Diffuse radio emission in MACS J1752.0+4440

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ABSTRACT

We report the discovery of large-scale diffuse radio emission in the galaxy cluster MACS J1752.0+4440 (z = 0.366). Using Westerbork Synthesis Radio Telescope (WSRT) observations we find that the cluster hosts a double radio relic system as well as a 1.65 Mpc radio halo covering the region between the two relics. The relics are diametrically located on opposite sides of the cluster center. The NE and SW relics have sizes of 1.3 and 0.9 Mpc, respectively. In case of an isolated binary merger event, the relative sizes of the relics suggest a mass ratio about 2 : 1. We measure integrated spectra of $-1.16 \pm 0.03$ for the NE and $-1.10 \pm 0.05$ for the SW relic. We conclude that this cluster has undergone a violent binary merger event and the relics are best explained by particles (re)accelerated in outwards traveling shock waves. The spectral indices suggest the relics trace shock waves with Mach numbers ($M$) of around 3.5 to 4.5. These relatively high Mach numbers derived from the radio spectral index are comparable to those derived for a few other recently discovered relics. This implies that merger shocks with $M > 3$ are relatively common in cluster outskirts if our understanding of diffusive shock acceleration is correct.

Key words: radio continuum: general – galaxies: clusters: individual: MACS J1752.0+4440 – cosmology: large-scale structure of Universe

1 INTRODUCTION

Giant radio relics are extended radio sources found in the outskirts of disturbed galaxy clusters. Particularly interesting are so-called double radio relics which are found on opposite sides of the cluster center and are believed to trace two shock waves created in the intracluster medium (ICM) during a binary merger event. In the case of advantageous inclination with respect to our line of sight the location of the relics makes it possible to directly constrain the merger geometry and together with modeling can be used to derive the mass ratio and impact parameter of the merger event (Roettiger et al. 1999; van Weeren et al. 2011).

Shock waves in galaxy clusters are proposed sites for particle acceleration, for example via the diffusive shock acceleration (DSA) mechanism (Drury 1983; Blandford & Eichler 1987; Jones & Ellison 1991). However, the efficiency with which collisionless shocks can accelerate particles might not be high enough to produce the observed radio brightness (e.g., Macario et al. 2011). The diffusive shock acceleration may be aided by the presence of relativistic particles in the upstream plasma (e.g., Markevitch et al. 2005; Giacintucci et al. 2008; Kang & Ryu 2011). Relics are expected to be preferably found in cluster outskirts because the kinetic energy dissipated in merger shocks peaks at a distance of about 1 Mpc from the cluster center (Vazza et al. 2012).

Radio halos are another class of diffuse extended radio sources found in merging clusters (e.g., Cassano et al. 2010). They have Mpc-sizes and are centrally located. Halos have been explained by in-situ acceleration of particles through merger generated turbu-
lence (Brunetti et al. 2001; Petrosian 2001) or by secondary electrons which are continuously injected into the ICM by inelastic collisions between relativistic and thermal protons (Dennison 1980; Blasi & Colafrancesco 1999; Dolag & Enßlin 2000). Secondary electrons show a bimodal distribution in the radio spectrum at higher-frequencies (e.g., fig. 1 in Cassano et al. 2010a). Recent LOFAR observations revealed that the radio spectrum of the radio halos (Brunetti et al. 2008), and so far no Gamma ray emission has been detected by the Fermi satellite at the levels expected (Jeltema & Profumo 2011). Clusters also show a bimodal distribution in the $P_{\nu} \propto \nu^{-\alpha}$–$L_X$ diagram, with only a minority of clusters hosting halos (Brunetti et al. 2009). However, Enßlin et al. (2011) claim that cosmic ray (CR) transport in clusters can also induce the radio bimodality as merging clusters should have a much more centrally concentrated CR population than relaxed ones, resulting in higher synchrotron emissivities. Basic turbulent re-acceleration models predict steepening of the radio spectrum at higher-frequencies (e.g., fig. 1 in Cassano et al. 2010a). Recent LOFAR observations revealed that the radio spectrum of the Abell 2256 radio steeps at low frequencies. This unexpected result shows that the formation process of halos might be more complex than previously thought (van Weeren et al. 2012).

Although more than 30 relics have been found, they are mostly located in clusters at $z \lesssim 0.3$, while based on simulations more relics at larger redshift are expected (Nuza et al. 2012). According to Nuza et al. (2012), the fraction of relics in X-ray selected cluster samples as function of redshift gives a powerful tool to constrain the evolution of magnetic fields and particle acceleration in the ICM. The few known $z > 0.3$ relics are MACS J0717.5+3745 (Edge et al. 2003; Bonafede et al. 2007; van Weeren et al. 2009), PLCK G287.0+32.9 (Bagchi et al. 2011; Planck Collaboration et al. 2011) and CL1446+26 (Giovannini et al. 2009). The extreme merger event of MACS J0717.5+3745 has been studied extensively (LaRoge et al. 2003; Ebeling et al. 2004; Kartaltepe et al. 2008; Ma et al. 2008, 2009; Zitrin et al. 2009; Ma & Ebeling 2011; Limousin et al. 2011), but the systems complexity also makes the interpretation of the results more difficult.

We embarked on a search for less complex, but still massive merging clusters in the MACS sample of X-ray luminous clusters at $z > 0.3$ (Ebeling et al. 2003; Mann & Ebeling 2012). A candidate for a $z > 0.3$ double relic system was reported by Edge et al. (2003) in MACS J1752.0+4440 with two radio sources found on opposite sides of the cluster center in NRAO VLA Sky Survey (NVSS, Condon et al. 1998) and Westerbork Northern Sky Survey (WENSS, Rengelink et al. 1997) images. Here we present WSRT and archival Very Large Array (VLA) observations of this cluster.

In Sect. 2 we report on the radio observations and data reduction. The results are presented in Sect. 3. We end with a discussion and summary in Sects. 4 and 5. Throughout this paper we assume a ΛCDM cosmology with $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$, and $\Omega_{\Lambda} = 0.73$. At the redshift of MACS J1752.0+4440 ($z = 0.366$) 1″ corresponds to 5 kpc. All images are in the J2000 coordinate system.

### 2 OBSERVATIONS

MACS J1752.0+4440 was observed with the WSRT in the L-band at 25, 21, 18 cm and in the S-band at 13 cm, see Table 1 for an overview. The data were calibrated with CASA. As a first step we removed time ranges affected by shadowing. Radio frequency interference (RFI) was flagged with the AOFlagger from Offringa et al. (2010). The data were corrected for the bandpass response and gain solutions were determined for the calibrator sources and transferred to the target source. The $\chi^2$-values for the calibrator sources were set by the Perley & Taylor (1999) extension to the Baars et al. (1977) scale. The data were further self-calibrated in the NRAO Astronomical Image Processing System (AIPS) package. Images were cleaned with manually placed clean boxes and corrected for the primary beam attenuation.

Archival VLA L-band B-array observations (project AE147; July 7, 2002) were obtained from the NRAO VLA Archive Survey (NVAS). From these data we created an image with a resolution of 5.1″ × 4.5″ (robust 1.0 weighting) and a noise of 28 µJy beam$^{-1}$. The resolution and noise levels for the WSRT images are reported in Table 1.

### 3 RESULTS

MACSJ1752.0+4440 was identified as a cluster at $z = 0.366$ by Edge et al. (2003) based on its detection in the ROSAT All-Sky Survey (RASS, Voges et al. 1999). At $L_X, 0.1–2.4$ keV = $8.2 \times 10^{44}$ erg s$^{-1}$, MACS J1752.0+4440 is one of the most X-ray luminous clusters known at $z > 0.3$. And SDSS image is shown in Fig. 1 (Abazajian et al. 2009). The WSRT 18 cm image reveals two arc-like radio sources on opposite sides of the cluster center (Fig. 1). Additional faint diffuse emission is present between these two sources. In the 21 and 25 cm WSRT images we also detect this low surface brightness emission, although with a lower signal to noise ratio (SNR), see Fig. 2. The brighter arc-like sources are also detected in VLA 1.4 GHz B-array and WSRT 13 cm images.

#### Table 1. WSRT observations

| Beam size | Total on-source time | Rms noise ($\sigma_{\text{rms}}$) | Robust weighting |
|-----------|----------------------|-------------------------------|-----------------|
| 28.9″ × 16.6″ | 10 hr | 35 $\mu$Jy beam$^{-1}$ | 1.0 |
| 27.1″ × 17.0″ | 12 hr | 26 $\mu$Jy beam$^{-1}$ | 1.0 |
| 17.3″ × 11.8″, 23.5″ × 15.9″ | 24 hr | 16, 18 $\mu$Jy beam$^{-1}$ | 0.0, 3.0 |
| 12.7″ × 8.9″ | 24 hr | 23 $\mu$Jy beam$^{-1}$ | 0.0 |

| Observation dates | Bandwidth, # channels per subband | 25 cm | 21 cm | 18 cm | 13 cm |
|-------------------|-----------------------------------|-------|-------|-------|-------|
| November 10, 2011 | 8 × 20 MHz, 64 | 8 × 20 MHz, 64 | 8 × 20 MHz, 64 | 8 × 20 MHz, 64 |
| 7 & 12 March, 2011 | 8 × 20 MHz, 64 | 8 × 20 MHz, 64 | 8 × 20 MHz, 64 | 8 × 20 MHz, 64 |
| May 23 & June 16, 2011 | 10 hr | 12 hr | 24 hr | 24 hr |
| July 5 & 6, 2011 | 10 hr | 12 hr | 24 hr | 24 hr |

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Figure 1. Left: WSRT 18 cm image. High-resolution image made with robust = 0 weighting. Red contour levels are drawn at $[1, 2, 4, \ldots] \times 3\sigma_{\text{rms}}$. Negative $-3\sigma_{\text{rms}}$ contours are shown by the dotted lines. Blue contours drawn at $54\mu\text{Jy beam}^{-1}$ are from a lower resolution image made with robust = 3 weighting to enhance diffuse emission. Right: SDSS DR7 color image ($g, r,$ and $i$ bands) of the cluster center overlaid with VLA radio contours. Contour levels are drawn at $[1, 2, 4, \ldots] \times 3\sigma_{\text{rms}}$. (Figs. 1 and 2). An XMM-Newton image (Fig. 2) reveals a disturbed and elongated ICM. Ebeling et al. will present an analysis of these X-ray observations.

There is a faint optical object (probably a galaxy) visible in the SDSS image about 5′′ to the south of a foreground star, at the center of the SW arc-like radio source. However, it is unlikely that the SW radio source can be classified as a radio galaxy because there is no compact radio core visible, which is expected for an active AGN. We classify the two arc-like sources as a double radio relic system because of (i) their morphology and sizes, (ii) location with respect to the cluster center, (iii) location along the merger axis, and (iv) perpendicular orientation with respect to the merger axis.

The NE and SW relics feature extents of 1.3 and 0.9 Mpc, respectively (Table 2). The relics have well defined sharp outer edges, while their surface brightness drops somewhat more gradually towards the cluster center, as is seen for most double radio relics. The NE relic is composed of two linear filaments. Across the length of the NE relic the emission fades more slowly towards the north than at the relic’s southern end.

The diffuse emission between the radio relics is classified as a 1.65 Mpc extended radio halo because the radio emission follows the X-ray emission from the ICM. Interestingly, a faint EW elongated smudge of emission is visible at the northern end of the radio halo, see Fig. 1. It could be a fainter radio relic but this is somewhat speculative as the feature has a low-surface brightness.

The flux densities for the two relics and radio halo are reported in Table 2. The two brightest compact sources between the two relics are probably AGN in the cluster, based on the colors of their optical counterparts visible in the SDSS image. They are slightly extended ($\sim 10 – 15''$) in the VLA-B array image. We obtained the integrated flux density of the halo from the 18 cm data as the halo is most clearly visible in this band (due to the longer integration time). We first subtracted the flux contribution from compact sources by creating a high-resolution image using uniform weighting and an inner uv-range cut of 200 m. The found clean components were subtracted from the uv-data and then we re-imaged the data with natural weighting. The halo flux density was calculated by summing over the entire area between the two relics. This have a flux density of $11.4 \pm 1.1$ mJy, corresponding to a 1.4 GHz radio halo luminosity $P_{1.4\text{GHz}} = 9.5 \times 10^{24}$ W Hz$^{-1}$ (assuming a spectral index of $-1.1$). The halo linear size and radio power are in agreement with the distribution presented in Giovannini et al. (2008). The X-ray luminosity and radio power are consistent with the $L_X - P_{1.4\text{GHz}}$ correlation for radio halos (e.g., Liang et al. 2000; Ewall-Wice & Röttgering 2002; Cassano et al. 2006, 2007; Brunetti et al. 2008; Murgia et al. 2009; Feretti et al. 2012). Although the halo is also detected in the 21 and 25 cm images, the SNR is too low and frequency span too small to obtain a useful spectral index estimate.

Integrated flux density measurements for the radio relics, from the WSRT, NVSS and WENSS images, are displayed in Fig. 3. A power-law fit through the measurements is also shown. This gives $\alpha = -1.16 \pm 0.03$ and $\alpha = -1.10 \pm 0.05$ for the NE and SW relic, respectively. The radio spectra appear to be straight over the observed frequency range.

4 DISCUSSION

In the linear test particle regime for DSA, the injection radio spectral index ($\alpha_{\text{inj}}$) is related to the Mach number ($M$) of a shock
We can thus assume the spectral index that is about 0.5 units steeper than the power-law, with a time, and the age of the relic is larger than the electron cooling time, if there are Mach number variations in the shock (since the radio luminosity strongly increases with Mach number, e.g., Hoeft & Brüggen 2007). Recent X-ray observations did reveal a $M > 3$ shock, corresponding to the relic in CIZA J2242.8+5301 (Ogrean et al. 2012; Akamatsu & Kawahara 2011). For MACS J1752.0+4440, a next step will be to directly measure $\alpha_{\text{inj}}$ at the front of the relic from a spectral index map. This requires additional observations which are currently obtained and the resulting spectral and polarization study will be presented in a forthcoming paper (Bonafede et al., MNRAS, submitted).

The presence of a radio halo in MACS J1752.0+4440 provides support for the hypothesis that halos are related to cluster merger events. It also indicates that while the main shock waves from the merger are already located in the cluster outskirts, particle acceleration is still ongoing in the central parts of the cluster, as expected for the turbulent re-acceleration model.

The XMM image (Fig. 2) suggests the cluster is undergoing a roughly equal mass binary merger event along in the NE-SW direction. The relative size of the two relics also gives an indication of the mass ratio of the merger event, while the brightness distribution along the length of the relics is related to the impact parameter. Taking the results from the simulations presented in van Weeren et al. (2011), this suggest a mass ratio about 2 : 1 and an impact parameter about 4 times the core-radius of the largest subcluster. These are very rough estimates though and the uncertainties are difficult to quantify. Moreover these simulations only hold under the assumptions of an isolated clean binary merger event (without any extra substructures). New simulations, in combination with X-ray and lensing analyses, are needed to produce a more detailed merger scenario.

5 SUMMARY

We reported the presence of a double radio relic system and radio halo in the X-ray luminous galaxy cluster MACS J1752.0+4440 at $z = 0.366$. This cluster is undergoing a binary cluster merger event, with the merger axis roughly located within the plane of the sky. For the radio halo we find a luminosity of $P_{1.4\text{GHz}} = 9.5 \times 10^{25} \text{ W Hz}^{-1}$ and a total extent of 1.65 Mpc. The relics have sizes of about 0.9 and 1.3 Mpc. The integrated spectral indices of

\[ \alpha_{\text{inj}} = \frac{1}{2} - \frac{M_2^2 + 1}{M_2^2 - 1}. \]
the relics are indicative of strong shock waves with $M > 3$, as is for the case for other recently discovered relics. This suggests that $M > 3$ shocks are not uncommon in the outskirts of merging clusters.

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REFERENCES

Abazajian K. N. et al., 2009, ApJS, 182, 543
Akamatsu H., Kawahara H., 2011, ArXiv e-prints
Baars J. W. M., Genzel R., Pauliny-Toth I. I. K., Witzel A., 1977, A&A, 61, 99
Bagchi J. et al., 2011, ApJ, 736, L8+
Blandford R., Eichler D., 1987, Phys. Rep., 154, 1
Blasi P., Colafrancesco S., 1999, Astroparticle Physics, 12, 169
Bonafede A. et al., 2009, A&A, 503, 707
Brunetti G., Cassano R., Dolag K., Setti G., 2009, A&A, 507, 661
Brunetti G. et al., 2008, Nature, 455, 944
Brunetti G., Setti G., Feretti L., Giovannini G., 2001, MNRAS, 320, 365
Brunetti G., Venturi T., Dallacasa D., Cassano R., Dolag K., Giacintucci S., Setti G., 2007, ApJ, 670, L5
Cassano R., Brunetti G., Röttgering H. J. A., Brüggen M., 2010a, A&A, 509, A68+
Cassano R., Brunetti G., Setti G., 2006, MNRAS, 369, 1577
Cassano R., Brunetti G., Setti G., Govoni F., Dolag K., 2007, MNRAS, 378, 1565
Cassano R., Ettori S., Giacintucci S., Brunetti G., Markevitch M., Venturi T., Gitti M., 2010b, ApJ, 721, L82
Condon J. J., Cotton W. D., Greisen E. W., Yin Q. F., Perley R. A., Taylor G. B., Broderick J. J., 1998, AJ, 115, 1693
Dennison B., 1980, ApJ, 239, L93
Dolag K., Enßlin T. A., 2000, A&A, 362, 151
Drury L. O., 1983, Reports on Progress in Physics, 46, 973
Ebeling H., Barrett E., Donovan D., 2004, ApJ, 609, L49
Ebeling H., Edge A. C., Henry J. P., 2001, ApJ, 553, 668
Ebeling et al., 2012, in preparation
Edge A. C., Ebeling H., Bremer M., Röttgering H., van Haarlem M. P., Rengelink R., Courtney N. J. D., 2003, MNRAS, 339, 913
Enßlin T., Pfrommer C., Miniati F., Subramanian K., 2011, A&A, 527, A99+
Enßlin T. A., Röttgering H., 2002, A&A, 396, 83
Feretti L., Giovannini G., Govoni F., Murgia M., 2012, ArXiv e-prints
Giacintucci S. et al., 2008, A&A, 486, 347
Giovannini G., Bonafede A., Feretti L., Govoni F., Murgia M., Ferrari F., Monti G., 2009, A&A, 507, 1257
Hoefl M., Brüggen M., 2007, MNRAS, 375, 77
Jaffe W. J., 1977, ApJ, 212, 1
Jeltema T. E., Profumo S., 2011, ApJ, 728, 53
Jones F. C., Ellison D. C., 1991, Space Science Reviews, 58, 259
Kang H., Ryu D., 2011, ApJ, 734, 18
Kardashev N. S., 1962, Soviet Astronomy, 6, 317
Kartaltepe J. S., Ebeling H., Ma C. J., Donovan D., 2008, MNRAS, 389, 1240
LaRoque S. J. et al., 2003, ApJ, 583, 559
Liang H., Hunstead R. W., Birkinshaw M., Andreani P., 2000, ApJ, 544, 686
Limousin M. et al., 2011, ArXiv e-prints
Ma C., Ebeling H., Barrett E., 2009, ApJ, 693, L56
Ma C.-J., Ebeling H., 2011, MNRAS, 410, 2593
Ma C.-J., Ebeling H., Donovan D., Barrett E., 2008, ApJ, 684, 160
Macario G., Markevitch M., Giacintucci S., Brunetti G., Venturi T., Murray S. S., 2011, ApJ, 728, 82
Mann A. W., Ebeling H., 2012, MNRAS, 420, 2120
Markevitch M., Govoni F., Brunetti G., Jobitz R., 2005, ApJ, 627, 733
Murgia M., Govoni F., Markevitch M., Feretti L., Giovannini G., Taylor G. B., Carretti E., 2009, A&A, 499, 679
Nuzza S. E., Hoefl M., van Weeren R. J., Gottlöber S., Yepes G., 2012, MNRAS, 420, 2006
Offringa A. R., de Bruyn A. G., Biehl M., Zaroubi S., Bernardi G., Pandey V. N., 2010, MNRAS, 405, 155
Ogrec G., Brüggen M., Röttgering H., Simionescu A., Croston J., van Weeren R., Hoefl M., 2012, ArXiv e-prints
Perley R. T., Taylor G. B., 1999, VLA Calibrator Manual. Tech. rep., NRAO
Petrosian V., 2001, ApJ, 557, 560
Planck Collaboration et al., 2011, A&A, 536, A8
Rengelink R. B., Tang Y., de Bruyn A. G., Miley G. K., Bremer M. N., Röttgering H. J. A., Bremer M. A. R., 1997, A&AS, 124, 259
Roettiger K., Burns J. O., Stone J. M., 1999, ApJ, 518, 603

Figure 3. NVSS, WENSS and WSRT flux density measurements for the NE and SW relics. Power-law fits through these measurements are also shown.
van Weeren R. J., 2011, PhD thesis, Leiden Observatory, The Netherlands
van Weeren R. J., Brüggen M., Röttgering H. J. A., Hoeft M., 2011, MNRAS, 418, 230
van Weeren R. J., Röttgering H. J. A., Brüggen M., Cohen A., 2009, A&A, 505, 991
van Weeren R. J., Röttgering H. J. A., Brüggen M., Hoeft M., 2010, Science, 330, 347
van Weeren R. J. et al., 2012, ArXiv e-prints
Vazza F., Brüggen M., van Weeren R., Bonafede A., Dolag K., Brunetti G., 2012, MNRAS, 421, 1868
Vazza F., Brunetti G., Gheller C., Brunino R., 2010, New Astronomy, 15, 695
Vazza F., Brunetti G., Kritsuk A., Wagner R., Gheller C., Norman M., 2009, A&A, 504, 33
Voges W., Aschenbach B., Boller T., Bräuninger H., Briel U., Burkert W., Dennerl K., et al., 1999, A&A, 349, 389
Zitrin A., Broadhurst T., Rephaeli Y., Sadeh S., 2009, ApJ, 707, L102

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