

The ultra low-frequency spectral properties of bright extended radio galaxies in the 3CRR catalogue

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ABSTRACT

Context. Active galactic nuclei (AGN) jets are fundamental drivers of galaxy evolution, injecting kinetic energy into their environments. The large-scale morphology and spectral properties of these radio galaxies are consequences of complex particle acceleration, energy loss, and absorption processes. While the shape of the synchrotron spectrum encodes the plasma’s energetic history, understanding the physics of particle acceleration and duty cycles has historically been limited by a lack of well-resolved observations at ultra-low frequencies (<100 MHz), where the oldest cosmic ray electron populations are traced.

Aims. This study aims to perform the first comprehensive multi-frequency analysis of bright extended radio galaxies down to 58 MHz. The goal is to study electron acceleration mechanisms, accurately measure the low-frequency spectral shape, and constrain the injection index (α_{inj}) for a sample of Fanaroff–Riley (FR) I and II galaxies using spectral ageing models.

Methods. Utilising new 58 MHz observations from the LOFAR Low Band Antenna (LBA) combined with LOFAR High Band Antenna (HBA; 144 MHz) and Rapid ASKAP Continuum Survey (RACS, 887 MHz & 943.5 MHz & 1367.5 MHz) data, a sub-sample of 22 extended sources from the 3CRR catalogue was selected, requiring the largest angular size to be at least 2.5′. The analysis involves constructing detailed spectral index maps and utilising radio colour-colour diagrams to interpret spectral shapes and constrain ageing model parameters across the radio lobes.

Results. This study presents the ultra-low frequency spectral index maps for this sample. For FR I galaxies, spectral indices range from ~ 0.5 near the core (consistent with first-order Fermi acceleration) to > 1.0 in the lobes. For FR II galaxies, hotspots exhibit steep low-frequency spectra (0.5–0.9), suggesting complex acceleration or absorption effects.

Conclusions. The addition of ultra-low frequency data is critical for understanding radio galaxy age, energetics, and accurately constraining the injection index. While some sources follow standard ageing models in colour-colour space, those with complex morphologies often deviate from them, indicating that simple ageing models may not be applicable to all radio galaxy structures.

Key words. techniques: interferometric – galaxies: active – galaxies: jets – radio continuum: galaxies

1. Introduction

Active galactic nuclei (AGN) jets play a central role in regulating galaxy formation and evolution through the injection of kinetic energy into their surrounding environments, and they are believed to be among the most influential drivers of galaxy evolution (Croton et al. 2006; Bower et al. 2006; Cattaneo & Best 2009). Besides this, the formation of hundreds of kilo- to megaparsec scale lobes also injects kinetic energy into much larger scales such as those of groups and clusters of galaxies (Konar et al. 2008; Brienza et al. 2021). However, the mechanisms by which jets accelerate these particles to relativistic energies, how efficiently it couples to their environments, and how they evolve over their lifetimes are poorly understood.

The large-scale morphology of AGN at radio frequencies is a result of the complex physics of particle acceleration and matter accretion by the central black hole and the interaction between the ejected plasma lobes and the environment. Studying these extended structures provides fundamental insight into the underlying physical processes. The shape of the synchrotron spectrum

contains information on both acceleration and loss processes, while the variations in the localised spectra across the lobes contain information on the characteristic age and life cycle of the radio galaxies (e.g. Brienza et al. 2020).

Generally, two morphologically distinct types of radio galaxies are identified: Fanaroff–Riley (FR) class I and II galaxies (Fanaroff & Riley 1974). The former refers to centre brightened structures where the radio lobes decrease in brightness further away from the central AGN, which is believed to be due to deceleration and de-collimation of the jet (Bicknell 1994; Laing & Bridle 2014). The latter of the two classes, on the other hand, are edge brightened, and almost always with distinctive hotspots at the terminal point of the jets. Another physical distinction between the two FR types is that for FR Is, the acceleration happens close to the central AGN while for FR IIs the acceleration is also manifested at the hotspots (e.g. Alexander 1987; Katz-Stone et al. 1993).

Despite their importance, our understanding of the physics, energetics, and duty cycles of radio galaxies has historically been based on small samples of bright, nearby objects due to the difficulty to constrain the key dynamic properties (e.g. Konar et al. 2008; Jamrozy et al. 2008). This is largely due

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to the fact that the radiating plasma records a complex history of particle acceleration, radiative ageing, and magnetic-field evolution that is not directly observable at a single frequency or epoch. Wide-area radio surveys are now transforming this picture. Large area surveys such as the Low Frequency Array (LOFAR; [van Haarlem et al. 2013](#)) Two Metre Sky Survey (LoTSS; [Shimwell et al. 2019](#)), the MeerKAT MIGHTEE survey ([Jarvis 2012](#)), and the Rapid ASKAP Continuum Survey (RACS, [McConnell et al. 2020](#)) provide large, homogeneous samples spanning a wide dynamic range in luminosity, redshift, and environment. However, a comprehensive study of resolved radio galaxies below 100 MHz is missing. This study presents the first such comprehensive multi-frequency analysis of radio galaxies down to 58 MHz using the LOFAR telescope.

The Low Band Antenna (LBA) system of LOFAR, operating between 10 and 90 MHz, in particular provides access to a spectral regime that has remained largely unexplored at angular resolutions below 30''. These frequencies trace the oldest electron populations – particles whose radiative lifetimes may exceed tens of millions of years – and therefore encode crucial information about past jet activity, duty cycles, and the integrated energy released by the AGN. A recent work by [Boxelaar et al. \(2025\)](#) produced maps of the entire Third Cambridge Catalogue of Radio Sources (3CRR; [Laing et al. 1983](#)) of the brightest radio galaxies in the northern sky. The 3CRR catalogue consists of the brightest extragalactic radio sources with flux densities $S_\nu > 10 \text{ Jy}$ at 178 MHz. Sources are constrained to have a declination $\delta > 10^\circ$, and to be more than 10° below or above the galactic plane. This sample contains 173 sources, among which are the most extended and bright FR I and IIs in the sky, and it provides an excellent opportunity to utilise the lowest frequencies to study the spectral and dynamical properties of bright radio galaxies.

For many years, workers in the field have tried to characterise the acceleration mechanism in radio galaxies by measuring the injection index α_{inj} ([Katz-Stone et al. 1993](#); [Katz-Stone & Rudnick 1997](#); [Hardcastle 1999](#); [Young et al. 2005](#); [Laing & Bridle 2013](#)), which as the name suggests is directly related to the energy spectrum of freshly injected plasma into the medium either at the core (for FR I) or at the hotspots (for FR II). The initial energy number density of the electrons injected into the medium is $N(E) = N_0 E^{-\delta}$ ([Pacholczyk 1970](#)), where δ is related to the injection index through $\delta = 2\alpha_{\text{inj}} + 1$. Different models of particle acceleration predict different distributions of values of α_{inj} that can be measured. First-order Fermi acceleration in strong, non-relativistic shocks ([Bell 1978](#)), for example, predict $\alpha_{\text{inj}} = 0.5$, while the limit for ultra-relativistic shocks is 0.615 ([Kirk et al. 2000](#)) and mildly relativistic shocks can produce a variety of spectral slopes (see [Summerlin & Baring 2012](#); [Laing & Bridle 2013](#) for a more comprehensive discussion). These works often expressed the need for more high-resolution low-frequency observations to better constrain the injection indices and be more conclusive regarding the possible acceleration mechanisms. In a previous work, we produced images at 15'' resolution at a frequency of 58 MHz for the entire 3CRR sample ([Boxelaar et al. 2025](#), hereafter Paper I). This allowed us to accurately measure α_{inj} with high-resolution radio data at frequencies <100 MHz for the first time.

This paper presents the methods, prospects and limitations for studying electron acceleration mechanisms with future LBA observations. We took a sub-sample containing the most extended sources presented in Paper I and combine it with higher frequency data from LOFAR HBA at 144 MHz and ASKAP-low

and ASKAP-mid to comprehensively measure the low frequency spectral index and constrain the injection index based on ageing models (see the next section for the definition). The sub-sample contains 22 3CRR sources and this allows us to present the most comprehensive comparison yet of the ultra-low frequency spectral structure of bright FR I and FR II galaxies. In Section 2 we further describe the sample and source selection, Section 3 shows the resulting spectral index maps and injection index measurements. We subsequently discuss the results and caveats of the analysis in Section 4 and list the conclusions in Section 5.

A key aspect of the study of radio galaxies is understanding their dynamical history and evolution. Through this evolution, we try to understand the (re-)acceleration mechanisms that allows the observation of up to mega parsec scale radio lobes ([Simonte et al. 2024](#); [Andernach & Brüggemann 2025](#)). Spectral analysis of radio galaxies reveals their dynamical history through observed synchrotron energy losses (see e.g. [Jamrozy et al. 2008](#); [Orrù et al. 2010](#); [Harwood et al. 2017](#); [Turner et al. 2018b](#); [Patra & Pal 2024](#)). Studying AGN plasma properties through the spectral signatures of synchrotron energy losses, also known as synchrotron ageing, has become common practice and allows us to infer the approximate age of the plasma as well as deriving order of magnitude estimations of the magnetic field strength (e.g. [Harwood et al. 2013](#); [Hardcastle 2013](#); [Harwood et al. 2015](#)). Low frequency observations are especially useful in spectral modelling as the slope of the low frequency end of the spectrum constrains one of the model parameters: the injection index α_{inj} .

Generally, five mechanisms of energy loss are considered: ionisation of the local medium, free-free radiation, synchrotron radiation, inverse Compton radiation ([Pacholczyk 1970](#)) and finally adiabatic losses due to expansion or compression, which become relevant at kiloparsec scales. The latter two losses have the same energy dependency and are often considered as the only dominant loss of electron energy for relativistic electrons ([Harwood et al. 2013](#)). The synchrotron radiation loss over time scales as $-AE^2$, where A is a time independent term depending on primarily the magnetic field and the angle of the magnetic field vector and the direction of motion of the electron ([Rybicki & Lightman 1979](#)). At higher electron energies (hence higher frequencies) the loss is greater and this is why a steepening towards higher frequency is expected. The two most widely used ageing models are the JP ([Jaffe & Perola 1973](#)) and KP ([Kardashev 1962](#); [Pacholczyk 1970](#)) models, both of which assume a single cosmic ray electron injection at $t = 0$. These models are especially useful for the study of resolved lobes and hotspots as there the assumption of a single energy injection has been shown to fit fairly well. This of course relies on the availability of spatially resolved, high fidelity radio observations at multiple frequencies, something that is often unavailable, especially at lower frequencies. With the data presented in this work, it becomes possible for the first time to extend the ageing analysis to the ultra-low frequency regime and study whether these ageing models still hold.

Because only a small portion of the sample is resolved at the level that the source is spanned by multiple beam sizes, one could consider adopting an alternative to the JP and KP models that is supposedly suitable for the study of unresolved sources. One variation assumes a continuous injection (CI) of new electrons which allows us to model the spectral ageing using the integrated spectrum of the entire radio source ([Pacholczyk 1970](#)). The CI model does however have some significant limitations and it has been argued by multiple authors that considering integrated spectra does not reflect the

physical properties of the radio source (e.g. Young et al. 2002, 2005; Harwood 2017; Jerrim et al. 2025). Another variation by Komissarov & Gubanov (1994) modifies JP and KP models to take into account the finite lifetime of the injection of relativistic particles. This variation works especially well for relic radio galaxies.

Assuming that a single population of plasma electrons is injected into the lobes with a single magnetic field strength B , with an initial power-law number density, the flux density at a fixed frequency S_ν is given by

$$S_\nu = C_1 \int_{\gamma_{\min}}^{\gamma_{\max}} \int_0^\pi F\left(\frac{\nu}{\nu_c}\right) n_e(\gamma) B \sin^2 \theta \, d\gamma d\theta. \quad (1)$$

In this equation, $C_1 = \sqrt{3}e^3 B / 8\pi\epsilon_0 c m_e$ (see Harwood et al. 2013), $F(\nu)$ describes the synchrotron emissivity of a single cosmic ray electron in a magnetic field (see Rybicki & Lightman 1979), n_e is the free electron number density as a function of Lorentz factor and θ is the pitch angle between the magnetic field vector and the velocity vector of the electrons. Following the derivations of Harwood et al. (2013, 2015) we adopted an electron energy density (as a function of the Lorentz factor γ) for the JP and KP models given by

$$n(\gamma) = n_0 \gamma^{-\delta} (1 - A_{JP} \gamma t)^{-\delta-2}, \quad (2)$$

where $A_{JP} = \frac{4\sigma_t}{6m_e^2 \nu_c^2 \mu_0} B^2$ and $\nu_c = 3\gamma^2 e B_\perp / 4\pi m_e c$ is the ‘critical frequency’. Although the models are slightly different, the resulting injection index is physically the same. For the KP model, $A_{KP} = A_{JP} \sin \theta$.

Currently accepted ageing models make assumptions on constant magnetic fields throughout the lobe or large portions of it and assume a single injection index, implicitly assuming a constant jet power over the AGN accretion history and a single dominant particle acceleration mechanism. Trying to fit the spectral shape in different parts of a lobe to different ageing models has become common practice. There are a few limitations to this practice (e.g. Harwood et al. 2013; Turner et al. 2018b,a; Mahatma et al. 2020; Wolnik et al. 2024). First, it is often difficult to obtain high-fidelity and high-resolution images of sources spanning a decent frequency range. This will naturally limit the number of measurements in frequency space and thus the accuracy of fits with a high degree of freedom for model parameters. Second, low frequency surveys like the VLA Low-Frequency Sky Survey (VLSS, Cohen et al. 2007) at 74 MHz have low resolution (1.4') and high-resolution surveys exist only above a few hundreds of GHz, often forcing the analysis to high frequency ranges which do not allow for a good constraint on the injection index of the observed plasma.

2. Observations and sample

In this paper we continued the work published recently by Boxelaar et al. (2025), where we presented the entire 3CRR catalogue observed with LOFAR at 58 MHz. The full description of the 3CRR sample and a comprehensive description of the observations and resulting maps are discussed there¹. This work takes a subset of that catalogue, complemented by observations at higher frequencies, to study the detailed spectral properties of these radio galaxies.

Table 1. Summary of observations.

Instrument	Freq. [MHz]	Median RMS mJy beam ⁻¹	Flux scale err.
LOFAR LBA ^a	57.7	10	10%
LOFAR HBA ^b	144	0.132	10%
RACS (low) ^c	887.5	0.266	7%
	943.5	0.205	7% ^c
RACS (mid) ^c	1367.5	0.198	7%
RACS (high) ^c	1655.5	0.209	7%

Notes. For every observation we note the central observing frequency, the median RMS noise and the flux scale error taken from the relevant reference. ^(a)Boxelaar et al. (2025); ^(b)Shimwell et al. (2019); ^(c)McConnell et al. (2020).

2.1. Sample of extended radio galaxies

With the new observations at 58 MHz, we have the unique opportunity to study FR I and FR II galaxies down to very low frequencies. Since this study requires sources to be rather extended, we have constructed a subsample of 3CRR containing only extended sources, i.e. large sources with a linear angular size (LAS) of at least ten beam-sizes in the LBA data. Furthermore, we required all sources to be covered by the same collection of surveys. The homogeneity requirement is not easy to uphold as there are virtually no surveys besides LoTSS (Shimwell et al. 2019) at 144 MHz with a full northern sky coverage, a resolution ~20'' and sensitivity to arc-minute scale diffuse emission. The survey that comes closest to the requirements is the Rapid ASKAP Continuum Survey (RACS, McConnell et al. 2020), having coverage <40° Dec and three frequency bands being RACS-low (887 MHz or 943.5 MHz, McConnell et al. 2020), RACS-mid (1367 MHz, Duchesne et al. 2023) and RACS-high (1655 MHz, Duchesne et al. 2025). Sources from ASKAP-low are observed at either 887 MHz or 943 MHz. We adopt 887 MHz as the representative frequency for RACS-low throughout to avoid confusion. Figures will always indicate the right frequency of the observation of that source. RACS images are reported to have a median noise of 330 μJy beam⁻¹. This is summarised in Table 1. The subsample of sources for which we can carry out the spectral analysis is constrained by:

- Part of the 3CRR sample
- Linear size larger than 10 LBA beams (15'')
- Covered by LoTSS DR3
- Dec < 40° (covered by RACS)

Table 2 shows the subsample and summarises some characteristics. The final beam refers to the resolution of the images used for the analysis in Section 3. As the beam of RACS maps tends to be quite elongated, due to the low elevation of most sources for RACS, we were forced to convolve with a relatively large beam ranging from 25'' × 25'' to 46'' × 46''. This is mainly due to the low resolution of RACS-low, but as it is an essential frequency to cover between LoTSS and GHz regime, we did not discard it. For the LoTSS DR3 (Shimwell et al. 2026) 144 MHz cutouts we used the 20'' maps (instead of the higher resolution 6'' variation) to be more sensitive to diffuse emission and since the poorer resolution of RACS-low does not compromise image quality. The resulting subsample containing 22 sources is summarised in Table 2. To the authors' knowledge, there are only two sources in this subsample which have been studied in the ultra-low frequency regime before. 3C 31 and 3C 223 are the only ones previously studied using LBA (Heesen et al.

¹ The LBA and HBA radio maps for all sources can be found at <https://www.lofar-surveys.org/3CRR-LBA.html>

Table 2. Subsample of extended sources used in spectral analysis.

Object	LAS ^a	FR type ^a	$S_{58\text{ MHz}}$ Jy	Dyn. range	σ_{rms} mJy beam ⁻¹	Final beam "×"
ASKAP available						
3C 192	3.34'	II	58.7	98	7.3	25.0 × 25.0
3C 223	5.11'	II	38.0	76	9.5	39.7 × 39.7
3C 236	40.76'	II	38.0	95	11.7	41.2 × 41.2
3C 264	6.60'	I	63.9	31	12.1	25.0 × 25.0
3C 284	2.96'	II	39.4	69	8.8	25.0 × 25.0
3C 296	7.00'	I	27.2	17	12.3	25.0 × 25.0
3C 31	44.19'	I	51.8	95	10.5	45.6 × 45.6
3C 310	5.09'	I	182.7	15	10.2	26.1 × 26.1
3C 326	20.15'	II	47.6	14	41.1	26.2 × 26.2
3C 33	4.15'	II	118.1	68	13.4	25.0 × 25.0
3C 382	3.20'	II	63.4	53	9.8	30.6 × 30.6
3C 442a	10.08'	II [†]	53.3	31	13.4	25.0 × 25.0
3C 449	24.97'	I	28.7	9	14.0	46.6 × 46.6
3C 452	4.53'	II	165.0	50	8.6	46.6 × 46.6
3C 457	3.49'	II	41.3	35	12.2	25.0 × 25.0
3C 46	2.63'	II	28.6	57	6.5	38.5 × 38.5
3C 465	9.75'	I	110.0	17	12.0	25.0 × 25.0
3C 76.1	3.32'	I	23.8	17	11.2	25.0 × 25.0
3C 98	5.11'	II	121.7	60	10.1	25.0 × 25.0
4C 12.03	3.59'	II	27.3	5	12.7	25.0 × 25.0
NGC 6109	14.74'	I	27.6	16	18.8	31.3 × 31.3
NGC 7385	13.83'	I	37.7	30	12.8	25.0 × 25.0
Poor LBA quality						
3C 293	4.28'	I	31.4	125	8.8	
3C 314.1	3.35'	I	37.35	33	39.91	
3C 315	3.36'	I	62.2	15	51.6	
3C 321	5.13'	II	45.4	118	8.8	

Notes. Of the sources at the bottom of the table, 3C 314.1 and 3C 315 was excluded from the analysis due to poor quality of the LBA image (calibration errors). 3C 293 and 3C 321 were excluded because there is no visible two sided lobes in this source, only the core and hotspots at the end of the lobes. [†]In the reference, this source is listed as FR I, but the colour-colour diagram is more consistent with an FR II. See Section 4 for a discussion. ^(a)<https://3crr.extragalactic.info/>

2018; Harwood et al. 2016) and 3C 223 has also been studied at 74 MHz using the VLA (Orrù et al. 2010). This emphasises the novelty of our ultra-low frequency maps. Notable extended sources at Dec > 40° missing from this list due to the lack of RACS data are e.g. 3C 35, 3C 83.1B, DA 240, 4C 73.08 and NGC 6251. The Perseus cluster (3C 83.1B & 3C 84) has also been observed with broadband observations by Groeneveld et al. (2026).

2.2. Spectral index maps

In order to study the radio spectral shape in Section 3.3 we need good spectral index maps. We constructed spectral index maps for all the extended sources by first convolving all images to a minimum common circular beam and regridding those images to equal world coordinate system projections. The astrometric alignment is done in an automated way based on the locations of various point sources in the field around the source of interest. Depending on the field and map noise there might not be many point sources bright enough to align with. Therefore in some cases additional manual, sub-pixel alignment was needed to obtain usable spectral index maps. We checked for flux density offsets by plotting integrated flux densities compared to expectations from the SEDs of Boxelaar et al. (2025) in Figure 1.

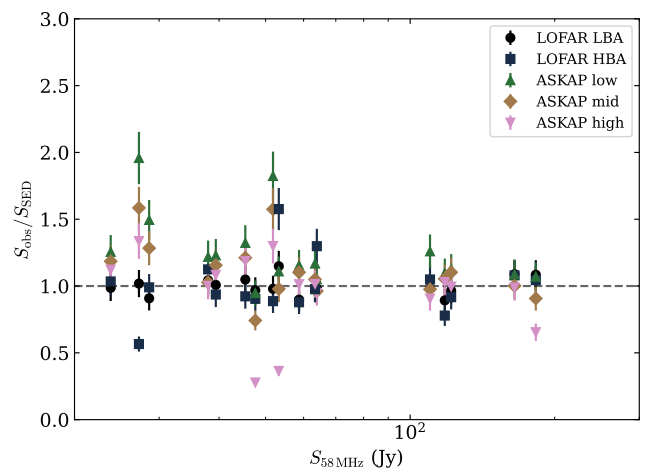


Fig. 1. Ratio of measured integrated flux density over the expected flux density from the SEDs from Boxelaar et al. (2025) for all frequency maps as a function of the LBA flux density.

Although we did not find significant offsets, this check did show that maps exhibit a larger scatter for low surface brightness

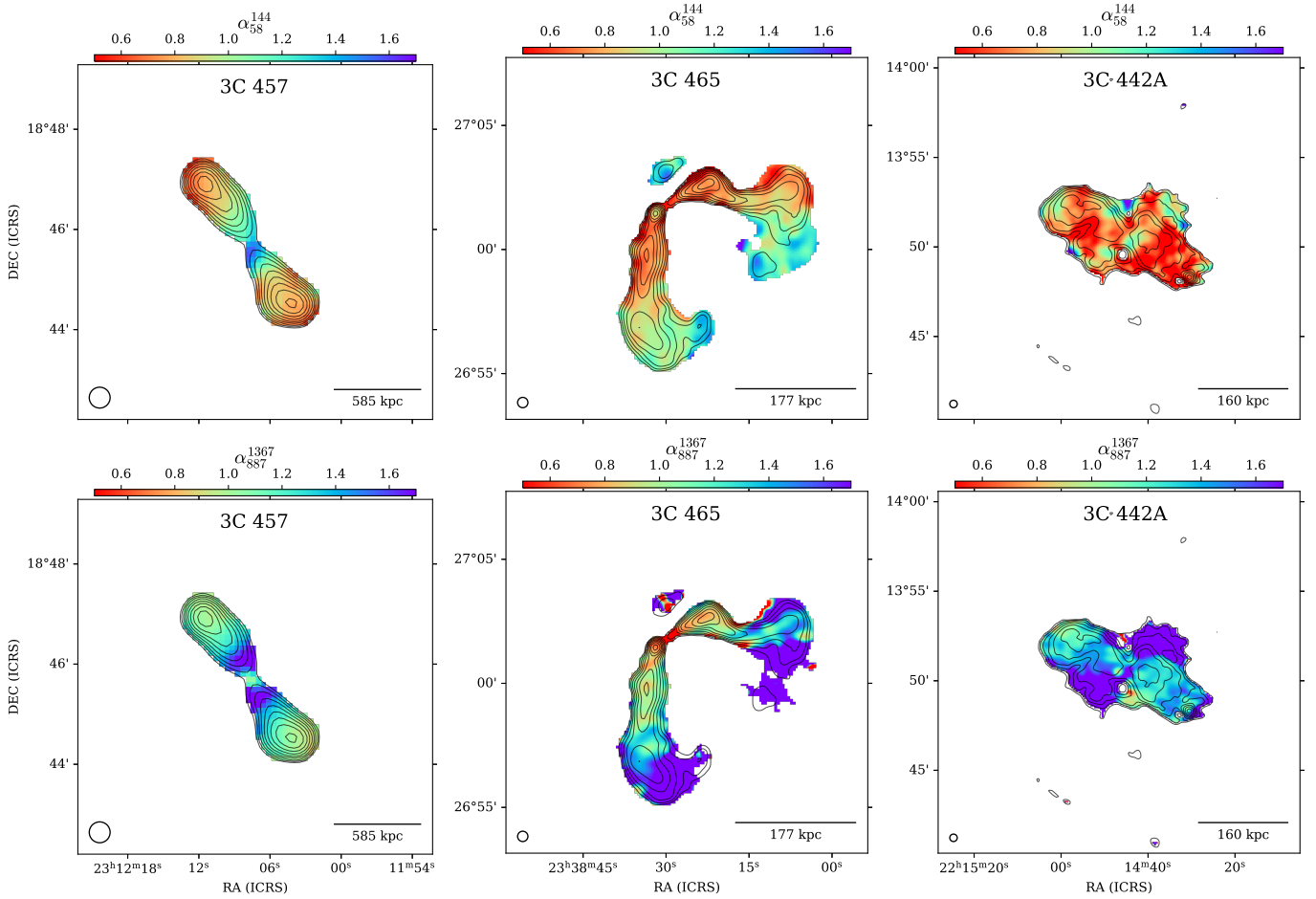


Fig. 2. Spectral index maps for 3C 457, 3C 465, and 3C 442A at $25'' \times 25''$. The colour scale is set between 0.5 and 1.7 for every image. The contours are drawn at $[3, 5, 10, 50, 100, 200] \times \sigma_{\text{rms}}$ of the LBA image. Every map shows spectral index values with a threshold of $2\sigma_{\text{rms}}$. Finally, the beam for that map and the physical scale of the source are also indicated.

sources, which will result in poor quality spectral index maps and colour-colour plots.

Uncertainties on spectral indices derived from integrated regions or single pixels may be divided into two different contributions. Uncertainties on the integrated flux densities are a combination of stochastic errors from underlying rms noise, independently distributed per beam area, and the systematic calibration error, which effects the entire image, or at least the source of interest, equally. For the purpose of interpreting the colour-colour diagrams in the next subsection it is useful to keep these uncertainty contributions separated, since one of the contributions is a systematic error that gives rise to a systematic shift rather than scatter in the colour-colour diagram. The total combined uncertainty on measured flux density is

$$\Delta S_\nu = \sqrt{\left(J\sigma_{\text{rms}} \sqrt{\frac{n_{\text{reg}}}{A_{\text{beam}}}}\right)^2 + \Delta S_{\text{cal}}^2}, \quad (3)$$

where $J = 3$ is the on-source noise multiplier as also used in spectral age fitting software BRATS (Harwood et al. 2013), n_{reg} is the number of pixels in the region over which the flux density is measured and A_{beam} is the beam area in pixels. ΔS_{cal} is the calibration error which normally takes the form $E_i S_\nu$ where E_i is a percentage and S_ν the measured flux density. Recently, Boxelaar et al. (2025) determined the calibration error for LBA to be 10%. For LoTSS DR2, the conservative estimate is 10%

(Shimwell et al. 2019), which we used here. For RACS: $\Delta S_{\text{cal}} = 0.05 \text{ mJy} + 0.07 S_\nu$ (McConnell et al. 2020). As we only considered two frequencies at a time the spectral index is simply given by $\alpha = (\log S_1 - \log S_2) / (\log \nu_1 - \log \nu_2)$ with uncertainty

$$\sigma_\alpha = \log^{-1} \left(\frac{\nu_1}{\nu_2} \right) \sqrt{\left(\frac{\Delta S_1}{S_1} \right)^2 + \left(\frac{\Delta S_2}{S_2} \right)^2}, \quad (4)$$

where ΔS_i refers to both the calibration or the flux density measurement error of Equation (3).

Figure 2 shows examples of the low- and high-frequency spectral index maps for three archetypic sources. FR II galaxy 3C 457, FR I galaxy 3C 465 and the FR II galaxy 3C 442A with a more irregular morphology. 3C 457 shows hotspots with low spectral index (~ 0.6) at very low frequencies which steepen towards the AGN. Due to the inverted spectrum of the central AGN, the LOFAR spectral index map does not detect it, while the contribution from the core is visible in the high frequency map. As this emission is distinct from the lobe and hotspot emission, the central regions are ignored when constructing the colour-colour diagrams. The spectral index maps of 3C 465 highlight the value of the 50 MHz LOFAR LBA observations. The LBA is sensitive to the emission far away from the core and we were able to measure the spectral index in those regions while this is not possible using the higher frequency data. 3C 442A shows something similar: the LOFAR spectral index map reveals

Table 3. Injection and spectral indices.

Object	FR type ^a	α_{inj}	α_{58}^{144} Hotspot	α_{58}^{144} Lobe
3C 192	II	0.70 ± 0.03	0.88	0.90–0.95
3C 223	II	0.46 ± 0.06	0.5	0.65–0.75
3C 236	II	0.57 ± 0.21	0.8	0.70–1.10
3C 264	I	0.51 ± 0.26	–	0.60–0.80
3C 284	II	0.84 ± 0.04	0.79	0.95–1.05
3C 296	I	0.43 ± 0.02	–	0.55–0.60
3C 31	I	0.38 ± 0.17	–	0.60–1.10
3C 310	I	0.60 ± 0.05	–	0.80–0.95
3C 326	II	0.60 ± 0.20	0.49	0.80–1.00
3C 33	II	0.53 ± 0.10	–	0.60–1.10
3C 382	II	0.69 ± 0.04	0.9	0.85–0.95
3C 442A	II	0.46 ± 0.09	0.75	0.50–0.80
3C 449	I	0.47 ± 0.18	–	0.50–1.00
3C 452	II	0.68 ± 0.02	0.75	0.85–1.00
3C 457	II	0.78 ± 0.09	0.80	0.90–1.40
3C 46	II	0.84 ± 0.02	0.80	0.85–0.95
3C 465	I	0.49 ± 0.10	–	0.65–1.15
3C 76.1	I	0.67 ± 0.13	–	0.85
3C 98	II	0.72 ± 0.06	0.61	0.70–1.05
4C 12.03	II	0.68 ± 0.07	0.81	0.95–1.05
NGC 6109	I	0.54 ± 0.21	–	0.70–1.00
NGC 7385	I	0.45 ± 0.10	–	0.80–1.50

Notes. Fitted injection indices of the sub-sample of extended radio galaxies. Uncertainties are obtained from the RMSD mentioned in Section 3.4. ^(a)<https://3crr.extragalactic.info/>

additional diffuse emission perpendicular to the bright east-west oriented lobe. The spectral index is relatively constant throughout the source compared to the other two sources in the figure.

3. Results

Throughout the remainder of this work, the injection index α_{inj} refers to the spectral index of the freshly injected cosmic ray population, defined through the initial power-law energy distribution $N(E) \propto E^{-\delta}$ with $\delta = 2\alpha_{\text{inj}} + 1$. It represents the flattest spectral index expected anywhere in the source, corresponding to zero-age plasma, and is one of the key parameters of the JP and KP ageing models described in Section 1. Its measurement from colour-colour diagrams is described in detail in Section 3.4.

Both low frequency spectral index maps (α_{58}^{144}) and high frequency spectral index maps (α_{887}^{1367}) are shown in Appendix A. The uncertainty on the spectral indices can be derived from the error bars in Appendix B.

3.1. FR Is

The overall low frequency spectral index α_{58}^{144} in the lobes of FR I type radio galaxies varies from 0.5 close to the core to above 1.0 far into the lobes. There is a great variety of spectral indices depending on the location in the lobe. Many FR Is have a spectral index of about 0.5 near the core, consistent with first-order Fermi acceleration. In Section 3.4 we showed that this value is consistent with most measured α_{inj} , which implies that the emission close to the core is representing the injected plasma. The spectral index maps of this class of radio galaxies are generally

more complex than for the FR IIs due to the low surface brightness in the far ends of the diffuse lobes.

3.2. FR IIs

The global low frequency spectral indices in the lobes and, for FR IIs, the hotspots are listed in Table 3. The low frequency spectral index in the hotspots vary between 0.5 and about 0.8, with values reaching up to 0.9 for 3C 192 and 3C 382. Values between 0.7 and 0.8 are not uncommon for higher frequency observations (Harwood et al. 2013, 2015). Furthermore, Harwood et al. (2016) has shown that hotspot spectra can remain steep to ultra-low frequencies. Table 3 reveals the spectral index in the hotspot is steeper than the measured injection index in almost every case. This was hinted at by Harwood (2017) for 3C 223 and 3C 452 using 144 MHz as their lowest frequency. Here we confirmed this observation for a larger sample while also including 58 MHz observations. The colour-colour diagrams of 3C 452, 3C 457, 3C 46 and 3C 284 (see Figure 3 for 3C 457, and Figure B.2 for the other sources) indeed show the hotspot regions (in red) never reach the solid line where we expect freshly injected electrons. This can be due to absorption or more complex acceleration mechanisms within the hotspots or mixing. In Section 4 we discuss the topic of mixing in more detail. Harwood (2017) found a α_{inj} of 0.68 for 3C 223 and 0.70 for 3C 452 through a grid search of the JP parameter space. While we found a similar value for 3C 452, we obtained a very flat $\alpha_{\text{inj}} = 0.46 \pm 0.06$ for 3C 223. The discrepancy can be due to the strong steepening at higher frequencies, driving up the α_{inj} measurement if ultra-low frequency data is missing.

3.3. Colour-colour diagram

The synchrotron colour-colour diagram is a way of examining the spectral shape of AGN lobes and other radio sources. It was first proposed by Katz-Stone et al. (1993) to characterise the spectral properties of Cygnus A. It has since then been used in multiple works as a way to fit ageing models to FR I and II type sources and radio relics (e.g. van Weeren et al. 2012; Rajpurohit et al. 2020; Bruno et al. 2024; Lusetti et al. 2024; Rajpurohit et al. 2025; De Rubeis et al. 2026). The colour-colour diagram is defined by the plane of two spectral indices between either three or four observing frequencies. In this work those could be either α_{144}^{57} or α_{887}^{57} against α_{1367}^{887} . The diagram provides visual information on the spectral shape of the lobe emission and the time evolution thereof. The line $\alpha_2^1 = \alpha_4^3$ defines the pure power-law with everything below it showing a steepening at higher frequency, and every point above the line showing a concave spectrum. Any line parallel to it encodes a spectrum of constant curvature.

Ageing models trace out curves in this diagram, where each point along a curve corresponds to a particular plasma age (see Katz-Stone et al. 1993, for details). The JP model produces a particularly simple curve: it follows the power-law line up to the injection index α_{inj} , then diverges steeply downwards. Only the injection index affects the shape of the curve (it sets the point along the power-law at which the curve begins) while the magnetic field strength only controls how quickly a source moves along the curve with increasing age.

A colour-colour diagram is particularly useful to obtain information on the global characteristics of the source. The single diagram contains both information about the injection index and how closely the source follows pure ageing models. Since all regions of the lobe are in one parameter plane this

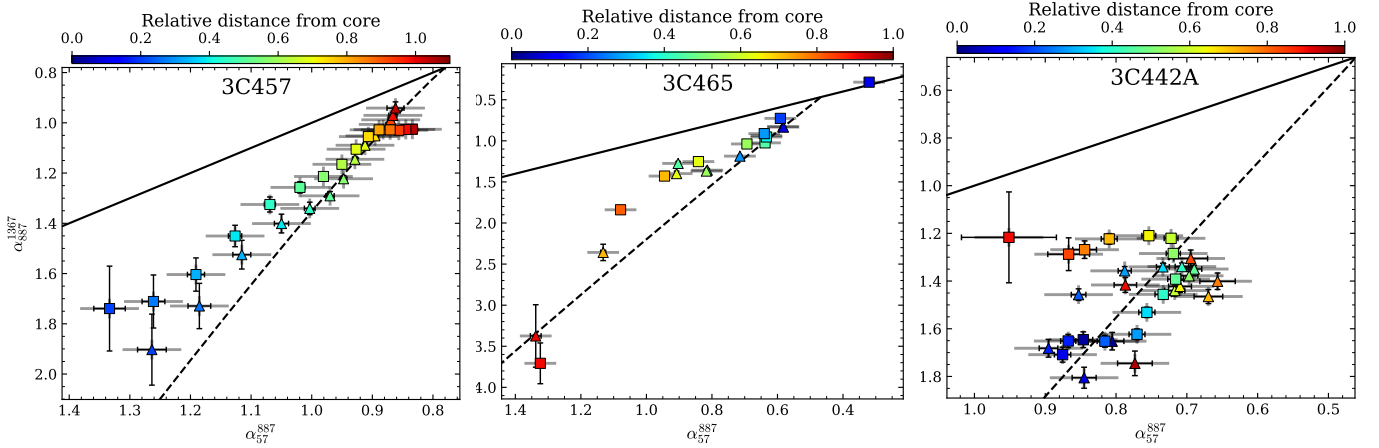


Fig. 3. Colour-colour diagrams for a typical FR II galaxy 3C 457 (left), a typical FR I galaxy 3C 465 (middle), and 3C 442A (right) in the $\alpha_{144}^{57} - \alpha_{1637}^{887}$ plane. The colour scale denotes the distance from the core relative to the approximate size in Table 2. The solid grey error bar denotes the possible systematic shift of data points due to calibration errors and the thin black error bars denote the rms flux uncertainty. The solid line denotes a pure power-law and the dashed line a JP model with $\alpha_{inj} = 0.78 \pm 0.09$ for 3C 457, $\alpha_{inj} = 0.5 \pm 0.1$ for 3C 465 and $\alpha_{inj} = 0.46 \pm 0.09$ for 3C 442A. The two lobes are differentiated by either showing a square or triangle. For both sources the region containing the core is excluded from the figure.

representation is more compact than e.g. point-by-point age fitting. In analysis involving age fitting, the magnetic field strength and age of the plasma are almost impossible to model accurately using just radio maps since the two parameters are fully degenerate. The degeneracy can be ignored in the colour-colour diagram as the curve of an ageing model is independent of magnetic field and age. The magnetic field only changes how ‘quickly’ a point moves along the curve per age interval. The slope of the diagram is inherent to the model and independent of any parameter. Only the injection index can tune its shape by translating its starting point along the power-law line.

Figure 3 shows the colour-colour diagrams of the same sources from Figure 2. To retain homogeneity across different sources, the colour coding in Figure 3 is the relative distance from the core where 1 denotes half the size from Table 2. In other words, the approximate maximum extent of the source relative to the core. Because of this definition, source 3C 236 has points exceeding one because it has asymmetric jets. The bold grey error bars denote the calibration error and are, due to the $\Delta S/S$ dependence in Eq. (4), equal for all data points in the diagram. The thin black error bars denote the rms uncertainty on the flux density measurement which depends on the signal to noise at the data point. The distinction makes clear which points in the diagram are from regions with very low surface brightness emission. Note that the grey error bars do not denote a 1σ uncertainty but rather the possible extent of any systematic offset due to the calibration error. This offset should affect all data points equally. The colour-colour diagrams for all sources in the sample are shown in Figures B.1 and B.2.

We adopted two strategies for obtaining the spectral index across the lobes. For morphologically straight sources (e.g. 3C 457), we regridded the image while rotating it to be aligned on the image x-axis and integrated the flux in regular intervals across the source. For sources that do not behave this way (see e.g. Figure 6 for regions of 3C 465) we placed circular regions along the lobe ridge lines. Four of the galaxies (see e.g. 3C 76.1, 3C 310, 3C 382 and 3C 442A in Appendix A) have ‘fat’² lobes

with no clear ridge line and the colour coding for those sources is therefore somewhat arbitrary.

From the colour-colour diagrams we pointed out several aspects. First, there is a large portion of sources where the colour-colour diagram is not well behaved, in the sense that they do not conform to expectations from previous work including Katz-Stone et al. (1993), i.e. a slim locus of points parameterised by the distance from the core. These are generally the sources with atypical lobe structure like fat-double radio galaxies. An example is 3C 310 which is known for its complex lobe structure in the form of a radio ring in the southern lobe (Gizani et al. 2002), which is unresolved at $15''$. Factors like the external environment and jet kinematics seem to influence the jets in such a way that it can no longer be described by a simple ageing model in a colour-colour diagram at the current resolution.

For this particular case, $6''$ LoTSS observations resolve the finer structures in 3C 310. It is clear the $15''$ LBA data is not sufficient. The low resolution and poor fidelity emphasise the need for higher resolution broad-band imaging with LBA, see the discussion for an outlook on this subject. This behaviour also results in high uncertainties on α_{inj} measurements which we discuss in Section 3.4.

Secondly, we note the locus of points does not reach the zero age power-law for FR II galaxies. This is telling us that we did not observe zero age emission in the hotspots, but instead either an already aged spectrum or a spectrum with a low frequency energy cut-off as suggested by Katz-Stone et al. (1993). 3C 284, 3C 457 and 3C 46 show signs of this behaviour. The colour-colour diagram of 3C 223 shows good agreement with JP but the hotspots are very far from zero age. This could again be due to the low resolution of our images where at the hotspot regions we summed over both hotspot and surrounding emission which will seemingly result in an aged spectrum.

In well-behaved sources, the colour-colour diagrams reveal a clear and systematic difference between FR I and FR II galaxies. For FR IIs, the data points closest to the hotspots lie nearest to the zero-age power-law line, with spectral steepening increasing monotonically towards the core, tracing the backflow of aged plasma away from the injection site. For FR Is, the behaviour is reversed: the flattest spectra are found closest to the core, with progressive steepening towards the outer lobes.

² With a fat lobed source we mean e.g. 3C 76.1, which is not morphologically elongated.

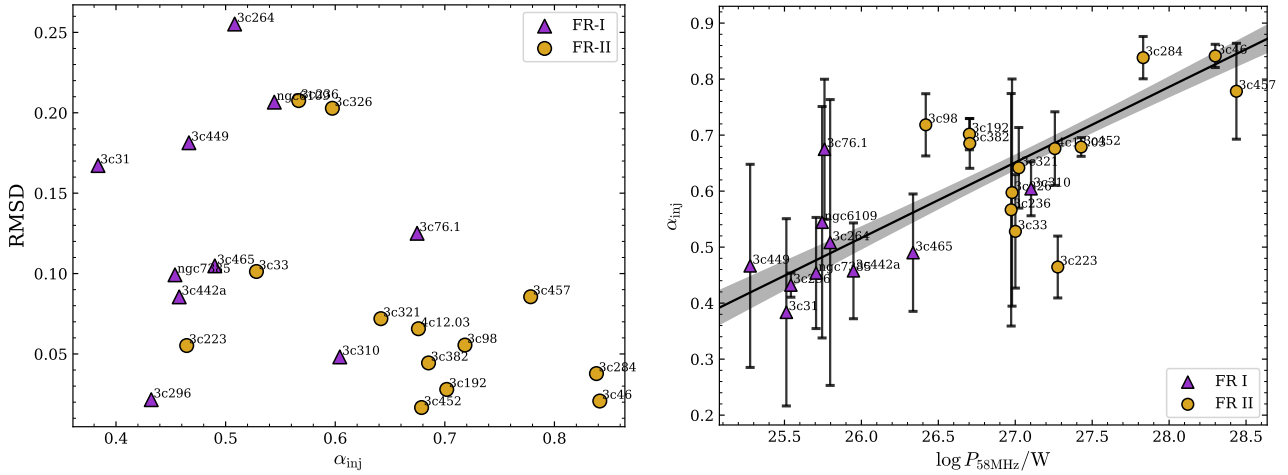


Fig. 4. Left panel: Measured injection index plotted against their uncertainty from RMSD where we differentiated between FR I and FR II type galaxies. Right panel: shows the apparent relation between the measured injection index and the total radio power. Purple triangles depict the FR I in our sample and the orange circles depict the FR IIs. The black line and shaded area are a linear MCMC fit and the uncertainty respectively.

Finally, we saw that the locus of points has less scatter in the $\alpha_{57}^{887} - \alpha_{887}^{1367}$ plane compared to the $\alpha_{57}^{144} - \alpha_{887}^{1367}$ plane. This is due to the larger frequency difference in the former. In the colour-colour diagrams we therefore plotted α_{887}^{1367} against α_{57}^{887} in favour of α_{57}^{144} due to the fact that the uncertainty due to flux density scale offsets is larger for smaller frequency intervals. The shift $\Delta\alpha$ in spectral index due to the relative flux density offsets δ of two flux density measurements is

$$\Delta\alpha = \frac{\log \delta_1 / \delta_2}{\log \nu_1 / \nu_2}. \quad (5)$$

For LOFAR LBA and HBA, for which δ is in between 0.9 and 1.1 given the flux density scale uncertainties (see Table 1), the shift in spectral index can be up to 0.2, while for LBA and ASKAP-low this offset can be only up to 0.06.

3.4. Measuring injection indices

We measured the injection index from the data points in the colour-colour diagram. The expected flux density at a certain frequency for an electron population of a certain spectroscopic age t in a magnetic field B and injection index α_{inj} is given by Equation (1). Since the age and magnetic field are degenerate parameters in the JP model, we fixed the magnetic field and let the age and injection index be the only relevant varying parameters. The magnetic field strength is set to $B = B_{\text{CMB}} / \sqrt{3}$ for the entire source as it was shown by Hardcastle (2013) that replacing B by a more physical Maxwell-Boltzmann distribution of the magnetic field does not significantly change the mean emissivity of the model.

Given a measured spectral index α_{12} at frequencies ν_i and ν_j , flux densities (from which we derived the injection index) are modelled by $S_{\nu_i}(t, \alpha_{\text{inj}})$ and $S_{\nu_j}(t, \alpha_{\text{inj}})$. We can summarise this by saying that the spectral index for a given frequency pair is given by $\alpha_j^i(t, \alpha_{\text{inj}})$. The location of a measurement in the colour-colour diagram depends on two of these spectral indices, e.g. α_j^i and α_k^l . To find the injection index corresponding to every measurement we numerically found the values of t and α_{inj} for which α_j^i and α_k^l correspond to the measured spectral indices.

We know that there is only one unique solution for the t , α_{inj} pair because we qualitatively know α_j^i is a strictly increasing

function of both t and α_{inj} (both an older plasma and a higher injection index steepens the spectral index). This means, given a value of α_j^i , there is at most one t for each α_{inj} , hence a strictly increasing or decreasing function in the (t, α_{inj}) plane. So, there can be at most one set of parameters for which the JP model goes through a point in the colour-colour diagram.

We found these sets of parameters using minimisation algorithms since the integral in Eq. (1) cannot be inverted analytically. The best fitting injection index ($\bar{\alpha}_{\text{inj}}$) for the entire source is then found by root mean square minimisation. The uncertainty on the obtained injection index is given by the root mean squared deviation (RMSD)

$$\alpha_{\text{inj,RMSD}} = \sqrt{\frac{1}{N} \sum_i (\alpha_{\text{inj},i} - \bar{\alpha}_{\text{inj}})^2}. \quad (6)$$

The measured injection indices and the RMSD uncertainties are shown in the left panel of Figure 4. The right panel of this figure shows the measured injection index against the total radio power of the source and hints at a relation between the total radio power and α_{inj} . Since the correlation, characterised by a correlation coefficient³ of 0.75, is significant, we fitted a linear function in the $\alpha_{\text{inj}} - \log P$ plane using a bivariate correlated errors and intrinsic scatter (BCES; Akritas & Bershadsky 1996) method implemented by Nemmen et al. (2012) and find $\alpha_{\text{inj}} = 0.135^{+0.014}_{-0.013} \log P - 3.00^{+0.36}_{-0.35}$. The separation of the two FR types is driven mostly by luminosity (noted already by Fanaroff & Riley 1974) but is enhanced by the injection index. In general, we observed FR I type galaxies to have a less well behaved colour-colour diagram compared to FR IIs. In Figure 3 however, the colour-colour diagram of 3C 442A shows more erratic behaviour near the source outskirts compared to other FR II sources. This could be attributed to missing flux in the ASKAP maps for the low surface brightness emission. Contrary to the literature cited in Table 2, the colour-colour diagram shows to be more consistent with a FR II type galaxy. The distance to the core is inversely proportional to the deviation from the perfect power-law spectrum.

³ When a correlation coefficient is mentioned, we refer to the Pearson correlation coefficient.

We suggest that environmental effects can have significant influence on the lobe plasma and induce local variations due to shocks and turbulence; this can be the case for e.g. 3C 264, 3C 465 and NGC 6109 which reside in dense cluster environments. Also re-acceleration can play a role in disturbing expected behaviour in colour-colour diagrams (see Section 4.2).

We did not observe significant differences between the two lobes when measuring the injection index, meaning that material in opposite hotspots and jets are similarly accelerated. Though for 3C 284 we did observe significantly different spectral index for the two lobes, 0.80 for the west lobe and 0.84 for the east lobe. In the radio maps the lobes are asymmetric, with the east lobe being brighter than the west lobe due to projection and beaming effects.

The luminosity-injection index relation has previously been reported by Jamroz et al. (2008) in a sample of FR II galaxies. Our results seem to suggest that the relation continues down to the FR I regime. However, the correlation coefficient for FR Is only is just 0.4 and considering the uncertainties, the injection index for this type of object does not correlate with the total radio power and the injection index is $\sim 0.50 \pm 0.08$. This result is fairly consistent with, though slightly lower than, spectral indices often quoted in the literature, such as 0.55 by Young et al. (2005). For FR IIs, the correlation is stronger and they tend to have higher injection indices for higher total radio luminosities. The injection indices are typically $\alpha_{\text{inj}} \gtrsim 0.6$ with values up to 0.85 for this sample. Only 3C 223 has a spectral index slightly lower at $\alpha_{\text{inj}} = 0.46 \pm 0.06$. Since at injection losses are negligible, the injection index should be characteristic of the acceleration mechanism. For example, first-order Fermi acceleration in strong, non-relativistic shocks (Bell 1978; Blandford & Ostriker 1978) has $\alpha_{\text{inj}} = 0.5$. Our measurements for FR I galaxies seem consistent with this mechanism, although, due to the high uncertainty on the injection index, we cannot make strong claims about possible (re)acceleration mechanisms with the current data.

4. Discussion

The analysis in this work is largely based on spectral index measurements. The main limitations of any spectral index measurement are flux scale errors of the used images, which are 10% for the observations at the lowest two frequencies. This, combined with the fact that the HBA frequency is only 2.5 times higher than the LBA frequency, can lead to systematic offsets of the spectral index of up to 0.2, which is significant for spectral index measurements down to 0.4. Another limitation for this work was the sometimes poor quality of the LBA data. This is due to the fact that the data have a limited bandwidth of only 3 MHz which leads to high RMS noise values and low signal to noise especially for regions with low surface brightness. The narrow bandwidth furthermore results in relatively poor uv-plane coverage and image fidelity. Despite these challenges we were able to produce spectral index maps below 150 MHz for 22 3CRR sources and estimate injection indices for them.

The colour-colour diagrams show a clear distinction between FR Is, showing increasing spectral steepening away from the core, and FR II galaxies, showing a backflow of aged plasma from the hotspots towards the core. This is consistent with the established physical picture of the two classes (e.g. Parma et al. 1999; Laing & Bridle 2014; Harwood et al. 2013; Brienza et al. 2020; Ricci et al. 2026). In FR IIs, particle acceleration occurs predominantly at the hotspots, where the jet terminates in a strong shock. Electrons then flow back into the lobes, losing energy through synchrotron and inverse Compton radiation as

they travel away from the hotspot, producing the observed gradient of spectral steepening from the hotspot inwards. In FR Is, in contrast, there are no hotspots; acceleration is believed to occur in the inner jet, close to the AGN, in the region where the jet decelerates and dissipates. Electrons then propagate outwards into the lobes, ageing progressively as they do so, which naturally produces spectral steepening with increasing distance from the core. Our measurements show that the low-frequency spectral steepening is less pronounced in FR Is, suggesting that synchrotron losses are not the driving factor in the spectral shape of this class of sources. The inclusion of 58 MHz data is particularly valuable here, as the ultra-low frequency spectral index is sensitive to the oldest electron populations and therefore provides a cleaner separation between injection and ageing signatures than is possible with higher frequency data alone. The colour-colour diagram at these frequencies thus provides a spatially resolved, largely model-independent confirmation of the FR I and FR II acceleration dichotomy.

4.1. Effects of mixing and complex spectral structures

One has to be careful of over-interpreting these diagrams since they are sensitive to shifts in flux scale and accuracy of the image alignment. The scaling of one of the considered flux densities for a given shift in a spectral index on the colour-colour plane becomes larger for larger ranges in frequency. For example, a shift in α_{57}^{144} of 0.1 corresponds to a flux scaling of $S_{57\text{MHz}}$ of 1.1, while the shift for a much larger frequency jump α_{57}^{887} of 0.1 the scaling of $S_{57\text{MHz}}$ is 1.3. Thus, the sensitivity to flux density uncertainties decreases for larger frequency intervals. Moreover, since we are dealing with a sub-optimal resolution of $25''$ there is likely mixing of electron populations within an observing beam especially for the least extended sources. There may also be multiple physical effects manifesting in the lobes that leave signatures in the diagram that are hard to separate. This can be changing magnetic field strengths, re-acceleration or changes in injection index along the lobe and to the hotspots related to the accretion history of the AGN.

Since it is possible that the magnetic field changes along the lobes it is challenging to measure the source age. Due to the low resolution there will be mixing of electron populations of different ages. We tested the influence of mixing on the measurement of the α_{inj} by measuring the injection index from the colour-colour plot using differently sized regions of the image. Using larger regions allows more electron population mixing. Figure 5 shows the colour-colour diagram for different region sizes.

The figure shows that depending on the regions, the data points translate on the diagram due to an effectively different measurement of the magnetic field. It is important to note that the points all stay on the same trajectory, meaning that the measurement of α_{inj} is not affected by the increased mixing of electrons of different ages or different magnetic field environments. If the injection index were influenced we would expect to observe a shift of the trajectory with respect to the solid power-law line. From this we can conclude that we are measuring the same value for the injection index as we would with higher resolution data.

It has been shown that some FR I galaxies show a two-component spectrum with a flat and steep component (see e.g. Katz-Stone & Rudnick 1997; Hardcastle 1999). Often this is characterised by a collimated jet surrounded by a more diffuse ‘sheath’ with a steeper spectrum. Even in resolved maps, some lobe regions exhibit this two-component spectrum, effectively mixing the components when trying to measure spectral index slopes. Since we assumed the lobes to be consistent with just a

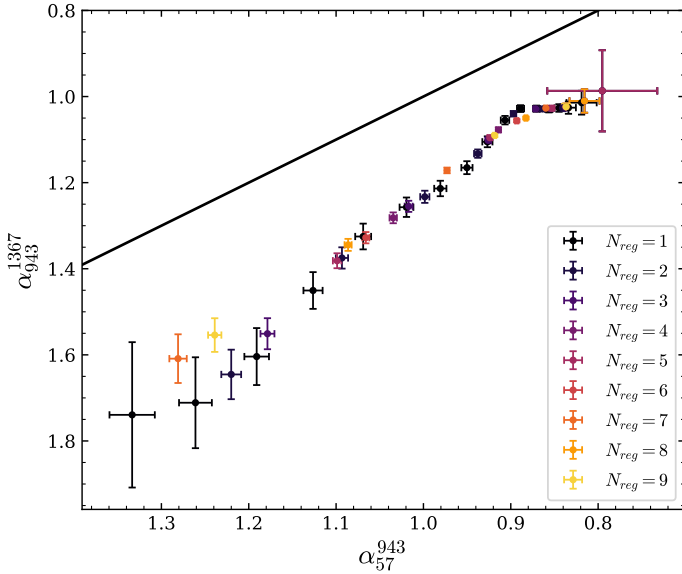


Fig. 5. Colour-colour diagram of 3C 457 to visualise the effect of mixing. The different colours indicate the measured spectral indices for different region sizes in pixels.

single component in estimating the injection index, the existence of multi-component lobes may, at first sight, slightly complicate the spectral modelling we carried out in this work.

This is not likely to be the case however, since, for colour-colour diagrams that are not well behaved, which is the majority of them, we cannot make any claims about the existence of multiple components and the estimate of the injection index will in any case have a high uncertainty. If, on the other hand, a colour-colour diagram is already fairly well behaved, and the lobes do not have multiple components everywhere, it is still possible to get accurate estimates for the low frequency injection index as we averaged over the entire source to find this index. We showed that the trend in a colour-colour diagram does not necessarily depend on the resolution, it is more likely related to the telescope sensitivity and source morphology.

Furthermore, if the diagram is well behaved it could be possible to identify the existence of a multi-component lobe. One of the more well behaved colour-colour diagrams, 3C 465, shows hints of a double-component lobe (see Figure 3). The regions close to the core are consistent with $\alpha_{\text{inj}} = 0.49 \pm 0.1$ while further away, at a relative distance to the core of 0.5, the lobes are more consistent with a steeper $\alpha_{\text{inj}} \approx 0.65$.

4.2. Re-acceleration

Another interpretation for the spectral structure of 3C 465 is re-acceleration. Figure 6 shows the LBA image of 3C 465 overlaid with the regions used to obtain the colour-colour diagram. The deviation from the fitted ageing model between region 6 and 7 in the eastern lobe and region 16 and 17 in the western lobe corresponds to the steepening of the low frequency spectral index (see top middle panel of Figure 2) from ~ 0.8 to ~ 1.0 . It also corresponds to the sudden reduction of surface brightness in for instance the LBA image (Boxelaar et al. 2025).

The right panel of Figure 6 shows a flattening of the high frequency part of the spectrum compared to ageing expectations around the previously mentioned points, while the low frequency spectral index is not significantly steeper or flatter.

This suggests that re-acceleration is happening along the lobes. 3C 465 is known to have hotspots (around region 11 and 14 in the figure) but the flattening happens beyond that point and is likely not related to the hotspot. A colour-colour diagram which includes very low frequencies is especially sensitive to re-acceleration. Since it mostly enhances high frequency flux density, re-acceleration can be made visible by a vertical offset upwards from the ageing expectation in this case. This is exactly what is visible in the figure.

With current low frequency data it is uncertain what is physically happening in the lobes. VLA (Bempong-Manful et al. 2020) and LoTSS images show some filamentary structure in the lobes at the flattening regions, but high-resolution ultra-low frequency data is missing to do a detailed analysis. After the upcoming upgrade of LOFAR 2.0, which coincides with a period of calmer ionospheric conditions, we will be able to obtain high-resolution images at 50 MHz.

4.3. Steep low frequency spectral index

We observed a significant steepening in the measured injection index of both FR I and FR II galaxies when we considered α_{144}^{58} instead of α_{887}^{58} . We also occasionally observed that the spectral index α_{144}^{58} between LBA and HBA is steeper than the spectral index α_{887}^{144} between HBA and ASKAP-low, contrary to what is expected from a typical ageing synchrotron spectrum. This could be explained by systematic overestimation of flux densities in LBA or underestimation in LoTSS. The flux density scales were thoroughly checked in Paper I for the LBA data. There, we observed an under estimation of flux in LoTSS by a few percent, which could explain the different measurements in injection index. As mentioned in Section 3.3, we measured α_{inj} from α_{58}^{887} to reduce the effect of possible flux scale offsets.

Assuming there is no issue with the flux scale and measurements of all images, a physical explanation for the steepening is re-acceleration of electrons in the lobes enhancing emission around GHz frequencies. Alternatively, we could be observing a superposition of electron populations which mix at our resolution and result in a deviation from a simple ageing model or power-law.

More high-resolution, multi-frequency observations are necessary to better understand particle acceleration and particle composition in the lobes of FR Is and FR IIs. A handful of 3C sources have been observed with LOFAR at 144 MHz and produced high fidelity sub-arcsecond images (Mahatma et al. 2023). Observation time has been allocated to observe 73 3CRR sources at high-resolution using JVLA in L-band and C-band. Additionally, observations with LOFAR LBA exist but have not yet been calibrated with long baselines due to the difficult ionospheric conditions at the time of observing. These new multi-frequency observations will enable us to understand the lobe structure and energetics in better detail.

5. Conclusions

This work has presented the first study of the well-resolved spectral structure of bright radio galaxies at ultra-low frequencies (<100 MHz) using spectral index maps of a sub-sample of extended sources in the 3CRR catalogue. This is the first spectral study of a medium-sized sample of 22 radio galaxies utilising the LOFAR LBA system at 58 MHz. These data have allowed us to study the low frequency spectral structure as well as to constrain the injection index α_{inj} using additional

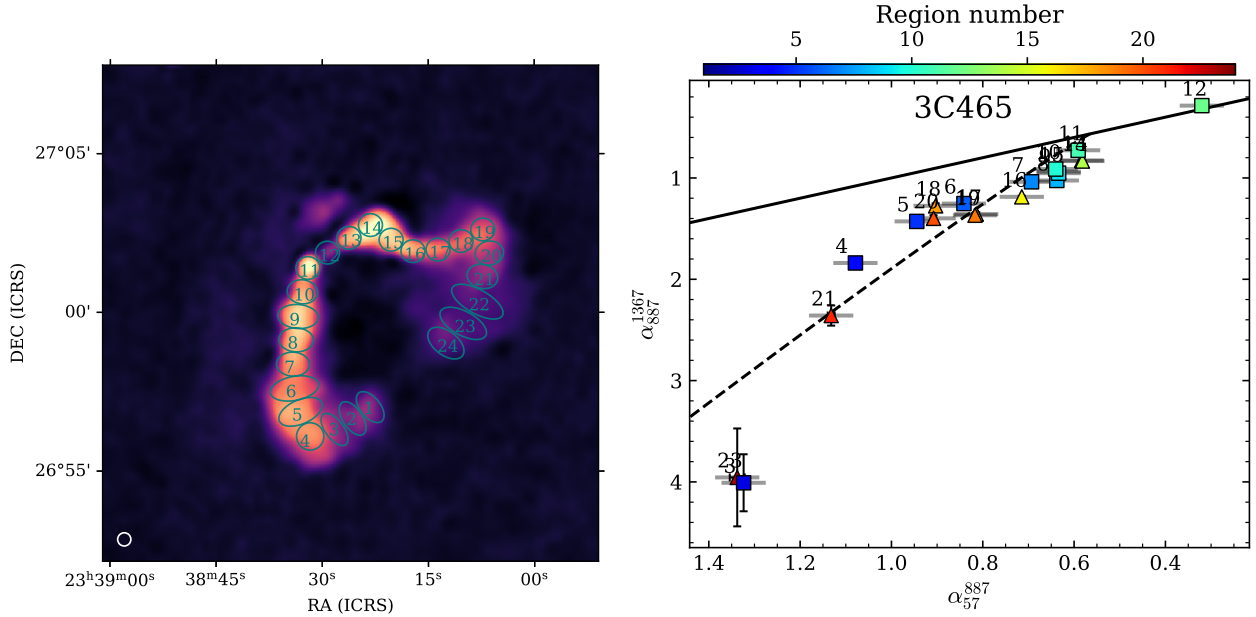


Fig. 6. Left panel: LBA image of 3C 465 overlaid with the numbered regions that were used to obtain the colour-colour diagram in blue. Right panel: colour-colour diagram of the same source with corresponding numbering. The colour map represents the region numbering.

high frequency data from LoTSS and ASKAP. Measurements of the injection index at the lowest frequencies have long been a missing piece to advance our knowledge of (re)acceleration mechanisms of electrons in the lobes of radio galaxies. We have produced low-frequency spectral index maps using complementary LoTSS DR3 data at 144 MHz and ASKAP-low and -mid data at 887 MHz and 1367 MHz respectively. We have additionally measured the injection index α_{inj} for these sources from colour-colour diagrams. The spectral indices and injection indices are summarised in Table 3. Besides these data products, the key results from this paper are as follows:

- (i) the low-frequency (<150 MHz) spectral index in the hotspots of FR II galaxies is steeper than the measured injection index of the same sources. The hotspot emission is thus not representative of the injected plasma which is ageing in the lobes. The hotspot emission is influenced by more complex processes, for which future higher resolution ultra-low frequency observations will be necessary.
- (ii) The FR II injection index is consistently ≥ 0.5 and correlates with the total luminosity of the source. Injection indices for FR IIs can reach up to 0.9.
- (iii) The low-frequency injection index of FR Is is around 0.5 close to the core which corresponds to the measured injection index. The obtained injection indices for the FR Is in our sample, despite their high uncertainty, suggest that the injection indices at ultra-low frequencies remain consistent with what has been found in earlier work.
- (iv) Approximately one in three sources has a spectral structure that is not well described by a JP ageing model, leading to high uncertainties on injection index. Due to the complex structure or projection effects seen in for instance 3C 76.1 or 3C 382, the question arises whether these sources are suitable for classic ageing analysis at all. X-shaped or fat lobes, in combination with projection effects and the limited resolution of the current data, can result in a superposition of emission from physically distinct regions along the line of sight, leading to spectral index structures that cannot be described by a simple ageing model.

- (v) Mixing of cosmic ray electron populations of different ages has minimal influence on the estimation of the injection index when measured through a colour-colour diagram. This is true under the assumption that all electrons of which emission is observed originate from the same injection source. Contrary to the injection index, the local spectral index is of course susceptible to mixing effects.

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Appendix A: Low- and high-frequency spectral index maps

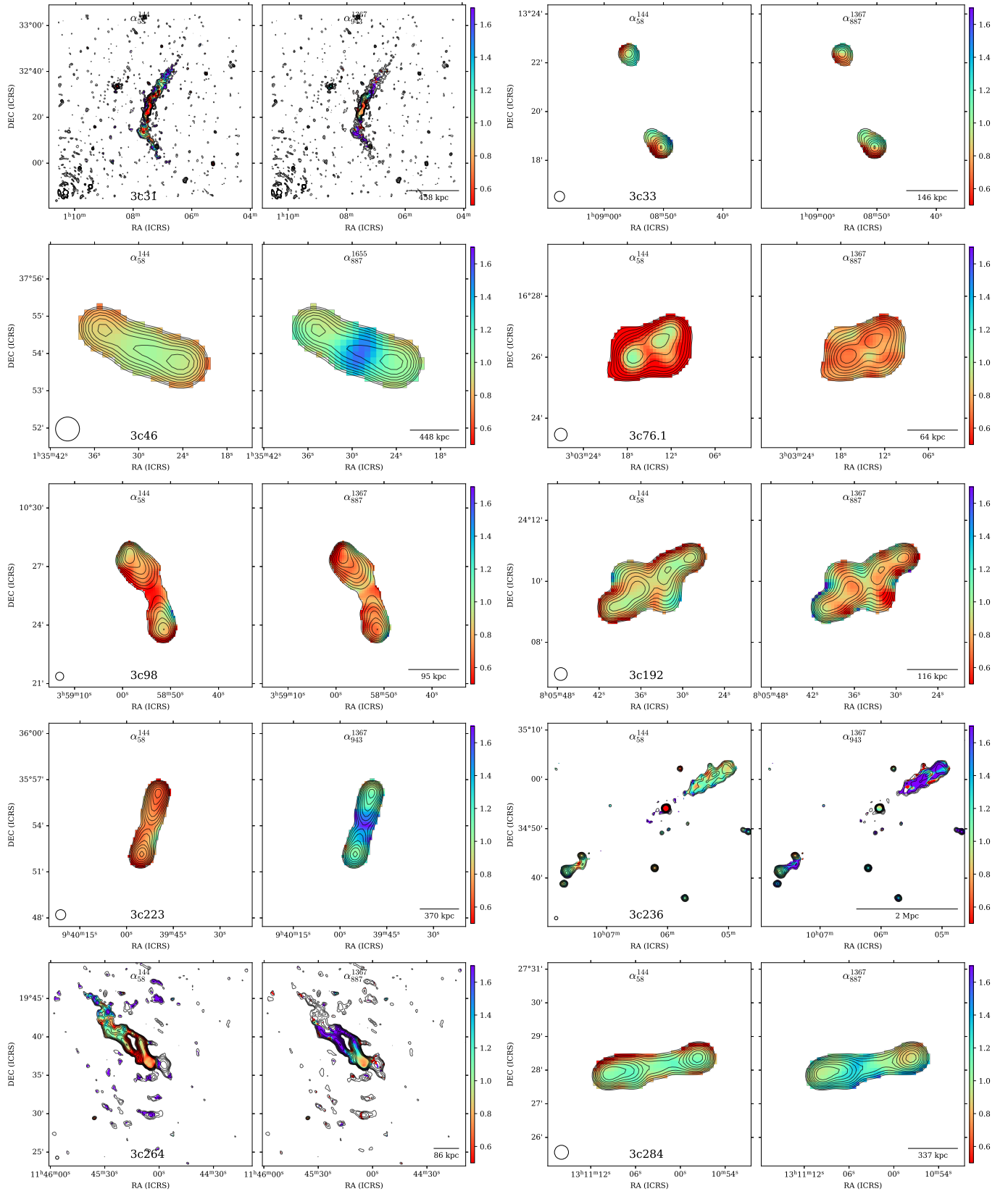


Fig. A.1. Radio maps of 3C sources in our sample. Same as Figure 2. The contours are drawn at $[9, 50, 100, 200] \times \sigma_{\text{rms}}$ by default, $[5, 10, 50, 100, 200] \times \sigma_{\text{rms}}$ for extended sources and $[3, 5, 10, 50, 100, 200] \times \sigma_{\text{rms}}$ for very extended sources.

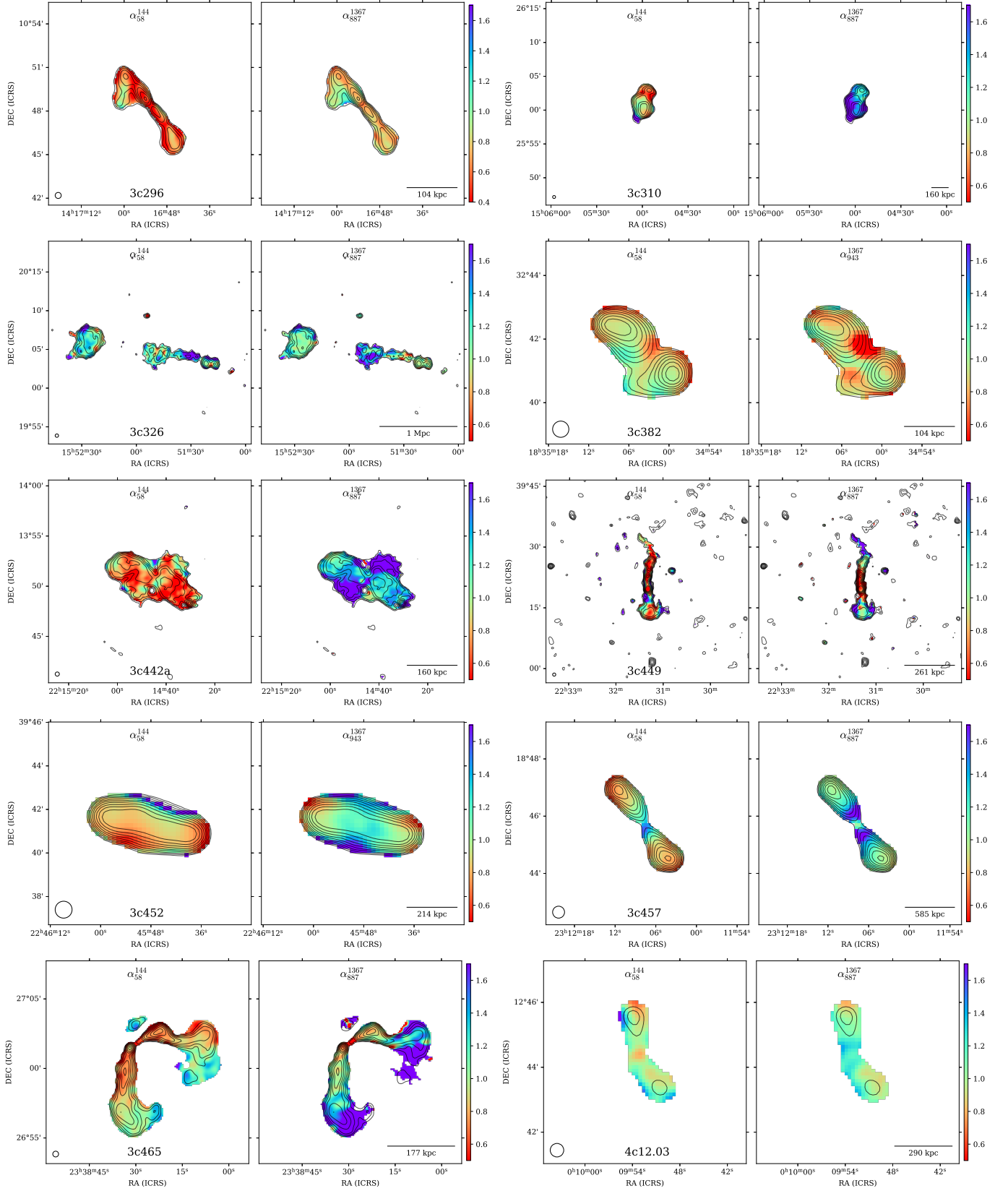


Fig. A.1. Continued

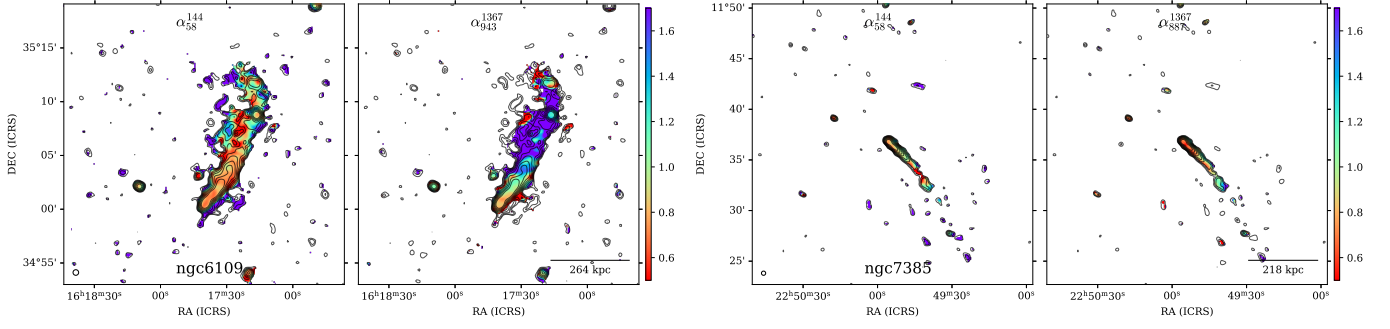


Fig. A.1. Continued

Appendix B: Colour-colour diagrams

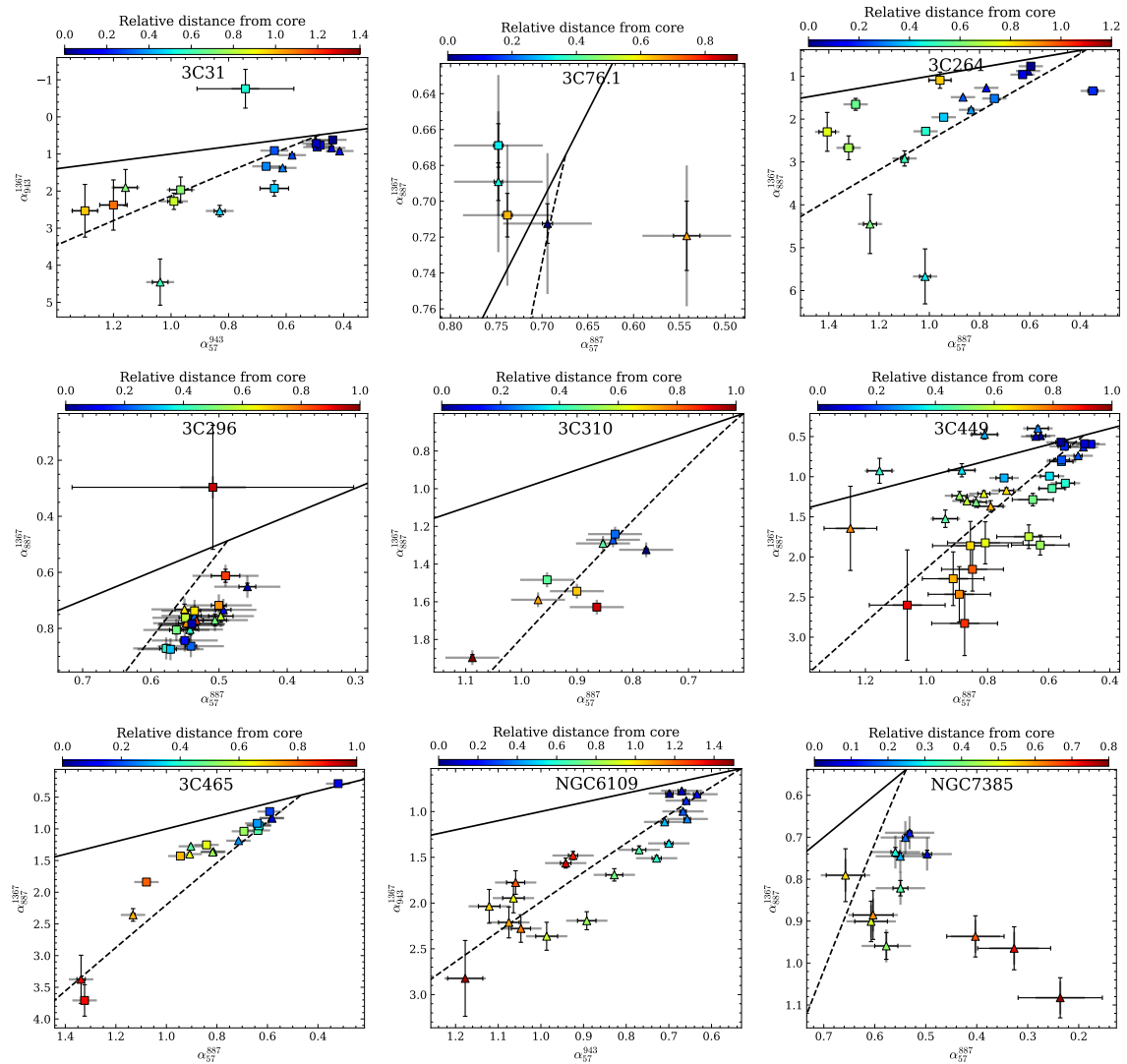


Fig. B.1. Colour-colour diagrams of FR I galaxies in Table 2 in the $\alpha_{57}^{144} - \alpha_{887}^{1637}$ (or $\alpha_{57}^{144} - \alpha_{943}^{1367}$) plane. The colour scale denotes the distance from the core relative to the approximate size in Table 2. The solid grey error bar denotes the possible systematic shift of data points due to calibration errors and the thin black error bars denote the rms flux uncertainty. The solid line denotes a pure power-law and the dashed line a JP model. The two lobes are differentiated by either showing a square or triangle. Regions containing the core are excluded from the figure.

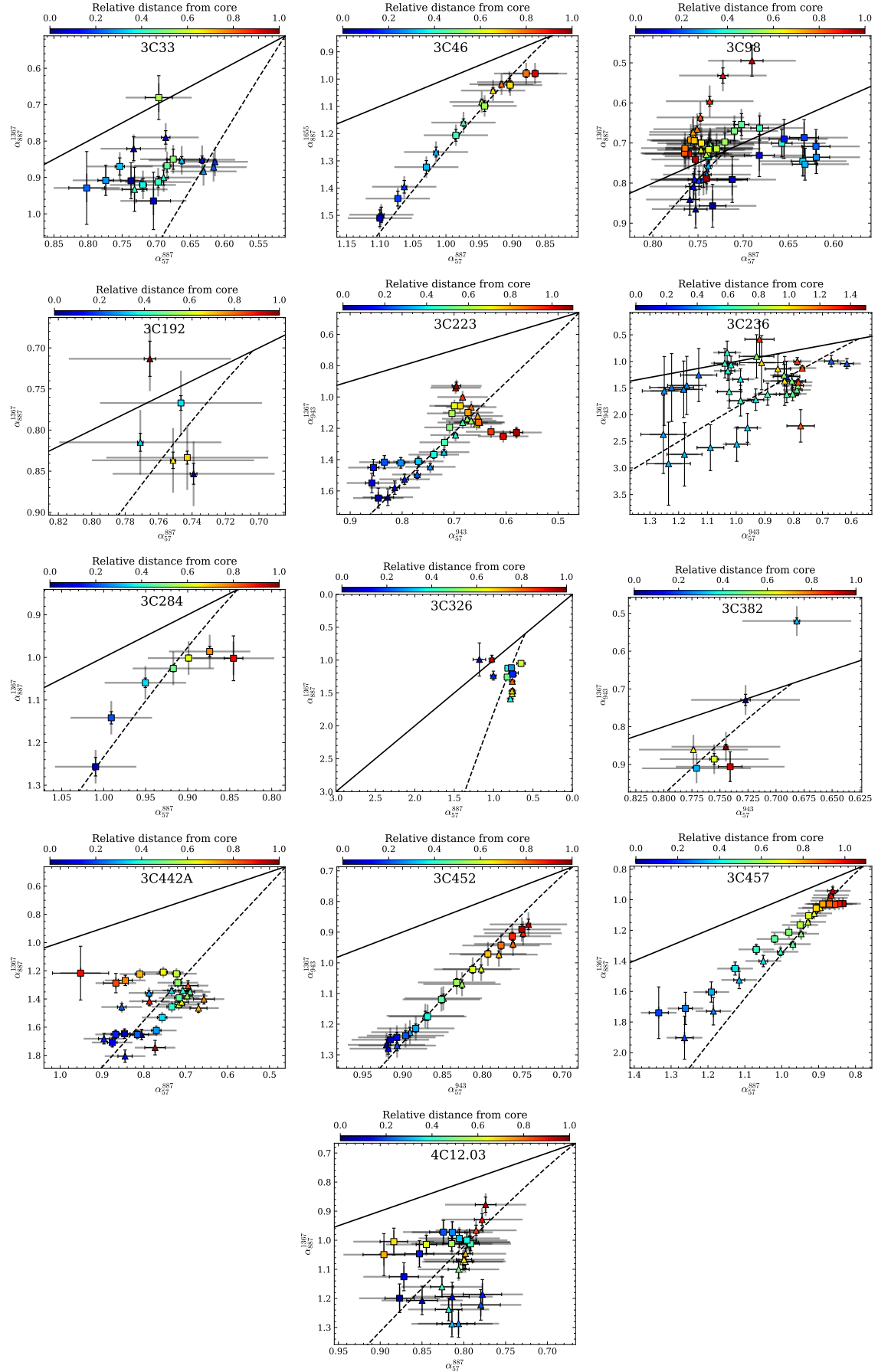


Fig. B.2. Same as Figure B.1, but for all FR II in the sample.