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# Radio spectral properties and jet duty cycle in the restarted radio galaxy 3C388

M. Brienza<sup>1,2,\*</sup>, R. Morganti<sup>3,4</sup>, J. Harwood<sup>7</sup>, T. Duchet<sup>5</sup>, K. Rajpurohit<sup>1</sup>, A. Shulevski<sup>6</sup>, M. J. Hardcastle<sup>7</sup>, V. Mahatma<sup>7</sup>, L. E. H. Godfrey, I. Prandoni<sup>2</sup>, T. W. Shimwell<sup>3,9</sup>, and H. Intema<sup>8,9</sup>

<sup>1</sup> Dipartimento di Fisica e Astronomia, Università di Bologna, via P. Gobetti 93/2, 40129, Bologna, Italy

<sup>2</sup> INAF – Istituto di Radioastronomia, Via P. Gobetti 101, 40129, Bologna, Italy

<sup>3</sup> ASTRON, the Netherlands Institute for Radio Astronomy, Postbus 2, 7990 AA, Dwingeloo, The Netherlands

<sup>4</sup> Kapteyn Astronomical Institute, Rijksuniversiteit Groningen, Landleven 12, 9747 AD Groningen, The Netherlands

<sup>5</sup> University of Orléans, 3A avenue de la Recherche Scientifique, 45071 Orléans cedex 2, France

<sup>6</sup> Anton Pannekoek Institute for Astronomy, University of Amsterdam, Postbus 94249, 1090 GE Amsterdam, The Netherlands

<sup>7</sup> Centre for Astrophysics Research, School of Physics, Astronomy & Mathematics, University of Hertfordshire, College Lane, Hatfield, Hertfordshire, AL10 9AB, UK

<sup>8</sup> International Centre for Radio Astronomy Research – Curtin University, GPO Box U1987, Perth, WA 6845, Australia

<sup>9</sup> Leiden Observatory, Leiden University, Niels Bohrweg 2, NL-2333CA Leiden, the Netherlands

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## ABSTRACT

**Context.** Restarted radio galaxies represent a unique tool to investigate the duty cycle of the jet activity in Active Galactic Nuclei. Due to a sharp discontinuity of the GHz spectral index distribution within its lobes, the radio galaxy 3C388 has for long been claimed to be a peculiar example of AGN with multi-epoch activity.

**Aims.** The goal of this work is to perform for the first time a spatially resolved study of the radio spectrum of this source down to MHz-frequencies, in order to investigate its radiative age and constrain its duty cycle.

**Methods.** We have used new low frequency observations at 144 MHz performed with the Low Frequency Array and at 350 MHz performed with the Very Large Array combined with archival data at higher frequencies (614, 1400, 4850 MHz).

**Results.** We find that the spectral indices in the lower frequency range 144–614 MHz have flatter values ( $\alpha_{\text{low}} \sim 0.55\text{--}1.14$ ) than those observed in the higher frequency range 1400–4850 MHz ( $\alpha_{\text{high}} \sim 0.75\text{--}1.57$ ) but follow the same distribution across the lobes, with a systematic steepening towards the edges. However, the spectral shape throughout the source is not uniform and often deviates from standard models. This suggests that mixing of different particle populations is occurring, although it remains difficult to understand whether this is caused by observational limitations (insufficient spatial resolution and/or projection effects) or by the intrinsic presence of multiple particle populations, possibly related to the two different outbursts.

**Conclusions.** By using single-injection radiative models we compute that the total source age is  $\lesssim 80$  Myr and that the duty cycle is about  $t_{\text{on}}/t_{\text{tot}} \sim 60\%$ , which is enough to prevent the intracluster medium from cooling according to X-ray estimates. While to date the radio spectral distribution of 3C388 remains a rare case among radio galaxies, multi-frequency surveys performed with new generation instruments will soon allow us to investigate whether more sources with the same characteristics do actually exist.

**Key words.** galaxies : active - radio continuum : galaxy - individual: 3C388

## 1. Introduction

Restarted radio galaxies represent one of the clearest indications that radio jets driven by Active Galactic Nuclei (AGN) can be episodic. In these sources we can simultaneously observe remnant lobes produced by a previous phase of jet activity and a pair of active, newly-born jets (see Saikia & Jamrozy 2009 for a review).

These sources offer us a unique opportunity to constrain the jet duty cycle in AGN, i.e. the time scales of the jet activity and quiescence (Morganti 2017). Indeed, the simultaneous modelling of the radio spectrum of the old and young lobes provides an estimate of their ages and of the duration of the inactive period in between.

This represents a crucial input parameter for galaxy evolution models and simulations, which require AGN feedback to

reproduce the observed galaxy mass function, as well as the correlation between the mass of the black hole and the galaxy bulge (e.g. Ferrarese & Merritt 2000, Di Matteo et al. 2005, Fabian 2012, Weinberger et al. 2017). Therefore, a comprehensive knowledge of the AGN duty cycle as a function of various source conditions, such as the black hole accretion mode, the host galaxy properties and the surrounding intergalactic environment, is vital.

Restarted radio galaxies have been known for a long time and various authors have discussed techniques to search for and study them. Only a few sources have been identified via their radio spectral properties (Parma et al. 2007; Murgia et al. 2011). Instead, most of them have been found based on their morphology, often showing a pair of aligned double lobes (in this case called ‘double-double radio galaxies’ (DDRGs), e.g. Lara et al. 1999; Schoenmakers et al. 2000; Nandi & Saikia 2012), or alternatively, bright compact radio jets/cores embedded in extended, low-surface brightness emission (e.g. Saripalli et al. 2012; Jam-

\* m.brienza@ira.inaf.it

rozy et al. 2007; Shulevski et al. 2012; Brienza et al. 2018). Other restarted radio galaxies have been individually identified through their peculiar morphologies, for example 3C338 (Burns et al. 1983), 4C 35.06 (Shulevski et al. 2015) and 3C219 (Clarke et al. 1992).

For a few double-double radio sources spectral ageing modelling, based on equipartition assumptions, has provided estimates of the duration of the quiescent phase, which is found to be in the range 0.1–10 Myr. This is usually at least a factor two shorter than the first active phase, which is observed to be of the order of a few tens up to a few hundreds of Myr (Konar et al. 2012, 2013; Orrù et al. 2015; Nandi et al. 2019).

Major steps forward in the selection and study of restarted radio galaxies have recently been allowed by the advent of the Low Frequency Array (LOFAR, van Haarlem et al. 2013) thanks to its unprecedented sensitivity and resolution at low frequency, where the remnant lobes are expected to be brighter (see e.g. Shulevski et al. 2015; Orrù et al. 2015; Brienza et al. 2018; Mahatma et al. 2019, Jurlin et al. submitted).

However, there is one peculiar class of restarted radio galaxies that we may still be missing, i.e. sources showing the footprint of their multi-epoch activity through spatial variations of their spectral index across their radio lobes. At least one such source has been suggested in the past, the radio galaxy 3C388 (see Fig. 1).

3C388 is associated with a very luminous cD galaxy located in a poor cluster at redshift  $z = 0.091$  (Prestage & Peacock 1988; Buttiglione et al. 2009) with a dense intracluster medium with temperature equal to 3.5 keV (Kraft et al. 2006; Ineson et al. 2015). The host galaxy is one of the most luminous elliptical galaxies in the local universe ( $M_B = -24.24$ ), it shows a weak stellar nucleus in the HST image and it is classified as a low-excitation radio galaxy (Jackson & Rawlings 1997). The radio galaxy 3C388 has an extension of about 1 arcmin, which corresponds to about 100 kpc at its redshift, and a radio luminosity equal to  $P_{178\text{MHz}} = 4 \times 10^{25} \text{ WHz}^{-1}\text{sr}^{-1}$ , lying just above the Fanaroff-Riley I/II (Fanaroff & Riley 1974) nominal border line ( $P_{178\text{MHz}} = 2 \times 10^{25} \text{ WHz}^{-1}\text{sr}^{-1}$ ). Its radio morphology consists of two large lobes with a broad central plateau of bright emission surrounded by extended low surface brightness emission of similar shape (see Fig. 1). A compact, hotspot-like emission is embedded in the Western lobe, well detached from the lobe edge, and is connected to the core by a narrow bent jet (Roettiger et al. 1994). Based on jet/counterjet brightness ratio considerations Leahy & Gizani (2001) estimated that the jet bends with an angle equal to  $\sim 50$  degrees with respect to the line of sight.

Burns et al. (1982) and Roettiger et al. (1994) studied the radio spectral index distribution of the radio lobes between 1.4 and 5 GHz and observed a sudden steepening towards the edges of the lobes (with maximum values of  $\sim \alpha_{1400\text{MHz}}^{4850\text{MHz}} = 1.6$ ,  $S \propto \nu^{-\alpha}$ ).

Since the curvature of the radio spectrum is related to the age of the plasma, the authors suggested that the duality in the spectral index distribution indicates the presence of two different electron populations related to two different jet episodes. In particular, they proposed that the two reborn jets are inflating new lobes within the old remnant lobes.

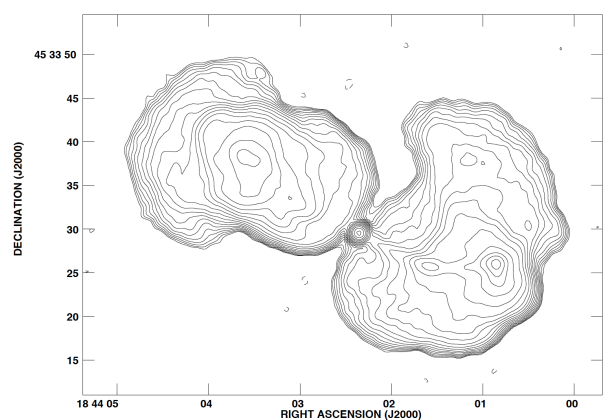
An alternative interpretation proposed by Burns et al. (1982) considers the source to be instead a wide-angle tail radio galaxy as seen in projection. In this occurrence, the brighter plateau of emission would represent the region closer to the observer and mostly located on the plane of the sky, while the outermost low surface brightness region would belong to the tails, which develop backwards and along the observer's line of sight. While

this scenario would require a very coincidental geometry and is not preferred by the authors, it is hard to completely prove it wrong.

Thanks to new generation instruments we are now able to get a resolved view of this well-known source in the MHz regime for the first time. In this paper we present a spatially resolved, multi-frequency radio analysis of 3C388 aimed at further investigating its restarting nature and at constraining the timescale of the jets duty cycle.

This paper is organized as follows: in Sect. 2 we describe the data and the data reduction procedures; in Sect. 3 we present the source morphology and the spectral analysis; in Sect. 4 we discuss the spectral properties of the source and the timescales of the jet activity.

The cosmology adopted in this work assumes a flat universe and the following parameters:  $H_0 = 70 \text{ km s}^{-1}\text{Mpc}^{-1}$ ,  $\Omega_\Lambda = 0.7$ ,  $\Omega_M = 0.3$ . At the redshift of 3C388  $z = 0.091$ , 1 arcsec corresponds to 1.696 kpc.



**Fig. 1.** Radio map of 3C388 at 1.4 GHz and 1.32 arcsec resolution taken from the online atlas by Leahy et al. (1996). The lowest contour is at 0.25 mJy beam<sup>-1</sup>, and contours are separated by a ratio of  $\sqrt{2}$ .

## 2. Data

In this section we describe the data collection and data reduction procedures that we have used to perform the spectral analysis of the source 3C388. We present here new dedicated observations at 144 MHz and 350 MHz, as well as archival data at 614, 1400 and 4850 MHz. When performing spectral analysis, especially on resolved scales, particular attention should be paid to matching the uv-coverage of different instruments at different frequencies. This is necessary to recover the same scales of emission and avoid deriving artificial spectral trends throughout the source (see e.g. van Breugel 1980). For this reason, all data were chosen to have the best match in uv-coverage, with special attention to the largest scale structure sensitivity. The largest angular scale observable by an interferometer is  $0.6\lambda/D_{min}$ , where  $D_{min}$  is its shortest baseline (Tamhane et al. 2015). Using this expression as a reference, we made sure that all the observations used were sensitive to angular scales  $\geq 1$  arcmin, which is the angular size of 3C388. A summary of the radio observations and image properties is presented in Table 1. In addition to the radio data, we also present archival Chandra observations, which we have used to search for X-ray inverse-Compton emission from the radio lobes, to get constraints on their magnetic field strength.

**Table 1.** Summary of the radio observation and image properties. All images have a restored beam of 6 arcsec  $\times$  6 arcsec. An asterisk \* indicates archival observations.

Telescope	Configuration	LAS <sup>1</sup> [arcmin]	Frequency [MHz]	Bandwidth [MHz]	Target TOS <sup>2</sup> [hr]	Calibrators	Observation date	Noise [mJy beam <sup>-1</sup> ]
LOFAR	HBA Inner	244	144	48	8	3C295	26 June 2019	0.8
VLA	A	2.5	350	256	~2	3C286	28 July 2015	1.5
GMRT	-	17	614	16	~4	3C48, 1829+487	29-30 May 2005*	0.8
VLA	B	4	1400	50	7	3C286, 1843+400	August 1986*	0.5
VLA	C	3.5	4850	50	~5	3C286, 1843+400	December 1986*	0.1

<sup>1</sup> Largest Angular Scale; <sup>2</sup> Time On Source.

### 2.1. LOFAR observations at 144 MHz and data reduction

We performed a targeted observation of the source 3C388 with the LOFAR High Band Antennas (HBA, 150 MHz) on March 2nd, 2014, in the framework of the Surveys Key Science Project (LC1\_034). However, the quality of this dataset did not allow us to reach a good enough sensitivity and image fidelity, even using the most advanced data reduction pipelines available to date.

Therefore, for this work we used a more recent dataset obtained on June 26th, 2019, as part of the LOFAR Two-metre Sky Survey (LoTSS, see Shimwell et al. 2019). The pointing reference code is P280+45 (project LT10\_010) and the target lies at a distance of 0.36 degrees from the field phase center. The observations were carried out using the standard survey setup, with 8 hours on-source time, 48 MHz bandwidth (244 subbands) and 1 second integration time. The entire LOFAR array was used in the observations (Dutch and international stations) but for this work we only exploit the data collected by the Dutch array, which consists of 64 stations and provides a maximum baseline of ~100 km. The source 3C295 was used as flux density calibrator and was observed for 10 minutes before and after the target observation. A full description of the observing strategy of the LoTSS pointings can be found in Shimwell et al. (2019).

The data were first pre-processed using the observatory pipeline (Heald et al. 2010), which includes automatic flagging of radio frequency interference (RFI) using the AOFlagger (Oftringa et al. 2012) and data averaging in time and frequency down to 5 seconds per sample and 4 channels per sub-band.

Afterwards, the calibration scheme and pipelines developed for LoTSS were applied (see Shimwell et al. 2019 for more details). In particular, the PREFACTOR pipeline (van Weeren et al. 2016; Williams et al. 2016) and version v2.2-167 of the DDFacet pipeline<sup>1</sup> (see Tasse et al. 2018; Tasse et al. in prep.) were used to perform direction independent and dependent calibration respectively, using the default parameters. The flux scale was set according to Scaife & Heald (2012).

To further improve the image quality of the target, after running the pipeline, we subtracted from the uv-data all the sources located in the field of view other than 3C388 and a few neighbour sources, and performed additional phase and amplitude self-calibration loops (van Weeren et al., in prep.). We then re-imaged the target using WSClean version 2.7 (Oftringa et al. 2014) with a uniform weighting scheme and a restoring beam of 6 arcsec  $\times$  6 arcsec. This final image has an average RMS of 0.8 mJy beam<sup>-1</sup>, which increases up to ~5 mJy beam<sup>-1</sup> close to the target due to dynamic range limitations.

The new radio map of the source is presented in Fig. 2 (top panel).

### 2.2. VLA observations and data reduction

#### 2.2.1. P-band

We observed the source with the Very Large Array (VLA) in A configuration on July 28th 2015 using the P-band receiver centered at 350 MHz. The target was observed for 2 hours while the flux density calibrator, 3C286, was observed for 10 minutes at the beginning of the observing run. We used a correlator integration time of 2 seconds and recorded four polarization products (RR, LL, RL, and LR). The total bandwidth, equal to 256 MHz in the range 224-480 MHz, was divided by default in 16 subbands of 16 MHz with 128 frequency channels.

The data were calibrated and imaged using the Common Astronomy Software Applications (CASA, version 4.7, McMullin et al. 2007) in the standard manner and following the guidelines set out in the online guidelines for continuum P-band data<sup>2</sup>. The flux scale was set according to Scaife & Heald (2012). Nine subbands spread across the band were discarded due to severe RFI contamination.

The remaining seven good sub-bands were imaged together using multiscale CLEAN with scales [0, 5, 15, 45] and nterms=2. This image was used as the starting model to perform phase self-calibration on each sub-band independently. To reduce the computational time during imaging, each sub-band was averaged down in frequency to 16 channels of 1 MHz bandwidth but no averaging in time was performed. The final image for each subband was made using Briggs weighting with a robust parameter of 0.0. The images were restored with a beam of 6 arcsec  $\times$  6 arcsec and have noise equal to ~ 1.5 mJy beam<sup>-1</sup>. The final image of the spectral window centered at 392 MHz is presented in Fig. 2 (bottom panel) for illustration purposes.

#### 2.2.2. L-band and C-band

We reprocessed the data used by Roettiger et al. (1994) at 1400 MHz and 4850 MHz. The data consists of observations in B array at 1400 MHz and in C array at 4850 MHz. The target was observed for 7 hours at 1400 MHz and for ~5 hours at 4850 MHz. The source 3C286 and 1843+400 were used as flux density calibrator and phase calibrator, respectively. The correlator integration time was set to 10 seconds.

All datasets were reduced with the standard approach using CASA (version 4.7). The data were manually flagged and calibrated using the flux scale of Perley & Butler (2013), which is consistent with the scale of Scaife & Heald (2012) at low frequency. Phase and amplitude self-calibration were performed. The final images were obtained using Briggs weighting with robust parameter equal to 0.0 and multiscale option with scales

<sup>1</sup> <https://github.com/mhardcastle/ddf-pipeline>

<sup>2</sup> [https://casaguides.nrao.edu/index.php/VLA\\_Radio\\_galaxy\\_3C\\_129:\\_P-band\\_continuum\\_tutorial-CASA4.7.0](https://casaguides.nrao.edu/index.php/VLA_Radio_galaxy_3C_129:_P-band_continuum_tutorial-CASA4.7.0)

[0, 5, 15, 45]. The images were restored with a beam of 6 arcsec  $\times$  6 arcsec and have a noise equal to 0.5 mJy beam<sup>-1</sup> at 1400 MHz and equal to 0.1 mJy beam<sup>-1</sup> at 4850 MHz.

### 2.3. GMRT observations at 614 MHz and data reduction

The target was observed with the legacy Giant Metrewave Radio Telescope (GMRT) at 614 MHz and 240 MHz in dual frequency mode and data were published in Lal et al. (2008). The observations were performed on July 29th and 30th, 2005. The target observation was divided into 5 time-scans for a total integration time of 4 hours. The source 3C48 was used as flux density calibrator and observed for 10 minutes at the beginning and the end of the observing session. Data were recorded using a correlator integration time of 16.1 seconds and a total bandwidth of 33-MHz divided into 512 channels of 65-kHz each.

For this work we reprocessed the archival data at 614 MHz using the SPAM pipeline (Intema 2014; Intema et al. 2017) and set the absolute flux scale according to Scaife & Heald (2012). The output calibrated visibility data were imported into CASA to produce images at different resolutions. The final image was obtained using a Briggs weighting scheme with a robust parameter equal to 0.0 and a restoring beam equal to 6 arcsec  $\times$  6 arcsec. The noise in the final image is equal to  $\sim$  0.8 mJy beam<sup>-1</sup>.

The available dataset at 240 MHz was not included in this analysis because of its lower spatial resolution.

### 2.4. Chandra data

3C388 was observed by Chandra on February 9th and 29th, 2004 with the ACIS-I detector (obs ID 4756 and 5295, respectively) and the data were published by Kraft et al. (2006). We reprocessed the archival observations using the Chandra Interactive Analysis of Observations CIAO software package (Fruscione et al. 2006) from the level 1 events files with CIAO 4.8 and CALDB 4.7.0. The *chandra\_repro* pipeline was subsequently used to reprocess the data to produce new level 2 events files using standard CIAO analysis methods. The *REPROJECT\_OBS* tool was used to merge the events files from the two observations, resulting in the 0.5-7.0 keV image shown in Fig. 4 (top panel).

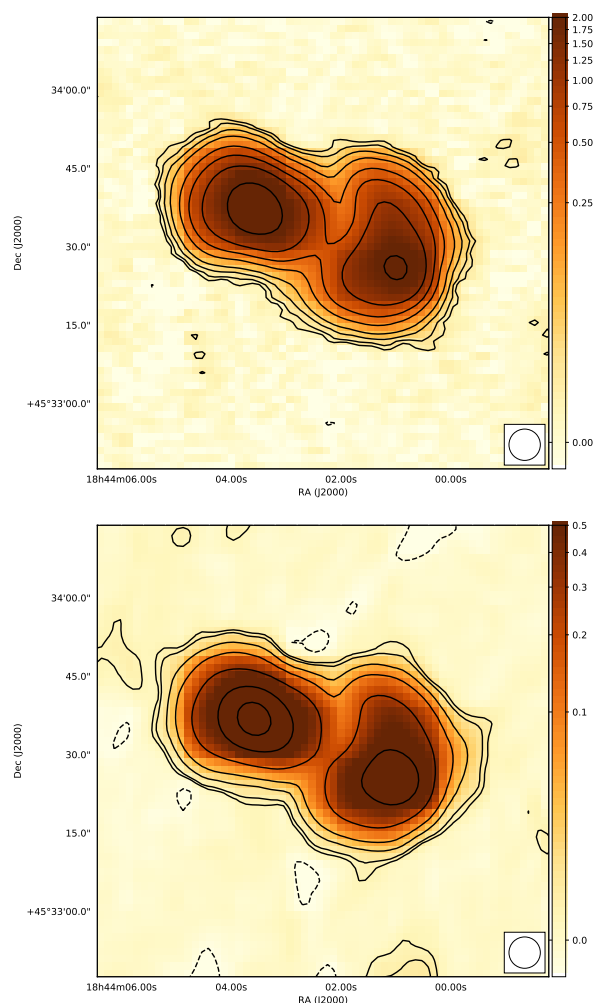
## 3. Analysis

In this section we combine the multi-frequency data presented in Sect. 2 to perform a complete analysis of the source 3C388.

### 3.1. Morphology

In Fig. 2 we show the new low frequency radio maps of the source at 144 and 392 MHz. The morphology of the source at low frequency is in agreement with previous observations at higher frequency (Burns et al. 1982; Roettiger et al. 1994; Leahy et al. 1996; Lal et al. 2008). Using both the LOFAR and the P-band VLA image we measure an angular size of  $\sim$ 1 arcmin, using the  $5\sigma$  contours as a reference, which corresponds to  $\sim$ 100 kpc at  $z = 0.091$ . This is consistent with previous estimates at higher frequencies.

Interestingly, in the LOFAR map we do not detect any extra low surface brightness emission beyond the known shape of the lobes at higher frequency. This might have been expected in case the source was actually a wide-angle tail as seen in projection as described in Sect. 1. Tailed radio galaxies in LOFAR images indeed often appear much more extended and asymmetric



**Fig. 2.** New low frequency radio maps of 3C388, where it can be seen that the morphology of the source is consistent with previous observations at GHz frequencies. *Top* - LOFAR 144-MHz map with contours equal to  $-3, 3, 5, 10, 20, 50, 100, 200, 500 \times \sigma_{144}$  where  $\sigma_{144} = 5$  mJy beam<sup>-1</sup>. *Bottom* - VLA 392-MHz map with contours equal to  $-3, 3, 5, 15, 40, 150, 500, 1000 \times \sigma_{392}$  where  $\sigma_{392} = 1.5$  mJy beam<sup>-1</sup>. Color-bars are expressed in Jy beam<sup>-1</sup>.

than what observed at higher frequency, with the most striking example to date being NGC 326 (Hardcastle et al. 2019). While limited in dynamic range, our current image seems therefore to suggest that the plasma of the lobes of 3C388 is well confined.

Finally, we note that the maximum resolution imposed by the low frequency (equal to 6 arcsec  $\times$  6 arcsec) does not allow us to investigate the small-scale structures recognized in previous studies, such as the narrow jet and hotspot in the Western lobe (Roettiger et al. 1994).

### 3.2. Integrated radio spectrum

In Fig. 3 we show the integrated radio spectrum of 3C388 that we have reconstructed to verify the quality of the flux calibration of our different observations with respect to previous works. The measurements presented in this paper (shown as black circles in the plot) are in good agreement with the overall spectral shape known in the literature (shown with red stars in the plot). The integrated flux density at each frequency has been measured using the  $5\sigma$  contours as a reference. In Table 2 we show the list of

flux density measurements with respective errors. We note that all measurements taken from the literature have been set to same flux scale used in Sect. 2. The errors on the flux densities have been computed by combining in quadrature the flux scale error and the image noise as shown in Klein et al. (2003). However, the main source of uncertainty is related to the flux scale. In particular, the flux scale error is considered to be 15 per cent for LOFAR (Shimwell et al. 2019) and GMRT measurements, 5 per cent for VLA measurements at P-band and 2 per cent at L- and C-band (Scaife & Heald 2012; Perley & Butler 2013).

As extensively described by Shimwell et al. (2019), the LOFAR flux scale may suffer from severe systematic offsets, therefore we have taken special attention to this. From Fig. 3 we can see that the LOFAR measurement at 144 MHz is well aligned with the 150 MHz all-sky radio survey (TGSS ADR1, Intema et al. 2017). While both the LOFAR and TGSS measurements appear to be slightly upscaled with respect to the general spectral trend, they are consistent with the general spectral shape within the applied errors, therefore we have not performed any extra flux scaling.

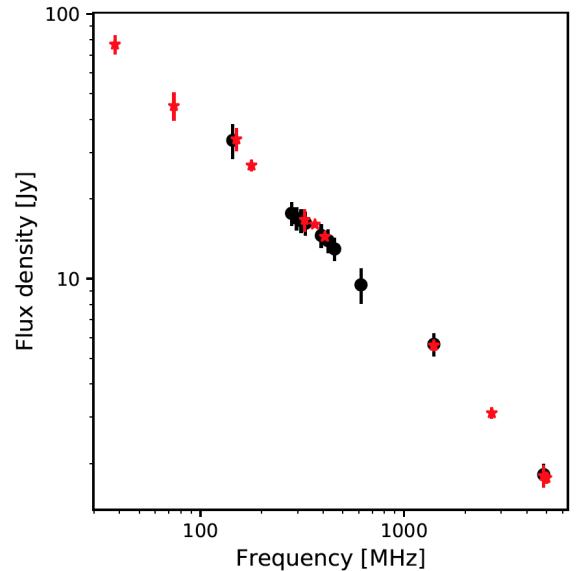
**Table 2.** Integrated flux densities of 3C388 at various frequencies both measured in this work and presented in the literature. All measurements taken from the literature have been set to same flux scale used in this work (see Sect. 2).

Frequency [MHz]	Flux density [Jy]	Reference
38	76.70±6.40	Kellermann et al. (1969)
74	44.97±5.46	Lane et al. (2012) (VLSSr)
144	33.30±5.00	this work
150	33.62±3.36	Intema et al. (2017) (TGSS)
178	26.80±1.34	Kellermann et al. (1969)
280	17.65±0.88	this work
296	16.93±0.85	this work
312	16.59±0.83	this work
325	16.70±1.60	Rengelink et al. (1997) (WENSS)
328	16.20±0.81	this work
365	16.04±0.40	Douglas et al. (1996) (TXS)
392	14.56±0.73	this work
408	14.42±0.29	Ficarra et al. (1985) (B3.1)
424	13.91±0.69	this work
456	12.95±0.64	this work
614	9.48±1.42	this work
750	9.40±0.47	Kellermann et al. (1969)
1400	5.60±0.28	Kellermann et al. (1969)
1400	5.60±0.19	Condon et al. (1998) (NVSS)
1400	5.65±0.11	this work
2696	3.11±0.15	Kellermann et al. (1969)
4850	1.82±0.04	this work
4850	1.80±0.17	Gregory et al. (1996) (GB6)
5000	1.77±0.09	Kellermann et al. (1969)

### 3.3. Magnetic field

As it regulates the amount of radiative losses in the lobes of radio galaxies at low redshift (where the inverse-Compton scattering with the cosmic microwave background, CMB, is not dominant), the magnetic field represents the most crucial input parameter of spectral ageing models, which are discussed later in Sect. 3.4.2.

A direct estimate of the magnetic field strength, as well as of the number density of the emitting particle in the lobes, can be obtained when the lobes are detected at both radio and X-ray frequencies. Indeed, X-ray emission in the lobes of radio galaxies, is thought to originate from inverse Compton (IC) scattering be-



**Fig. 3.** Integrated radio spectrum of the source 3C388, where it can be seen that the measurements presented in this work (black circles) are in good agreement with the spectral behaviour already known from the literature (red stars). All measurements taken from the literature have been set to same flux scale used in this work (see Sect. 2). The list of all flux densities is presented in Table 2.

tween the same relativistic electrons that produce the observed radio synchrotron radiation and the CMB (Harris & Grindlay 1979).

In case X-ray observations are not available, it is common practice to rely on the equipartition assumption for the magnetic field calculation.

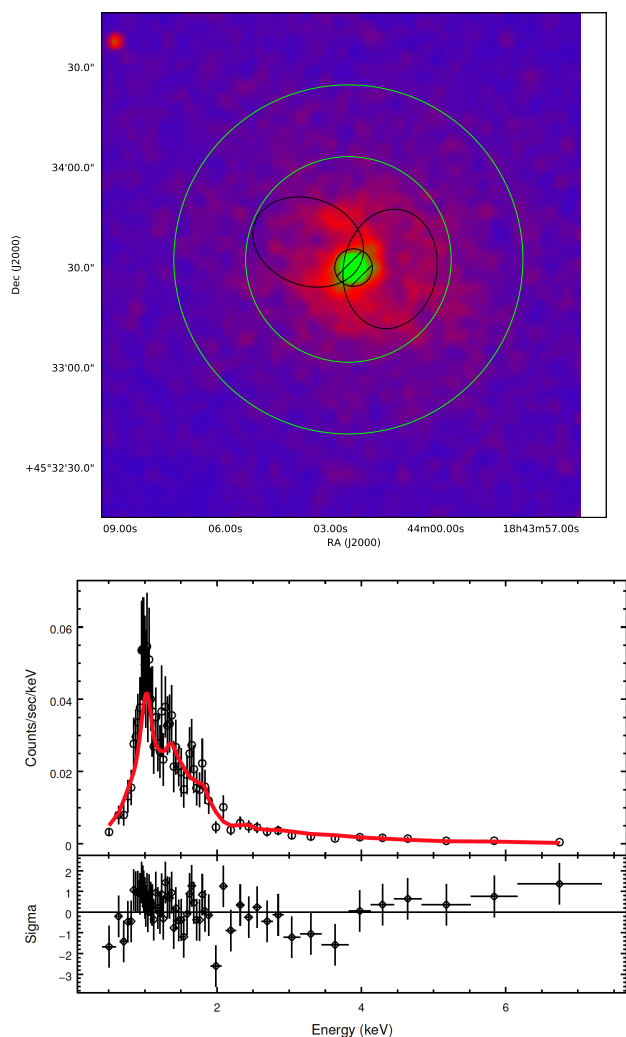
However, in the recent years an increasing number of studies on samples of FR II radio galaxies have demonstrated that magnetic field strengths in these sources are typically a factor of 2 - 3 below the equipartition values (e.g. Croston et al. 2005, Kataoka & Stawarz 2005, Migliori et al. 2007 and Ineson et al. 2017, Turner et al. 2018).

In order to assess in the best possible way the magnetic field strength of the source 3C388, we have both computed the equipartition value  $B_{eq}$  and attempted to derive the magnetic field  $B_{IC}$  from the X-ray inverse-Compton emission as described below. In the rest of the paper we consider both magnetic field values in performing the spectral modelling to explore the resulting variations in the source age.

#### 3.3.1. Inverse-Compton constraints to the magnetic field

In order to get a measurement of the inverse-Compton emission in the lobes of 3C388 and a constraint on the magnetic field strength, we have used the Chandra X-ray data described in Sect. 2.4 following the strategy presented below.

We have chosen to use a circular annulus surrounding the radio lobes as a reliable region to estimate the required background subtraction, so as to remove foreground cluster emission in front of the lobes. We have also removed the central AGN component, which may contaminate the desired lobe spectrum. We have extracted count rates from the individual observations, which were then combined, using CIAO tools. The background regions and the lobe regions used to extract the spectrum are shown in Fig. 4 (top panel).



**Fig. 4.** *Top:* Chandra X-ray map of 3C388 (0.5-7 keV). The green annulus has been used for background subtraction, while the black regions have been used to extract the source spectrum. The central circle with a diagonal line shows the central AGN core, which was masked out from the analysis. *Bottom:* Chandra background-subtracted X-ray spectrum for 3C388 extracted from the black regions shown in top panel. The red solid line indicates the best fit to the data as described in Sect. 3.3.1, while the lower panel indicates the reduced  $\chi^2$  statistics at each data point.

We have then used the Sherpa application (Freeman et al. 2011) as a platform to load the spectra and to perform background subtraction and model fitting. Bad data have been removed using the `ignore_bad()` command, removing bins based on bad data flags.

We have fitted the lobe spectrum using a combination of a non-thermal power-law emission model, describing the inverse-Compton emission, and a thermal model (APEC), describing collisionally-ionised diffuse gas, as it is predominantly expected from X-ray emission of the ICM. A photo-electric absorption model has been also added as a multiplicative component to the APEC model to account for the absorption of X-ray photons by foreground atomic matter such as hydrogen atoms in cold gas. The Galactic absorbing column density has been fixed at  $6.32 \times 10^{20}$  atoms  $\text{cm}^{-2}$  (Dickey & Lockman 1990). The temperature of the APEC model has been set to the X-ray temperature in the lobe regions equal to 3.5 keV as measured by Kraft et al. (2006). We note that hints of a temperature variation in different

regions of the source have been presented by Kraft et al. (2006). Such variations, however, are not very significant, as the measured temperatures are affected by large uncertainties. For this reason we prefer to assume a single temperature average value throughout the source.

Subsequent fitting resulted in the power-law photon index  $\Gamma$  being unconstrained, and hence we have fixed this value at  $\Gamma = 1.57$ , owing to our best fit injection spectral index equal to  $\alpha_{inj} = 0.57$  (see Sect. 3.4.2 for a full discussion), since  $\Gamma = \alpha_{inj} + 1$ . The use of the injection index is justified but the fact that it is the low-energy electrons ( $\gamma \sim 1000$ ) that scatter the CMB to X-ray energies. The re-fitting of the model with only the power-law and thermal normalization as free parameters, is consistent with a non-detection of non-thermal power-law emission, with a reduced  $\chi^2 = 0.8$ . The best fit is shown in Fig. 4 (bottom panel). A  $3\sigma$  upper limit flux density on the inverse-Compton emission is found at 1 keV equal to  $0.0102 \mu\text{Jy}$ .

We then have used the SYNCH code (Hardcastle et al. 1998) to determine the magnetic field strength that could match at the same time the observed radio flux densities reported in Table 2 (including those from literature) and the X-ray flux density upper limit derived from the Chandra image. Using a model that assumes no proton content in the lobes, we have found a lower limit on the magnetic field strength of  $B_{IC} > 3 \mu\text{G}$ .

### 3.3.2. Equipartition magnetic field

As the magnetic field estimate based on the inverse-Compton emission  $B_{IC}$  described in Sect. 3.3.1 only provided us with a lower limit, we also derived the equipartition magnetic field value equal to  $B_{eq} = 15.8 \mu\text{G}$  using the derivation by Worrall & Birkinshaw (2006). This relies on the assumption of equipartition conditions between particles and magnetic field over the entire source. For the calculation we have assumed a power-law particle distribution of the form  $N(\gamma) \propto \gamma^{-p}$  between a minimum and maximum Lorentz factor of  $\gamma_{min} = 10$  and  $\gamma_{max} = 10^6$ , with  $p$  being the particle energy power index. The value of  $p$  relates to the injection spectral index  $\alpha_{inj}$  of the synchrotron power spectrum ( $S \propto \nu^{-\alpha_{inj}}$ ) as  $p = 2\alpha_{inj} + 1$  and therefore has been set to  $p = 2.1$  following the best fit value equal to  $\alpha_{inj} = 0.57$  (see Sect. 3.4.2 for a full discussion). The ratio between proton and electron content inside the lobes is assumed to be  $k = U_p/U_e = 0$ , as suggested to be the case in many FR II radio galaxies (e.g. Croston et al. 2005). To calculate the volume of the source we have assumed the two lobes to be ellipsoids with major axis equal to  $a=34$  arcsec and  $a=36$  arcsec and minor axis equal to  $b=26$  arcsec and  $b=28$  arcsec, for the Western and Eastern lobe respectively. A value of  $S_{1400} = 5.6$  Jy is used as a reference.

We note that the lower limit of the magnetic field obtained from the X-ray data equal to  $B_{IC} > 3 \mu\text{G}$  is a factor  $\sim 5$  lower than the equipartition value. This is consistent with what has been observed in many sources as discussed in Sect. 3.3, suggesting that the real magnetic field value of 3C388 lies in the range  $3 \sim 15.8 \mu\text{G}$  and likely closer to the computed  $B_{IC}$ .

### 3.4. Spatially resolved spectral analysis

The shape of the radio spectrum of jetted AGN can give interesting insights into the physics of the electron population responsible for the emission. To investigate the spectral shape of the plasma in different regions of the lobes we have performed a spatially resolved analysis as described below. We have imaged all the data using the same pixel size equal to 1.2 arcsec and a

final restoring beam equal to  $6 \text{ arcsec} \times 6 \text{ arcsec}$ . Moreover, we have spatially aligned the maps to correct for any possible spatial shifts introduced by the imaging and phase self-calibration process, which would compromise the reliability of the spectral analysis. To do this we have fitted a point source located near the target with a 2D-Gaussian function in all the available images and derived the central pixel position. We have then used one image as a reference and aligned all the others to it, using the tasks IMHEAD and IMREGRID in CASA. After this procedure, we find a maximum residual offset between the images  $\leq 0.1$  pixels, which is sufficiently accurate for our analysis.

For the spectral analysis, we have used the Broadband Radio Astronomy ToolS software package<sup>3</sup> (BRATS, Harwood et al. 2013, 2015). Here we describe the procedures used in this analysis and we refer the reader to the cookbook for a complete description of the methods underlying the software.

### 3.4.1. Spectral index maps

We have computed two spectral index maps at low and high frequency respectively, using the weighted least squares method and only considering pixels above  $5\sigma$  in each single-frequency map. For the low frequency spectral index map we have used all the images in the range 144-614 MHz, while for the high frequency spectral index map we have used the images at 1400 and 4850 MHz. We note that from the following analysis we have excluded the P-band image centered at 280 MHz (see Table 2) due to its poor image fidelity. As our final goal is to analyze the spectral behaviour of the lobes, we have excluded from the analysis the region corresponding to the core of the radio galaxy, which is not well described by any of the spectral ageing models presented in Sect. 3.4.2. The spectral index maps are shown in Fig. 5, left and middle panels. The errors in the low frequency spectral index map vary from 0.1 up to 0.2 in the most external regions, while in the high frequency spectral index map vary from 0.01 up to 0.05 in the most external regions.

To further quantify the spectral index variation throughout the lobes we have plotted its value along two slices drawn in the Western and Eastern lobe for comparison to Roettiger et al. (1994) (Fig. 6). The slices were chosen as to go from the flattest region within the lobes to the outermost edges (see Fig. 5, middle panel). Finally, using the spectral index maps described above we have computed a spectral curvature (SPC) map defined as  $\alpha_{1400\text{MHz}}^{4850\text{MHz}} - \alpha_{144\text{MHz}}^{614\text{MHz}}$  (Fig. 5, right panel).

### 3.4.2. Spectral age maps

The curvature of the radio spectrum of a source is dictated by the amount of radiative losses that the particles have experienced and therefore it is directly related to the plasma age following the equation:

$$t_s = 1590 \frac{B^{0.5}}{(B^2 + B_{\text{CMB}}^2) \sqrt{\nu_b(1+z)}}, \quad (1)$$

where  $t_s$  is the age in Myr,  $B$  and  $B_{\text{CMB}} = 3.25 \cdot (1+z)^2$  are the magnetic field and inverse Compton equivalent field in  $\mu\text{G}$ ,  $\nu_b$  is the break frequency in GHz and  $z$  the redshift. From this expression it is clear that the age  $t_s$  directly scales with the magnetic field strength  $B$ .

In order to estimate the age of a source, two approaches can be taken. The most historical approach is based on the spectral break measurement and on the use of the analytical equation shown above. The second approach consists, instead, in fitting the observed radio spectrum with a modeled spectrum, which is obtained via numerical integration of the equations that describe the radiative losses of the plasma via synchrotron emission and inverse-Compton scattering with the CMB.

In this work we have used BRATS, which follows this second approach (for a full derivation of the underlying equations we refer the reader to Harwood et al. 2013).

In particular, to describe the spectral shape of a source various models have been proposed, which rely on different initial assumptions.

One category of models assumes that the electrons are accelerated in a single event at a time  $t_0$  with an energy distribution equal to  $N(E, t) = N_0 E^p$  (where  $p$  is the particle energy power index), which translates into a power law spectrum of the form  $S \propto \nu^{-\alpha_{inj}}$  (where  $\alpha_{inj}$  is the injection spectral index and has typical values in the range 0.5-0.8). As the particles age, the high frequency tail of the radio spectrum undergoes a steepening due to preferential cooling of high energy particles.

The Kardashev-Pacholczyk model (KP, Kardashev 1962; Pacholczyk 1970) and the Jaffe-Perola model (JP, Jaffe & Perola 1973) are two classical models of this kind and assume a uniform magnetic field distribution across the source. The main difference between the two concerns the micro-physics of the electron population. While in the KP model the pitch angle (the angle between the velocity's vector and magnetic field) of individual electrons is considered to be constant, the JP model assumes a more realistic situation where single particles are subject to many scattering events that randomize their pitch angle. This, in practice, is equivalent to assuming a time-scale for the isotropisation of the electrons much longer than the radiative timescale. This different assumption naturally leads to differences in the spectrum curvature. In particular, for a given age the KP model is relatively flatter than its JP counterpart at high frequencies. This is due to the presence of high energy electrons at small pitch angles, which are able to radiate at higher frequencies.

A third model is the Tribble model (Tribble 1991, 1993), which includes a more realistic magnetic field distribution. In particular, it assumes the magnetic field to be spatially non-uniform, which, in the weak field strong diffusion case (i.e. free streaming), can be described by a Maxwell-Boltzmann distribution within each volume element of the lobe. This has been expanded to an implementable form by Hardcastle (2013) and Harwood et al. (2013).

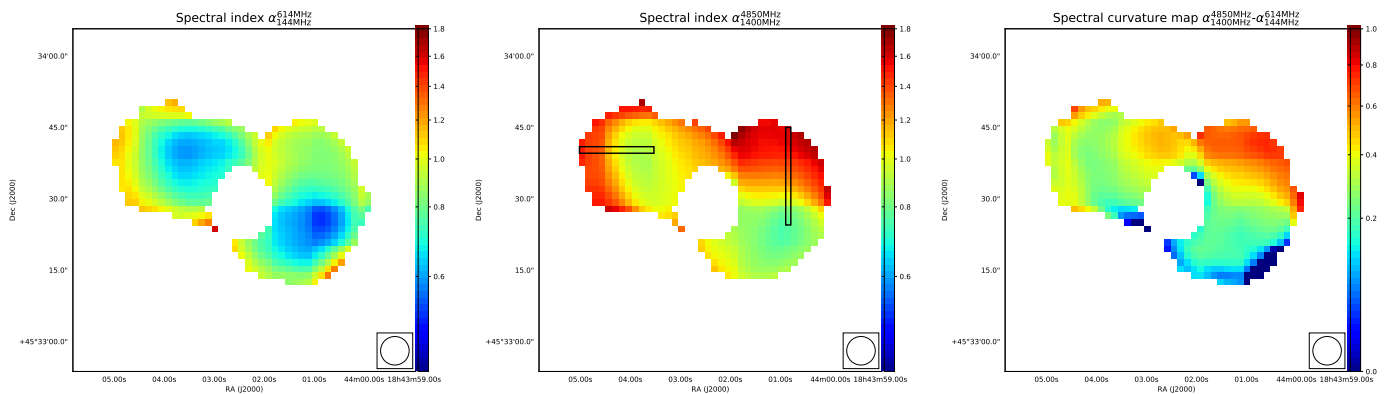
In the case this approximation does not hold, there is a second category of models that assume a continuous injection of particles throughout the source lifetime. These are constructed by summing individual JP or KP spectra related to particle populations of different ages. In particular, the continuous injection (CI) model (Pacholczyk 1970) best describes active sources where the injection of fresh particles is still ongoing, while the so-called CIOFF or KGJP/KGKP model (Komissarov & Gubanov 1994), assumes that the particle injection in the source is continuous for a certain amount of time and then stops.

The assumption of a single injection made in the JP, KP and Tribble models can work reasonably well for resolved spectral studies since, on small scales, particles can most likely be considered as being part of the same acceleration event.

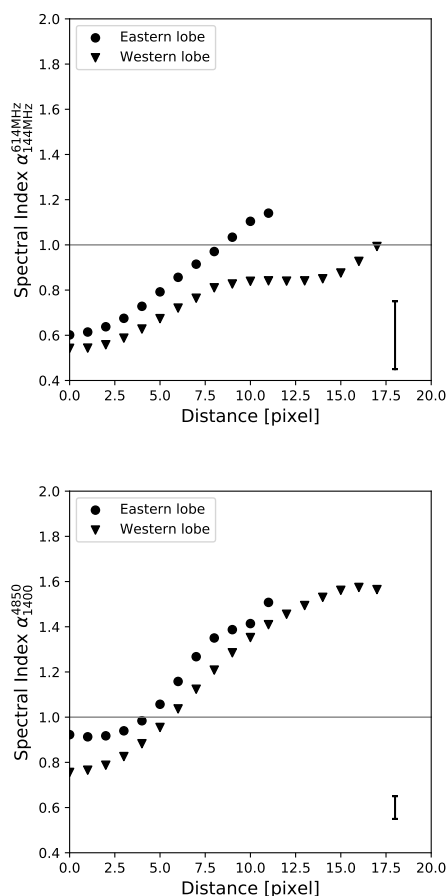
In particular, in the following analysis we have performed a spatially resolved (pixel-by-pixel) spectral modelling considering the JP and the Tribble models, since they implement a

<sup>3</sup> <http://www.askanastronomer.co.uk/brats/>



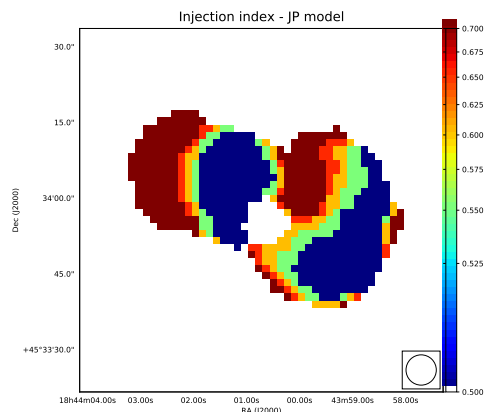


**Fig. 5.** *Left:* spectral index map in the range 144–614 MHz; *Middle:* spectral index map in the range 1400–4850 MHz; *Right:* spectral curvature map  $SPC = \alpha_{4850\text{MHz}} / \alpha_{1400\text{MHz}} - \alpha_{614\text{MHz}} / \alpha_{144\text{MHz}}$ . All three maps show a clear steepening moving from the inner regions of the lobes towards the edges of the lobes. The spatial resolution of all radio maps is  $6 \text{ arcsec} \times 6 \text{ arcsec}$ . The black rectangular regions in the middle panel have been used to study the spectral index variations throughout the lobes (see Fig. 6).



**Fig. 6.** Variation of the spectral index along the radio lobes at low frequency  $\alpha_{614\text{MHz}} / \alpha_{144\text{MHz}}$  (top panel) and at high frequency  $\alpha_{4850\text{MHz}} / \alpha_{1400\text{MHz}}$  (bottom panel). In both cases the spectral index shows a systematic and quick steepening going from the inner region of the lobes towards the edges. Values have been extracted from the black rectangular regions shown in Fig. 5-middle panel. The gray line represents a spectral index equal to  $\alpha = 1$  as a reference. The 0 value on the x-axis corresponds to the most internal point in each lobe, where the flattest spectral index is measured. We note that one beam corresponds to five pixels. An average errorbar is shown in the bottom left corner of both plots.

more realistic physics. As a first step we have derived the best value for the injection index,  $\alpha_{\text{inj}}$  to be used in the final age estimate. To do this we have performed a series of fitting iterations over the entire source using both the JP and the Tribble models. While keeping all the other parameters fixed, we have firstly varied  $\alpha_{\text{inj}}$  over a grid ranging between 0.5 and 1 with a step size of 0.05. Secondly, we have refined our grid to a step size of 0.01 around the previous minimum. The best fit value over the entire source obtained using both models is equal to  $\alpha_{\text{inj}} = 0.57$ , consistent with the low frequency spectral index measured in the Western hotspot.



**Fig. 7.** Pixel-by-pixel best fit injection index value obtained using the JP model. The value of injection index appears to be correlated with the position within the radio lobes of the radio galaxy.

We note that, for both models, the best value of  $\alpha_{\text{inj}}$  does strongly correlate with the position in the radio lobe, with values up to  $\alpha_{\text{inj}} \sim 0.7$  in the outer lobes and values of  $\alpha_{\text{inj}} \sim 0.5$  in the inner regions of the lobes (see Fig. 7). The observed systematic spatial trend seems to suggest an intrinsic variation of the plasma properties in the different regions of the source, possibly related to the two claimed jet episodes. However, given the large errorbars on the low frequency spectral index, confirming this trend remains challenging.

We therefore decided to use as injection index the best fit value over the entire source equal to  $\alpha_{\text{inj}} = 0.57$  for the final spectral age derivation. We have run the final model fitting iteration using both JP and Tribble models and both magnetic field values described in Sect. 3.3 ( $B_{\text{eq}} = 15.8 \mu\text{G}$  and  $B_{\text{IC}} = 3 \mu\text{G}$ ). The

**Table 3.** Model fitting results. Col. 1 model used for the fitting; Col. 2 magnetic field in  $\mu\text{G}$ ; Col. 3 injection index; Col. 4 mean  $\chi^2_{\text{Red}}$  over all regions; Col. 5 pixel with maximum age in Myr; Col. 6 pixel with minimum age in Myr; Col. 7 number of pixels whose  $\chi^2$  values fall within a specific confidence range; Col. 8 whether the goodness of fit over all the regions is rejected; Col. 9 confidence level at which the model can be rejected over the entire source.

Model	B [ $\mu\text{G}$ ]	$\alpha_{\text{inj}}$	Mean $\chi^2_{\text{Red}}$	Max age [Myr]	Min age [Myr]	Confidence bins					Rejected	Median confidence
						<68	68-90	90-95	95-99	$\geq 99$		
JP	15.8	0.57	2.13	16.78 <sup>+2.68</sup> <sub>-2.14</sub>	1.99 <sup>+0.09</sup> <sub>-0.62</sub>	246	145	75	138	275	No	<68
Tribble	15.8	0.57	2.08	18.48 <sup>+3.07</sup> <sub>-1.92</sub>	1.99 <sup>+0.44</sup> <sub>-0.58</sub>	249	150	65	129	286	No	<68
JP	3	0.57	2.11	82.05 <sup>+13.79</sup> <sub>-9.44</sub>	9.05 <sup>+2.65</sup> <sub>-2.29</sub>	249	148	71	137	274	No	<68
Tribble	3	0.57	2.06	90.95 <sup>+0.0</sup> <sub>-11.39</sub>	9.95 <sup>+2.09</sup> <sub>-3.04</sub>	255	157	64	125	278	No	<68

final fitting results are presented in Table 3. In Fig. 8 we also show the final spectral age maps obtained using the JP model with respective error maps and  $\chi^2_{\text{red}}$  (8 degrees of freedom). One representative spectral plot (flux density vs frequency) for an individual pixel with good fitting results is also shown in Fig. 9 for illustration purposes. The fits obtained using the Tribble model provide age and  $\chi^2_{\text{red}}$  distributions comparable with the JP model within the errors and therefore we do not show their maps here.

As it can be seen from Table 3 the overall fitting results are poor with a mean  $\chi^2_{\text{red}} \sim 2$  over the entire source. All models cannot be rejected at the 68 per cent confidence level over the entire source and we note that there is a significant number of regions that can be rejected at the 95 or 99 per cent confidence level. These regions are also clearly visible as red pixels in the  $\chi^2_{\text{red}}$  maps in Fig. 8 This suggests that the spectral shape is not constant throughout the source as further discussed in Sect. 4.2.

Finally, following the injection index best fit distribution within the lobes (see Fig. 7), we have investigated how the aforementioned results would vary in case we assumed an injection index equal to 0.7 for the outer lobe regions and an injection index equal to 0.5 for the inner lobe regions. With these new sets of input parameters we find deviations in the final ages up to a few Myr, values which lie well within the considered final error on the ages. For these reason, we do not report these results here and we only consider in the following analysis the ages obtained using a common injection index throughout the source equal to  $\alpha_{\text{inj}}=0.57$  as described above.

### 3.4.3. Color-color diagram

Given the complexity of the source, we have further investigated the spectral shape of different regions of plasma within the source lobes using the "color-color" diagram ( $\alpha_{\text{high}}$  vs  $\alpha_{\text{low}}$ , Katz-Stone et al. 1993; Katz-Stone & Rudnick 1997; van Weeren et al. 2012; Shulevski et al. 2015). This plot is useful to inspect and compare the curvature of the radio spectrum in different regions/pixels of the source, independently of the assumption on magnetic field and on the presence of adiabatic compression or expansion. Indeed, these mechanisms can only cause a shift of the spectrum in frequency but do not affect its actual shape. Therefore, it allows us to discriminate among different radiative models, as well as to probe the presence of multiple particle populations.

In Fig. 10 we show the color-color diagram  $\alpha_{1400\text{MHz}}^{4850\text{MHz}}$  vs  $\alpha_{144\text{MHz}}^{614\text{MHz}}$  obtained for the Western lobe. We restrict the analysis to this lobe due to its larger extension allowing for a more detailed analysis of the difference between the inner and outer lobe. As circles we show the pixel-based values extracted from the region shown in Fig. 8 top-left panel, colored according to their position within the lobe. Black diamonds and squares repre-

sent instead the values computed by integrating the flux density in the regions shown in Fig. 8, bottom-left panel, for the inner and outer lobe respectively. Finally, we plot the lines corresponding to some spectral models as a reference: 1) a JP model with  $\alpha_{\text{inj}}=0.57$  (dash-dotted green line); 2) a JP model with  $\alpha_{\text{inj}}=0.7$  (dotted blue line); 3) a CI model with  $\alpha_{\text{inj}}=0.45$  (dashed black line); 4) a CIOFF model with  $\alpha_{\text{inj}}=0.45$  (solid black line). Note that for this last model we have fixed the magnetic field to  $B=3 \mu\text{G}$  and the source active phase to 20 Myr.

From the plot it is clear that the spectral shape is not uniform throughout the source. A full discussion of the observed trends is presented in Sect. 4.2.

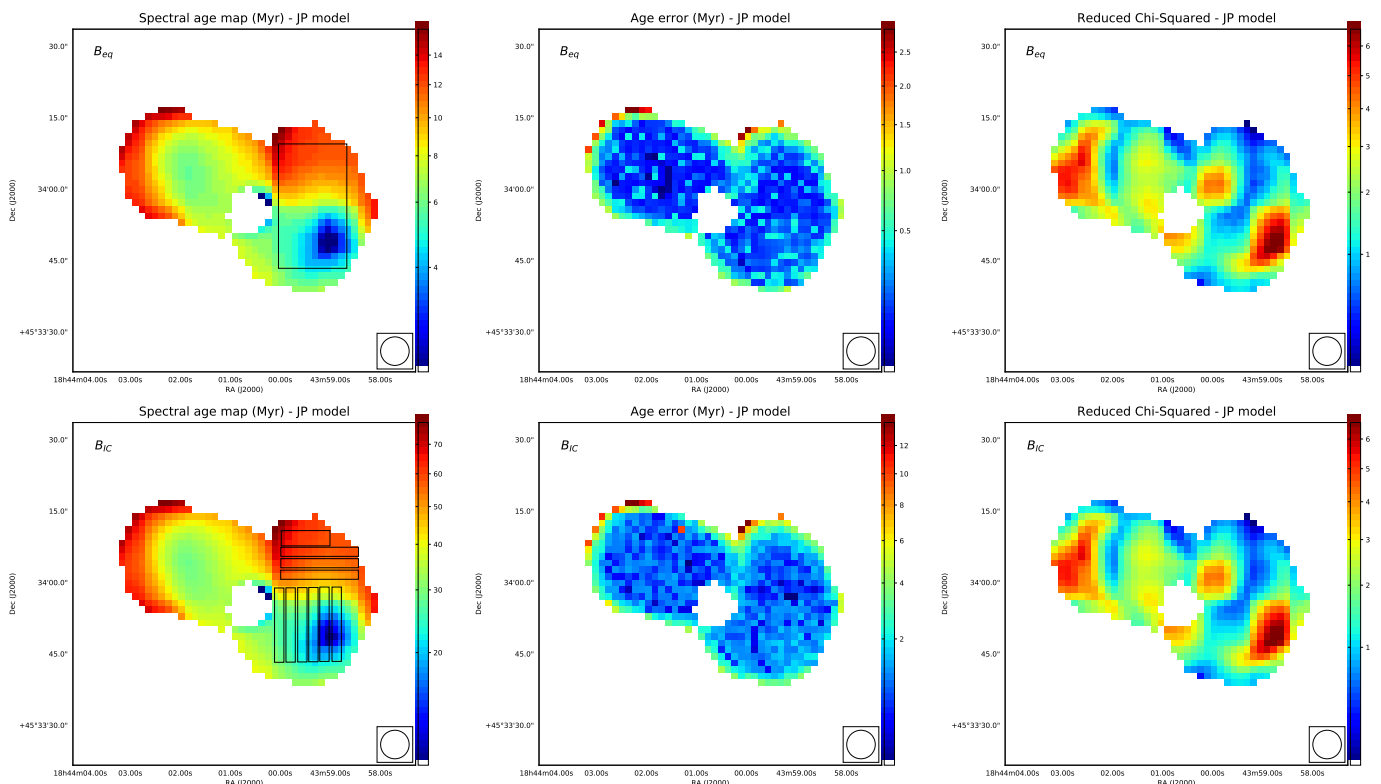
## 4. Discussion

### 4.1. Spectral index distribution

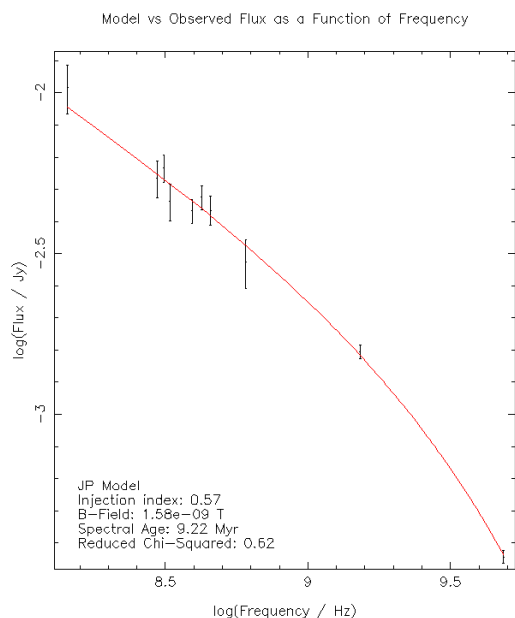
The spatial distribution of spectral index that we have computed in the range 1400-4850 MHz (see Fig. 5, middle panel) is consistent with previous results by Roettiger et al. (1994). By studying the spectral index variation along the radio lobes at high frequency (see Fig. 6, bottom panel) we also confirm the rapid steepening towards the edges previously identified. The gradient we observe is smoothed with respect to what presented by Roettiger et al. (1994) due to the effect of a larger beam in our images (a factor 4 larger). In particular, in the Western lobe the spectral index varies from  $\alpha_{1400\text{MHz}}^{4850\text{MHz}}=0.75$ , in the centre of the compact, hotspot-like emission, to  $\alpha_{1400\text{MHz}}^{4850\text{MHz}}=1.56$ , in the most external edge of the radio lobe. In the Eastern lobe, instead, the spectral index varies from  $\alpha_{1400\text{MHz}}^{4850\text{MHz}}=0.89$ , in the centre of the diffuse hotspot, to  $\alpha_{1400\text{MHz}}^{4850\text{MHz}}=1.51$ , in the most external edge of the radio lobe.

The spectral index distribution at low frequencies is presented in this work for the first time (Fig. 5, left panel) and shows similar trends to the one observed at high frequency, with flatter spectral indices in the vicinity of the centre of the radio lobes and steeper spectral indices towards the edges of the lobes. However, as expected by spectral evolution models, the spectral indices at low frequency are systematically flatter than those at high frequency over the entire source. As it can be seen in Fig. 6 (top panel) the variation of the spectral index  $\alpha_{144\text{MHz}}^{614\text{MHz}}$  across the two lobes is milder than what observed at higher frequencies, with values ranging from  $\alpha_{144\text{MHz}}^{614\text{MHz}} \sim 0.55$  to  $\sim 0.9$  in the Western lobe and from  $\alpha_{144\text{MHz}}^{614\text{MHz}} \sim 0.60$  to  $\sim 1.14$  in the Eastern lobe.

Thanks to the availability of the new low frequency data we could also investigate the spectral curvature distribution across the lobes (see Fig. 5, right panel), from which the overall spectral shape in different regions of the source can be better appreciated. We observe that in the inner regions of both lobes the spectral curvature has values in the range  $0.1 \leq \text{SPC} \leq 0.3$ ,



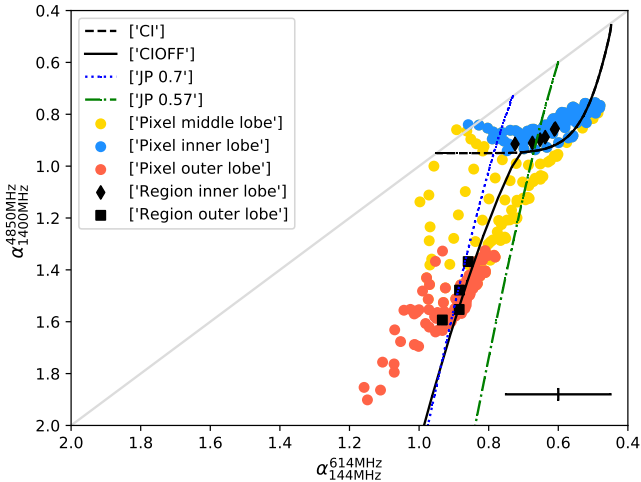
**Fig. 8.** Spectral age maps of the source 3C388 (left) and relative age error maps (middle) and reduced chi-squared maps (right) obtained using the JP model. In the top row maps have been produced assuming a magnetic field equal to the equipartition magnetic field  $B_{eq}$  and in the bottom row equal to  $B_{IC}$ . A clear increase of spectral age can be seen going from the inner lobes towards the source edges. The chi-squared maps also show that the goodness of the fit is not uniform across the source possibly due to mixing of different particle populations. The black rectangle in the top-left panel represents the region from which pixel-based values have been used for the color-color diagram analysis presented in Sect. 3.4.3 (circles in the plot). The black rectangles in the bottom-left panel represent instead the regions from which integrated values have been computed for the color-color diagram analysis presented in Sect. 3.4.3 (squares and diamonds in the plot).



**Fig. 9.** Representative radio spectrum (flux density vs frequency) for an individual pixel with a good fitting result. Black points are observational data and the red solid line is the best fit using the JP model. Model parameters, ages (in Myr) and statistics are shown in the bottom-left corner of the panel.

which are compatible with the plasma being still accelerated by the jets. Moving to the outer edges of both lobes, instead, and especially in the Western lobe, the spectral curvature increases significantly with values up to  $SPC=0.7-0.8$ . This extreme curvature is typical of old ageing plasma that is not replenished with new, freshly injected particles, supporting the idea of a remnant electron population. We also note that in some pixels at the lobe edges the spectral curvature is highly reduced. Whether this effect is real or not is difficult to assess as the image fidelity at the source border is often poor (see Harwood et al. 2013, 2015).

In light of the results at both low and high frequency, the spectral behaviour of 3C388 is difficult to reconcile with what observed in classical radio galaxies. FR II sources typically show the flattest spectral indices at the lobe edges in correspondence of the hotspots, where the particle acceleration occurs, and the steepest spectral indices in the regions surrounding the core, where the oldest accelerated particles are located (e.g. Carilli et al. 1991; Orrù et al. 2010; McKean et al. 2016). In FR I radio galaxies the spectral index may both steepen from the core outward or from the lobe outer edges inward, depending on the source morphology (Parma et al. 1999). Lobed FR I radio galaxies tend to show the flattest spectral index values all along the jets up to the lobe edges and the steepest spectral index values in the surrounding regions (Laing et al. 2011). Instead, plumed (or tailed) FR I radio galaxies have the flattest spectral indices in the core regions, which then get increasingly steeper with distance (Laing et al. 2008; Heesen 2015).



**Fig. 10.** Color-color diagram of the Western lobe showing that the spectral shape of the plasma located in different regions follows different radiative model curves. Pixel-based values are shown as circles (blue=inner lobe, red=outer lobe, yellow=middle region of the lobe). Black diamonds and squares are the values computed by integrating the flux density in the regions shown in Fig. 8 bottom-left panel, for the inner and outer lobe respectively. The gray solid line represents  $\alpha_{1400\text{MHz}}^{614\text{MHz}} = \alpha_{1400\text{MHz}}^{4850\text{MHz}}$ . The other lines indicate the spectral index evolution of aging particles for various models. In particular, the black dashed line represents a CI model with  $\alpha_{\text{inj}} = 0.45$ , while the black solid line represents a CIOFF model with  $\alpha_{\text{inj}} = 0.45$ ,  $B=3 \mu\text{G}$  and  $t_{\text{on}} = 20$  Myr. The blue dotted line represents a JP model with  $\alpha_{\text{inj}} = 0.7$  and the green dash-dotted line represents a JP model with  $\alpha_{\text{inj}} = 0.57$ . In the bottom right corner an average errorbar on the spectral indices is shown as a reference.

None of the spectral classes described above completely matches what we observe in 3C388, which remains to date a special case. The only source in the literature showing a similar spectral trend to 3C388 is Hercules A (3C348), where a sharp gradient in spectral index is also observed, between the inner, brighter regions of the lobes, and the surrounding diffuse ones (Gizani & Leahy 2003). In the case of 3C348 high resolution radio images clearly show that this trend can be attributed to the presence of a new-born jet pushing away and compressing the old lobe material from a previous outburst. A similar scenario can therefore be suggested for 3C388.

In alternative, the observed spectral distribution could be dictated by a combination of source bending and projection effects. While this scenario would require a very peculiar geometry as discussed in Burns et al. (1982), we think that this possibility cannot be completely discarded. Recent studies also suggest that atypical morphologies and spectral distributions in radio galaxies are likely attributed to these effects (Harwood et al. 2019).

#### 4.2. Spectral ages and models

As expected, the spectral age distribution follows the observed spectral index distribution, with younger ages in the inner lobes and older ages at the lobe edges (see Fig. 8). Again we underline that, contrary to typical FR IIs where the youngest regions correspond to the hotspots at the very edge of the lobes, in 3C388 the youngest ages are observed in the location of the compact hotspot in the Western lobe and diffuse hotspot in the Eastern

lobe, as defined by Roettiger et al. 1994), both embedded in the lobes.

From Table 3 we can see that the results obtained using the two different radiative models (Tribble and JP) are consistent within the errors. Because of this, we only refer to the JP model results in the discussion below. We stress that the largest uncertainties on the age estimate are dictated, as expected, by the different assumptions on the magnetic field. The absolute age values increase by about a factor of 5 when using  $B_{\text{IC}} = 3 \mu\text{G}$  ( $t_{\text{max}} \sim 80$  Myr -  $t_{\text{min}} \sim 9$  Myr) with respect to the simple equipartition assumption  $B_{\text{eq}} = 15.8 \mu\text{G}$  ( $t_{\text{max}} \sim 16$  Myr -  $t_{\text{min}} \sim 2$  Myr).

As the oldest age found in the resolved spectral analysis can be considered representative of the first particle acceleration in the source, we can infer that the total age of the source is  $\lesssim 80$  (for the most realistic assumption of magnetic field close to the inverse-Compton limit). This value is compatible with the dynamical age of the radio source equal to  $< 65$  Myr, estimated to first order by Kraft et al. (2006) by assuming the lobes to be buoyant bubbles expanding in the ambient medium at a velocity equal to half the sound speed.

Another interesting point to highlight is that, as already mentioned in Sect. 3.2, the overall fitting results over the entire source cannot be rejected with only 68 per cent confidence, meaning that there is a significant number of regions that shows poor results. This can be appreciated from Table 3 and Fig. 8 right panels, where it is clear that there are regions with  $\chi_{\text{Red}}^2$  values up to 10. The location of these poorly fitted regions does not correlate with either both the outer or inner lobes, instead it mainly corresponds to the hotspot in the Western lobe and the outer edges of the Eastern lobes.

This finding seems to suggest that there are regions in the lobes of this radio galaxy where the physical conditions of the plasma cannot be described by the spectral models that we have used. A possible cause of the poor fitting results may be the presence of strong mixing of different particle populations within the lobes of the source. Indeed, such particle mixing would make the simple assumption of a single injection event, used in the JP and Tribble models, invalid.

This possibility has already been discussed from an empirical stand point (e.g. Harwood et al. 2017, 2019; Mahatma et al. 2019), as well as supported through modelling considerations and numerical simulations (Rudnick 2002; Turner et al. 2017), which show that the mixing of different aged electrons strongly affects the spectrum at each point of the radio source leading to poor spectral age estimates.

This mixing may have both an observational origin, in case the resolution of the observation is not high enough to distinguish different particle populations or in case of projection effects (see Harwood et al. 2019), and an intrinsic origin in case there is an actual mixing of particles accelerated by different events (i.e. having different physical properties such as injection index and magnetic field) or at different times.

In FR II radio galaxies, for example, this may be particularly relevant in the backflow region, where freshly injected electrons from the hotspots are carried back towards the AGN core causing a significant mixing of particle populations. In the case of 3C388 mixing may become even more relevant if we assume that newly started jets are expanding in old ageing lobes as suggested by the restarting AGN scenario (Roettiger et al. 1994). All this reflects on the uncertainties of the derived spectral age, which should therefore taken with care.

In this context, the color-color diagram gives us some further insights on the spectral shape of the plasma in different regions

of the source 3C388. From the plot shown in Fig. 10, it is clear that, despite the large errorbars, the points related to the middle/outer and inner lobe follow two very distinct trends. This conclusion remains valid both when using the pixel-based information (circles) and the region-based one (squares and diamonds), and supports again the idea that we are looking at two distinct electron populations suffering very different amounts of radiation losses.

In particular, the points related to the inner lobe follow quite impressively the CI model trend. We note though that the points do not reach the single power-law (grey) line in correspondence of the injection value, possibly due to particle mixing. To the contrary they touch the single power-law (grey) line at the bottom of the curve, showing an upturn with respect to the plotted CI model. The fact that the CI model best describes the spectral shape in the inner lobe explains why bad fitting results using the JP model are obtained in correspondence of the hotspot (see Fig. 8-right).

The points related to the middle/outer lobe, instead, clearly deviate from the CI curve showing much stronger steepening. The pixel-based points show a large scatter, which is hard to reconcile with one single model. This might be an indication of different physical conditions in different regions of the plasma but also simply the effect of the large errorbars. We can, however, see that the region-based points show an impressively good agreement with a CIOFF model with an active time of  $t_{\text{on}}=20$  Myr with  $B=3 \mu\text{G}$ . This may be suggesting that the remnant plasma of the outer lobe was produced by an episode of jet activity similar to the one currently ongoing (that well matches the CI trend described above) and that switched off after 20 Myr. A more thorough investigation of the jet activity timescales is presented in the next section.

### 4.3. Duty cycle

In this section we investigate the duty cycle of 3C388 under the assumption that the discontinuity observed in the spectral distribution is not purely due to projection effects but is actually indicating a restarting jet activity, as proposed in the case of Hercules A (see discussion in Sect. 4.1).

As already done for the analysis of the color-color plot we focus on the Western lobe, where the remnant plasma is much more extended allowing for a more detailed analysis. For deriving the duration of the older jet activity phase we use the same approach as in Shulevski et al. (2017): we compute the difference between the age of the oldest particle population (82.05 Myr for  $B_{\text{IC}}$  and 16.78 Myr for  $B_{\text{eq}}$ ) and the youngest one (50.95 Myr for  $B_{\text{IC}}$  and 10.38 for  $B_{\text{eq}}$ ) measured in the outer Western lobe (the remnant lobe). The duration of the first phase of jet activity found in this way is  $t_{1,\text{on},B_{\text{IC}}} \sim 30$  Myr and  $t_{1,\text{on},B_{\text{eq}}} \sim 7$  Myr, respectively.

We note that a reliable measure of the age of the youngest electron population in a remnant lobe comes from the region where the particle acceleration was occurring during the active phase (e.g. a fading hotspot). In this region indeed we can measure the age of the particles that were last accelerated before the switch off. Unfortunately, contrary to isolated remnant sources or double-double radio galaxies, where the outer lobes are well detached from the inner lobes, in 3C388 the particle acceleration region of the first period of jet activity is challenging to determine, as it is likely currently mixed with the inner lobes. For this work we have extracted the age of the youngest particles of the outer Western lobe from a region including all the pixels showing a spectral curvature  $\text{SPC} > 0.5$ , indicating very strong ra-

diative losses typical of a remnant radio lobe. However, due to the abovementioned limitations these numbers can only be considered as upper limits on the actual switch off time.

For estimating the duration of the second episode of jet activity instead, we use the maximum age measured in the region closest to the core in the Western lobe. Indeed, within the inner lobe, we observe the typical trend of FR II radio sources (see Fig. 8 left) in which the plasma closer to the nucleus is the oldest and it gets younger moving towards the hotspot where the current acceleration is taking place (e.g. Harwood et al. 2016). In this way we get an estimate of the second period of activity equal to  $t_{2,\text{on},B_{\text{IC}}} \sim 30$  Myr and  $t_{2,\text{on},B_{\text{eq}}} \sim 6$  Myr, respectively.

Using the aforementioned values we can compute a first order estimate of the duty cycle of the radio jets in 3C388. In the case of  $B_{\text{IC}}$  we find that the first jet episode lasted  $t_{1,\text{on},B_{\text{IC}}} \gtrsim 30$  Myr. This was followed by a period of inactivity that lasted  $\lesssim 20$  Myr, which is computed as the difference between the youngest age of the outer lobe, equal to 50.95 Myr, and the oldest age in the inner lobe, equal to 31.05 Myr. Finally, the current jet episode has lasted  $\sim 30$  Myr. If we use the values obtained assuming  $B_{\text{eq}}$  instead, the duty cycle gets much shorter. Following the same procedure we obtain that the first jet episode lasted  $\gtrsim 7$  Myr and was followed by an inactivity period of  $\lesssim 4$  Myr, followed by a second episode of jet activity  $\sim 6$  Myr long.

In both cases the derived numbers provide a duty cycle of  $\gtrsim 60\%$  defined as  $t_{\text{on},1}/(t_{\text{on},1} + t_{\text{off}})$  in agreement with Bîrzan et al. (2012). The timescales of the jet activity derived here are summarised in Table 4. We stress that, as the most likely value of the magnetic field is close to the inverse-Compton limit (see Sect. 3.3.2), we consider the ages obtained with this values the closest to reality.

**Table 4.** Duty cycle timescales estimated using spectral age results obtained using the JP model on the Western lobe and different values of magnetic field (see Sect. 4.2).

Jet phase	JP ( $B_{\text{eq}}$ )	JP ( $B_{\text{IC}}$ )
First episode $t_{\text{on},1}$ [Myr]	$\gtrsim 7$	$\gtrsim 30$
Inactive time $t_{\text{off}}$ [Myr]	$\lesssim 4$	$\lesssim 20$
Second episode $t_{\text{on},2}$ [Myr]	$> 6$	$> 30$
Fractional duty cycle	$\gtrsim 60\%$	$\gtrsim 60\%$

Despite the variations obtained with different magnetic field assumptions and all the possible sources of error for the age described in Sect. 4.2, the duty cycle estimated for the source 3C388 seem to be consistent with the average values obtained from other studies of restarted radio galaxies.

In the specific case of Hercules A, the AGN has been claimed to have effectively ceased for a short period of  $\sim 1$  Myr and then restarted with a fluctuating jet activity of 250-800 kyr, which is responsible for the rings observed in the radio morphology of the source (Gizani & Leahy 2003).

More in general, the typical estimated inactive period between two phases of activity vary in the range a few Myr to a few tens of Myr for restarted radio galaxies of various morphologies, including the well-known double-double radio galaxies (e.g. Schoenmakers et al. 2000; Saikia et al. 2006; Konar et al. 2012; Konar & Hardcastle 2013; Shulevski et al. 2015; Brienza et al. 2018). Typically the duration of this quiescent phase is shorter or at most comparable to the duration of the previous phase of activity, which is usually found to be in the range few tens to few hundreds of Myr. The fact that we tend to detect sources with short quiescent periods is likely an observa-

tional bias dictated by the fact that the remnant plasma becomes quickly undetectable with current instruments even at MHz frequencies. This is becoming increasingly evident thanks to recent observational campaigns of remnant radio galaxies detecting small fractions, up to 10%, of these sources (see e.g. Brienza et al. 2017; Godfrey et al. 2017; Mahatma et al. 2018), as well as thanks to radio galaxy modelling and simulations, which predict a visibility timescales for the remnant plasma of the order of a few tens of Myr (e.g. Brienza et al. 2017; Godfrey et al. 2017; Hardcastle 2018; English et al. 2019).

Other constraints to the duration of the jet quiescent phase in radio galaxies come from the study of multiple-generation of X-ray cavities at the centre of galaxy clusters. For a sample of eleven sources, Vantyghem et al. (2014) find that the typical time interval between the two AGN outbursts that created the two pairs of X-ray cavities varies in the range  $\sim 1$ -10 Myr, which is consistent with quiescent time estimates of restarted radio galaxies from radiative ages as discussed above.

By comparing the outbursts intervals with the gas cooling time in the respective clusters, the authors find that the AGN in these systems restart on a timescale of about a factor 3 smaller than the gas cooling time, making it an effective mechanism to suppress cooling flows.

Following a similar argument, Kraft et al. (2006) show that for 3C388 the jet mechanical power can easily quench the gas cooling if a duty cycle of only about 5% with similar power is assumed. This requirement is much smaller than the value we have actually computed equal to  $t_{\text{on},1}/(t_{\text{on},1} + t_{\text{off}}) = 60\%$ . While it is impossible to predict whether the duty cycle that we have probed will remain constant throughout the entire evolution history of the source, we can confirm that in this phase the timescales of the jet activity in 3C388 are consistent with expectations from the X-ray analysis.

## 5. Summary and future prospects

Because of its morphology and spectral index distribution at high frequency the radio galaxy 3C388 has long been claimed to be a restarted radio galaxy. In this work, we have expanded the spectral study of the source to a much broader frequency range (144-4850 MHz) and estimated to first order the timescales of the jet activity. Here we summarize our main findings.

(i) As expected by radiative evolution models, the spectral indices in the range 144-614 MHz are systematically flatter ( $\alpha_{\text{low}} \sim 0.55$ -1.14) than those at higher frequency ( $\alpha_{\text{high}} \sim 0.75$ -1.57). However, the spectral distribution within the radio lobes at low frequencies reflects what has been observed at higher frequency (1400-4850 MHz) by Roettiger et al. (1994) i.e. an increasing steepening from the inner regions of the lobes toward the lobe edges. This kind of spectral distribution remains to date very unusual, and has only been observed in another radio galaxy, Hercules A, that is also claimed to be a restarted source.

(ii) By combining the new low frequency spectral index map with the high frequency one, we have studied the spectral curvature and have found values up to 0.7-0.8, especially in the outskirts of the Western lobe, compatible with old ageing plasma that is not replenished with newly accelerated particles.

(iii) We have used single-injection models to investigate the age of the source and found that the total source age is equal to  $\lesssim 80$  Myr. This is consistent with a first order estimate of the dynamical age of the radio source equal to  $< 65$  Myr by Kraft et al. (2006).

(iv) Considering 3C388 to be a restarted radio galaxy we have estimated the timescales of its duty cycle:  $t_{\text{on},1} \gtrsim 30$  Myr,  $t_{\text{off}} \lesssim 20$  Myr,  $t_{\text{on},2} > 30$  Myr for  $B=B_{\text{IC}}$ . These values are consistent with duty cycle estimates derived from other restarted radio galaxies, as well as from multiple generations of X-ray cavities in galaxy clusters.

(v) The fitting results using single-injection models (JP and Tribble) over the entire source cannot be rejected with only 68 per cent confidence. Indeed there is a significant number of poorly fitted regions, suggesting that the spectral shape is not constant throughout the source. This is further enlightened by the color-color plot, which shows that the spectra of the Western inner lobe better follow a CI model and those of the outer lobe best follow a CIOFF model curve. Mixing of particle populations is the most probable explanation for this behaviour. However understanding whether this is originated by observational limitations (e.g. insufficient resolution and/or projection effects) or by the intrinsic presence of multiple particle populations remains challenging.

To date the radio spectral distribution of 3C388 remains a very peculiar case among radio galaxies. However, in the near future it will be much easier to investigate whether more sources with the same characteristics exist. Indeed, the combination of multi-frequency new generation instruments and surveys like for example LoTSS (Shimwell et al. 2019), uGMRT (Gupta et al. 2017), VLA, APERTIF (Oosterloo et al. 2009), MIGHTEE (Jarvis et al. 2016), offer us now unprecedented opportunities to perform statistical studies of the spatially resolved spectral properties of restarted radio galaxies, and radio galaxies in general (Harwood & Morganti 2016, Brienza et al. in prep).

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