An elusive radio halo in the merging cluster Abell 781?

T. Venturi,1⋆ G. Giacintucci,1,2 D. Dallacasa,1,3 G. Brunetti,1 R. Cassano,1,3 G. Macario1 and R. Athreya4

1INAF - Istituto di Radioastronomia, via P. Gobetti 101, I-40129 Bologna, Italy
2Department of Astronomy, University of Maryland, College Park, MD 20742–2421, USA
3Dipartimento di Astronomia, Università di Bologna, via Ranzani 1, I-40127 Bologna, Italy
4Indian Institute of Science Education and Research, Central Tower, Sai Trinity Building, Sutarwadi Road, Pashan, Pune 411021, India

Accepted 2011 April 1. Received 2011 March 31; in original form 2011 February 24

ABSTRACT
Deep radio observations of the galaxy cluster Abell 781 have been carried out using the Giant Metrewave Radio Telescope at 325 MHz and have been compared to previous 610-MHz observations and to archival Very Large Array (VLA) 1.4-GHz data. The radio emission from the cluster is dominated by a diffuse source located at the outskirts of the X-ray emission, which we tentatively classify as a radio relic. We detected residual diffuse emission at the cluster centre at the level of $S_{25MHL} \sim 15–20$ mJy. Our analysis disagrees with Govoni et al., and on the basis of simple spectral considerations, we do not support their claim of a radio halo with the flux density of 20–30 mJy at 1.4 GHz. Abell 781, a massive and merging cluster, is an intriguing case. Assuming that the residual emission is indicative of the presence of a radio halo barely detectable at our sensitivity level, it could be a very steep spectrum source.

Key words: radiation mechanisms: non-thermal – galaxies: clusters: general – galaxies: clusters: individual: Abell 781 – radio continuum: general.

1 INTRODUCTION
Cluster major mergers are among the most energetic phenomena in the Universe. They release a total energy of the order of $10^{63}–10^{64}$ erg, and it is nowadays accepted that they are the key ingredient to explain the origin and rarity of radio haloes in galaxy clusters: shocks and turbulence are generated during such energetic events and they deeply affect the thermal and non-thermal properties of the intracluster medium (ICM).

Radio haloes are the signposts of the non-thermal components in galaxy clusters. They are diffuse radio sources, whose size and morphology are similar to those of the underlying hot ICM (e.g. Ferrari et al. 2008; Cassano 2009; Venturi 2011, for recent reviews). Their spectrum (defined as $5 \propto \nu^{-\alpha}$) is steep, with typical values of the spectral index $\alpha$ in the range 1.2–1.4. However, recent high-sensitivity low-frequency imaging led to the discovery of radio haloes with much steeper spectra (Venturi 2011), with the spectral index $\alpha \sim 1.8–2$ [e.g. Abell 521, Brunetti et al. 2008, Dallacasa et al. 2009; Abell 697 (hereinafter A697) Macario et al. 2010].

Combined radio and X-ray studies provide strong support to the idea that radio haloes are found only in unrelaxed clusters. Buote (2001) first showed a correlation between the 1.4-GHz radio power of haloes, $P_{1.4\text{GHz}}$, and the dipole power ratio $P_{d}/P_{o}$ in the hosting cluster; based on Chandra temperature maps, Govoni et al. (2004) found evidence for the merging activity in clusters with radio haloes. Venturi et al. (2008, hereinafter V08) showed that all radio haloes in the Giant Metrewave Radio Telescope (GMRT) radio halo survey are located in clusters with signs of dynamical disturbances.

More recently, Cassano et al. (2010, hereinafter C10) carried out a quantitative analysis of the radio halo–cluster merger scenario. They used all clusters in the GMRT radio halo–cluster sample (Venturi et al. 2007, hereinafter V07; V08) with available high-quality Chandra images (a total of 32 clusters) to characterize the presence of substructures by three different methods. They showed that clusters with and without radio haloes are well segregated according to all parameters indicating substructure: radio haloes are associated with clusters currently undergoing a merger, while clusters without radio haloes are usually more ‘relaxed’. Four clusters, however, are notable outliers in the correlations, being disturbed systems with no detectable radio halo at the sensitivity limit of the 610-MHz GMRT survey (V07; V08). One of the outliers, Abell 781 (hereinafter A781), has been observed by us with the GMRT at 325 MHz in a low-frequency follow-up project of the GMRT radio halo survey (Venturi et al., in preparation). In this Letter, we report on our study on A781 and discuss the results in light of the scenario of the merger-induced formation of radio haloes.

We adopt the $\Lambda$ cold dark matter cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_{m} = 0.3$ and $\Omega_{\Lambda} = 0.7$. At the redshift of A781 ($z = 0.2984$), 1 arcsec $= 4.404$ kpc.

2 A781 AND ITS RADIO EMISSION
A781 (RA$\text{J2000} = 09^h 20^m 23^s.2$, Dec$\text{J2000} = +30^\circ 26' 15''$, $z = 0.2984$) is known to host a diffuse radio source to the south-east.
of its centre, tentatively classified as a relic on the basis of GMRT 610-MHz observations (V08).

The X-ray luminosity of the cluster, reported in the NORAS, is $L_{0.1–2.4\text{keV}} = 4.6 \times 10^{44} \text{ erg s}^{-1}$ (Böhringer et al. 2000). This value is three times lower than in the BCS catalogue (Ebeling et al. 1998, 2000) – our reference in the selection of the GMRT radio halo sample – and it is in line with measurements based on recent Chandra observations (Wittman et al. 2006; Maughan et al. 2008) and derived from a shallow ROSAT HRI exposure (S. Ettori, private communication). The X-ray brightness distribution is very complex, with multiple peaks in the central region and a secondary south-eastern condensation at $\sim 7$ arcmin, associated with the galaxy cluster CXOU J 092053+302800 located at $z = 0.291$ (Geller et al. 2005). The candidate radio relic is located at the border of the X-ray emission from A781, in the direction of CXOU J 092053+302800 (see fig. 5 in V08).

### 2.1 The radio observations

The cluster was observed with the GMRT at 325 MHz in 2007 January, as part of a project devoted to a low-frequency follow-up study of all radio haloes and relics belonging to the GMRT radio halo survey (Venturi et al., in preparation). The GMRT is excellent for imaging the diffuse extended emission in crowded fields, allowing for the accurate subtraction of individual sources to properly image diffuse large-scale emission.

A781 was observed for a total of 8 h, using the upper and lower side bands (USB and LSB, respectively), left-hand and right-hand polarization, for a total observing bandwidth of 32 MHz. The data were collected in the spectral-line mode with 128 channels per band, leading to a spectral resolution of 125 kHz per channel. The USB and LSB data sets were calibrated and reduced individually using the NRAO AIPS (Astronomical Image Processing System) package. Beyond the normal flagging of bad baselines, antennas and time ranges, a very accurate editing was carried out to identify and remove those data affected by radio frequency interference (RFI). The bandpass calibration was performed using the flux density calibrator (3C 147). Due to strong RFI in the LSB data set, only the upper portion of the band was used in the final imaging. Self-calibration and imaging were carried out using the same approach as described in Macario et al. (2010) for A697. We estimate that amplitude residual calibration errors are of the order of $\sim 8$ per cent.

We produced images in the resolution range $11.6 \times 9.2 \rightarrow 40 \times 37.0$ arcsec$^2$, with a $1\sigma$ noise $\sim 0.15–0.40$ mJy beam$^{-1}$ going from high to low resolution. We finally imaged the cluster at the resolution of $61.6 \times 51.9$ arcsec$^2$, reaching the noise of $1\sigma \sim 1$ mJy beam$^{-1}$.

### 2.2 The peripheral candidate relic

Fig. 1 shows the cluster radio emission at full and low resolution, overlaid on the optical and X-ray emission, respectively. Beyond the individual sources, labelled S1–S6 in the left-hand panel (all resolved at this resolution), the candidate relic is the most striking feature in the A781 field. As clear from Fig. 2, the source is much more extended at 325 MHz, compared to the 610-MHz image, with a largest angular size $\sim 2$ arcmin (i.e. $\sim 790$ kpc). Its radio brightness is peaked in the southernmost part of the source, which is also edge-brightened, in agreement with the 610-MHz images. The flux density at 325 MHz is $S_{325\text{MHz}} = 93.3 \pm 7.5$ mJy, fairly consistent at all resolutions. The corresponding radio power is $P_{325\text{MHz}} = 2.61 \times 10^{25}$ W Hz$^{-1}$. The flux density in the 610-MHz image does not increase even after integrating over the same extent imaged at 325 MHz. As mentioned in V08, the source is well visible on the NVSS at 1.4 GHz.

We looked into the NRAO VLA data archive in search for observations at higher frequencies. Two short observations exist: one at 1.477 GHz (C configuration, project AM469 observed on 1995 March 15) and the other at 1.398 GHz (D configuration, project AO48 observed on 1984 May 4). We reanalysed both data sets and the resulting L-band VLA images are shown in Fig. 3 overlaid on the 325-MHz cluster field. The flux density of the candidate relic is consistent with the measurement from the NVSS and amounts to $S_{1.4\text{GHz}} = 15.3 \pm 0.5$ mJy. The spectral index in the range 325 MHz–1.4 GHz is $\alpha = 1.25 \pm 0.06$. The 610-MHz flux density ($S_{610\text{MHz}} = 32 \pm 2$ mJy, V08) is slightly below the 325 MHz–1.4 GHz fit of the spectrum (by a factor of $\sim 20$ per cent). In V08, we discussed the
missing flux for the diffuse radio emission of the 610-MHz GMRT Radio Halo Survey, and the missing flux in A781 is within the limits of our analysis. We checked the flux density of the sources reported in Table 1 at 325 MHz, 610 MHz and 1.4 GHz (VLA-C array) using images of comparable resolution (of the order of 15 arcsec). The flux density at 610 MHz is slightly underestimated in all cases, while the 325-MHz flux density values agree within 1σ with those estimated from the Westerbork Northern Sky Survey (Rengelink et al. 1997) image. The spectral index between 325 MHz and 1.4 GHz is consistent with the nuclear emission from active galactic nuclei, that is, α_{1.4GHz}^{325MHz} in the range 0.6–0.8 except for source S5, which has α_{1.4GHz}^{325MHz} ≈ 1.4.

An accurate analysis to thoroughly correct the 610-MHz flux density values is, however, beyond the scope of this Letter, and we assume α_{1.4GHz}^{325MHz} = 1.25. We point out that this value is the average over the whole emission at 325 MHz, but the size of the emission at 1.4 GHz and 610 MHz is considerably smaller. The spectral index in the common portion of the emission is α_{1.4GHz}^{325MHz} ∼ 1, allowing for the difficulties in ‘isolating’ the 325-MHz flux density, while for the remaining part, we estimate a lower limit α_{1.4GHz}^{325MHz} < 2. Such sharp jump in the spectral index is intriguing, and it is worthy of further investigation.

The nature of this source remains uncertain. Its overall properties – morphology and linear size, location at the border of the X-ray emission in the direction of the secondary X-ray peak associated with CXOU J092053+302800, and the steep spectrum – coupled with the lack of an obvious optical counterpart suggest that it might be a cluster radio relic (see also V08). However, the uneven distribution of the spectral index and the southern edge brightening at all frequencies are fairly unusual for relics, and we cannot rule out other possibilities, such as a tailed radio source.

2.3 Radio emission from the central cluster region

We checked for a possible extension of the relic towards the centre of A781 and/or for a radio halo undetected at higher frequencies. We carried out flux density measurements over the inner ∼1.5 Mpc around the cluster centre on the low-resolution images (from 30 × 30 to 62 × 52 arcsec^2) and on a residual image obtained after the subtraction of the clean components associated with the individual radio sources (left-hand panel of Fig. 1 and Table 1). We imaged the ‘subtracted’ u–v data set using natural weighting to enhance any possible presence of diffuse emission. Our images are shown as the colour scale and contours in Fig. 4. The residual image (Fig. 4, right-hand panel) clearly shows that the relic extends towards the centre of A781, in the direction of the double source S6.

The flux density measured in a central region of ∼1.5 Mpc in diameter, estimated by subtracting the contribution of the individual sources (S4, S6 and the relic), does not appreciably change with the resolution and is of ∼15–20 mJy. Considering that the total flux density of S4, S6 and the relic is 379.4 mJy (see Table 1), the residual flux density is ∼5 per cent of this value. A similar value is found by integrating the residual image over the same 1.5-Mpc region. We thus consider this value an upper limit for the flux density of possible diffuse emission at the centre of A781, on a linear scale of the order of 1.5 Mpc.

The VLA L-band images we reanalysed (Fig. 3) are in agreement with our 325-MHz results. The different frequencies of the two observations do not allow an accurate subtraction of the individual sources from the VLA-C to the VLA-D data set, since spectral effects would result in the residual flux density from the individual sources subtracted in the 1.398-GHz VLA-D array image. Moreover, the flatter spectrum of the individual sources compared...
to diffuse cluster sources (see Section 2.2 and Table 1) makes the source subtraction at 1.4 GHz more critical than at lower frequencies. Hence, we simply compared the sum of the flux density of the individual sources S4, S6 and the relic to the total flux density of the L-band images by integrating over the whole area encompassing them. No difference is detected in either image, and in both cases the values agree within ≲2 per cent.

The results of our analysis disagree with Govoni et al. (2011), who recently claimed the detection of a radio halo (with flux 20–30 mJy at 1.4 GHz) using a conservative limit, $S_{325} \leq 20$ mJy, puts a conservative limit to the 1.4-GHz radio luminosity of the halo is still consistent with our $L_{1477} \sim 3 \times 10^{23}$ W Hz$^{-1}$ (where $S_{325}$ is the flux at 325 MHz in mJy).

### Table 1. GMRT 325-MHz flux density of the discrete radio sources and spectral properties.

| Source | RA$^a$ (h m s) | Dec.$^a$ (°′″) | $S_{\text{peak}}$ (mJy beam$^{-1}$) | $S_{\text{tot}}$ (mJy) | $\alpha_{325}^{1477}$ |
|--------|---------------|----------------|-----------------------------------|----------------------|---------------------|
| S1     | 09 20 01.6    | +30 34 06      | 27.3 ± 2.2                        | 73.7 ± 5.9           | 0.75                |
| S2     | 09 20 08.3    | +30 21 15      | 17.2 ± 1.4                        | 41.6 ± 3.3           | 0.58                |
| S3     | 09 20 07.9    | +30 29 51      | 5.3 ± 0.4                         | 23.2 ± 1.9           | -                   |
| S4     | 09 20 14.1    | +30 29 01      | 23.8 ± 1.9                        | 50.8 ± 4.1           | 0.77                |
| S5     | 09 20 22.1    | +30 32 25      | 8.9 ± 0.7                         | 16.6 ± 1.3           | 1.41                |
| S6     | 09 20 22.7    | +30 29 47      | 77.8 ± 6.2                        | 225.3 ± 18.0         | 0.77                |
| Relic  | 09 20 31.2    | +30 27 35      | 5.7 ± 0.4                         | 93.3 ± 7.5           | See text            |

Note. Flux density values taken from the image shown in the left-hand panels of Figs 1 and 4 (11.6 × 9.2 arcsec$^2$) after the primary beam correction. $^a$Coordinates of the radio peak. $^b$Total flux density measured using the AIPS task TVSTAT. $^c$Spectral index derived from flux density measurements at the resolutions of 17 × 11 arcsec$^2$ at 325 MHz and 16 × 13 arcsec$^2$ at 1477.40 MHz.

### Figure 4. Left-hand panel: GMRT 325-MHz image of A781 at the resolution of 40 × 37 arcsec$^2$, PA = 12°6 (blue scale) with 11.6 × 9.2-arcsec$^2$ contours overplotted. Contours are spaced by a factor of 2, starting from ±0.45 mJy beam$^{-1}$. Right-hand panel: GMRT 325-MHz residual image at the resolution of 30 × 30 arcsec$^2$ with contours overlaid. Contours start from ±0.5 mJy beam$^{-1}$ ($\sim$2$\sigma$) and are spaced by a factor of 2.

## 3 IS THERE A RADIO HALO IN A781?

A statistical connection between the dynamical state of massive clusters in the GMRT sample (V07; V08) and the presence of radio haloes has been derived by C10, confirming the picture where mergers switch-on radio haloes in galaxy clusters. A781 is one of the few outliers in the C10 diagrams, lying in the region of dynamically disturbed clusters, but with no detected radio halo at 610 MHz (V08).

The observations at 325 MHz presented in this Letter do not allow for a firm detection of a radio halo in the central region (~1.5 Mpc) of A781. If we consider a spectral index $\alpha \sim 1.3$ between 325 and 1400 MHz, the residual diffuse emission measured in our images, $S_{325\text{MHz}} \sim 20$ mJy, puts a conservative limit to the 1.4-GHz luminosity of a halo in A781, $P_{1.4\text{GHz}} \leq 6 \times (S_{325\text{MHz}}) \times 10^{23}$ W Hz$^{-1}$ (where $S_{325}$ is the flux at 325 MHz in mJy).

Our results do not challenge the cluster merger–radio halo connection. On the basis of the $P_{1.4\text{GHz}}$–$L_X$ correlation, the expected 1.4-GHz radio luminosity of the halo is still consistent with our upper limit. As a matter of fact, the four known radio haloes with radio power ~10$^{23}$ W Hz$^{-1}$ hosted in clusters with the X-ray luminosity $L_X \leq 5 \times 10^{44}$ erg s$^{-1}$ (i.e. A2255, A2256, Coma and A754) are only detected at low redshift, $z \leq 0.1$. On the other hand, if we assume the 1.4-GHz luminosity recently claimed by Govoni et al. (2011), the halo would lie about an order of magnitude above...
An elusive radio halo in A781?

4 SUMMARY AND CONCLUSIONS

We have presented deep GMRT 325-MHz observations of the unrelaxed and luminous cluster A781, which is a notable outlier in the quantitative correlations connecting cluster mergers and the presence of a radio halo (C10). Our images show that the peripheral diffuse source is the dominant radio feature of the cluster and only residual emission at the level of \( S_{325\,\text{MHz}} \sim 15\text{--}20\,\text{mJy} \) is found in a region of \( \sim 1.5\,\text{Mpc} \) around the cluster centre (implying a conservative flux density limit of \( S_{325\,\text{MHz}} \sim 30\text{--}40\,\text{mJy} \)). This value improves the upper limit given in Govoni et al. (2011) by almost a factor of 5, and rules out their claim of a detection of a radio halo at 1.4 GHz on the basis of simple spectral considerations.

With our data we cannot confirm the presence of a radio halo at the centre of A781. If the 325-MHz residual emission is real, then it might trace an underlying halo with a steep spectrum. Future high-sensitivity observations at lower frequencies combined with deeper observations at 610 MHz will allow us to clarify the nature of the residual emission.

ACKNOWLEDGMENTS

We thank S. Ettori for his help in the X-ray checks. The GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research. Partial support was provided by Chandra grant AR0-11017X, NASA contract NAS8-39073 and the Smithsonian Institution. SG acknowledges support by NASA through Einstein Postdoctoral Fellowship PF0-110071 awarded by the Chandra X-ray Center which is operated by the Smithsonian Astrophysical Observatory under contract NAS8–03060. This work is partially supported by the INAF and ASI-INAF under grants PRIN–INAF2007, PRIN–INAF2008 and I/088/06/0.

REFERENCES

Bohringer H. et al., 2000, ApJS, 129, 435
Brunetti G. et al., 2007, ApJ, 670, L5
Brunetti G. et al., 2008, Nat, 455, 944
Buote D. A., 2001, ApJ, 553, L15
Cassano R., 2009, in Saikia D. J., Green D., Gupta Y., Venturi T., eds, ASP Conf. Ser. Vol. 407, The Low Frequency Radio Universe. Astron. Soc. Pac., San Francisco, p. 223
Cassano R., Brunetti G., Setti G., 2006, MNRAS, 369, 1577
Cassano R. et al., 2010, ApJ, 721, L82 (C10)
Dallacasa D. et al., 2009, ApJ, 699, 1288
Ebeling H. et al., 1998, MNRAS, 301, 881
Ebeling H. et al., 2000, MNRAS, 318, 333
Ferrari C. et al., 2008, Space Sci. Rev., 134, 93
Geller M. J. et al., 2005, ApJ, 635, L125
Govoni F. et al., 2004, ApJ, 605, 695
Govoni F. et al., 2011, A&A, 529, 69
Macario G. et al., 2010, A&A, 517, 43
Maughan B. J. et al., 2008, ApJS, 174, 117
Rengelink R. B. et al., 1997, A&AS, 124, 259
Venturi T., 2011, in Ferrari C., Bruggen M., Brunetti G., Venturi T., eds, Non-thermal Phenomena in Colliding Galaxy Clusters. Mem. Soc. Astron. Ital., Vol. 82, preprint (arXiv:1102.1572)
Venturi T. et al., 2007, A&A, 463, 937 (V07)
Venturi T. et al., 2008, A&A, 484, 327 (V08)
Wittman D. et al., 2006, ApJ, 643, 128

This paper has been typeset from a \( \LaTeX \) file prepared by the author.