ABSTRACT

1. Cluster radio relics and the case of A 521

The radio emission from clusters of galaxies comes into two flavours. In addition to the individual radio sources associated with cluster galaxies, a fraction of massive and X-ray luminous clusters with clear signature of ongoing mergers, hosts large scale diffuse radio sources, known as radio halos, if located at the cluster centre, and relics, if located in peripheral regions. The synchrotron emission in these diffuse sources arises directly within the intracluster medium (ICM), and probes the existence of non-thermal components spread over the cluster scale (e.g., the review paper by Feretti 2005).

Particle acceleration via turbulence injected in the cluster volume during mergers represents a promising possibility to understand the origin of radio halos (see the review papers by Brunetti 2003, 2004; Sarazin 2004; Petrosian & Bykov 2008). Recent statistical analysis (e.g., Kuo, Hwang & Ip 2004; Cassano & Brunetti 2005; Cassano, Brunetti & Setti 2006; Cassano et al. 2007) and deep radio observations of samples of galaxy clusters (Brunetti et al. 2007; Venturi et al. 2007; Venturi et al. 2008) have provided further support to this scenario. On the other hand, our understanding of the origin of relics is still limited. Only a handful of radio relics have been observed in some detail (e.g., A 2256, Clarke & Enßlin 2006; A 3667, Röttgering et al. 1997; A 2744, Orrú et al. 2007). Integrated radio spectra over a wide range of frequencies are available for few relics only (e.g., 1257+275 in the Coma cluster; Andernach et al. 1984, Thierbach, Klein & Wielebinski 2003 and references therein). All models proposed so far for the relic formation invoke the presence of a shock within the X-ray gas (Enßlin et al. 1998; Roettiger et al. 1999; Enßlin & Gopal-Krishna 2001; Hoeft & Brüggen 2007).

Here we focus our attention on the radio relic in A 521 (Ferrari et al. 2006; Giacintucci et al. 2006, hereinafter GVB06), an X-ray luminous and massive galaxy cluster (\(L_X \sim 8 \times 10^{44} \text{erg s}^{-1}\); virial mass \(M_v \sim 1.9 \times 10^{15} \text{M}_\odot\) at redshift \(z=0.247\). Multiple merging episodes are known to be occurring in this very disturbed cluster, whose properties are indicative of an object in a complex dynamical state, and still accreting a number of smaller mass concentrations (e.g., Maurogordato et al. 2000; Ferrari et al. 2003) and 2006; see also Fig. 1 in GVB06 for a sketch of the multiple optical and X-ray substructures in the cluster).

A radio study of A 521 based on 610 MHz Giant Metrewave Radio Telescope (GMRT) observations (GVB06) shows that the relic is a diffuse elongated structure located in the south-eastern periphery of A 521, at the edge of a dynamically active region where galaxy group infalls into the main cluster are taking place (Maurogordato et al. 2000; Ferrari et al. 2003). The relic is at the boundary of the X-ray emission from

1. from the correlation between the X-ray luminosity and \(M_v\) reported in Cassano, Brunetti & Setti (2006).
Table 1. Summary of the radio observations.

| Telescope | RA_{2000} (h, m, s) | DEC_{2000} (°, ′, ″) | Observation date | ν MHz | Δν MHz | t min | HPBW, p.a. (full array, °, ′, ″) | rms μJy b^{-1} |
|-----------|---------------------|---------------------|-----------------|--------|--------|------|-------------------------------|----------------|
| GMRT      | 04 54 09.00         | −10 14 19.0         | Nov 06          | 327    | 16     | 330  | 10.6×0.6, −19                 | 90−100          |
| VLA–BnA   | 04 54 16.28         | −10 16 05.9         | Jun 06          | 4860   | 50     | 110  | 1.0×0.8, −68                  | 10              |
| VLA–CnB   | 04 54 16.28         | −10 16 05.9         | Oct 06          | 4860   | 50     | 60   | 4.0×2.0, −82                  | 15              |
| VLA–BnA   | 04 54 16.28         | −10 16 05.9         | Jun 06          | 8430   | 50     | 170  | 0.6×0.5, 82                   | 8               |

* The observations were performed using a total bandwidth of 32 MHz (USB+LSB), but only the USB dataset was used for the analysis (see Sec. 2.1);
* The rms noise level in the region of the relic is ~ 90 μJy b^{-1}, and increases up to 100 ~ μJy b^{-1} in the outer parts of the A 521 field due to the presence of strong radio sources.

the intracluster gas, at a projected distance of ~ 930 kpc from the cluster X-ray centre, and it is apparently connected to the most powerful radio galaxy in A 521 (J0454–1016a) by a faint bridge of radio emission. Even though projection effects should be taken into account, this situation is similar to what is observed in the Coma cluster, where a bridge of radio emission connects the tails of the radio galaxy NGC 4789 to the prototype relic source 1253+275 (Giovannini, Feretti & Stanghellini [1991]).

In this paper we present a study on the origin of the relic based on new GMRT 327 MHz high sensitivity observations of A 521 and new high frequency and high resolution images of the relic region obtained from Very Large Array (VLA) observations at 4.9 and 8.5 GHz. The amount of radio information available allows us to study in detail the spectral properties of the source (integrated and point–to–point) over a relatively wide range of frequencies, and compare them to the expectations from models for its origin. The paper is organised as follows: Sec. 2 describes the radio observations and data reduction; the new GMRT 327 MHz images of the A 521 field and relic region are presented in Sec. 3; in Sec. 4 we report on the analysis of the VLA 4.9 and 8.5 GHz images; Sec. 5 deals with the study of the spectral index image; the source integrated radio spectrum is analysed in Sec. 6; the proposed scenarios for the relic origin are discussed in Sec. 7; finally a summary of our results is given in Sec. 8.

We adopt the ΛCDM cosmology with H_0=70 km s^{-1} Mpc^{-1}, Ω_m = 0.3 and Ω_Λ = 0.7. At the redshift of A 521 this cosmology leads to a linear scale of 1° = 3.87 kpc. The spectral index α is defined according to $S \propto \nu^{-\alpha}$.

2. Radio observations and data reduction

We carried out high sensitivity observations of A 521 using the GMRT at 327 MHz. In order to image the sky region close to the relic at higher frequency and resolution, and resolve the inner structure of the radio galaxy J0454–1016a, we performed VLA observations at 4.9 GHz in the hybrid BnA and CnB configurations, and at 8.5 GHz in the BnA configuration. In Table 1 we summarise the details on all the radio observations presented in this paper. Columns in the table provide the following information: telescope/array; J2000 coordinates of the pointing centre; observing day; frequency; total bandwidth; total time on

2.1. GMRT observations at 327 MHz

A 521 was observed using the GMRT at 327 MHz in November 2006 for a total integration time of 5.5 hours (Tab. 1). The observations were performed using both the upper and lower side band (USB and LSB, respectively) for a total observing bandwidth of 32 MHz. The data were collected in spectral–line mode with 128 channels/band, and a spectral resolution of 125 kHz/channel.

The USB and LSB datasets were calibrated and analysed individually using the NRAO Astronomical Image Processing System (AIPS) package. The bandpass calibration was performed using the flux density calibrator. A RFI–free channel was chosen to normalise the bandpass for each antenna. The calibration solutions were applied to the data by running the AIPS task FLGIT, which subtracts a continuum from the channels in the u–v plane, determined on the basis of the bandpass shape and using a specified set of channels. The data whose residuals exceed a chosen threshold are then flagged. Despite this flagging procedure, both the USB and LSB datasets were still affected by strong residual radio frequency interferences (RFI). Hence, a very accurate editing of the visibility data was carried out in order to identify and remove those data affected by RFI.

In order to find a compromise between the size of the dataset and the need to minimise bandwidth smearing effects within the primary beam, the central channels were averaged to 6 channels of ~2 MHz each after bandpass calibration. Given the large field of view of the GMRT, in each step of the data reduction we implemented the wide–field imaging technique to minimise the errors due to the non–planar nature of the sky. We used 25 facets covering a total field of view of ~ 2.7 × 2.7 square degrees. After a number of phase self–calibration cycles, the final USB and LSB datasets were further averaged from 6 channels to 1 single channel.

Due to residual phase errors in the LSB dataset, the USB–LSB data combination led to images with a quality worse than those obtained from the USB alone. For this reason only the USB dataset was used for the analysis presented in this present paper. A very high sensitivity (1σ) latitude and longitude coordinates of the pointing centre; observing day; frequency; total bandwidth; total time on source; half power bandwidth (HPBW) and rms level (1σ) in the full resolution image.

Bandwidth smearing is relevant only at the outskirts of the wide field, and does not significantly affect the region presented and analysed in this paper.
Fig. 1. GMRT 327 MHz contours of the 30′ × 30′ region containing A 521. Contour levels are spaced by a factor 2 starting from 5σ = ±0.5 mJy b−1. The resolution is 10.6′′ × 9.6′′, in p.a. −19°. The cross marks the X-ray centre of the cluster (Arnaud et al. 2000). The radius of the solid circle corresponds to the cluster virial radius RV = 2.8 Mpc (GVB06). The dashed circle has a radius of ∼1 Mpc, and indicates the region covered by the optical analysis in Ferrari et al. (2003).

was achieved in our final full resolution image (Tab.I): from ∼90 μJy b−1 in the region of the relic to ∼100 μJy b−1 in the outer parts of the A 521 field, where the quality of the image is limited by the presence of strong radio sources. The residual amplitude errors are of the order of ∼5%.

2.2. VLA observations at 4.9 and 8.5 GHz

The 4.9 GHz observations of the relic region were carried out using the VLA in the hybrid BnA and CnB configurations. The 8.5 GHz observations were performed in the BnA configuration (see Tab. I for details). A bandwidth of 50 MHz was used for each of the two IF channels at each frequency. All observations included full polarisation information. The data were calibrated and reduced using the pilot semi–automatic pipeline for the VLA data processing, a facility recently developed at NRAO and implemented in the AIPS package. The pipeline provided high quality calibrated datasets at each frequency. These latter were further phase self–calibrated in AIPS, in order to correct for residual phase variations, and used to produce the final images. The rms noise level achieved in the final images are reported in Tab. I. The average residual amplitude errors in the data are of the order of ∼5% both at 4.9 and 8.5 GHz.

3. A 521 at 327 MHz

3.1. The field

In Fig. 1 we present the GMRT full resolution image at 327 MHz covering the region within the cluster virial radius (RV = 2.78 Mpc; GVB06), which is delimited by the solid circle. The figure shows the same ∼30′ × 30′ field presented at 610 MHz in Fig. 2 of GVB06. The cross marks the centre of the cluster X–ray emission as detected by ROSAT HRI (Arnaud et al. 2000). The dashed circle has a radius corresponding to ∼1 Mpc, and indicates the area covered by the analysis of the optical substructures in Ferrari et al. (2003). The radio contours are plotted starting from ± 0.5 mJy b−1, which corresponds to the 5σ level in the region with the highest noise.
Fig. 2. Left panel: full resolution GMRT contours at 327 MHz of the relic, overlaid on the red POSS–2 optical image. The resolution is 10.6″ × 9.6″, in p.a. −19°. Contours are spaced by a factor 2 starting from ±3σ = 0.27 mJy b−1. A, B and C indicate the position of the radio galaxies embedded in the relic emission. Right panel: low resolution GMRT image at 327 MHz of the relic (contours and grey scale). The resolution is 15″ × 12.0″, in p.a. 0°. Contours are spaced by a factor 2 starting from ±3σ = 0.27 mJy b−1.

Three very extended radio sources are visible in the image: the radio relic, in the south–eastern outskirts of the cluster, and the two radio galaxies J0453–0957 and J0454–1006, located North of A 521, and analysed at 610 MHz in GVB06.

In addition to discrete point sources, positive residuals of radio emission are detected within the dashed circle in Fig. 1, suggesting the presence of diffuse emission at the cluster centre. The investigation of this point is beyond the purpose of the present paper, and will be addressed in a forthcoming paper (Brunetti et al. to be submitted).

3.2. The radio relic at 327 MHz

As observed at higher frequencies, the 327 MHz radio emission within the inner ∼ 1 Mpc radius is clearly dominated by the relic. Fig. 2 zooms into the 327 MHz image of the relic. In the left panel we show the full resolution contours overlaid on the optical POSS–2 frame (grey scale). Labels A, B and C indicate the position of the radio galaxies embedded in the diffuse relic emission, and optically identified in GVB06. In the right panel we show an image at the resolution of 15.0″ × 12.0″ with grey scale and contours overlaid in order to better highlight the distribution of the radio surface brightness across the source. The relic exhibits a highly elongated and arc–shaped structure with an angular size of ∼ 4.3″, which corresponds to a linear size of ∼ 1 Mpc. The overall morphology and total extent in Fig. 2 are in good agreement with the images at 610 MHz (GVB06; also reported in Fig. 5) and at 1.4 GHz (Ferrari et al. 2006) of similar resolution. The relic emission along the minor axis appears on the average slightly wider in the 327 MHz image (∼ 1.0″, i.e., ∼ 230 kpc) than at higher frequencies (∼ 200 kpc at 610 MHz and ∼ 160 kpc at 1.4 GHz).

Table 2. Properties of the radio galaxy J0454–1016a.

| Frequency  | Peak flux (mJy) | Brightness Temperature (K) |
|------------|----------------|---------------------------|
| 327 MHz    | 46.0 ± 2.3 i)  |                           |
| 610 MHz    | 27.7 ± 1.4 ii) |                           |
| 1.4 GHz    | 15.0 ± 0.8 iii)|                           |
| 4 GHz      | 6.2 ± 0.3 iv)  |                           |
| 8.5 GHz    | 3.6 ± 0.2 v)   |                           |
| P1.4 GHz   | 24.41          |                           |
| log(P1.4 GHz) (W Hz−1) | 0.79±0.13       |                           |

Notes to Tab. 2: i) from Fig. 2 (left panel); ii) from GVB06; iii) from VLA archival data (Obs. Id. AF 0390); iv) from panel b) of Fig. 3; v) from panel d) of Fig. 3.

4. The relic region at 4.9 and 8.5 GHz

4.1. The radio galaxy J0454–1016a

Source A in Fig. 2 is the cluster radio galaxy J0454–1016a. A faint bridge of emission is clearly detected between the northern part of the relic and this radio galaxy, which is located at ∼ 350 kpc (projected) from the relic. This emission was also observed at 610 MHz, and suggested the presence of a physical link between the two objects (GVB06). We investigated the possible connection between the relic and J0454–1016a by means of VLA 4.9 and 8.5 GHz observations (Tab. 1), aimed to resolve the inner structure of the source, and search for evidence of a connection with the nearby relic, for example in the form of bent jets and/or extended emission in that direction.

J0454–1016a is the most powerful radio galaxy in A 521 (GVB06; Tab. 2), and is identified with the galaxy #143 (v=74282 km s−1, I=17.00) in the optical catalogue by
Fig. 3. Panel a) – GMRT 610 MHz full resolution contours of the relic on the POSS–2 image. The HPBW is $5.0'' \times 4.0''$. The $1\sigma$ noise level is 40 $\mu$Jy $b^{-1}$. A, B and C indicate the position of radio galaxies embedded in the relic emission. Panel b) – VLA–CnB 4.9 GHz contours of J0454–1016a on the POSS–2; HPBW $= 4.0'' \times 2.0''$; $1\sigma$=15 $\mu$Jy $b^{-1}$. Panel c) – VLA–BnA 4.9 GHz image (contours and grey scale) of J0454–1016a; HPBW $= 1.0'' \times 0.8''$; $1\sigma$=10 $\mu$Jy $b^{-1}$. Panel d) – VLA–BnA 8.4 GHz image (contours and grey scale) of J0454–1016a. HPBW $= 0.6'' \times 0.5''$; $1\sigma$=8 $\mu$Jy $b^{-1}$. In all the panels the contour levels are spaced by a factor 2 starting from $\pm 3\sigma$.

Ferrari et al. (2003). Fig. 3 shows the region of the relic and J0454–1016a (labelled as A) in increasing frequency (from 610 MHz to 8.5 GHz) and resolution order ($\sim 5''$ to $\sim 0.5''$) going from panels a) to d). Panel a) shows the full resolution image at 610 MHz. The VLA–CnB 4.9 GHz image of J0454–1016a is presented in panel b); the BnA full resolution images at 4.9 and 8.5 GHz are shown in panels c) and d), respectively. J0454–1016a appears extended in all the images with a largest linear size of $\sim 30$ kpc. Its radio structure is consistent with a head–tail morphology. The compact component, detected at 4.9 and 8.4 GHz (panels c and d), is coincident with the nucleus of the host galaxy.

The extended emission is entirely located South–West of the compact component, and there is no evidence of any emission in the direction of the radio bridge detected at 327 MHz (Fig. 2) and 610 MHz (panel a). This result might rule out a physical connection between the diffuse emission from the relic and this radio galaxy, whose tail extends (at least in projection) in a nearly opposite direction.
Fig. 4. Integrated radio spectrum of J0454–1016a between 327 MHz and 8.5 GHz. The solid line is the best fit of the CI model. The value of $\alpha_{\text{inj}}$ provided by the fit, along with the reduced $\chi^2$, is also reported.

The flux densities available for J0454–1016a are collected Tab. 2 where we also report the 1.4 GHz radio power (from VLA archival data, Obs. Id. AF 0390, re-analysed in Giacintucci 2007), and the spectral index in the 327 MHz–8.5 GHz interval. The flux density measurements on both frequencies are consistent within the errors. Fig. 3 shows the integrated radio spectrum of J0454–1016a between 327 MHz and 4.9 GHz, derived using the values in Tab. 2.

We fitted the spectrum with the Synage++ package (Murgia 2001) assuming a continuous injection model (CI; Kardashev 1962). The best fit is shown as solid line in Fig. 4 and provides an injection spectral index $\alpha_{\text{inj}} = 0.70^{+0.10}_{-0.14}$. Even though there is an indication of a spectral steepening above 4.9 GHz, the spectrum is consistent with a single power law with slope $\alpha = \alpha_{\text{inj}}$.

The spectral shape in Fig. 4 is similar to what is observed in other active and low luminosity radio galaxies (e.g., Parma et al. 2002).

4.2. The radio relic at 4.9 GHz

The most interesting result of the VLA 4.9 GHz observations is the detection of the radio relic, shown in Fig. 5. This is the second detection of a radio relic at a frequency as high as 4.9 GHz, after the relic source 1253+275 in the Coma cluster (Andernach et al. 1984; Thierbach, Klein & Wielebinski 2003). The image was obtained from the VLA–CnB data (Tab. 1), tapered to a resolution of $22.0'' \times 15.0''$.

In the left panel the relic is shown as contours, while in the right panel the 4.9 GHz emission is reported in grey scale with the GMRT 610 MHz contours overlaid (GVB06). The faintest features of the relic emission are significant at the 3$\sigma$ level (1$\sigma = 15 \mu$Jy b$^{-1}$), and the peaks at the level of 12$\sigma$. We point out that, given the short observing time (Tab. 1) and lack of short baselines (minimum baseline $\sim 1$ k$\lambda$), the u–v coverage of the 4.9 GHz observations is not adequate to properly image the whole diffuse emission associated with the relic. For this reason the details of the structure of the source in Fig. 5 might not be fully reliable, and deeper 4.9 GHz observations with a more appropriate array and u–v coverage are needed to better determine the relic morphology at this frequency.

5. Spectral index image of the relic

Spectral index imaging of cluster radio relics is a powerful tool to investigate and understand their origin, evolution, and connection with the merging activity of the hosting cluster. In particular, the spectral index images provide important information on the energy spectrum of the radio emitting electrons and magnetic field distribution in these sources (e.g., Clarke & Enßlin 2006).

We obtained the image of the spectral index distribution in the A 521 relic in the frequency range 327–610 MHz, by comparing the GMRT image at 327 MHz shown here (Fig. 2; right panel) with the GMRT 610 MHz image obtained from the observations presented in GVB06. The images were produced with the same cell size, u–v range, and restoring beam. For the details we refer to Tab. 3 where we provide the u–v range, beam and noise level (1$\sigma$) of the two images. The images were aligned, the pixels with brightness below the 3$\sigma$ level were blanked, and finally the image combination was carried out to create the spectral index image using the Synage++ package. The resulting spectral index image is shown in Fig. 6 (colour), with the 610 MHz contours overlaid.

5.1. General features of the spectral index image

The distribution of the spectral index in Fig. 6 shows different features along the two axis of the relic. Along the major axis a number of irregularities provide a rather patchy appearance of the spectral index image. Such patchiness might arise from irregularities in the u–v coverage occurring at different spacings at the two frequencies. Along the minor axis a steepening of the spectral index from the eastern edge of the relic toward the western border is visible. This trend is real and not driven by a misalignment between the images at 327 and 610 MHz. We carefully checked the correct alignment of the images using the point sources in the relic region: the spectral index distribution appears uniform in each of them and consistent with the value of $\alpha$ obtained from their total flux density at the two frequencies. This is also clear from Fig. 6 where for example the radio galaxy J0454–1016a (labelled as A) has an average spectral index $\alpha = 0.75 \pm 0.05$, which is in good agreement with the source integrated spectrum shown in Fig. 4 (see also Tab. 2).
5.2. Analysis of the radial steepening

In order to check the significance of the spectral steepening visible in Fig. 6 we determined the average spectral index in 3 independent strips of 14′′ × 80′′ size in the northern region of the relic and 3 independent strips of 14′′ × 100′′ size in the southern part. These two regions are labelled respectively N and S in the left panel of Fig. 6. The central portion of the relic was excluded from the analysis because which may affect the spectral trend. The strips were set parallel to the edge of the relic, i.e., at a position angle of 5° and 32° in the N and S regions, respectively. For each strip we integrated the flux density on the 327 MHz and 610 MHz images individually, and then calculated the corresponding spectral index values. The average 327–610 MHz spectral index in each strip is shown in the right panel of Fig. 6. The spectral index trend shows a gradual steepening going westwards both in the N and S regions. In particular α ranges from \( \approx 1.0 \pm 0.1 \) to \( \approx 2.1 \pm 0.1 \) in the southern part (empty triangles), and from \( \approx 1.3 \pm 0.2 \) to \( \approx 2.3 \pm 0.1 \) across the northern region (filled triangles).

A steepening from the outer to the inner edge of the relic with available spectral index images has been observed also in few other cases, as for example in A 3667 (Röttgering et al. 1997) and A 2744 (Orrú et al. 2007). A more detailed study of the spectral index gradient, similar to the analysis presented in this paper, has been carried out for the relic in A 2256 by Clarke & Enßlin (2006), who found a significant steepening of α between 1369 MHz and 1703 MHz from the external edge of the relic toward the cluster core, i.e., the same kind of gradient found in the A 521 relic.

6. Integrated radio spectrum of the relic

The wealth of multifrequency radio observations available for the relic in A 521 allows the determination of its integrated spectrum over almost two orders of magnitude in frequency.

In Tab. 4 we report all the available flux densities of the relic, along with the resolution of the images used for the measurement. In order to obtain a consistent measurement of the total flux densities, we integrated over the same region in all the images, and subtracted the flux density of the embedded point-sources, as measured on the corresponding full resolution images. The source subtraction could not be applied for the 74 MHz value, since the low resolution (80′′ × 80′′) of the Very Low-frequency Sky Survey (VLSS) image does not allow to perform such operation. Furthermore the extended structure visible in the VLSS image is not fully consistent with the relic morphology at higher frequencies, probably due to the different angular resolution and the much lower sensitivity of the VLSS (average rms noise of the order of \( 1 \sigma = 0.1 \) Jy b\(^{-1} \)). For these reasons the flux density measurement at 74 MHz is very uncertain.

The integrated spectrum of the relic is shown in Fig. 8. The spectrum does not show any steepening up to 4.9 GHz and is well fitted by a single power law with slope \( \alpha = 1.48 \pm 0.01 \) (solid line) between 235 MHz and 4.9 GHz. Given its large uncertainty, the 74 MHz data point was not included in the fit. We note that the 4.9 GHz flux density should be

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3 The table provides also the source flux density at 235 MHz measured on a preliminary image from very recent GMRT observations (see Appendix).

4 http://lwa.nrl.navy.mil/VLSS/
considered a lower limit, given the array, \(u-v\) coverage and resolution which led to its detection (see Sec. 4.2).

New deep observations carried out with the VLA at 74 (October 2007) will allow us to better constrain the low frequency end of the radio spectrum.

7. Discussion

A preliminary discussion on the formation of the radio relic in A 521 was carried out in GVB06, where a number of possible theoretical frameworks were taken into account, all related to the assessed ongoing merging activity in this cluster. Two possible scenarios were considered, both invoking a tight connection with the presence of a merger–driven shock front at the location of the relic. Such a shock may accelerate electrons to ultra–relativistic energies (Enßlin et al. 1998; Roettiger et al. 1999; Hoeft & Brüggen 2007), or it may revive fossil radio plasma through adiabatic compression of the magnetic field (Enßlin & Gopal–Krishna 2001).

A third alternative scenario was also proposed, based on the hypothesis of a physical link between the diffuse emission of the relic and the nearby radio galaxy J0454–1016a, as suggested by the faint radio bridge of emission between the two sources observed at 610 MHz (e.g., Fig. 5 right panel). The high frequency images of J0454–1016a (Fig. 5) and the spectral analysis of the radio relic presented in this paper (Secs. 5 and 6) allow us to carry out a more detailed comparison between the expectations from the models and the observed properties of the relic.
shock with Mach number \( M > \) of the galaxy itself, should be estimated that the infall velocity of the merging group, or projected distance of J 0454 ii region, or by either i) GVB06 proposed that the relic might be the result of the 7.1. Connection of J0454–1016a with the radio relic

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Fig. 8. Radio spectrum of the radio relic between 74 MHz and 4.9 GHz. The solid circle is the relic flux density measured on the new GMRT image at 327 MHz. The empty triangles are the 610 MHz data point from GVB06, and the 1.4 GHz value from VLA archival data. The solid triangle is the source flux density measured on the new VLA image at 4.9 GHz. The empty circle is the flux density from a preliminary GMRT image at 235 MHz (see Appendix). The empty square is the 74 MHz flux density from the VLSS image. The solid line represents the linear fit to the data by using the points between 327 MHz and 4.9 GHz.

7.1. Connection of J0454–1016a with the radio relic

GVB06 proposed that the relic might be the result of the ram pressure stripping of the radio lobes of J0454–1016a by either i) group merging activity in the southern cluster region, or ii) the infall of the radio galaxy itself into the cluster. On the basis of pressure arguments, and given the projected distance of J0454–1016a from the relic, they estimated that the infall velocity of the merging group, or of the galaxy itself, should be \( \geq 3000 \text{ km s}^{-1} \) (leading to a shock with Mach number \( M > 2 \)) to allow the electrons in the radio lobes to still emit in the radio band.

The high resolution and high frequency observations presented in Sec. 4 do not seem to support this scenario, since there is no obvious morphological link between the relic and J0454–1016a. The radio galaxy has a head–tail morphology, whose tails extend (in projection) in a direction nearly opposite to the relic region and to the faint bridge of emission connecting the galaxy and the relic (Fig. 3). Even though the origin of the faint bridge remains unclear, it seems to be unrelated to the current AGN activity of J0454–1016a.

7.2. Basic expectations from the shock scenarios and comparison with the observations

The shock scenarios for the origin of radio relics provide a number of expectations which can be tested by means of the comparison with the observed properties of the source.

a) Shock acceleration – In this scenario the relic emission is produced by electrons accelerated from the thermal gas to relativistic energies by the passage of a merger shock wave (Enßlin et al. 1998; Roettiger et al. 1999; Hoeft & Brüggen 2007). Assuming linear shock acceleration theory, in the case of a fully ionised plasma as the ICM, the steady state energy spectrum of the electrons in the relic is a power law whose slope \( \delta \) is related to the shock Mach number \( M \) according to the following equation (e.g., Blandford & Eichler 1987):

\[
\delta = \frac{2M^2 + 1}{M^2 - 1} + 1
\]  

where the effect of particle aging \( \Delta(\delta) = 1 \) (from the combined effect of inverse Compton energy losses and continuous injection) is included (Sarazin 1999). The ensuing integrated radio emission of the relic has a single power law spectrum with \( \alpha = (\delta - 1)/2 \), which is thus related to the Mach number of the shock through Eq. [1]. More specifically, the total spectrum results from the combination of the aged spectrum of the injected electrons: once accelerated, the electrons are short–lived because of the inverse Compton and synchrotron energy losses, and their spectrum will rapidly steepen with the distance from the shock rim. Thus, the spectral index distribution of the relic synchrotron radio emission would exhibit a progressive steepening going from the current location of the shock (where the observed \( \alpha \) is the injection spectral index) to the trailing edge.

b) Adiabatic compression – In this scenario the relic is the result of the adiabatic compression exerted by a merger shock on a region containing fossil radio plasma (Enßlin & Gopal–Krishna 2001). Such compression might increase the magnetic field strength and re–energize the electron population in the fossil plasma, thus leading to observable radio emission. In this case the relativistic electrons are expected to produce diffuse radio emission in front of the bow shock, and then rapidly lose their energy while moving away from the front. Hence a transversal steepening in the spectral index distribution of the relic may be expected also in this model. Unlike the shock acceleration case, this scenario predicts a curved integrated radio spectrum showing a spectral steepening at high frequency, at least for relatively weak shocks (\( M \lesssim 3 \)).

c) Shock re–acceleration – This scenario was discussed by Markevitch et al. (2005) for the origin of the radio edge coincident with the shock front in A 520. In this case the relic is produced by re–acceleration of fossil electrons in the ICM by the shock. The basic expectations for the spectral properties of the relic are similar to the shock acceleration scenario (a).

The results of the spectral analysis presented in this paper provide insightful information to discriminate between the models described above. In the case of the relic in A 521, a significant steepening of the spectral index was found going from the eastern edge of the source toward the western border (Fig. 7). This behaviour is in line with the expectations of all the scenarios. It implies that the shock is expected to be moving outwards with respect to the cluster centre, and its current location should be approximately coincident with the eastern edge of the
relic. In Sec. 6 we showed that the integrated spectrum of the relic is well reproduced by a single power law with steep spectral index ($\alpha \sim 1.5$), and with no evidence of high frequency steepening up to 4.9 GHz (Fig. 8). Such a spectral shape is expected only in the framework of the shock acceleration and re-acceleration scenario.

The adiabatic compression scenario should produce curved spectra with a high frequency cut-off in the case of moderate or weak shocks, such as those expected to be developed during cluster mergers (e.g., Gabici & Blasi 2003; Ryu et al. 2003; Pfrommer et al. 2006, and references therein). In principle a cut-off just above 5 GHz cannot be ruled out. The compression enhances the magnetic field and the particle energy density, moving the break frequency in the synchrotron spectrum at higher frequencies. Assuming thermal and relativistic particles mixed into the fossil plasma, the ratio of the post-compression and initial break frequencies ($\nu_{\text{post}}^b$ and $\nu_{\text{0}}^b$, respectively) is (e.g., Markevitch et al. 2005):

$$\frac{\nu_{\text{post}}^b}{\nu_{\text{0}}^b} = \left( \frac{4M^2}{M^2 + 3} \right)^{4/3} < 6$$

This value is not high enough to explain the lack of a cut-off in the observed spectrum of the relic.

This factor can be strongly increased if the shock compression acts on a ghost of purely relativistic plasma (i.e., not mixed with the thermal ICM). In this case (Enßlin & Gopal–Krishna 2001):

$$\frac{\nu_{\text{post}}^b}{\nu_{\text{0}}^b} \approx \frac{P_2}{P_1} \approx \frac{5M^2 - 1}{4}$$

where $P_1$ and $P_2$ are the pre- and post-shock thermal pressures. To produce a spectral break at $\nu \geq 5$ GHz, a shock with $M \geq 7$ is required, which however would imply a very unlikely pre-shock temperature of $T < 1$ keV for A 521.

An additional point is that the injection spectrum of the fossil radio plasma in this scenario should be roughly equal to the observed one ($\alpha \sim 1.5$), which however is much steeper than typical spectra of radio galaxies.

To summarise, our spectral analysis suggests that the origin of the relic in A 521 is consistent with the shock acceleration scenario. According to Eq. 1 we can estimate the Mach number of the shock responsible for the electron acceleration. The spectral fit provided a total spectral index $\alpha = 1.48 \pm 0.01$ (Sec. 6), which corresponds to $\delta = 3.96 \pm 0.02$, and thus $M(\delta) = 2.27 \pm 0.02$. Such Mach number is in reasonable agreement with the values expected for the cluster merger shocks, and indeed observed in merging clusters (e.g., Markevitch & Vikhlinin 2007). As argued in GVB06, the relic is located in a peripheral region of A 521 which is expected to be dynamically active (Maurogordato et al. 2000; Ferrari et al. 2003 and 2006; see also Fig. 2 in GVB06). Thus the presence of a shock front at the relic location is likely.

7.3. A shock front coincident with the radio relic?

Using the available Chandra X-ray archive data of A 521, we checked if there is indeed a shock front in the cluster gas at the position of the relic. Shock fronts in clusters are observed very rarely. Only two unambiguous examples, exhibiting both a sharp gas density edge and a clear gas temperature jump, have been discovered by Chandra so far, those in the merging clusters 1E 0657–56 (Markevitch et al. 2002) and A 520 (Markevitch et al. 2005). Their rarity is due to the fact that the viewing geometry and the moment of our observation must be very favourable: a merger shock
quickly moves to the cluster outskirts where it cannot be detected.

For A 521 two observations are available in the Chandra public archive, one performed with ACIS–I and another with ACIS–S, with ∼40 ks exposure each (Ferrari et al. 2006). Unfortunately, the relic lies right at the S3 chip boundary in the ACIS–S observation, so we could use only the ACIS–I observation (OBSID 901) for our purpose. We cleaned the data and modeled the detector background and instrumental spatial response as described most recently in Vikhlinin et al. (2005).

In Fig. 9 we show the resulting Chandra image in the 0.5–4.0 keV energy range. The background was subtracted and the image was divided by the exposure map, and then smoothed with a σ = 6″ Gaussian. In the right panel the GMRT 610 MHz contours are overlaid on the same X–ray image. The image reveals a clear brightness edge coincident with the outer edge of the radio relic.

The radial brightness profile in Fig. 10 (left panel) shows this edge more clearly. The profile was extracted from the unsmoothed image in the sector shown in the left panel of Fig. 9, which is centred on the centre of curvature of the relic and spans the angle covered by the source. Discrete X–ray sources were excluded for the profile derivation. For comparison, in the right panel we plot the X–ray brightness profiles extracted from three other sectors of the cluster. Neither of them shows such an edge, consistently with the visual inspection of the image shown in Fig. 9.

The X–ray edge in Fig. 10 (left panel) has the characteristic shape that corresponds to a projection of a spherical density discontinuity. To quantify this discontinuity, we tried to fit this brightness profile in the immediate vicinity of the edge with a gas density model consisting of two power laws and an abrupt jump, with power laws and the position and amplitude of the jump being free parameters (as in Markevitch et al. 2000). A continuous density profile (i.e., no jump, but a possible break), shown by the red line in Fig. 11 is inconsistent with the data at about 4.5σ. If one assumes a 6 keV gas temperature just inside the edge (Ferrari et al. 2006, determined from this and the ACIS–S Chandra observations) and converts brightness in the Chandra 0.5–4 keV band into plasma emission measure self–consistently, the best–fit density jump (the model shown by green line) corresponds to M ≈ 7. However, as mentioned
above, such a shock would imply a pre-shock temperature of \( \sim 0.4 \) keV, which is very unlikely close to the center of such a hot cluster. A shock with \( M = 2.3 \), predicted from the radio spectrum (Sec. 7.2), corresponds to an edge shown by the blue line in Fig. 11; this fit is only 1.8\( \sigma \) away from the best fit, which we consider a good agreement.

Unfortunately, the accuracy of the existing Chandra observation is not sufficient to measure the gas temperature on the faint side of the edge. Thus, we cannot rule out other interpretations for this feature, e.g., a cold front (Markevitch & Vikhlinin 2007). However, a cold front with such a density contrast would correspond to an outer gas temperature in excess of 15 keV — quite unlikely in a cluster of this X-ray luminosity. We conclude that the X-ray edge is most likely a shock front — found at a location and with an amplitude exactly as needed to produce the radio relic via the shock acceleration mechanism.

8. Summary and Conclusions

We presented new deep radio images of the radio relic in A 521 obtained using the GMRT at 327 MHz and the VLA at 4.9 and 8.5 GHz. We performed a study of the spectral properties of the source by combining the new radio information with our previous GMRT data at 610 MHz (GVB06) and 1.4 GHz observations available in the VLA public archive and re-analysis in Giacintucci (2007).

In the following we summarise the main results of our analysis:

1. The relic morphology at 327 MHz is in overall agreement with the structure observed at 610 MHz and 1.4 GHz.
2. The relic was detected at 4.9 GHz at a high level of significance (from 3\( \sigma \) in the fainter regions to 12\( \sigma \) at the peaks). This is the second detection of a radio relic at a frequency as high as 4.9 GHz after the relic source 1253+275 in the Coma cluster (Thierbach, Klein & Wielebinski 2003).
3. A faint bridge of emission is clearly detected between the northern part of the relic and the cluster radio galaxy J0454–1016a. This emission was also observed at 610 MHz, and suggested the existence of a physical connection between the two sources. The high resolution images at 4.9 and 8.5 GHz seem to rule out such hypothesis: J0454–1016a has a head–tail structure extending in a direction opposite with respect to the bridge, whose origin remains thus unclear.
4. The spectral index image of the relic between 327 and 610 MHz looks rather patchy and irregular. However our analysis revealed a significant overall gradual steepening of the spectral index along the source minor axis, from the outer edge of the relic toward the cluster centre. A similar trend has been observed in few other relics with available spectral index images, as for example the case of A 2256 where a spectral study similar to the analysis presented in this paper was performed by Clarke & Enßlin (2006).
5. We derived the integrated spectrum of the relic over almost two orders of magnitude in frequency. Such a frequency coverage is available for very few relics only (e.g., the Coma cluster relic; Thierbach, Klein & Wielebinski 2003). The spectrum of the relic in A 521 is well fitted by a power law with a steep spectral index (\( \alpha \sim 1.5 \)), with no evidence of a steepening in the high frequency regime (up to 4.9 GHz). This situation is similar to the Coma relic, which shows a single power law spectrum with \( \alpha \sim 1.2 \).
6. We analysed the archival Chandra observation of A 521 and discovered a clear X-ray brightness edge at the position of the outer border of the radio relic. This edge can be the shock front responsible for the electron acceleration. The present X-ray data accuracy is insufficient to confirm that it is a shock front, but the coincidence is tantalizing.

The results of our spectral analysis were discussed in the framework of the possible models for the relic origin considered in GVB06. We concluded that the more plausible scenario is the shock acceleration, while adiabatic compression seems to be ruled out by the present data. In the shock acceleration case, the flattest spectrum emission of the relic (i.e., the outer region) would mark the position of the shock front, where the electron acceleration is expected to be currently ongoing. This suggests that the shock wave is propagating from the north–western direction toward South–East (projected on the plane of the sky). The possible merging scenario for A 521 (Ferrari et al. 2003 and 2006) might be consistent with such hypothesis. The presence of an edge in the X-ray surface brightness in the relic region is suggestive of the existence of a shock front which may be responsible for the electron acceleration in the relic. Deeper X-ray observations are needed to confirm the presence of such a shock.

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Appendix A: Preliminary results of the GMRT follow up at 235 MHz

In this Appendix we present the preliminary 235 MHz image of the relic obtained from very recent GMRT data. The source was observed on 2007, November 11th and 13rd, for a total integration time of \( \sim 18 \) hours. The observations were carried out in spectral line mode using only the USB for a total bandwidth of 8 MHz (128 channels, spectral resolution 62.5 kHz/channel). The data reduction was performed as described in Sec. 2.1.

The full resolution image shown in Fig. A.1 was produced using only the data from the first day (i.e., \( \sim 9 \) hours). The image has a very high sensitivity level (1\( \sigma = \)270 \( \mu \)Jy b\(^{-1} \)), and the relic is clearly detected and imaged in its whole extent. Given the high quality of this image we are confident that the flux density given in Tab. 4 is definitely reliable, with an error of the order of 5%. The analysis of the entire dataset (i.e., from the combination of the two observing days) will be presented in a forthcoming paper.
Fig. A.1. Preliminary GMRT image (contours and grey scale) of radio relic at 235 MHz. The resolution is 15.6′′ × 12.4′′, in p.a. 56. The noise level is 1σ = 270 µJ b⁻¹. Contours are spaced by a factor 2 starting from ±3σ.

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