High-frequency Radio Imaging of 3CR 403.1 with the Sardinia Radio Telescope

Valentina Missaglia1,2,3, Matteo Murgia4, Francesco Massaro1,2,3, Alessandro Paggi1,2,3, Ana Jimenez-Gallardo1,2,3, William R. Forman4, Ralph P. Kraft5, and Barbara Balmaverde2

1 Dipartimento di Fisica, Università degli Studi di Torino, via Pietro Giuria 1, I-10125 Torino, Italy; valentina.missaglia@unito.it
2 INAF-Osservatorio Astrofisico di Torino, via Osservatorio 20, I-10025 Pino Torinese, Italy
3 INFN-Istituto Nazionale di Fisica Nucleare, Sezione di Torino, I-10125 Torino, Italy
4 INAF-Osservatorio Astronomico di Cagliari, Via della Scienza 5, I-09047 Selargius (CA), Italy
5 Center for Astrophysics | Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA

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Abstract

We present multifrequency observations of the radio source 3CR 403.1, a nearby ($z = 0.055$), extended ($\sim0.5$ Mpc) radio galaxy hosted in a small galaxy group. Using new high-frequency radio observations from the Sardinia Radio Telescope (SRT), augmented with archival low-frequency radio observations, we investigated radio spectral and polarimetric properties of 3CR 403.1. From the MHz-to-GHz spectral analysis, we computed the equipartition magnetic field in the lobes to be $B_{eq} = 2.4 \mu$G and the age of the source to be $\sim100$ Myr. From the spectral analysis of the diffuse X-ray emission we measured the temperature and density of the intracluster medium (ICM). From the SRT observations, we discovered two regions where the radio flux density is below the background value. We computed the Comptonization parameter both from the radio and from the X-ray observations to test whether the Sunyaev–Zel’dovich effect is occurring here and found a significant tension between the two estimates. If the negative signal is considered as real, then we speculate that the discrepancy between the two values could be partially caused by the presence of a nonthermal bath of mildly relativistic ghost electrons. From the polarimetric radio images, we find a net asymmetry of the Faraday rotation between the two prominent extended structures of 3CR 403.1 and constrain the magnetic field strength in the ICM to be 1.8–3.5 $\mu$G. The position of 3CR 403.1 in the magnetic field–gas density plane is consistent with the trend reported in the literature between central magnetic field and central gas density.

1. Introduction

The Third Cambridge Catalog (3C) of Radio Sources is a northern hemisphere sample of radio galaxies and quasars, originally detected at 159 MHz. Its first edition was published in 1959 (Edge et al. 1959), while two revised versions were released in 1962 (i.e., the 3CR; Bennett 1962) and later in 1983 (i.e., the 3CRR; Laing et al. 1983), both performed at 178 MHz with the same threshold of 9 Jy for the limiting flux density. The 3C catalog and all its revised versions (Minkowski 1960; Lynds et al. 1965; Sandage 1966, 1967; Smith et al. 1976; Smith & Spinrad 1980). These then evolved into more complete studies with wider broadband coverage using several telescopes (e.g., Karl G. Jansky Very Large Array, Spitzer, Herschel, Hubble Space Telescope; Harvanek & Hardcastle 1998; Chiaberge et al. 2000; Cleary et al. 2007; Podigachoski et al. 2015; Tremblay et al. 2009; Madrid et al. 2006). These campaigns were recently augmented thanks to X-ray observations of the 3CR Chandra Snapshot Survey started in 2008 (Massaro et al. 2010, 2013). The main aim of this high-energy survey is to detect X-ray emission arising from nuclei, lobes, jet knots, and hot spots, as well as that of the intergalactic medium for those radio sources harbored in galaxy-rich large-scale environments (Madrid et al. 2018; Ricci et al. 2018; Paggi et al. 2021; Jimenez-Gallardo et al. 2021a). Moreover, one of the underlying objectives of this X-ray snapshot survey is to identify new 3C sources that could merit additional follow-up observations as is the case presented here: 3CR 403.1 (see, e.g., Hardcastle et al. 2010, 2012; Orienti et al. 2012; Dasadia et al. 2016, for details on other follow-up Chandra observations of 3CR sources).

During a follow-up analysis of several targets of the 3CR Chandra Snapshot Survey, we discovered extended X-ray emission around this nearby radio galaxy (Massaro et al. 2012; Jimenez-Gallardo et al. 2021b), at larger scales with respect to previous literature analyses. 3CR 403.1 (aka 4C $–01.51$) is a classical FR II radio galaxy (Fanaroff & Riley 1974) at $z = 0.055$. As reported in Bolton & Ekers (1966), the optical counterpart is elliptical, and it has a low-ionization galaxy-like optical spectrum (Baldi et al. 2010). Hα and [O III] λ5007 luminosities are in the range between $10^{39}$ and $10^{40}$ erg s$^{-1}$ (Buttiglione et al. 2011), while the radio luminosity at 178 MHz is $log_{10}(P_{178}) = 32.98$ (Spinrad et al. 1985). In radio archival images, 3CR 403.1 shows two prominent radio lobes, extending in the northwest-to-southeast direction on a scale of $\sim0.5$ Mpc and thus being the second
most extended 3C source among the 37 sources at redshift $z < 0.1$. In particular, the large-scale structure of 3CR-403.1, including the two lobes, is visible at 1.4 GHz in the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) and at lower frequencies at 74 MHz in the Very Large Array Sky Survey (VLSSr; Lane et al. 2014) observations, as well as in the GaLactic and Extragalactic All-sky MWA (GLEAM) Survey, which is a continuum survey conducted using the Murchison Widefield Array between 72 and 231 MHz (Wayth et al. 2015). At all radio frequencies, the radio core and lobes are detected above $5\sigma$ level of confidence. The radio morphology of 3CR-403.1 is peculiar since at low radio frequencies (i.e., archival VLA P-band observation, 230–470 MHz) it shows two radio knots elongated on the west–east direction, separated by 105 kpc, and perpendicular to the radio axis marked by its large-scale structure detected at low frequencies, which correspond to small-scale cavities in the X-rays (Jimenez-Gallardo et al. 2021b). This emission lies also at the opposite sides of the radio core, detected in the Very Large Array Sky Survey at 2–4 GHz (VLASS; Lacy et al. 2020). In FR II sources, as shown in Massaro et al. (2011), X-ray emission is usually detected along the large-scale radio structure. Such emission is typically thought to be due to X-rays produced by relativistic electrons in the lobes that upscatter ambient cosmic microwave background (CMB) photons via inverse Compton scattering (IC/CMB) from lobes (see, e.g., Harris & Krawczynski 2002). However, diffuse X-ray emission surrounding 3CR-403.1 is detected perpendicular to the large-scale radio structure, and thus it is most likely due to thermal emission from the intracluster medium (ICM; see, e.g., results in Jimenez-Gallardo et al. 2021b). Therefore, given its proximity, 3CR-403.1 is a good candidate to study the relationship between the ambient ICM and the radio structure at comparatively high spatial resolution.

Here we present follow-up observations of 3CR-403.1 with the Sardinia Radio Telescope (SRT; Bollì et al. 2015; Prandoni et al. 2017). These observations were carried out at the end of 2019 to (1) investigate the spectral shape at higher frequency of the radio structure; (2) perform a spatially resolved, spectral analysis at radio frequencies, given the clear detection of the radio components shown in Figure 1; and (3) carry out radio polarimetric observations. Polarimetric radio observations, in combination with X-ray observations, permit the study of the properties of the magnetic field permeating the ICM in which radio lobes are embedded.

This work is organized as follows. In Section 2 we provide details about the available archival radio data and the data reduction procedure adopted for SRT and Chandra observations. In Section 3 we report a brief optical overview of the source and discuss (i) the radio spectral analysis, (ii) the test performed to confirm the presence of a possible Sunyaev–Zel’dovich (SZ) effect, and (iii) the measurements of the magnetic field by means of the rotation measure (RM). Finally, Section 4 is dedicated to our summary, conclusions, and future perspectives.

We adopt cgs units for numerical results, and we assume a flat cosmology with $H_0 = 69.6$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.286$, and $\Omega_{\Lambda} = 0.714$ (Bennett et al. 2014) through the whole manuscript and unless otherwise stated. Thus, according to these cosmological parameters, $1''$ corresponds to 1.076 kpc at the 3CR-403.1 redshift (i.e., $z_{\text{src}} = 0.055$), while its luminosity distance is 246.9 Mpc. Spectral indices $\alpha$ are defined by flux density $S_\nu \propto \nu^{-\alpha}$ and indicating as flat spectra those with $\alpha < 0.5$.

2. Data Reduction

2.1. Archival Data

As already stated, we found a suite of available archival radio observations of 3CR-403.1 (see Figure 1). In particular, this radio source was observed with the VLA as part of the NVSS in 1993, as part of the VLSSr in 2003, and with the MWA as part of the GLEAM Survey in 2013. The NVSS Catalog covers the sky north of $-40^\circ$ decl. ($\sim 35,000$ deg$^2$). The images all have 45'' FWHM angular resolution and nearly uniform sensitivity, with rms brightness fluctuations of approximately 0.45 mJy beam$^{-1} = 0.14$ K (Stokes I). The VLSSr has a resolution of 75'' and an average map rms noise level of $\sigma \sim 0.1$ Jy beam$^{-1}$. GLEAM covers $\sim 30,000$ deg$^2$ above an irregular southern boundary. GLEAM is an all-sky survey at 74–231 MHz, with angular resolution of 100'' and sensitivity between 6 and 10 mJy beam$^{-1}$, covering a sky area of $\sim 30,000$ deg$^2$.

2.2. SRT Observations

We collected new SRT data to deeply investigate the radio components of 3CR-403.1. The SRT is a fully steerable 64 m single-dish telescope equipped with a computer-controlled active surface composed of about 1000 individual panels,
which make it capable to operate with high efficiency in the frequency range from 0.3 to 100 GHz.

We pointed at 3CR 403.1 with the SRT K-band seven-feed receiver between 2020 November 19 and December 19 (project ID 30–29; see Table 1 for details). We imaged a field of view of about $15' \times 15'$ centered on R.A. $J2000 = 19^h51^m52^s30^\prime$ and decl.$J2000 = -01^\circ17^\prime235''$. We acquired multiple on-the-fly scans in the equatorial frame, moving at a speed of $1.5$ s$^{-1}$ along the orthogonal R.A. and decl. directions. The scanning speed was set as a compromise between mapping efficiency and the need to reduce the $1/f$ noise produced by the atmospheric and receiver gain fluctuations.

We observed in full-Stokes spectral–polarimetric mode in the frequency range from 18.0 to 19.2 GHz with a central frequency of 18.6 GHz, using the SARDARA back end (Melis et al. 2018). We acquired data at a rate of about 33 spectra s$^{-1}$ at a spectral resolution of 1.46 MHz. The full width at high maximum (FWHM) of the SRT beam at this frequency is 57$''$, and we used a pixel size of 15$''$ in the imaging to match the transverse separation between the subscans. In this way, the separation of the subscans is equivalent to 1 pixel, and the beam FWHM is sampled with about 4 independent pixels. For each pixel, we collected eight different spectra, which we averaged to increase the signal-to-noise ratio.

Data reduction and imaging were performed using the SCUBE software package (Murgia et al. 2016). We corrected for both the variation of telescope gain and atmospheric opacity with elevation. We flagged about 6% of the data that were affected by the radio frequency interference (RFI) in both the frequency and time domain. The flux density was brought to the scale of Perley & Butler (2017) using the calibrators 3C 147 and 3C 286. The latter was also used as absolute reference for the linear polarization position angle. We also calibrated for the on-axis instrumental polarization using the radio source 3C 84 (J0319+4130), which is assumed to be virtually unpolarized.6

We removed the baseline emission from each individual subscan by fitting a second-order polynomial to the “cold-sky” region around 3CR 403.1. To this aim, we masked the emission from the entire radio source using a circular region of 9.5$'$ in diameter, and we also use the NVSS image to identify and mask the point sources in the field of view. We then subtracted from the original subscan data the best-fit polynomial model we obtained from the unmasked portions of the image. In this way, we removed the unwanted contributions from the receiver noise, the atmospheric emission, and the large-scale foreground sky emission, and we retained the target emission only.

We produced the spectral cubes of the full-Stokes parameters $R, L, U$, and $Q$ using a pixel size of 15$''$. To reduce the scanning noise, we combined the R.A. and decl. images of all seven feeds by using the wavelet stacking algorithm described in Murgia et al. (2016). To further increase the sensitivity, we averaged all the spectral channels to produce the final images of total intensity and polarization (see Figure 2).

### Table 1

Details of the SRT Observations of 3CR 403.1

| Frequency (GHz) | Resolution (arcsec) | TOS (hr) | Observing Date | OTF Mapping | Calibrators | SRT Project |
|-----------------|---------------------|----------|----------------|-------------|-------------|-------------|
| 18–19.2         | 57                  | 7        | 19-Nov-2020    | 10 R.A. × 10 Decl. | 3C 286, 3C 84, 3C 147 | 30–20        |
| 6               | 20-19-Nov-2020      | 9 R.A. × 9 Decl. | 3C 286, 3C 84, 3C 147 | 30–20        |
| 7               | 19-Dec-2020         | 10 R.A. × 9 Decl. | 3C 286, 3C 84, 3C 147 | 30–20        |

*Note.* Column (1): SRT frequency range. Column (2): SRT resolution. Column (3): time on source. Column (4): date of observation. Column (5): number of images on the source. Column (6): calibrators. Column (7): SRT project name.

![Figure 2](image-url)  
**Figure 2.** 3CR 403.1 total intensity image at 18.6 GHz. Contours start at 1.2 mJy beam$^{-1}$ ($3\sigma$) and increase by $\sqrt{2}$. The negative green contour is traced at $-1.2$ mJy beam$^{-1}$.

2.3. Chandra Observation

3CR 403.1 was observed for $\sim$8 ks with Chandra X-ray Observatory in 2010 (see Figure 3), as part of the 3CR Chandra Snapshot Survey (Massaro et al. 2010) in Observation Cycle 22 (proposal no. 12700211). In the first analysis, presented in Massaro et al. (2012), only a marginal X-ray detection of a relatively weak radio core was reported. In Jimenez-Gallardo et al. (2021b) the same Chandra observation was reanalyzed, and X-ray extended emission on a scale of tens of kiloparsecs, aligned with radio emission detected only at $\sim 250$ MHz, was claimed at 5$\sigma$ level of significance.

We reanalyzed the Chandra data set and used it to carry out an X-ray spectral analysis. Chandra data reduction was performed

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6 https://science.nrao.edu/facilities/vla/docs/manuals/obsguide/modes/pol
using the Chandra Interactive Analysis of Observations (CIAO v4.12; Fruscione et al. 2006), using standard procedures and threads, and the Chandra Calibration Database v4.8.2. Images are all produced according to the same procedure followed for all observations of the 3CR Chandra Snapshot Survey (see, e.g., Massaro et al. 2015, for more details). Spectral analysis, in particular for the extended X-ray emission, was also performed according to methods described in our previous investigations (see, e.g., Missaglia et al. 2021, for a recent analysis). Here we report a brief overview of the analysis procedures.

Level 2 event files were created using the CIAO task chandra_repro. For the spectral analysis we used unbinned and unsmoothed X-ray images restricted to the 0.5–7 keV energy range to select both source and background regions. No astrometric registration was performed since the position of the X-ray nucleus is not clearly detected (as already noticed in Jimenez-Gallardo et al. 2021b). Light curves were extracted in source-free regions to check for the presence of high background intervals, which were not detected. For all analyses, blank-sky background files were used to estimate the background level at the source position. For the spectral analysis, the exposure time of the blank-sky files was adjusted so that their count rates matched those of the source data in the 9.5–12 keV band (Hickox & Markevitch 2006).

3. A Multiwavelength Study of 3CR 403.1

3.1. MUSE Overview

3CR 403.1 was recently observed as part of the MUSE RA dio Loud Emission line Snapshot survey (MURALES; Balmaverde et al. 2019, 2021); thus, optical spectroscopic observations of surrounding galaxies are reported here aiming at confirming the presence of a galaxy group around 3CR 403.1.

As reported in Balmaverde et al. (2019), the line morphology in this source is particularly complex, and the observations reveal the presence of a central region (∼9 kpc in size), with well-ordered rotation and elongated structures with knots (eastern and southeastern directions), extending up to ∼35 kpc from the galaxy nucleus, with similar velocities and redshifted by ∼150–200 km s$^{-1}$. These structures are due to ionized gas, visible as line-emitting gas (mainly H$\alpha$). The spatial distribution of the ionized gas has a “ring-like” shape, as with the other companion galaxies in the group. There are several galaxies in the MUSE field of view, but only a few emission-line knots are associated with them.

Thanks to the MUSE observations, we were able to identify and estimate the redshift for several companion galaxies around 3CR 403.1. To obtain the redshift, we fitted each line with a Gaussian, using QFitsView,$^8$ which also takes into account the continuum. Spectra were extracted in each case from a circular region of 5-pixel radius, i.e., 1″ to match the seeing of the MUSE observation, using QFitsView. We discovered five nearby companions all marked in Figure 4 together with their redshifts. We measured the velocity dispersion of the five nearby companions, obtaining a value of the sample estimate of the radial velocity dispersion to be $\sigma_v = 143$ km s$^{-1}$. According to the analysis we carried out in Massaro et al. (2020), assuming that this group is virialized and that galaxies have random uncorrelated velocity vectors, we estimate the total mass of the large-scale environment, including dark matter, galaxies, and ICM within a radius of 158 kpc (that is, the equivalent radius of the elliptical region chosen for the X-ray spectral analysis; see Section 3.3) as $M_{\text{env}} = 7.5 \times 10^{11} M_\odot$. Since this estimate of $M_{\text{env}}$ is achieved with a low number of sources, we did not compute the statistical uncertainty. Given the mass of the environment, the size (∼2–3 kpc), and optical luminosities (∼10$^9$ L$_\odot$) obtained from Pan-STARRS r-filter magnitudes; see Staveley-Smith et al. 1992 for comparison) of the sources, this is in agreement with 3CR 403.1 belonging to a small group of dwarf galaxies (for typical masses of a small group of dwarf galaxies see, e.g., Makarov & Uklein 2012). The mass estimate was computed using only six sources for which the signal-to-noise ratio of their spectra allowed us to

$^7$ http://cxc.harvard.edu/ciao/threads/

$^8$ https://www.mp.e.mpg.de/~ott/dpuser/qfitsview.html
Figure 5. Total radio spectrum of 3CR 403.1. Black circles represent the flux densities measured in this work, complemented with values taken from the literature. The solid black line is the best fit of the CI model and shows the presence of a spectral break at a frequency of 1.9 GHz, followed by a moderate steepening. Blue squares, green triangles, and red stars represent the spectra of the north lobe, the south lobe, and the core regions, respectively (highlighted in the image added on the plot). We modeled these components using a Jaffe–Perola whose best fit is represented by the blue dotted, green short-dashed, and red long-dashed lines. See Section 3.2 for more details.

### 3.2. Radio Spectral Analysis of the Extended Structure

We first measured the flux density of 3CR 403.1 in four radio bands (VLSSr at 74 MHz, GLEAM at 230 MHz, NVSS at 1.4 GHz, and SRT at 18.6 GHz) for the entire source, and we compared these values with other global measurements taken from the literature. The global radio spectrum is determined by the sum of the spectra of both (a) the freshly accelerated electrons, whose spectrum we assume to be a power law, and (b) the spectra of the older electron populations, whose spectrum cuts off at high frequency because of the radiative losses. For this reason, we make the hypothesis that the radio source is currently in the active phase, during which the radio lobes are continuously replenished with new particles by the AGN. We then analyzed the spatially resolved spectra at an intermediate resolution for three components: the northern lobe, the southern lobe, and the inner region in between correspondent to the radio core. All components are defined using a 3σ limit. The flux density of the entire source was measured convolving with the VLSSr beam (75′′) and using the 3σ level contour from the NVSS image. For the radio components, we convolved all the images with the GLEAM beam (∼11′′) and then used the new 3σ level limit of the images to define the components. We then investigated the spectral index image of the source between 1.4 and 18.6 GHz at a slightly finer angular resolution of about 57′′. Measurements are summarized in Table A1 in Appendix A.

In Figure 5, we compare our total integrated flux measurements with literature data taken from the NASA/IPAC Extragalactic Database9 and Astrophysical CATalogs support System,10 finding a good agreement.

We fitted the integrated spectrum with a continuous injection model (C.I.; Pacholczyk 1970) making use of the SYNAGE software (Murgia et al. 1999). This model is characterized by three free parameters: the injection spectral index (α_inj), the break frequency (ν_b), and the flux normalization. In the context of the C.I. model, it is assumed that the spectral break is due to the energy losses of the oldest relativistic electrons in the source. For high-energy electrons, energy losses are primarily due to the synchrotron radiation itself and to inverse Compton scattering on CMB photons. The spectral break marks the transition to high-frequency power law characterized by a steeper index α = α_inj + 0.5. During the active phase, the evolution of the integrated spectrum is determined by the shift with time of ν_b to lower and lower frequencies. Indeed, the spectral break can be considered to be a clock indicating the time elapsed since the injection of the first electron population. The best fit of the C.I. model yields ν_b = 1.9 ± 0.7 GHz.

We estimated the equipartition field, B_eq, following the same procedure discussed in Murgia et al. (2012), and we obtained a value of B_eq = 2.4 µG, which led to a spectral age of the source of ~93 Myr, evaluated according to the equation

\[
\tau_{\text{syn}} = \frac{1590}{(B^2 + B^2_{\text{CMB}})(1 + z)\nu^3_b \nu_{\text{sync}}} \text{ Myr}, \tag{1}
\]

where B and B_{CMB} = 3.25(1 + z)^2 µG are the source magnetic field and magnetic field with the same energy density of the CMB, respectively, and assuming an isotropic distribution of electron pitch angles (see, e.g., Murgia et al. 2011; Massaro & Ajello 2011).

The spectra of the three components are plotted in Figure 5 along with the fit of the JP model (Jaffe & Perola 1974). The JP model describes the radiative aging of a single population of electrons with an initial power-law distribution, assuming that energy losses due to the inverse Compton scattering of seed photons arising from the CMB are as relevant as radiative losses due to synchrotron emission. In these conditions, the initial power law with index α_inj develops a high-frequency exponential cutoff beyond a break frequency ν_b. The radiative age and the break frequency are related again by Equation (1).

The spatially resolved spectral analysis, shown in Figure 5, indicates that the spectrum of the inner parts of the radio lobes (those close to the radio source’s core) is steeper than that of the outer lobes. Using basic physics, we conclude that this is due to the presence of a spectral break that shifts to lower frequencies. Indeed, in 3CR 403.1 we find that the oldest electrons are close to the core, while we find that the electrons are younger at the tip of the lobes. This is the typical scenario found in type 2 sources (see Parma et al. 1999), where radio jets have deposited old electrons back as they make their way through the ambient gas.

We further investigate the spectral properties of 3CR 403.1 at a slightly higher angular resolution by analyzing the spectral index map of the source between 1.4 (NVSS) and 18.6 GHz (SRT) (see Figure 6) according to the following steps: (1) we smoothed the NVSS image to the same resolution as that of the SRT (57′′), (2) we aligned the two images using as a reference
the point-like source southwest of the northern lobe, and (3) we regridded the images with the new coordinates. In the spectral index map, only pixels with surface brightness above 3σ, both in the NVSS and in the SRT images, were used. Uncertainties are computed using standard uncertainty propagation formulae. We observe a steepening of the spectral index from the lobe outer edge inward to the core region, indeed confirming the characteristic trend typical of spectral type 2 sources.

3.3. Testing the “SZ” Signatures

In the SRT total intensity image we noticed two regions, lying on opposite sides of the large-scale radio structure, along the west–east direction, where we measure a negative intensity at 18.6 GHz with respect to the image background, as already highlighted in Figure 2.

We estimate that the radio intensity decrement at 18.6 GHz is significant at more than a 3σ level with respect to the fluctuations of the background in the SRT image (rms = 4.66 × 10^{-4} Jy beam\(^{-1}\)).

The negative signal in the SRT image is spatially associated with the extended X-ray emission revealed in the Chandra image (see the magenta ellipse in Figure 3). The X-ray emission is interpreted as thermal radiation from the gas of the ICM because it is not spatially associated with either GHz or MHz radio counterparts. In order to carry out a deeper investigation into the origin of the negative radio signal, we compared its properties with the values we measured for the X-ray spectral parameters for the surrounding medium of 3C 403.1.

Assuming that a fraction of the radio background of the SRT observations is due to CMB, when looking in the direction of the galaxy cluster we expect a decrease of the radio intensity due to inverse Compton emission by relatively hot electrons of the ICM that upscatter the CMB radiation (Sunyaev & Zeldovich 1972). Since all flux measurements are reported with respect to the background level, constituted by the CMB radiation and corresponding to the “zero level,” we can consider the SZ effect a “true” negative signal in the radio images (Birkinshaw 1999). Thus, we estimated the Comptonization parameter \(y\) from both radio and X-ray observations, respectively, and compared them.

At radio frequencies we computed the \(y_R\) parameter starting from the change in temperature of the CMB due to the SZ effect:

\[
\frac{\Delta T}{T_{\text{CMB}}} = f(x)y_R,
\]

(2)

with \(f(x)\) being the frequency spectrum of the temperature variation and \(y_R\) the Comptonization parameter.

In the Rayleigh–Jeans approximation for the blackbody spectrum of the CMB at 18.6 GHz we have \(f(x) = -2\), and then Equation (2) becomes

\[
\frac{\Delta T_{\text{RJ}}}{T_{\text{CMB}}} = -2y_R.
\]

(3)

At radio frequencies, we use a simplified expression for the flux intensity in a given instrument beam as reported in Basu et al. (2016):

\[
\left( \frac{I_\nu}{\text{mJy beam}^{-1}} \right) = \frac{1}{340} \left( \frac{\Delta T_{\text{RJ}}}{\text{mK}} \right) \left( \frac{\nu}{\text{GHz}} \right)^2 \left( \frac{\Omega_{\text{beam}}}{\text{arcmin}^2} \right).
\]

(4)

Replacing the expression of \(\Delta T_{\text{RJ}}\) of Equation (3) in (4), we obtain

\[
y_R = -170 \left( \frac{I_\nu}{\text{mJy beam}^{-1}} \right) \left( \frac{\nu}{\text{GHz}} \right)^2 \left( \frac{T_{\text{CMB}}}{\text{mK}} \right) \left( \frac{\Omega_{\text{beam}}}{\text{arcmin}^2} \right) \left( \frac{1.13 \theta_{\text{FWHM}}^2}{\text{1.13 \theta_{\text{FWHM}}^2}} \right).
\]

(5)

where the solid angle \(\Omega_{\text{beam}}\) can be approximated as \(\Omega_{\text{beam}} = 1.13 \theta_{\text{FWHM}}^2\), where \(\theta_{\text{FWHM}}\) is the half-power beamwidth.

We measured the decrease of the flux intensity in an elliptical region with semiaxes \(\sim 125 \times 254\) kpc (see magenta ellipse in Figure 3) with an area equal to 0.1 Mpc\(^2\), corresponding to 15.1 SRT beams, encompassing the nucleus of 3C 403.1 (masking the nucleus and the jets), where we detected the highest value of the negative signal. We obtained a flux intensity equal to \(I_\nu = -0.9 \pm 0.1\) mJy beam\(^{-1}\) that corresponds to an integrated flux \(S_\nu = -21 \pm 2\) mJy (22.3 SRT beams, assuming that the masked 7.2 beams have the same intensity). From our SRT observations we have \(\theta_{\text{FWHM}} = 0.95\)″, and assuming \(T_{\text{CMB}} = 2726\) mK, this leads to an estimate of \(y_R = (2.0 \pm 0.2) \times 10^{-4}\), corresponding to a value of \((2.0 \pm 0.4) \times 10^{-5}\) Mpc\(^2\) when measured per unit of area.

In the X-rays the Comptonization parameter \(y_X\), is indeed related to the line-of-sight integral of the ICM pressure distribution, according to the following equation:

\[
y_X = \frac{\sigma_T}{mc^2} \int \ell O.S. P_\nu(r) dl,
\]

(6)

where \(P_\nu(r) \sim n_e kT\) is the pressure profile of the thermal electrons in the ICM, while \(n_e\) and \(T\) are the gas density and temperature, respectively.

We analyzed the X-ray spectrum extracted from an elliptical region copatial with the flux decrement in the background CMB radiation (see Figure 3), adopting a thermal APEC model with Galactic absorption. We have excluded a 2″ circular region centered on the location of the radio core where we expect to find most of the nuclear emission. Adopting for the thermal component a heavy-element abundance equivalent to 0.25 solar, a redshift \(z = 0.055\), and Galactic absorption equal to \(0.117 \times 10^{22} \text{cm}^{-2}\) as reported in HI4PI Collaboration et al. (2016), we obtained a value for the temperature \(kT = 0.85^{+0.02}_{-0.02}\) keV and a gas density \(n_e = (4.6 \pm 0.3) \times 10^{-3} \text{cm}^{-3}\). The mass of the gas in this ellipsoidal volume estimated as reported in Messias et al. (2021) is equal to \(M_{\text{gas}} \simeq (2.2 \pm 0.1) \times 10^{11} M_\odot\).

We estimated \(y_X\) using the values of temperature and density obtained from the spectral fit in the ellipse. With \(P_\nu \sim n_e kT\) we obtained \(P_\nu = 6.11^{+0.63}_{-0.69} \times 10^{-13}\) erg cm\(^{-3}\). Assuming a constant value for \(P_\nu\), from Equation (6) we obtained \(y_X = 3.82^{+0.40}_{-0.43} \times 10^{-7}\), corresponding to a value of \(3.82^{+0.40}_{-0.43} \times 10^{-5}\) Mpc\(^2\) when measured per unit area.

The two values we obtained from the X-ray and radio analysis are not in agreement, with a discrepancy of three orders of magnitude.

The thermal energy of a gas can be computed starting from the ideal gas law as \(E_{\text{th}} = \frac{3}{2} n k T V\), where in this case \(n\) and \(T\) are respectively the density and temperature obtained from the X-ray spectral analysis in the ellipsoidal volume \(V = 4.9 \times 10^{43}\) cm\(^3\). This expression results in \(E_{\text{th}} = 4.46^{+0.50}_{-0.50} \times 10^{59}\) erg. We can calculate the thermal energy also making use of the
We indeed considered the possibility that the negative bowl in the radio image is an artifact left from the data reduction process. We ran numerous tests to determine whether the radio diminution could be considered an artifact or not, such as comparison of the first and last SRT observations, baseline subtraction, and more tailored masking, but the results are not conclusive (see details in Appendix B).

If we assume that the negative signal is not affected by artifacts, we can then make the hypothesis that the discrepancy of the radio and X-ray values of the Comptonization parameter could be partially due to the presence in the ICM around 3CR 403.1 of a pool of nonthermal, mildly relativistic “ghost” electrons, produced during a past activity of the radio source. We assume that the electrons should be mildly relativistic; otherwise, a thermal bath of electrons would have a same total thermal energy of a relatively massive group or cluster, making this unreliable. These electrons have energy to radiate at such low radio frequencies that cannot be detected, but they could still scatter the CMB photons, causing the observed negative signal around 3CR 403.1 at 18.6 GHz. Another hint to the AGN past activity is also the presence of the radio knots seen in the archival VLA P-band observation (not shown), in the same direction as the negative radio signal.

To summarize, there are many possibilities for this decrement (real and artifacts): (1) SZ effect from ICM; (2) imaging artifacts; and (3) a pool of nonthermal, mildly relativistic “ghost” electrons emitted during a past activity of the radio source, which then cooled and can partially explain the discrepancy of the X-ray and radio Comptonization parameter values (see Appendix B for more details). We also highlight that this is the first time a similar effect has been detected in a radio galaxy at such low redshift; thus, deeper observations are needed to investigate this effect in more detail.

### 3.4. Magnetic Field Measurements

We used SRT data combined with NVSS to derive the rotation measure (RM) image of 3CR 403.1 (see Figure 7). The RM provides information on the intracluster magnetic fields, since a magnetized plasma changes the properties of the polarized emission coming from a radio source embedded in (or in the background of) the galaxy group/cluster. The position angle of the linearly polarized radiation rotates by an amount that is proportional to the integral of the magnetic field along the line of sight times the electron density of the ICM (Faraday rotation effect, Dennison 1979).

In the case of an external Faraday screen, i.e., if the magnetoionic medium is located between the radio source and the observer, the polarization angle rotates according to the $\lambda^2$-law:

$$\psi_{\text{obs}}(\lambda) = \psi_{\text{int}} + \frac{\chi_{\text{RM}}}{\lambda^2}$$

where $\psi_{\text{obs}}$ is the observed polarization at wavelength $\lambda$, while $\psi_{\text{int}}$ is the intrinsic polarization angle (see, e.g., Govoni & Feretti 2004).

By measuring the angle at different frequencies, it is possible to derive the RM by a linear fit to Equation 7. In our case we simply measured the difference $\Delta \psi$ in the polarization angle between the SRT and the NVSS images (see Figure 8), and we computed the RM as

$$\text{RM} = \Delta \psi / \left( \frac{\lambda_1^2 - \lambda_2^2}{\lambda_1} \right) \text{ rad m}^{-2},$$

where $\lambda_1 = 0.016$ m and $\lambda_2 = 0.21$ m are the wavelengths corresponding the SRT and NVSS images.
The RM image is shown in Figure 7 and has been derived considering only those pixels where the uncertainty in the polarization angle is less than 10° and the total intensity is above the 3σ level at both frequencies. The SRT data provide a polarization angle very close to 0°, since the rotation is negligible at such a high frequency for typical cluster RMs. However, since we have only two measurements, it is not possible to resolve possible nπ-ambiguities on the observed polarization angle in the NVSS image. We observe a net asymmetry in the RM of the two lobes. As shown in Figure 7, the southern lobe has an average RM $\simeq -26$ rad m$^{-2}$, while for the northern lobe we observe an average Faraday rotation as low as RM $\simeq 1$ rad m$^{-2}$.

We modeled the observed RM asymmetry assuming that 3CR 403.1 is located at the center of the galaxy group and is inclined with respect to the plane of the sky so that the southern lobe has a larger Faraday depth in comparison to the northern lobe (see, e.g., Laing et al. 2008).

We considered an idealized situation in which the magnetic field is composed by uniform “cells” of size $\Lambda_B$ with random direction in space, and we used the software FARADAY (Murgia et al. 2004) to calculate the variance of the Faraday rotation ($\sigma_{\text{RM}}^2$) from a depth $L$ and a projected radius $r_\perp$:

$$\sigma_{\text{RM}}^2(L) = 812^2\Lambda_B \int_L^{+\infty} (nB_\perp)^2 dl \quad \text{(rad}^2\text{m}^{-4}),$$  

where the cluster’s midplane is located at $L = 0$, the cluster far side is located at $L < 0$, and the cluster near side is at $L > 0$ (e.g., Lawler & Dennison 1982; Tribble 1991; Feretti et al. 1995; Felten 1996). In Equation (9), the magnetic field strength is in $\mu$G, the density is in cm$^{-3}$, and the field scale and the physical depth are in kpc.

If the electron gas density is described by the $\beta$-model (Cavaliere & Fusco-Femiano 1976),

$$n = n_0 \left(1 + \frac{r_\perp^2}{r_c^2}\right)^{-\frac{\beta}{2}},$$  

with $r_c$ being the core radius of the gas distribution, and we assume that the magnetic field strength scales with the gas density according to

$$B = B_0 (n/n_0)^{\beta/2},$$

then, by substituting in Equation (9), we find

$$\sigma_{\text{RM}}^2(L, r_\perp) = 812^2\Lambda_B n_0^2 B_0^2 \int_L^{+\infty} \left(1 + \frac{r_\perp^2}{r_c^2}\right)^{-\beta/2} \left(1 + \frac{r^2}{r_c^2} + \frac{r^2}{r_c^2}\right)^{-3/2} \frac{1}{l} dl \quad \text{rad}^2\text{m}^{-4},$$

where $r_\perp$ is the impact parameter from the cluster center, and we assume that the magnetic field is isotropic so that $B_l = B/\sqrt{3}$.

For the $\beta$-model we assumed a core radius $r_c = 200$ kpc and $\beta = 0.6$, while for the magnetic field model we assumed a correlation length of $\Lambda_B = 20$ kpc and $\eta = 1$. These are the best-fit parameters found for A194 by Govoni et al. (2017). The central gas density in A194 is similar to that of 3CR 403.1, and we speculate that the properties of the intracluster magnetic field derived for A194 using high-resolution RM data can be assumed as a reference also for the case of 3CR 403.1. Indeed, we fixed $\Lambda_B$ and $\eta$, and we deduce the combinations of the central magnetic field strength, $B_0$, and the source inclination with respect to the plane of the sky that explain the observed RM asymmetry between the two lobes.

In the top right panel of Figure 7 we show the expected RM profiles as a function of the depth for three values of the...
magnetic field strength at the galaxy group center. The circles represent the measured RM values for the south and north lobe if an inclination of 60° is assumed. For the southern lobe we considered a projected distance of \( r_\perp = 119 \) kpc, while for the northern lobe we considered \( r_\perp = 194 \) kpc. In the bottom right panel of Figure 7 we show the RM difference between the two lobes versus the source’s inclination. The shaded horizontal stripe represents the measured RM difference. We do not have any a priori hint about the source inclination. However, in 68% of the cases (inclination > 30°) the observed RM can be used to constrain the cluster magnetic field strength, \( B_0 \), between 1.75 and 3.5 \( \mu G \). This is the magnetic field at the cluster center. Note that according to Equation (11) with \( \eta = 1 \), the field strength decreases with radius following the gas density.

In Figure 9 we plot 3CR 403.1 in the \( B_0 \)–density plane from Govoni et al. (2017). The position of the radio source in the plane is consistent with the correlation observed for other galaxy clusters for which the magnetic field strength was determined from the RM analysis. The low central magnetic field found in this work for the poor galaxy cluster around 3CR 403.1 confirms the general trend that fainter central magnetic fields seem to be present in less dense galaxy clusters (Govoni et al. 2017).

4. Summary and Conclusions

We have presented a spectral-polarimetric study of the FR II radio galaxy 3CR 403.1, hosted in a small galaxy group of dwarf galaxies, as shown in the observations performed by VLT/MUSE as part of the MURALES survey (see Figure 4). This study was carried out using new high-frequency radio data from the SRT and archival data from VLA and MWA. Radio data were complemented with X-ray data from Chandra, obtained as part of the 3CR Snapshot Survey (see also recent observations in Massaro et al. 2018; Stuardi et al. 2018; Jimenez-Gallardo et al. 2020) and optical observations available from the MURALES survey.

Assuming that this group is virialized, we used the velocity dispersion of the five companion galaxies detected with MUSE to estimate the total mass of the system as \( M_{\text{enc}} = 7.5 \times 10^{11} M_\odot \).
We measured the flux density of 3CR 403.1 for the entire source and its components, radio core region and lobes, separately, using new SRT observations, complemented with archival NVSS, GLEAM, and VLSSr radio data (lower frequencies). Results of the spectral analysis are shown in Figure 5.

Given the values of the parameters obtained from the fit of the radio spectrum for the entire radio source (injection spectral index and break frequency), we measured the equipartition magnetic field, finding a value of $B_{eq} = 2.37 \, \mu G$. This value was used to compute the spectral age of the source, being 93 Myr.

From the new high-frequency SRT data at 18.6 GHz we unexpectedly observed a flux depression in two regions perpendicular to the radio axis (see green contours in Figure 3) with a level of significance higher than 3σ. This negative radio signal is cosepital with the extended X-ray emission detected in the Chandra observation, which we interpreted as thermal radiation from the hot ICM surrounding 3CR 403.1.

Thus, we reanalyzed the Chandra observation, focusing on the region of the radio flux depression (see Figure 3). We performed a spectral analysis of the X-ray emission to estimate the temperature and density of the ICM in that region. We found $kT = 0.85^{+0.07}_{-0.08} \, \text{keV}$ and $n_e = (4.6 \pm 0.3) \times 10^{-4} \, \text{cm}^{-3}$, which corresponds to a gas mass equal to $M_{gas} \approx (2.2 \pm 0.1) \times 10^{11} \, M_\odot$.

The radio Comptonization parameter would require a much larger ICM pressure than that estimated from the X-rays, and therefore we investigated the possibility that the negative signal in the SRT image is an artifact, but the results were not conclusive. We obtained an estimate of the Comptonization parameter both in the radio ($\gamma_R = (2.0 \pm 0.4) \times 10^{-5} \, \text{Mpc}^2$) and in the X-ray ($\gamma_X = 3.82^{+0.40}_{-0.43} \times 10^{-8} \, \text{Mpc}^2$) from an elliptical region encompassing the nucleus of 3CR 403.1, where we detected the highest value of the negative signal. From these calculations we find that the Comptonization parameter values obtained with the radio ($\gamma_R$) and X-ray ($\gamma_X$) are not consistent. We investigated the possibility that the negative signal in the SRT image is an artifact, but the results were not conclusive. If the negative signal is considered as real, then this implies that (i) the X-ray observations are not deep enough to allow us to make a more accurate estimate, or (ii) we speculate that part of the discrepancy of the two values is due to the presence of a pool of nonthermal, mildly relativistic old electrons, ejected from the radio source’s core in a past episode of activity (as suggested by a VLA P-band observation).

Due to the low statistics of the available X-ray data, no firm estimate of the Comptonization parameter can be drawn. We plan to collect more radio data to investigate the emission detected by the VLA in P band, possibly related to past AGN activity and thus the presence of cold electrons responsible for the flux decrease observed in SRT data.

Finally, we used SRT data combined with NVSS to derive the RM images of 3CR 403.1 (see Figure 7). From this estimate we concluded that the ICM surrounding 3CR 403.1 is permeated by a magnetic field with strength between 1.75 and 3.5 \, \mu G. Thus, we compared this value of the magnetic field with the density found from the X-ray analysis. The position of the radio source in the plane is consistent with the correlation observed for the other galaxy clusters for which the magnetic field strength was determined from the RM analysis.

We want to stress that the SRT observations of 3CR 403.1 gave intriguing results, but this should be a starting point for an exploratory program of powerful radio sources looking for similar effects, opening a new window on the scientific results achievable with the SRT.

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Facilities: Chandra, MWA, SRT, VLA, VLT/MUSE.

Software: CASA (McMullin et al. 2007), CIAO (Fruscione et al. 2006), FARADAY (Murgia et al. 2004), SCUBE (Murgia et al. 2016), Sherpa (Freeman et al. 2001; Doe et al. 2007; Burke et al. 2020), SYNA GE (Murgia et al. 1999).

Appendix A

Radio Fluxes

In this appendix we report the flux densities of 3CR 403.1 and of its radio components, using the GLEAM convolved beam (see Table A1).
Appendix B
SRT Background Tests

We analyzed separately the images of the two observing days 2020 November 19 and December 19, which have comparable noise levels (see Figure 10). Although the signal-to-noise ratio is lower than that of the combined image, there is a hint that the negative signal is present in both the individual images. This would exclude that it is an artifact due to peculiar atmospheric fluctuations not captured by the baseline subtraction.

We then repeated the baseline subtraction by (i) using a linear fit instead of a second-order polynomial fit and (ii) dropping the mask completely and using just the 10% of data from the beginning and end of each individual subscan to define the “cold sky.” In both the cases the negative signal around the source is still observed.

We also repeated the baseline subtraction by using a smaller, more tailored mask for 3CR 403.1 at 18.6 GHz based on the NVSS 3σ contour level; see Figure 11. In this case the negative signal disappears. However, this test is not conclusive since the negative signal could have been captured and removed along with the cold-sky emission. We concluded that new observations over a larger field of view are probably necessary to firmly determine the nature of the negative radio brightness.

**Table A1**

Flux Densities of 3CR 403.1 and of Its Morphological Features

| Frequency (GHz) | Flux Density Core Region (mJy) | Flux Density Southern Lobe (mJy) | Flux Density Northern Lobe (mJy) | Flux Density Entire Source (mJy) |
|-----------------|-------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 0.074           | 4210 ± 580                    | 5560 ± 690                      | 4500 ± 610                      | 14,800 ± 200                    |
| 0.230           | 2000 ± 230                    | 2000 ± 230                      | 2820 ± 300                      | 3490 ± 100                      |
| 1.4             | 394 ± 40                      | 455 ± 50                        | 672e ± 70                       | 1500 ± 1                        |
| 18.6            | 2.51 ± 1.39                   | 16.9 ± 2.2                      | 47 ± 5                          | 67.4 ± 0.5                      |

*Note.* Fluxes of core and lobe regions have been measured using the GLEAM convolved beam. Column (1): frequency. Column (2): flux density of the core region. Column (3): flux density of the southern lobe. Column (4): flux density of the northern lobe. Column (5): flux density of the entire source.

**Figure 10.** Comparison of the 2020 November 19 (left panel) vs. December 19 (right panel) session. The rms noise levels are 0.60 and 0.52 mJy beam$^{-1}$, respectively. Contours are traced at $-3\sigma$, $3\sigma$ and scale by $\sqrt{2}$. Negative contours are represented in green.
Figure 11. Images obtained using the circular mask with a diameter of 9.5′ (top left) and the tailored NVSS mask (bottom left). The rms noise level is 0.39 mJy beam$^{-1}$ for both images. Contours are traced at $-3\sigma$, $3\sigma$ and scale by $\sqrt{2}$ (negative contours are represented in green). Top right and bottom right panels show the mask (black pixels) defining the cold-sky region (white pixels) used for the baseline fit.

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