DEEP 1.4 GHz FOLLOW-UP-OF THE STEEP SPECTRUM RADIO HALO IN A521

D. Dallacasa1, G. Brunetti2, S. Giacintucci3, R. Cassano2, T. Venturi2, G. Macario1,2, N. E. Kassim4, W. Lane4, and G. Setti1,2

1 Dipartimento di Astronomia, Università di Bologna, via Ranzani 1, I-40127 Bologna, Italy
2 INAF-Istituto di Radioastronomia, via Gobetti 101, I-40129 Bologna, Italy
3 Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
4 Naval Research Laboratory, Code 7213, Washington, DC 20375-5320, USA

Received 2009 March 20; accepted 2009 May 7; published 2009 June 19

ABSTRACT

In a recent paper, we reported on the discovery of a radio halo with very steep spectrum in the merging galaxy cluster A521 through observations with the Giant Metrewave Radio Telescope. We showed that the steep spectrum of the halo is inconsistent with a secondary origin of the relativistic electrons and supports a turbulent acceleration scenario. At that time, due to the steep spectrum, the available observations at 1.4 GHz (archival NRAO–Very Large Array–VLA–CnB-configuration data) were not adequate to accurately determine the flux density associated with the radio halo. In this paper, we report the detection at 1.4 GHz of the radio halo in A521 using deep VLA observations in the D configuration. We use these new data to confirm the steep spectrum of the object. We consider A521 the prototype of a population of very steep spectrum halos. This population is predicted assuming that turbulence plays an important role in the acceleration of relativistic particles in galaxy clusters, and we expect it will be unveiled by future surveys at low frequencies with the LOFAR and LWA radio telescopes.

Key words: acceleration of particles – galaxies: clusters: individual (A521) – radiation mechanisms: non-thermal – radio continuum: general

1. INTRODUCTION

Galaxy clusters are the largest virialized structures in the universe. They contain about $10^{15} M_\odot$ in the form of hot gas, galaxies, dark matter, and nonthermal components. The latter, such as magnetic fields and high-energy particles, may play key roles by controlling transport processes in the intergalactic medium (IGM) and are sources of additional pressure and energy support (Ryu et al. 2003; Schekochihin et al. 2005; Lazarian 2006).

The origin of the nonthermal particles is likely connected with the cluster formation process. A fraction of the energy is dissipated in the form of shocks and turbulence during cluster mergers. The accretion of matter may be channeled into the acceleration of particles, thus leading to a complex population of nonthermal primary particles in the IGM producing synchrotron and inverse Compton (IC) radiation (Roettiger et al. 1999; Sarazin 1999; Ryu et al. 2003; Brunetti et al. 2004; Brunetti & Lazarian 2007; Hoeft & Brüggen 2007; Pfrommer et al. 2008). Relativistic protons are expected to be the dominant nonthermal particle component (e.g., Blasi et al. 2007); collisions between relativistic and thermal protons in the IGM inject secondary electrons and neutral pions that can also produce synchrotron (plus inverse Compton) and gamma-ray emission, respectively (Voelk et al. 1996; Berezinsky et al. 1997; Blasi & Colafrancesco 1999; Pfrommer & Ensslin 2004; Brunetti & Blasi 2005).

The most prominent examples of nonthermal activity in galaxy clusters are giant radio halos. They are low surface brightness, Mpc-scale diffuse sources of synchrotron radiation produced by relativistic electrons moving into $\mu G$ magnetic fields, which are frozen in the hot cluster gas (e.g., Feretti 2003). Two main mechanisms may account for the relativistic electrons emitting the observed radiation: either injection of secondary electrons by collisions between relativistic and thermal protons in the IGM (Dennison 1980; Blasi & Colafrancesco 1999), or in situ acceleration of relativistic electrons by shocks and turbulence generated during cluster mergers (Brunetti et al. 2001; Petrosian 2001).

Recent observations of radio halos suggest that magnetohydrodynamics (MHD) turbulence, injected during cluster mergers, may play an important role in the process of particle acceleration (e.g., reviews by Brunetti 2008; Ferrari et al. 2008; Cassano 2009). Spectral studies are extremely important to address this issue: the detection of radio halos with very steep spectrum, $\alpha > 1.5 (S \propto \nu^{-\alpha})$, supports stochastic particle acceleration (e.g., due to MHD turbulence) and disfavors a secondary origin of the electrons, due to the large proton-energy budget that this scenario requires (Brunetti 2004).

In a recent paper, we reported on the discovery of a radio halo with very steep synchrotron spectrum, $\alpha \approx 2$, associated with the merging galaxy cluster A521 (Brunetti et al. 2008).

In this paper, we report on 1.4 GHz follow-up deep observation of the radio halo in A521 with the VLA5 in the D configuration. We successfully detected the radio halo and derived the overall spectrum between 240 MHz and 1.4 GHz. In Section 2, we report on these new observations, in Section 3 we discuss the results, while in Section 4 we give our conclusions.

A $\Lambda$CDM concordance model with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ is used.

2. A521

A521 is an X-ray luminous ($8.2 \times 10^{44}$ erg s$^{-1}$ in the band 0.1–2.4 keV) and massive ($\approx 2 \times 10^{15} M_\odot$) galaxy cluster at $z = 0.247$ with ongoing multiple merging episodes (Arnaud et al. 2000; Ferrari et al. 2003). A radio relic is located on the southeastern boundary of the cluster (Ferrari et al. 2006; Giacintucci et al. 2006) and is found to coincide with a possible

---

5 The VLA is operated by the National Radio Astronomy Observatories, which is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.
shock front, generated by the recent infall of a subcluster along the northwest/southeast direction, where relativistic electrons are currently accelerated (Giacintucci et al. 2008).

Brunetti et al. (2008) reported on the detection of a Mpc-scale radio halo with the Giant Metrewave Radio Telescope (GMRT) at 240, 330, and 610 MHz.

The halo has an angular size of about 4′ with a rather smooth brightness distribution. Available archival VLA observations at 1.4 GHz in the BnC configuration (project AF390), re-analyzed in Brunetti et al. (2008), lacked both the sensitivity and the short baseline coverage to reliably detect the halo, and prevented us from a proper flux density measurement. Therefore, only an upper limit on the total flux density could be placed. The observed integrated radio spectrum has been found very steep, $\alpha = 2$ (Brunetti et al. 2008). We observed A521 at 1.4 GHz with the VLA in the D configuration whose short spacings are well suited to study the halo and match those provided by the GMRT at 240 MHz, allowing a reliable measurement of the spectral index.

3. OBSERVATIONS AT 1.4 GHz

We observed A521 on 2008 August 24, with the VLA in the D configuration for a total time on source of about 5.5 hr. Observations were made using a multichannel continuum mode to permit radio frequency interference (RFI) excision and prevent bandwidth smearing of field sources. Seven 6.25 MHz channels were combined to create an effective bandwidth of 43.75 MHz centered at 1364.9 MHz.

The data were calibrated in a standard way, with amplitude, phase, and bandpass calibration carried out after accurate editing of raw data on both the primary (3C48) and secondary (0423-013) calibration sources. The accuracy of the flux density scale is within 3% as estimated from the variation of the gain solutions over the whole observation. The last hour of the observation was affected by some RFI covering the whole observing bandwidth; this clearly showed up when circular polarization (Stokes V) was considered. The telescopes were pointing at low elevation and it is likely that some signal of human origin entered their beams. Therefore, we decided to drop that part of the observation in the imaging process.

After self-calibration, the edited D-configuration data were imaged. The final D-configuration image has a resolution of 58″ × 35″. We measured emission in the 1 Mpc halo region as in Brunetti et al. (2008) and found $S_{1.4\text{ GHz}} = 10.1$ mJy, including the contribution from discrete sources.

In order to obtain a more sensitive image we combined our D-configuration data set with the archival VLA BnC-configuration data (total time ~5 hr), adopting the following procedure. We first made an image of the A521 D-configuration region setting a number of additional facets on all the confusing sources within the primary beam but far from the field centre. Then we removed the clean components of such sources from the visibilities, and averaged the seven 6.25 MHz channels. The same kind of subtraction was applied to the archival data before proceeding with the combination of the two data sets.

A proper sampling of the short spacings is a key issue in the correct determination of the flux density of extended and low surface brightness sources like the halo in A521. A comparison between the inner portion of the uv coverage at the various frequencies is reported in Figure 1. Visibility corresponding to baselines shorter than 1 k\(\lambda\) have been plotted. The angular size of the halo (around 4′) is sampled by the visibilities shorter than about 0.9 k\(\lambda\). It is clear that the data at 240 and 1400 MHz are those better suited to determine the flux density of the halo since they have comparable uv coverages. At 330 MHz, the density of the samples starts to get sparse. At 610 MHz, the shortest spacings are poorly sampled, leading to an underestimate of the total flux density of the halo.

The final images from the combined data set were obtained after a number of phase-only self-calibrations. We first made an image using baselines longer than 0.8 k\(\lambda\) to find the point sources embedded in the halo region. After choosing an appropriate weighting we obtained an image with a resolution of $13″/7′×6′/6$ (with P.A. = 80 deg) and 14 \(\mu\)Jy rms noise. Eleven point sources in the central region of A521, with peak flux density exceeding 6\(\mu\)Jy, were fitted with individual Gaussians and subtracted from the data. A lower resolution image was then made to highlight the halo structure and provide a good comparison to lower frequency images.

Figure 2 (right panel) shows the $30″×30″$ resolution image of the halo at 1.4 GHz: the radio halo is well detected with a morphology similar to that found at lower frequencies (240 MHz, Figure 2 (left panel)). The halo becomes progressively less dominant at higher frequencies implying that its spectrum is considerably steeper than that of the relic, $\alpha \approx 1.5$ (Giacintucci et al. 2008). The halo emission has low surface brightness at 1.4 GHz: we find $6.4 \pm 0.6$ mJy of diffuse emission in the 1 Mpc diameter circular region (as in Brunetti et al. 2008) centered on the central cluster galaxy. The error considered here includes the uncertainty in the flux density arising from the subtraction procedure of the discrete sources. The flux density of the halo emission is about 30% larger than the upper limit in Brunetti et al. (2008) that was estimated through the injection of fake radio halos in the uv data of the archive BnC–VLA observations available at that time. Most likely, differences arise from the real profile of the halo, which has some substructures and is slightly flatter than that adopted in the modeling.

Some weak diffuse radio emission extends slightly beyond the region (1 Mpc in diameter), which has been used in the flux density measurements at the various frequencies (see Brunetti et al. 2008). Such emission is visible at all frequencies and would increase all the flux densities of a few percent, thus not affecting the total spectral index.

We confirm that the spectrum of the halo is very steep: we find $\alpha = 1.86 \pm 0.08$ between 330 and 1400 MHz. For comparison, the typical slope of giant radio halos is $\alpha \approx 1.2–1.3$ (e.g., Feretti et al. 2004). The spectrum of the halo in A521 could be even steeper if we consider the possible contribution to the flux density of the diffuse emission arising from cluster sources that are not detected in our radio maps (and whose spectral index are generally around 0.7–0.8); this should be more relevant at 1.4 GHz, due to the steep spectrum of the radio halo. We do not expect this to be an large effect because, based on the average radio luminosity functions of radio sources in X-ray luminous clusters (e.g., Branchesi et al. 2006), we estimate this contribution within $\approx 0.2–0.4$ mJy at 1.4 GHz.

4. DISCUSSION

The radio spectrum of the halo is shown in Figure 3. The measurement at 610 MHz is a factor $\approx 1.6$ below the overall spectral shape marked by the data points at 240, 330, and 1400 MHz. This can be explained if we consider the sparse short baselines uv coverage associated with the $\approx 2$ hr observations of the 610 MHz GMRT Radio Halo Survey (Venturi et al. 2007, 2008). Such observations were aimed to reveal radio halos in
X-ray luminous clusters at intermediate redshift, and do not have the sensitivity and short baseline coverage to provide detailed images of the faintest halos.

The deep observations at 240, 330, and 1400 MHz and their excellent uv coverage matched to the spatial scales of the halo show a gradual steepening of the halo spectrum with increasing frequency (Figure 3), although the steepening cannot be large since our observations cover only a factor of $\approx 5$ in frequency.

Spectral steepening is a key feature of turbulent acceleration in merging clusters (Schlickeiser et al. 1987; Brunetti et al. 2004). To highlight this point, Figure 3 includes an example of a theoretical spectrum of synchrotron emission from A521 in the case of magnetosonic re-acceleration of low-energy seed relativistic electrons (Brunetti & Lazarian 2007). Besides the spectral curvature, we stress that the observation of a very steep spectrum in these environments provides evidence for turbulent acceleration in the IGM (e.g., Brunetti 2004, 2008; Cassano 2009).

On the other hand, due to straightforward energy arguments, such a very steep spectrum of the radio halo in A521 is not consistent with a secondary origin of the emitting electrons. In the secondary electron model, the primary relativistic protons collide with the thermal protons: they inject the secondary electrons whose energy spectrum is $\delta = 2\alpha$, or even slightly steeper when the logarithmic behavior of the p–p cross section with the proton energy is taken into account (e.g., Dermer 1986; Brunetti & Blasi 2005).

We adopt the formalism in Brunetti & Blasi (2005) to calculate the injection rate of secondary electrons assuming the same parameters for the thermal IGM as in Brunetti et al. (2008). To match the flux density of the radio halo measured at 330 MHz, we would need a relativistic proton population whose energy density exceeds that of the thermal IGM in A521, as it is derived from observations under the assumption of a reasonable value of the magnetic field averaged in the halo volume: $B \lesssim 7 \mu G$. As remarked in Brunetti et al. (2008), this yields only a lower limit to the energy density of high energy
Abell 0521  IPOL  240.187 MHZ
DECLINATION (J2000)  RIGHT ASCENSION (J2000)
04 54 30  15 00 53 45
-10 08  10 12 14 16 18 20
Abell 521  IPOL  1385.100 MHZ
DECLINATION (J2000)  RIGHT ASCENSION (J2000)
04 54 30  15 00 53 45
-10 08  10 12 14 16 18 20

Figure 2. Images of the radio halo region: in both cases, contour levels are $-1, 1, 2, 4, 8, 16, \ldots$, times the first contour. Left: GMRT 240 MHz contours (data presented in Brunetti et al. 2008). The restoring beam is $38'' \times 35''$ in P.A. 0° and the first contour is 0.5 mJy beam$^{-1}$. Right: The new VLA image at 1.4 GHz obtained from a combination of D- and BnC-configuration data and restored with a $30''$ circular beam. The rms noise in the image plane is about $30 \mu$Jy beam$^{-1}$ and the first contour is $85 \mu$Jy beam$^{-1}$. Point sources derived from a full resolution image (13'' $\times$ 7'' in P.A. 76°, not shown) have been subtracted out from the region covered by the halo (crosses mark these locations).

Figure 3. Synchrotron spectrum of the radio halo in A521. Measurements at 74, 240, 330, 610 MHz are taken from Brunetti et al. (2008), the flux density at 1.4 GHz (this paper) is $6.4 \pm 0.6$ mJy. The re-acceleration model shown in the figure assumes that 18% of the thermal energy is in magnetosonic waves. The synchrotron emission and particle acceleration of low energy seed relativistic electrons is calculated following Brunetti & Lazarian (2007), assuming physical parameters of A521 (from Arnaud et al. 2000), a central value of the magnetic field $B_0 = 3.5 \mu$G and a scaling $B \propto n_0^{1/2}$, $n_0$ being the thermal density.

protons since, for $\delta > 3$, an additional (dominant) contribution to the energy comes from suprathermal particles with kinetic energies $\lesssim 1$ GeV.

The turbulent acceleration scenario predicts that radio halos will be more easily revealed at low frequencies (few hundred MHz), since the electrons emitting at these frequencies can be accelerated also during less energetic mergers, which are more frequent than major mergers in the universe (Cassano et al. 2006). These low frequency halos have a steep spectrum and they may have been missed by present high frequency (at 1.4 GHz) surveys. A521 illustrates this point; it was not detected by earlier observations at 1.4 GHz (Ferrari et al. 2006). Based on evidence from low frequency GMRT data, some residual radio emission was detected in the halo region at 1.4 GHz from a re-analysis of those BnC-configuration data (Brunetti et al. 2008), yet it was also clear that a proper deep VLA observation was necessary to accurately image the diffuse emission associated with this cluster.

Future surveys at low frequencies with LOFAR and LWA will enter an unexplored territory providing a chance to detect many of these radio halos and unveil their properties. In this respect we believe that the case A521 provides a glimpse of what these surveys might find.

5. CONCLUSIONS

We report on VLA–D-configuration 1.4 GHz observations of the steep spectrum giant radio halo in the merging cluster A 521, recently discovered thanks to GMRT low radio frequency observations. The combination of our new deep observations obtained with the VLA in the D configuration with archival 1.4 GHz data (VLA, BnC configuration), allowed us to greatly improve the uv coverage of the interferometric observation and to successfully detect the faint diffuse emission associated with A 521 also at this frequency. The 1.4 GHz flux density of the giant radio halo, derived after subtraction of the embedded discrete sources, confirms that the integrated spectrum of the radio halo has a very steep slope, with $\alpha = 1.86 \pm 0.08$. The very steep spectrum and the hint of spectral curvature confirm the idea that turbulence plays an important role in the acceleration of relativistic particles in this cluster.

Our results are inconsistent with a secondary acceleration scenario. The new observations detect $\sim 30\%$ more flux at 1.4 GHz than previously constrained, implying that the spectrum of relativistic protons in the secondary electron scenario
is slightly flatter than adopted in Brunetti et al. (2008) ($\Delta \delta \sim 0.3$). However, this reduces the energy budget required to match the radio emission only by a factor of 2–2.5, and thus does not change the unrealistic secondary electron scenario, in which protons exceed the cluster energy budget.

The work presented here also underlines that observational selection effects against steep spectrum sources like A521 have likely missed plenty of similar halo sources, associated with more numerous but less energetic merging clusters. Current studies on radio halos are mostly based on observations at 1.4 GHz, where steep spectrum objects like A521 halos are revealed much harder than at lower frequencies (100–300 MHz)

This work is partially supported by INAF under grant PRIN-INAF2007 and by ASI under grant ASI-INAF I/088/06/0. Basic research in radio astronomy at the Naval Research Laboratory is supported by 6.1 base funds. The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. The GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research.

REFERENCES

Arnaud, M., Maurogordato, S., Slezak, E., & Rho, J. 2000, A&A, 355, 461
Berezinsky, V. S., Blasi, P., & Ptuskin, V. S. 1997, ApJ, 487, 529
Blasi, P., & Colafrancesco, S. 1999, Astropart. Phys., 12, 169
Blasi, P., Gabici, S., & Brunetti, G. 2007, Int. J. Mod. Phys. A, 22, 681
Branchesi, M., Gioia, I. M., Fanti, C., Fanti, R., & Perley, R. 2006, A&A, 446, 97
Brunetti, G. 2004, J. Korean Astron. Soc., 37, 493
Brunetti, G. 2008, arXiv:0810.0692
Brunetti, G., & Blasi, P. 2005, MNRAS, 363, 1173
Brunetti, G., Blasi, P., Cassano, R., & Gabici, S. 2004, MNRAS, 350, 1174
Brunetti, G., & Lazarian, A. 2007, MNRAS, 378, 245
Brunetti, G., Setti, G., Feretti, L., & Giovannini, G. 2001, MNRAS, 320, 365
Brunetti, G., et al. 2008, Nature, 455, 944
Cassano, R. 2009, arXiv:0902.2971
Cassano, R., Brunetti, G., & Setti, G. 2006, MNRAS, 369, 1577
Dennison, B. 1980, ApJ, 239, L93
Dermer, C. D. 1986, A&A, 157, 223
Feretti, L. 2003, in ASP Conf. Ser. 301, Matter and Energy in Clusters of Galaxies, ed. S. Bowyer & C.-Y. Hwang (San Francisco, CA: ASP), 143
Feretti, L., Brunetti, G., Giovannini, G., Kassim, N., Oord, E., & Setti, G. 2004, J. Korean Astron. Soc., 37, 315
Ferrari, C., Arnaud, M., Ettori, S., Maurogordato, S., & Rho, J. 2006, A&A, 446, 417
Ferrari, C., Govoni, F., Schindler, S., Bykov, A. M., & Rephaeli, Y. 2008, Space Sci. Rev., 134, 93
Ferrari, C., Maurogordato, S., Cappi, A., & Benoist, C. 2003, A&A, 399, 813
Giacintucci, S., Venturi, T., Bardelli, S., Brunetti, G., Cassano, R., & Dallacasa, D. 2006, New Astron., 11, 437
Giacintucci, S., et al. 2008, A&A, 486, 347
Hoeft, M., & Brüggen, M. 2007, MNRAS, 375, 77
Lazarian, A. 2006, ApJ, 645, L25
Petrosian, V. 2001, ApJ, 557, 560
Pfrommer, C., & Ensslin, T. A. 2004, A&A, 413, 17
Pfrommer, C., Ensslin, T. A., & Springel, V. 2008, MNRAS, 385, 1211
Roettiger, K., Burns, J. O., & Stone, J. M. 1999, ApJ, 518, 603
Ryu, D., Kang, H., Hallman, E., & Jones, T. W. 2003, ApJ, 593, 599
Sarazin, C. L. 1999, ApJ, 520, 529
Schekochihin, A. A., Cowley, S. C., Kulsrud, R. M., Hammett, G. W., & Sharma, P. 2005, ApJ, 629, 139
Schlickeiser, R., Sievers, A., & Thiemann, H. 1987, A&A, 182, 21
Venturi, T., Giacintucci, S., Brunetti, G., Cassano, R., Bardelli, S., Dallacasa, D., & Setti, G. 2007, A&A, 463, 937
Venturi, T., Giacintucci, S., Dallacasa, D., Cassano, R., Brunetti, G., Bardelli, S., & Setti, G. 2008, A&A, 484, 327
Voelk, H. J., Aharonian, F. A., & Breitschwerdt, D. 1996, Space Sci. Rev., 75, 279