Radio multifrequency observations of galaxy clusters. The Abell 399–401 pair

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ABSTRACT

Galaxy clusters are assembled via merging of smaller structures, in a process that generates shocks and turbulence in the intracluster medium and produces radio emission in the form of halos and relics. The cluster pair A 399–A 401 represents a special case: both clusters host a radio halo and recent LOFAR observations at 140 MHz revealed the presence of a radio bridge connecting the two clusters and two candidate relics, one South of A 399 and the other in between the two clusters, in proximity of a shock front detected in X-ray observations. In this paper we present Westerbork observations at 1.7, 1.4, 1.2 GHz and with a 125 ± 6 mJy flux density. Its spectral index between 140 MHz and 346 MHz is \( \alpha = 1.75 \pm 0.14 \). The two candidate relics are also seen at 346 MHz and we determined their spectral index to be \( \alpha = 1.10 \pm 0.14 \) and \( \alpha = 1.46 \pm 0.14 \). The low surface brightness bridge connecting the two clusters is below the noise level at 346 MHz, therefore we constrained the bridge average spectral to be steep, i.e. \( \alpha > 1.5 \) at 95% confidence level. This result favours the scenario where dynamically-induced turbulence is a viable mechanism to reaccelerate a population of mildly relativistic particles and amplify magnetic fields even in cluster bridges, i.e. on scales of a few Mpc.

Key words: galaxies: clusters: general - galaxies: clusters: individual: Abell 399 - radio continuum: general

1 INTRODUCTION

Clusters of galaxies are located at the nodes of the cosmic web and formed by subsequent merging of smaller structures. These merger events are likely accelerating particles and amplifying magnetic fields in the intra-cluster medium, generating diffuse radio sources observed in clusters like radio halos and relics (see Brunetti & Jones 2014; van Weeren et al. 2019, for recent reviews on the topic). Although it is largely accepted that radio halos are generated by merger-induced turbulence (e.g., Cassano & Brunetti 2005; Brunetti & Lazarian 2016; Pinzke et al. 2017) and radio relics by shocks (e.g., Hoefl & Brüggen 2007; Kang & Ryu 2016), several questions on the acceleration efficiency and, therefore, the details of the re-acceleration mechanism remain still open (e.g., Brunetti 2016; Wittor et al. 2017). The A 399–A 401 pair has a special place in the cluster landscape. It is a local pair \( (z = 0.0718 \text{ and } z = 0.0737, \text{ respectively, Oegerle & Hill 2001}) \), separated by a projected distance of \( \sim 3 \) Mpc. Their masses are \( 5.7 \times 10^{14} \text{ M}_\odot \) and \( 9.3 \times 10^{14} \text{ M}_\odot \) respectively, with similar gas temperatures, \( kT \approx 7 \) and 8 keV respectively (Fujita et al. 1996; Fabian et al. 1997; Markevitch et al. 1998), with a filament of X-ray emitting gas in the interconnecting region (Akamatsu et al. 2017). Both X-ray and optical observations (Bonjean et al. 2018) indicate that the system is likely in the early phase of a merging event. Observations of the Sunyaev-Zeldovich effect (Bonjean et al. 2018; Hincks et al. 2022) confirmed the presence of a connecting bridge between the two clusters, with a \( 4.3 \times 10^{-4} \text{ cm}^{-3} \) gas density (Bonjean et al. 2018).

At radio wavelengths, both clusters host a radio halo whose integrated flux density at 1.4 GHz is \( S = 20.4 \text{ mJy} \) and \( S = 19.3 \text{ mJy} \) respectively (Murgia et al. 2010; Govoni et al. 2019). The A 399 halo has a typical roundish morphology and extends for \( \sim 570 \) kpc, whereas the A 401 halo has a more irregular morphology and extends up to \( \sim 350 \) kpc. This pair was the target of recent, deep LOFAR observations at 140 MHz (Govoni et al. 2019) that detected both radio halos, extending up to 970 kpc and 800 kpc respectively. These observations also revealed a series of diffuse emission features not visible at GHz frequencies, in particular, a bridge of radio emission connecting the two halos, providing the first evidence of relativis-
tic particles and magnetic fields on a few Mpc scales, at distances comparable or greater than the cluster virial radius (together with the A 1758 double system; Botteon et al. 2018, 2020).

Radio emission on such large scales may be due to a distribution of weak shocks that fill the bridge volume and reaccelerate a preexisting population of mildly relativistic particles (Govoni et al. 2019). Conversely, Brunetti & Vazza (2020) propose an alternative scenario where acceleration happens via second order Fermi mechanisms: relativistic particles scatter with magnetic field lines diffusing in super-Alfvenic turbulence which also amplifies magnetic fields. In this case, steep-spectrum synchrotron emission can be generated in the entire intra-cluster bridge region. Spectral index measurements of the bridge emission are therefore necessary to understand the particle acceleration mechanism in action here.

In this paper we present observations at 1.7, 1.4, 1.2 GHz and 346 MHz (18, 21, 25 and 92 cm respectively) of the A 399-A 401 cluster pair, aimed to characterize the properties of their diffuse radio emission. The paper is organized as follows: observations and data reduction are described in Section 2, results are presented in Section 3 and conclusions are offered in Section 4. Throughout the paper we used the Planck cosmology (Planck Collaboration et al. 2020), where $1'' = 1.345 \text{kpc}$ at the distance of the cluster pair.

2 OBSERVATIONS AND DATA REDUCTION

Observations were carried out with the Westerbork Synthesis Radio Telescope (WSRT) at 346 MHz. The WSRT is an aperture synthesis array composed of 14 dishes with a diameter of 25 m, arranged on an east-west track, that uses the Earth rotation to fill the $uv$ plane in a 12 hour synthesis observation. Ten telescopes have a fixed location, and are spaced by a distance of 124 m whereas the four remaining dishes (identified with the A, B, C and D letters respectively) can be moved along two rail tracks to provide different array configurations.

Observations were conducted during night time in December 2010 for the 1.7 and 1.4 GHz bands and in November 2011 for the 1.2 GHz and 346 MHz bands, pointed at the centre of the A 399 cluster. The so called Maxi-Short configuration\(^1\) was used for both the 1.7 and 1.4 GHz observations with the aim to provide good sensitivity to extended structures with dense $uv$ coverage between 36 and 2760 m baselines. Four different configurations were used at 1200 MHz where the four movable telescopes were moved by 18 m increments, from 36 to 90 m, therefore pushing the grating lobe out to a radius of $\sim 1''$. Six configurations were used for the 346 MHz observations, with the four movable telescopes stepped at 12 m increments and the shortest spacing ran from 36 to 96 m. This provided continuous $uv$ coverage with baselines ranging from 36 to 2760 m (Figure 1). Table 1 presents the details of the observing set up.

Each observing run included a $\sim 20$ minute observation of a calibration source. The absolute flux calibration was set to the Scaife & Heald (2012) scale using observations of 3C295 at 346 MHz. The observed polarization calibrator was DA240. Data were initially tapered using a Hanning window; the edges of each sub-band were discarded and Radio Frequency Interference (RFI) were identified and flagged using the AOPflagger package (Offringa et al. 2010). Data were further reduced using the CASA\(^2\) software and integrated with routines specifically developed for calibration of WSRT data (Bernardi et al. 2009, 2010). The reduction of the 1.7 GHz data can be summarized by the following steps. An initial bandpass calibration was derived from observations of 3C48 and applied to the target field. A dirty image was generated by Fourier transforming the visibilities. All the sub bands were combined together using the multifrequency synthesis algorithm with uniform weights. The dirty image was then deconvolved using the Cotton–Schwab algorithm down to a threshold of 0.1 mJy beam\(^{-1}\), corresponding to the first negative model component. Such model was used for self–calibration where antenna based phase solutions were computed every minute. Self–calibration solutions were applied to the data and further flagging was performed on the residual visibilities. A new dirty image was then generated and deconvolved down to a final threshold of 80 $\mu$Jy beam\(^{-1}\).

The reduction of the 1.4 GHz and the 1.2 GHz band data was carried out in a similar fashion. At 1.4 GHz, the deconvolution and self–calibration followed the same path as the 1.7 GHz band reduction, with phase solutions computed every minute. The final image was deconvolved down to a 0.15 mJy beam\(^{-1}\) threshold.

At 346 MHz the initial bandpass calibration was derived from observations of 3C295 for each night and applied to the data. All the six configurations and eight sub bands were imaged jointly using the multifrequency synthesis algorithm. The subsequent deconvolution and self–calibration followed the same path as the 1.7 GHz band reduction but with phase solutions computed every 10 seconds. The final image was obtained after deconvolution down to a 3 mJy beam\(^{-1}\) threshold.

The system noise between the calibrator and the target field can vary significantly at low frequencies and cannot be safely calibrated using the WSRT online loop gain system due to the RFI contamination. We estimated these variations by calculating the total power spectrum between the calibrator and the target field in clean areas of the spectrum (e.g., Brentjens 2008; Pizzo & de Bruyn 2009; Bernardi et al. 2009). We found the ratio to be $\sim 5\%$ averaged over the 346 MHz band and the visibility data were corrected accordingly.

\(^1\) see https://www.astron.nl/radio-observatory/astronomers/wsrt-guide-observations/3-telescope-parameters-and-array-configuration for a description of he configurations in terms of antenna separations.

\(^2\) http://casa.nrao.edu
3 RESULTS

Our 1.2 – 1.7 GHz observations are not deeper than Murgia et al. (2010) in terms of brightness sensitivity and do not detect the A 399 halo, conversely, the 346 MHz image clearly detects it (Figure 2). The size of the A 399 halo at 346 MHz is \( \sim 650 \) kpc, somewhat more extended than at 1.4 GHz (\( \sim 570 \) kpc) and its flux density (integrated above the 4\( \sigma \) contour) is \( 125 \pm 6 \) mJy.

There is no clear detection of the A 401 halo neither at GHz frequencies nor at 346 MHz. The pointing was centred on A 399, i.e. 45’ away from A 401, a distance that corresponds approximately to the first primary beam null at GHz frequencies, i.e. a significant attenuation of the sky emission. The radio emission observed at 346 MHz is likely the blend of two compact sources at \( (\text{RA}_{\text{J}2000} = 2^{h}50^{m}9^{s}, \text{DEC}_{\text{J}2000} = 13^\circ 39'14''') \) and \( (\text{RA}_{\text{J}2000} = 2^{h}59^{m}1^{s}, \text{DEC}_{\text{J}2000} = 13^\circ 37'41''') \) respectively, whereas there is no clear emission where the 1.4 GHz halo is detected by Murgia et al. (2010) - likely due to the sensitivity loss away from the pointing centre.

Figure 3 shows the 1\( ^{\circ} \)-wide contours at 140 MHz (Govoni et al. 2019) overlaid on the 346 MHz image, with a zoom into the A 399 radio halo in Figure 4. The halo appears less extended and with a somewhat less regular morphology at 346 MHz compared to 140 MHz. The peak of its brightness distribution is offset by \( \sim 2 \) arcmin with respect to the 140 MHz observations.

Given that the 346 MHz observations have an essentially complete \( \nu \)-coverage up to 1\( ^{\circ} \) scales, we derived a spectral index\( ^{3} \) map of the A 399 halo between 346 MHz and 140 MHz. For this purpose, the 346 MHz and 140 MHz images were convolved at the same resolution of 205’’ \( \times \) 72’’. We calculated spectral index uncertainty maps \( \Delta \alpha \) as:

\[
\Delta \alpha(x, y) = \sqrt{\left( \frac{\sigma_{\nu_1}}{S_{\nu_1}(x, y)} \right)^2 + \left( \frac{\sigma_{\nu_2}}{S_{\nu_2}(x, y)} \right)^2} \ln \frac{\nu_2}{\nu_1}
\]

where \( (x, y) \) indicate the pixel of the map, \( \nu_1 = 346 \) MHz and \( \nu_2 = 140 \) MHz, and \( \sigma \) is the uncertainty calculated as the quadrature sum of the image noise map and the absolute flux density calibration uncertainty, assumed to be 5% and 15% at 346 MHz and 140 MHz respectively. The spectral index distributions and their relative uncertainties are shown in Figure 5.

The spectral index between 140 MHz and 346 MHz appears in the 1.5 < \( \alpha \) < 2 range and its distribution is rather smooth, although some of the uniformity may be due to the limited angular resolution that would average out small scale variations. The spectral index can be assumed essentially uniform across the halo within the uncertainties. The spectral index integrated over the whole radio halo emission is \( \alpha = 1.75 \pm 0.14 \), slightly steeper than what found by Govoni et al. (2019) in the 140 – 1400 MHz range, although consistent within the uncertainties, placing it amongst the class of ultra steep radio halos (e.g. Macario et al. 2013; Wilber et al. 2018). Its radio power at 1.4 GHz is therefore \( P_{1.4} = 1.1410^{23} \) W Hz\(^{-1}\) well below the correlation between radio halo power and cluster mass (e.g., Cassano et al. 2013; Cuciti et al. 2021b; Duchesne et al. 2021) where ultra steep spectrum radio halos are indeed expected (Cassano et al. 2013).

3.1 Bridge and candidate relics at 346 MHz

As mentioned in the introduction, Govoni et al. (2019) detected a bridge of radio emission connecting A 339 and A 401 with a \( \sim 1.4 \) mJy arcmin\(^2\) average surface brightness at 140 MHz. The presence of radio emission produces by relativistic particles on scales of a few Mpc poses a question on their acceleration mechanism. Due to synchrotron and inverse Compton losses, the particle life time at 140 MHz is of the order of 10\(^8\) years (Govoni et al. 2019), therefore particles can only travel one tenth of the bridge extension in their life time, requiring a mechanism of in situ particle acceleration. Govoni et al. (2019) investigated diffuse shock acceleration, normally considered responsible for radio emission from cluster relics. They found that shock acceleration of thermal electrons would not be sufficiently efficient to achieve the observed emissivity levels, however, re-acceleration of a pre-existing population of mildly relativistic electrons by a population of weak shocks (Mach number of the order of 2 – 3) that fills the bridge volume may be able to produce the observed radio emission. In this case, the spectral index of the bridge would be \( \alpha \approx 1.2 – 1.3 \), similar to that observed in relics. Our 346 MHz observations offer the opportunity to constrain the bridge spectral

\(^{3}\) We used the notation \( S_{\nu} \propto \nu^{-\alpha} \), where \( S_{\nu} \) is the flux density at the frequency \( \nu \).

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Table 1. Observational details. Each observing band is divided into 8 contiguous sub bands for a total 80 MHz bandwidth at 92 cm and 150 MHz at each of the higher frequencies. Noise levels are calculated at the edge of the field of view where the primary beam attenuates the intrinsic sky emission.

| Reference wavelength (cm) | Frequency range (GHz) | Channel width (MHz) | Integration time (hours) | Synthesized beam (arcsec) | Noise rms (mJy beam$^{-1}$) |
|--------------------------|----------------------|---------------------|--------------------------|---------------------------|----------------------------|
| 18                       | 1.64 – 1.79          | 1.17                | 12                       | 53 × 9                    | 0.078                      |
| 21                       | 1.30 – 1.46          | 1.17                | 12                       | 53 × 11                   | 0.059                      |
| 25                       | 1.15 – 1.29          | 1.17                | 4 × 12                   | 58 × 12                   | 0.063                      |
| 92                       | 0.31 – 0.38          | 0.156               | 6 × 12                   | 205 × 43                  | 1.2                        |

Figure 3. 140 MHz contours (Govoni et al. 2019) overlaid on the 346 MHz WSRT image. The resolution of the 140 MHz image is 72" × 72". The first contour is drawn at 1 mJy beam$^{-1}$, increasing by a factor of two. Other than the two clusters A 399 and A 401, labels indicate diffuse sources $d$ and $f$, identified at 140 MHz (Govoni et al. 2019). Arrows indicate the synchrotron bridge connecting both clusters. White dashed circles indicates the 1.5 Mpc virial radius, similar for both clusters (Sakelliou & Ponman 2004). The 346 MHz image is not corrected for the primary beam. The 346 MHz observations are pointed at the centre of the A 399 cluster.
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Figure 4. 140 MHz contours of the A 399 radio halo (Govoni et al. 2019) overlaid on the 346 MHz image. The first contour is drawn at 1.5 mJy beam$^{-1}$, with other contours spaced by a factor of two. The halo at 140 MHz extends further than at 346 MHz.

index and, potentially, discriminate between particle re-acceleration mechanisms.

The comparison between the 140 MHz and the 346 MHz images (Figure 3), shows no evidence of the bridge emission at 346 MHz. As the bridge is an extended, low surface brightness region, the simple image rms does not represent a reliable estimate of the upper limit on its flux density as it would be for point sources. We therefore adopted a procedure similar to the one used to quantify upper limits on the radio halo flux density in cluster observations (e.g., Venturi et al. 2007; Kale et al. 2015; Bernardi et al. 2016; Cuciti et al. 2021a) in order to set an upper limit on the bridge flux density at 346 MHz, which, conversely, turns into a lower limit on its spectral index:

- we first selected the model image of the bridge emission from the LOFAR image at $v_1 = 140$ MHz. It consists of the emission above the $3\sigma$ contour in a $2 \times 3$ Mpc box centered on the bridge - essentially the same region defined in Govoni et al. (2019);
- the bridge model image was extrapolated to $v_2 = [368, 359, 350, 341, 333, 324, 315]$ MHz, corresponding to the central frequencies of the WSRT spectral windows, using a single spectral index:

$$S_{m,v_2}(x,y,\alpha) = S_{m,v_1}(x,y) \left(\frac{v_2}{v_1}\right)^{-\alpha}, \quad (2)$$

where $S_{m,v}$ is the flux density of the model image at the frequency $v$ and position $(x,y)$. The extrapolated model images were attenuated using the WSRT primary beam model (e.g., Bernardi et al. 2010);

- The primary beam-attenuated model images were Fourier transformed into visibilities, added to the calibrated visibilities, then imaged and deconvolved following the same procedure described in Section 2. This procedure takes care of the proper sampling of the bridge emission by the WSRT $uv$-coverage. We introduced the ratio $R(\alpha)$:

$$R(\alpha) = \frac{\sum_{x,y=1}^{N} S_{w}(x,y)}{\sum_{x,y=1}^{N} S_{w}(x,y) + S_{m,v_2}(x,y,\alpha)}, \quad (3)$$

where $S_w$ is the 346 MHz image and $N$ is the total number of pixels of the model image. The numerator of equation 3 is essentially the flux density calculated over the bridge area from the 346 MHz image and the denominator is flux density of the 346 MHz image after the bridge model was added to (“injected” into) the visibilities. Examples of the “injected” images are displayed in Figure 6. We notice that $R(\alpha)$ is a monotonically increasing function $\alpha$: $\lim_{\alpha \to \infty} R(\alpha) = 1$, i.e. in the limit of no bridge emission “injected” the ratio is unity. Conversely, it has a minimum smaller than unity for $\alpha = 0$. This means that there must exist a spectral index value $\alpha_r$, for which $R(\alpha_r)$ is significantly smaller than one, i.e. the injected halo should be detectable above the noise of the 346 MHz observations. Conversely, spectral indices greater than $\alpha_r$ are all consistent with the 346 MHz observations, i.e. $\alpha_r$ represents a spectral index lower limit;

- we determined the spectral index lower limit by calculating $R(\alpha)$ for $0 < \alpha < 5$, with $\Delta \alpha = 0.25$ steps, and constructing its cumulative distribution function $P(< \alpha)$ normalized to unit area over the chosen interval. We found that $P(< \alpha) = 95\%$ for $\alpha_r = 1.5$, in other words, the probability to find an excess flux density with respect to the 346 MHz observations would be 95% if the spectral index of the bridge were smaller than 1.5. Given no detection at 346 MHz, this result sets a lower limit on the spectral index of the bridge $\alpha > 1.5$ at 95% confidence level.

Govoni et al. (2019) also detected two diffuse sources - $d$ and $f$ in Figure 3 - with no obvious optical counterpart and that could not be unambiguously classified. Their high resolution (10 arcsec) observations show head-tail morphologies for both sources indicating that they may be faint radio galaxies with switched-off tails. The observations show head-tail morphologies for both sources indicating that they may be faint radio galaxies with switched-off tails. The presence of an X-ray shock (Akamatsu et al. 2017) in the proximity of source $d$, would support the relic hypothesis - at least for that source. Both sources are visible at 346 MHz, with a similar morphology compared to the 140 MHz (Figure 7 and 8). Source $d$ is somewhat resolved in two brightness peaks at 346 MHz, and the interconnecting region appears to be at the noise level.

The spectral index distribution has a trend across source $d$, with steep values ($\alpha \sim 1.2 - 1.3$) corresponding to the brightness distribution peaks, and values that become ultra-steep ($\alpha > 2$) in the interconnecting region. In the case of source $f$, the core emission shows a flatter spectral index ($\alpha \sim 0.5 - 0.8$) which becomes steeper ($\alpha > 1.5$) across the source. Results for both sources are consistent with the spectral index distributions derived between 140 MHz and 1.4 GHz derived in Govoni et al. (2019), albeit at higher angular resolution (10 arcsec).

We integrated the brightness distribution at 346 MHz above the 5$\sigma$ contour at 140 MHz and obtained flux densities $S = 90 \pm 5$ mJy and $S = 141 \pm 7$ mJy for sources $d$ and $f$ respectively, yielding steep spectral indices $\alpha = 1.10 \pm 0.14$ (source $d$) and $\alpha = 1.46 \pm 0.14$ (source $f$). Integrated spectral indexes are also consistent with Govoni et al. (2019), albeit a bit steeper for source $f$, likely due to the fact that our observations are more sensitive to the steep spectrum region compared to the 1.4 GHz data used in Govoni et al. (2019).

4 DISCUSSION AND CONCLUSIONS

We presented radio observations of the A 399–A 401 cluster pair at 1.7, 1.4, 1.2 GHz and 346 MHz with the WSRT telescope, focused on the analysis of the diffuse radio emission. This cluster pair is a rare case: it appears to be a system in its early merging state, connected by a 3 Mpc-long mass filament with a $4.3 \times 10^{-4}$ cm$^{-3}$ density. Both clusters host a radio halo, detected at 1.4 GHz (Murgia et al. 2010) and 140 MHz (Govoni et al. 2019). Observations at 140 MHz also reveal the presence of a low surface brightness radio bridge.
Figure 5. Left: 140 MHz contours (Govoni et al. 2019) overlaid on the radio spectral index map evaluated using the 140 MHz and 346 MHz observations smoothed to the same angular resolution of $205'' \times 72''$. Right: Same as left panel, but overlaid on the radio spectral index error map. In both panels the first contours are drawn at 5 mJy beam$^{-1}$ and then spaced by a factor of two.

Figure 6. Example of 346 MHz images where the simulated bridge was “injected” into visibilities. Discrete sources were subtracted before visibilities are imaged. The bridge spectral index is $\alpha = 0$ in the left image and $\alpha = 1.5$ in the right image. Diffuse emission that is clearly visible in the left image with respect to the right one.

connecting both clusters as well as other two diffuse features that may be either switched-off, tailed radio galaxies or relics.

Our observations at GHz frequencies were not sufficiently deep to improve the existing radio halo images at 1.4 GHz. At 346 MHz we detected the A 399 radio halo at high significance, with a $125 \pm 6$ mJy flux density. Its size is smaller compared to the 140 MHz observations, with a similar, round-shaped morphology.

Eventually we searched for the presence of the 3 Mpc-extended synchrotron emission bridge that connects both halos observed at 140 MHz and the two diffuse emission features with no obvious optical counterparts (Govoni et al. 2019) in our 346 MHz image. Both diffuse sources are visible at 346 MHz and their spectral index between 346 MHz and 140 MHz is $\alpha = 1.1 \pm 0.14$ (source $d$) and $\alpha = 1.46 \pm 0.14$ (source $f$). The values of the integrated spectral index together with a spectral index steepening across the source - in both cases - suggest that they are more likely switched off radio galaxies rather then relics, or relic emission connected with a radio galaxy (e.g. Bonafede et al. 2014).
Figure 7. Left: 140 MHz contours of the diffuse source $d$ (Govoni et al. 2019) overlaid on the 346 MHz image. Both images were smoothed to the same angular resolution of $205'' \times 72''$ (same as Figure 3). The first contour is drawn at 4 mJy beam$^{-1}$ (3σ, with an rms noise of 1.3 mJy beam$^{-1}$), and the following ones are spaced by a factor of two. The surface brightness peaks match very well between the two observing frequencies, although the interconnecting region is not very visible at 346 MHz. Right: Same contours as left, but overlaid on the radio spectral index map of sources $d$ between 140 MHz and 346 MHz. We note a steepening of the spectral index across the source. Blank regions correspond to pixels fainter than 5σ at either 140 MHz or 346 MHz.

Figure 8. Same as Figure 7 but for source $f$. As for source $d$, the spectral index is steeper in low surface brightness regions.

The bridge was not visible in the 346 MHz data and we used them, together with the 140 MHz observations, to set a constrain on its average spectral index through the “injection” method. We found a lower limit on the spectral index to be $\alpha > 1.5$ at 95% confidence level. Such steep spectral index value cannot be easily explained by diffusive shock acceleration even if an initial population of mildly relativistic electrons is assumed (Govoni et al. 2019), and, instead, is more aligned with the expectations of second order Fermi mechanisms where particles are accelerated and magnetic fields amplified by turbulence (Brunetti & Vazza 2020).

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DATA AVAILABILITY

The data presented in this paper and the software used can be shared upon reasonable request to the corresponding author.
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