0.1	
7	16 28 53.7	82 43 45.7	7.9 ± 0.1	
8	16 30 08.4	82 46 16.1	6.5 ± 0.2	
9	16 30 49.6	82 41 27.3	86.1 ± 0.1	
10	16 34 29.1	82 38 14.4	9.6 ± 0.1	
11	16 35 28.7	82 46 19.9	54.5 ± 0.3	extended
12	16 38 09.4	82 40 42.0	2.7 ± 0.1	confused
13	16 44 02.2	82 35 21.6	5.2 ± 0.1	
14	16 44 13.2	82 23 04.1	87.7 ± 0.1	
15	16 46 42.4	82 39 21.7	101.7 ± 0.1	
16	16 47 04.9	82 09 32.0	3.7 ± 0.1	
17	16 47 33.7	82 08 24.4	4.2 ± 0.1	
18	16 48 15.5	82 07 44.6	4.3 ± 0.1	
19	16 48 45.7	82 09 09.8	5.3 ± 0.1	
20	16 48 59.8	82 07 40.6	15.0 ± 0.1	
21	16 50 15.4	82 17 15.7	32.5 ± 0.3	extended
22	16 50 43.5	82 09 39.4	152.0 ± 0.1	
23	16 51 37.8	82 25 05.6	25.0 ± 0.1	
24	16 52 04.7	82 15 07.0	25.0 ± 0.2	confused
25	16 53 13.0	82 21 27.1	27.3 ± 0.2	confused

“Extended” means sources with a deconvolved axis in α , $\delta \geq 30''$ of the fitted ellipse.

The global structure of this source does not vary significantly at different frequencies. The western lobe is narrow, as is particularly evident at 10.6 GHz. The low-frequency WSRT maps do not have sufficient north-south resolution to reveal this, owing to the relatively low declination of 3C 326. The eastern lobe is extended perpendicular to the source axis with a narrow protrusion emerging to the east. The linear polarization maps disclose a more complex structure, with up to three components in the eastern lobe. The point sources at $\alpha_{50} = 15^{\text{h}}48^{\text{m}}54^{\text{s}}.7$,

$\delta_{50} = 20^{\circ}11'01''$ and $\alpha_{50} = 15^{\text{h}}49^{\text{m}}41^{\text{s}}.0$, $\delta_{50} = 20^{\circ}18'18''$ are background sources as already noted by other authors. The eastern component of the western lobe is seen to broaden southwards. The western lobe also shows significant polarization ($p \sim 10\%$) in its central and western components, whereas the broader eastern component of this lobe is more weakly polarized. The large-scale isotropic orientation of the magnetic field is obvious over an extent of $6'.3$, corresponding to a linear size of 600 kpc.

The overall (projected) source morphology suggests an intrinsically rather symmetric structure, but with the eastern lobe probably bending away from its original orientation, perpendicular to the sky plane.

3.5. NGC 6251

This source was discovered by Waggett et al. (1977) who presented maps of the entire source or only the core at various frequencies between 38 MHz and 15.4 GHz. Stoffel & Wielebinski (1978) published a 2.7-GHz map observed with the Effelsberg telescope. The polarization characteristics have been studied by Willis et al. (1978). Detailed investigations of the jet have been performed by Saunders et al. (1981) and Perley et al. (1984) using high-frequency interferometric maps. Willis et al. (1982) presented a 609-MHz map observed with the WSRT which has been superseded by new 609-MHz observations with the upgraded instrument (Jägers 1987a).

The north-western lobe appears to consist of two regions, a brighter one which extends symmetrically around the jet, and a fainter part which expands in a south-western direction. This confirms the impression suggested by the 151-MHz map of the north-western lobe (Waggett et al. 1977) that it is very extended in the south-western direction.

The faint part has a steep spectrum, indicating a higher particle age although parts of the very extended structure may have been filtered out in the interferometer maps, especially at 609 MHz. The strong gradients at the northern edges of both lobes delineate the genuine boundaries of the lobes. The jet can be traced out to about $10'$. It consists of a luminous part up to $5'$ from the core, and a fainter section which curves towards the hot spot. The counter-jet is detected close to the core along the first $3'$, disappears and lights up again some $20'$ further out. The 326-MHz data confirm this feature being part of the counter-jet on its way to the hot spot as already suggested by Willis et al. (1982). Although less obvious in the 609-MHz map, the connection of feature B to the south-eastern hot spot also becomes clear when this map is smoothed to the resolution of the 326-MHz map. At the lower resolution our 609-MHz map is also consistent with that obtained by Willis et al. (1978).

The high-frequency maps emphasize the most active parts of the radio galaxy, viz. the core, the jet, and the hot spots. Unfortunately, the 2.7-GHz and 4.8-GHz maps

Table 7. Integrated flux densities of NGC 315

No.	component	S_{tot} [mJy]				
		326 MHz	609 MHz	2695 MHz	4750 MHz	10550 MHz
1 – 10	total	9706.6±123.6	5332.1±95.2	3373.3±89.8	2461.2±74.9	2194.4±81.1
1	core+innerjet	3521.3± 42.3	2432.4±33.6	1602.4±26.7	1434.3±22.8	1303.2±25.7
2	jet knot	234.0± 9.3	119.2± 9.3	95.1± 7.0	47.1± 5.7	29.0± 7.8
3	hot spot	1008.3± 20.6	595.7±18.8	284.4±13.1	229.7±11.4	174.7±16.6
4	bright lobe	703.0± 18.1	501.2±17.8	89.6±10.5	147.3±10.9	120.1±15.0
5	weak lobe	297.7± 14.5	109.1±14.5	261.9±20.4	42.2± 9.6	118.4±13.6
6	back lobe	1311.1± 33.2	529.9±31.7	273.2±20.6	149.2±18.6	203.2±29.1
7	counter-jet	158.1± 12.4	62.7±12.5	46.9± 9.0	13.6± 8.1	47.9±10.7
8	bgs (counter-jet)	152.8± 16.4	74.3±16.5	44.8±13.7		8.5±15.0
9	bright south eastern lobe	1362.8± 22.8	613.8±19.5	406.6±14.0	261.9±11.8	186.9±15.9
10	weak south eastern lobe	1009.4± 28.2	312.3±26.4	207.0±21.4	19.7±19.1	36.2±25.0
11	bgs1 south eastern	316.0± 8.7	154.4± 8.6	54.6± 6.6	52.2± 4.7	30.0± 6.7
12	bgs north western jet	57.4± 6.8	8.4± 6.9	8.5± 4.7	12.0± 4.5	15.0± 5.7
13	bgs2 south eastern	152.8± 9.4	18.8± 9.2	23.1± 6.3	11.8± 6.1	34.7± 8.5

Table 8. Integrated flux densities of DA 240

No.	component	S_{tot} [mJy]				
		326 MHz	609 MHz	2695 MHz	4750 MHz	10550 MHz
1 – 4	total	17054.0±199.4	9234.2±130.2	2712.7±59.5	1767.4±37.8	1040.9±46.5
1	eastern lobe	10299.0±120.4	5688.7± 78.1	1809.6±31.2	1186.6±23.4	749.3±27.8
2	western lobe	6109.8± 84.8	3147.1± 60.2	721.9±30.8	456.5±19.4	195.7±24.6
3	core	549.4± 12.8	374.3± 11.2	189.2± 6.5	121.9± 3.9	76.6± 5.2
4	bgs north western	194.9± 13.0	67.4± 11.3			21.8± 5.5

Table 9. Integrated flux densities of 3C 236

No.	component	S_{tot} [mJy]				
		326 MHz	609 MHz	2695 MHz	4750 MHz	10550 MHz
1 – 6	total	13132.0±140.0	8227.7±90.8	3652.0±71.2	2353.5±41.7	1274.7±31.7
1	core	7409.5± 76.0	4999.4±51.9	2355.5±31.1	1579.1±19.3	875.6±14.1
2	western lobe	588.1± 22.3	348.6±18.3	153.0±18.3	36.4±14.4	40.3±13.6
3	western hot spot	1275.1± 16.5	761.1±11.5	263.4± 8.5	176.4± 6.7	115.8± 7.0
4	eastern lobe	1908.1± 25.5	1008.5±17.3	353.3±13.3	179.9±10.8	75.3±10.7
5	bgs east	660.0± 10.1	444.1± 7.8	149.3± 5.0	152.2± 5.0	99.3± 5.2
6	eastern hot spot	1062.6± 18.6	513.2±11.9	283.2±13.4	221.2± 9.6	76.7± 8.9
7	bgs south eastern	342.1± 12.7	203.1±11.6	106.1± 9.4	25.3± 6.1	10.6± 6.7
8	bgs south	702.1± 15.6	408.0±11.6			41.7± 8.2
9	bgs north	306.4± 10.6	189.3± 8.5	76.0± 6.0	56.9± 5.9	29.2± 6.5

Table 10. Integrated flux densities of 3C 326

No.	component	S_{tot} [mJy]				
		326 MHz	609 MHz	2695 MHz	4750 MHz	10550 MHz
1 – 5	total	11955.4±128.0	7398.2±108.9	2222.1±73.8	1301.2±13.3	434.3± 16.0
1	eastern lobe	6797.6± 72.7	4088.6± 47.2	1275.3±30.9	717.9± 7.3	235.9± 8.5
2	centre	3382.0± 38.7	2164.3± 27.9		319.8± 3.3	86.7± 6.4
3	western lobe	1534.6± 22.9	982.5± 18.8	933.6±43.7	232.1± 2.4	114.1± 5.6
4	bgs west	122.0± 13.4	62.6± 12.1		15.6± 0.5	
5	bgs north	129.1± 10.0	111.4± 10.3		19.6± 0.4	

had to be cut at their north-western and south-western edge (owing to limited observing time) but they can still yield valuable information on intensities and polarization characteristics of the major part of the source. For a complete 2.7-GHz map we refer to Stoffel & Wielebinski (1978), which confirms our results. The polarization maps show that the north-western lobe is strongly polarized, with degrees of polarization as high as 70% (609 MHz). Polarized radiation is detected in most parts of the lobe. In contrast, the south-eastern lobe shows much less extended polarization, but again with high degrees ($\sim 50\%$). The jet is weakly polarized ($p < 5\%$) close to the core. This suddenly changes beyond $3'3''$ where the map of polarized intensity shows its maximum. The fractional polarization increases to 23%. It is striking that it coincides with the edge of the diffuse lobe emission. The orientation of the $\mathbf{E}$ -vectors indicates the presence of magnetic fields coherent over several arcminutes at 326 MHz. At 609 MHz these scales are even larger, suggesting the patchy structure of a depolarizing sheath.

4. The integrated spectra

We have determined the total flux densities of the entire sources and – where possible – of individual components. All maps, except the 2.7-GHz data, have been smoothed to a common beam size of $150'' \times 150''$ (determined by the resolution at 4.8 GHz). In the case of 3C 326 the final beam size in declination is defined by the original resolution of the 326-MHz map ($150'' \times 161''$). At 2.7 GHz we took the original beam of $261'' \times 261''$. Because of this lower resolution it was difficult in some cases to integrate across the same areas. The larger beam may also lead to higher flux densities because of confusion. Their effect will disappear in most cases when determining spectral indices pixel by pixel which will be reported in a forthcoming paper. The 609-MHz data are affected by missing-spacing effects, which implies that the flux densities are lower limits.

As already mentioned, the 2.7- and 4.8-GHz maps had to be cut in some cases. When that happened we did not give flux densities. The error calculation includes errors introduced by zero-level uncertainty, errors coming from the map noise, and calibration errors. Since systematic errors such as missing flux due to missing spacings, variable baselines, or different noise levels across the map cannot be included, the error ranges might be underestimated in some cases. Therefore, we also show the flux densities in graphic form and comment on the spectra where necessary. For the sake of clarity we do not show any spectra of the background sources (bgs). All individual areas used to integrate the various component flux densities, their numbers given in Tables 7-11, are shown shaded in the finding charts (Fig. 5).

4.1. NGC 315

The spectrum ($S_\nu \sim \nu^{-\alpha}$) of the entire source is obviously dominated by the core which reveals a significant flattening towards higher frequencies ($\alpha_{\text{low}} = 0.59 \pm 0.01$; $\alpha_{\text{high}} = 0.12 \pm 0.01$). Here α_{low} is the spectral index between 326 and 609 MHz, α_{high} is determined between 4.8 and 10.6 GHz. We have determined the spectrum of the south-eastern lobe in both the southern brighter and the northern fainter part. The spectrum of the brighter part is straight, with $\alpha = 0.55 \pm 0.05$. The flux densities of the weak part are much more scattered, but the steeper spectral index of $\alpha = 0.82 \pm 0.23$ is obvious.

If the 2.7-GHz point is excluded, the bright western lobe has an almost straight spectrum, with $\alpha = 0.53 \pm 0.04$. The determination of a spectrum of the weak part of the western lobe is not possible since the flux densities are too strongly distorted. The spectrum of the western hot spot flattens towards high frequencies ($\alpha_{\text{low}} = 0.85 \pm 0.01$; $\alpha_{\text{high}} = 0.34 \pm 0.01$). The counter-jet region has a typical jet spectrum ($\alpha = 0.60 \pm 0.25$) up to 4.8 GHz. The bright knot within the jet has a spectral index of $\alpha = 0.60 \pm 0.01$. The possible background source in the counter-jet area possesses a spectrum of $\alpha = 0.70 \pm 0.24$, with a slight trend for a steepening towards higher frequencies. The spectrum of the huge backlobe of NGC 315 is still not well determined. The appearance of a typical spectrum with $\alpha = 0.72 \pm 0.11$ between 326 MHz and 4.8 GHz is in contrast to the excess at 10.6 GHz, which has already been noticed by Klein et al. (1994), and is still significant even after CLEANing.

4.2. DA 240

The total spectrum is obviously dominated by the influence of the very bright hot spot within the eastern lobe, which shows a flattening of the spectral index towards higher frequencies ($\alpha_{\text{low}} = 0.95 \pm 0.01$; $\alpha_{\text{high}} = 0.58 \pm 0.01$). The spectra of the western lobe and the core are almost straight, with $\alpha = 0.98 \pm 0.01$ and $\alpha = 0.56 \pm 0.01$, respectively. The slight relative excess of the 2.7-GHz flux density can be explained by confusion of the core region when observed with the $261'' \times 261''$ beam.

4.3. 3C 236

The spectrum of the entire source shows a deficit of the 609-MHz value, which can be explained by missing spacings of the interferometer. The core spectrum shows excessive 2.7- and 4.8-GHz values, most likely because of confusion of the western lobe, and possibly owing to CLEAN artifacts. The overall core spectrum between 326 MHz and 10.6 GHz is $\alpha = 0.61 \pm 0.01$.

The eastern lobe spectrum reveals similar problems. The 609-MHz flux density is too low relative to the other values, which can again be explained by missing zero spacings. The 2.7-GHz and maybe also the 4.8-GHz

Table 11. Integrated flux densities of NGC 6251

No.	component	$S_{\text{tot}} [\text{mJy}]$				
		326 MHz	609 MHz	2695 MHz	4750 MHz	10550 MHz
1 – 8	total	11551.0 $\pm$ 175.9	6930.4 $\pm$ 123.4			1548.4 $\pm$ 55.0
1	core+jet	4739.9 $\pm$ 52.1	3390.8 $\pm$ 37.8	2098.0 $\pm$ 27.2	1637.6 $\pm$ 18.7	1129.5 $\pm$ 14.3
2	western lobe	3120.9 $\pm$ 85.8	1595.5 $\pm$ 63.4			213.5 $\pm$ 26.4
3	hot spot western lobe	572.0 $\pm$ 10.9	388.1 $\pm$ 7.8	170.0 $\pm$ 4.8	116.2 $\pm$ 3.9	70.2 $\pm$ 4.3
4	bgs1 western lobe	208.1 $\pm$ 6.7	125.4 $\pm$ 5.1		21.8 $\pm$ 2.6	16.3 $\pm$ 3.0
5	bgs2 western lobe	24.1 $\pm$ 6.4	7.6 $\pm$ 4.2			
6	counter-jet	323.5 $\pm$ 33.0	121.7 $\pm$ 25.7	24.6 $\pm$ 16.9		47.1 $\pm$ 13.5
7	hot spot eastern lobe	205.0 $\pm$ 8.2	143.2 $\pm$ 6.1	107.6 $\pm$ 6.3	4.4 $\pm$ 3.5	2.2 $\pm$ 3.5
8	eastern lobe	2402.8 $\pm$ 64.4	1365.3 $\pm$ 48.4			8.7 $\pm$ 25.3

point suffer from confusion with the core emission. If the 4.8-GHz point is regarded as real, a slight convex curvature of $\Delta\alpha = 0.2$ is indicated. Between 326 MHz and 10.6 GHz a spectral index of $\alpha = 0.93 \pm 0.01$ has been derived. The western lobe spectrum ($\alpha = 0.77 \pm 0.01$) has also been determined using the measurements at the lowest and highest frequency only, since the 2.7-GHz flux density is too high (confusion) and the 4.8-GHz value is uncertain because of an artificial depression in this part of the map. The western hot spot again reveals a slight flattening ($\alpha_{\text{low}} = 0.83 \pm 0.01$; $\alpha_{\text{high}} = 0.53 \pm 0.01$). The measurements in the eastern hot spot area and of the background source west of the hot spot are too uncertain to determine the overall spectrum, owing to confusion.

4.4. 3C 326

All spectra determined here show a clear steepening towards higher frequencies. The low- and high-frequency spectral indices have been compiled in Table 12.

Table 12. Spectral indices of 3C 326 (Errors are in all cases ≤ 0.01)

	total	centre	east lobe	west lobe
α_{low}	0.77	0.72	0.82	0.72
α_{high}	1.38	1.64	1.40	0.89

4.5. NGC 6251

At 2.7 and 4.8 GHz, there are no reliable flux densities available for the two lobes, nor for the entire source, as the maps had to be restricted in size at these frequencies. The spectral indices between 326 MHz and 10.6 GHz are $\alpha = 0.77 \pm 0.04$ in the western lobe, and $\alpha = 0.58 \pm 0.01$ for the entire source. In the case of the eastern lobe we can only determine a low-frequency spectral index of $\alpha = 0.90 \pm 0.07$. The core spectrum is almost straight, with a

slight indication of a flattening towards high frequencies. The (straight) spectral index is $\alpha = 0.40 \pm 0.01$. The hot spot spectra are straight within the errors, with a large difference in the spectral indices between the eastern ($\alpha = 1.41 \pm 0.13$) and the western one ($\alpha = 0.60 \pm 0.02$). In the latter the influence of confusion is high because of the close neighbourhood of bright sources.

5. Summary

We have presented radio continuum maps of the five “classical” giant radio galaxies NGC 315, DA 240, 3C 236, 3C 326, and NGC 6251 at five different frequencies between 326 MHz and 10.6 GHz. All observations were obtained with full polarization information. We have integrated the intensities of the entire sources and also within individual components to derive spectra of these areas. We have obtained reliable data across almost the entire radio spectrum for these complex radio galaxies. In general, a spectral steepening is found for the diffuse components, indicating particle ageing. Quantitative analyses will follow in forthcoming papers.

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Fig. 1. Map of the total intensity of NGC 315 at λ 92 cm. Also shown are the $\mathbf{E}$ -vectors of the linearly polarized emission. Their lengths are proportional to the polarized intensity

Fig. 2. Map of the linearly polarized intensity of NGC 315 at λ 92 cm. The $\mathbf{E}$ -vectors have lengths proportional to the fractional polarization

Fig. 3. Map of the total intensity of NGC 315 at λ 49 cm (same layout as in Fig. 1)

Fig. 4. Map of the linearly polarized intensity of NGC 315 at λ 49 cm (same layout as in Fig. 2)

Fig. 5. Map of the total intensity of NGC 315 at λ 11 cm (same layout as in Fig. 1)

Fig. 6. Map of the linearly polarized intensity of NGC 315 at λ 11 cm (same layout as in Fig. 2)

Fig. 7. Map of the total intensity of NGC 315 at λ 6.3 cm (same layout as in Fig. 1)

Fig. 8. Map of the linearly polarized intensity of NGC 315 at λ 6.3 cm (same layout as in Fig. 2)

Fig. 9. Map of the total intensity of NGC 315 at λ 2.8 cm (same layout as in Fig. 1)

Fig. 10. Map of the linearly polarized intensity of NGC 315 at λ 2.8 cm (same layout as in Fig. 2)

Fig. 11. Map of the total intensity of DA 240 at λ 92 cm (same layout as in Fig. 1)

Fig. 12. Map of the linearly polarized intensity of DA 240 at λ 92 cm (same layout as in Fig. 2)

Fig. 13. Map of the total intensity of DA 240 at λ 49 cm (same layout as in Fig. 1)

Fig. 14. Map of the linearly polarized intensity of DA 240 at λ 49 cm (same layout as in Fig. 2)

Fig. 15. Map of the total intensity of DA 240 at λ 11 cm (same layout as in Fig. 1)

Fig. 16. Map of the linearly polarized intensity of DA 240 at λ 11 cm (same layout as in Fig. 2)

Fig. 17. Map of the total intensity of DA 240 at λ 6.3 cm (same layout as in Fig. 1)

Fig. 18. Map of the linearly polarized intensity of DA 240 at λ 6.3 cm (same layout as in Fig. 2)

Fig. 19. Map of the total intensity of DA 240 at λ 2.8 cm (same layout as in Fig. 1)

Fig. 20. Map of the linearly polarized intensity of DA 240 at λ 2.8 cm (same layout as in Fig. 2)

Fig. 21. Map of the total intensity of 3C 236 at λ 92 cm (same layout as in Fig. 1)

Fig. 22. Map of the linearly polarized intensity of 3C 236 at λ 92 cm (same layout as in Fig. 2)

Fig. 23. Map of the total intensity of 3C 236 at λ 49 cm (same layout as in Fig. 1)

Fig. 24. Map of the linearly polarized intensity of 3C 236 at λ 49 cm (same layout as in Fig. 2)

Fig. 25. Map of the total intensity of 3C 236 at λ 11 cm (same layout as in Fig. 1)

Fig. 26. Map of the linearly polarized intensity of 3C 236 at λ 11 cm (same layout as in Fig. 2)

Fig. 27. Map of the total intensity of 3C 236 at λ 6.3 cm (same layout as in Fig. 1)

Fig. 28. Map of the linearly polarized intensity of 3C 236 at λ 6.3 cm (same layout as in Fig. 2)

Fig. 29. Map of the total intensity of 3C 236 at λ 2.8 cm (same layout as in Fig. 1)

Fig. 30. Map of the linearly polarized intensity of 3C 236 at λ 2.8 cm (same layout as in Fig. 2)

Fig. 31. Map of the total intensity of 3C 326 at λ 92 cm (same layout as in Fig. 1)

Fig. 32. Map of the linearly polarized intensity of 3C 326 at λ 92 cm (same layout as in Fig. 2)

Fig. 33. Map of the total intensity of 3C 326 at λ 49 cm (same layout as in Fig. 1)

Fig. 34. Map of the linearly polarized intensity of 3C 326 at λ 49 cm (same layout as in Fig. 2)

Fig. 35. Map of the total intensity of 3C 326 at λ 11 cm (same layout as in Fig. 1)

Fig. 36. Map of the linearly polarized intensity of 3C 326 at λ 11 cm (same layout as in Fig. 2)

Fig. 37. Map of the total intensity of 3C 326 at λ 6.3 cm (same layout as in Fig. 1)

Fig. 38. Map of the linearly polarized intensity of 3C 326 at λ 6.3 cm (same layout as in Fig. 2)

Fig. 39. Map of the total intensity of 3C 326 at λ 2.8 cm (same layout as in Fig. 1)

Fig. 40. Map of the linearly polarized intensity of 3C 326 at λ 2.8 cm (same layout as in Fig. 2)

Fig. 41. Map of the total intensity of NGC 6251 at λ 92 cm (same layout as in Fig. 1)

Fig. 42. Map of the linearly polarized intensity of NGC 6251 at λ 92 cm (same layout as in Fig. 2)

Fig. 43. Map of the total intensity of NGC 6251 at λ 49 cm (same layout as in Fig. 1)

Fig. 44. Map of the linearly polarized intensity of NGC 6251 at λ 49 cm (same layout as in Fig. 2)

Fig. 45. Map of the total intensity of NGC 6251 at λ 11 cm (same layout as in Fig. 1)

Fig. 46. Map of the linearly polarized intensity of NGC 6251 at λ 11 cm (same layout as in Fig. 2)

Fig. 47. Map of the total intensity of NGC 6251 at λ 6.3 cm (same layout as in Fig. 1)

Fig. 48. Map of the linearly polarized intensity of NGC 6251 at λ 6.3 cm (same layout as in Fig. 2)

Fig. 49. Map of the total intensity of NGC 6251 at λ 2.8 cm (same layout as in Fig. 1)

Fig. 50. Map of the linearly polarized intensity of NGC 6251 at λ 2.8 cm (same layout as in Fig. 2)

Fig. 51. “Finding charts” of GRGs, delineating the individual regions where integrated flux densities have been determined (Tables 7-11).

Fig. 52. Spectra of NGC 315

Fig. 53. Spectra of DA 240 **Fig. 54.** Spectra of 3C 236

Fig. 55. Spectra of 3C 326

Fig. 56. Spectra of NGC 6251