ИЗВЕСТИЯ
КРЫМСКОЙ
АСТРОФИЗИЧЕСКОЙ
ОБСЕРВАТОРИИ

Изв. Крымской Астрофиз. Обс. 103, № 3, 37 – 42 (2007)

УДК 523.947

Radio Relics in Clusters of Galaxies: A unique case of Abell 548b

G. Tsarevsky[1,4], *L. Feretti*[2], *H. Andernach*[3], *M. Bacchi*[2], *O.B. Slee*[4], *G. Giovannini*[5,2], *F. Govoni*[2,6]

[1] Astro Space Center, Academy of Science, 84/32 Profsoyuznaya St., Moscow, 117910 Russia
[2] INAF Istituto di Radioastronomia, via P. Gobetti 101, I–40129 Bologna, Italy
[3] Departamento de Astronomía, Universidad de Guanajuato, AP 144, Guanajuato CP 36000, Mexico
[4] Australia Telescope National Facility, CSIRO, P.O. Box 76, Epping, NSW 1710, Australia
[5] Dipartimento di Astronomia, Univ. Bologna, via Ranzani 1, I-40127 Bologna, Italy
[6] INAF Osservatorio Astronomico di Cagliari, Loc. Poggio dei Pini, Strada 54, 09012 Capoterra, Italy

Поступила в редакцию 1 марта 2006 г.

Abstract. Currently about 30 clusters of galaxies are known to have diffuse radio sources (so-called relics), but detailed studies are available for only a few. A548b, a rich and X-ray bright cluster of galaxies, is one of only three clusters (together with A3376 and A3667) known to contain two relics. From our investigation based on multi-wavelength ATCA and VLA observations, we found that both relics (A and B), located on the same side of the cluster's center, show similar flux, extent, shape, high level of polarization and very steep spectral index. We conclude that these sources are likely related to the merger activity in the cluster. We have also possibly detected a centrally projected third relic (C). If confirmed, it would make A548b a unique triple-relic cluster.

Key words: Radio continuum: general – Galaxies: clusters: general – Galaxies: clusters: individual: A548b – diffuse radiation

1 Introduction

Diffuse radio sources in clusters of galaxies can be divided into radio halos which tend to permeate cluster centers, and sources in the cluster peripheries - so-called relics (cf. Feretti 2003). Relics show a very steep spectrum, high degree of linear polarization and no obvious association with any cluster galaxy. They have been suggested to originate along cluster merger shocks, either by diffusive shock acceleration of electrons (Enßlin et al. 1998) or adiabatic recompression of fossil radio plasma (Enßlin & Brüggen 2002). Currently about 30 clusters are known to have relics, but detailed studies are available for only a few (see e.g. Giovannini & Feretti 2004 for a review). In two clusters, A3376 and A3667, the relics are double and located on opposite sides with respect to the cluster center (Johnston-Hollitt et al. 2003). New data on relic sources are important to study whether their different structures and locations imply different physical properties.

The cluster A548, at an average redshift z=0.04 (Smith et al. 2004), shows a rather complex structure both in the optical and in the X-ray band. Based on ROSAT X-ray data, Davis et al. (1995) pointed out the existence of three main sub-clusters. These are confirmed by optical data which indicate also significant further substructures, some of which overlap along the line of sight (e.g., Nikogossian 2001). The combination of X-ray and optical data indicates that A548 is in a collapsing phase and not yet dynamically relaxed. The presence of a relic source in A548 was suggested by Giovannini et al. (1999) based on the NRAO VLA Sky Survey (NVSS, Condon et al. 1998). The source is located in subcluster A548b, referred to in the literature also as A548S or A548W or A548SW, at z=0.0424 (Den Hartog & Katgert 1996).

Here we present radio observations of A548b with the Very Large Array (VLA) and the Australia Telescope Compact Array (ATCA). The VLA observations were aimed at imaging the diffuse emission with improved sensitivity and resolution with respect to the NVSS. The aim of the ATCA observations was to search for fine structure in the radio relic similar to that seen in four relics by Slee et al. (2001), and resolve possible discrete sources. A detailed presentation of our results can be found in Feretti et al. (2006).

To calculate intrinsic parameters we adopt H_0=70 km s^{-1} Mpc^{-1}, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$. The luminosity distance D_L of A548b is 188 Mpc, and $1''$ corresponds to 0.84 kpc.

2 Radio Observations

We observed A548b at 1.4 GHz with the VLA in C configuration for 1.8 h to achieve good sensitivity to the extended low-brightness structure. Shorter exposures were also obtained in BnA configuration at 1.4, 4.8 and 8.4 GHz, centred on two unresolved sources in the diffuse emission region to obtain their structure and spectra. The data were calibrated and reduced within AIPS with several cycles of imaging and self-calibration. For the C configuration data, separate images for each of the two observing frequencies (1365 and 1435 MHz) were produced to estimate spectral indices. We also mapped polarized intensity.

A548b was imaged at 1.4, 1.7 and 2.5 GHz with the ATCA in two 6-km configurations. The data were reduced with the MIRIAD software including iterations of both phase and amplitude SELFCAL. To search for fine structure in the radio relic we imaged with the highest angular resolution available in the 1.4 and 2.5 GHz bands. Though this is not adequate to reproduce a smooth image of several arcmin extent as detected in the NVSS at 1.4 GHz (Giovannini et al. 1999) any fine-scale structure up to $\sim 1'$, if present, would have been detected in the 6A and 6B configurations we used.

3 Results

3.1 Low-resolution VLA images and comparison with X-rays

The 1.4-GHz image (Fig. 1) shows the diffuse emission to be quite complex. The diffuse source A, located $\sim$10$'$ NW of the cluster's X-ray peak is of quite regular morphology, not associated with any galaxy, and confirms the emission seen in the NVSS. The diffuse emission region B is filamentary and irregular, located $\sim$10$'$ N of the X-ray peak, and is in agreement with the traces of faint diffuse radio emission in the NVSS image. Region B features a strong pointlike radio source identified with PGC 17735, which is located near its southern boundary. The two diffuse sources A and B are strikingly similar in the total 1.4-GHz flux ($\sim$60 mJy), radio power ($P_{1.4} \sim 2.5 \times 10^{23}$ W Hz^{-1}), and size ($\sim$300 kpc). Our estimate of the spectral index α (defined via $S(\nu) \propto \nu^\alpha$) of relics A and B, comparing the 1365-MHz and 1435-MHz images, yields a steep spectrum with $\alpha \sim -2 \pm 1$. Relics A and B are polarized at a level of $\sim$30%.

Another apparently diffuse source (C) is detected $\sim 1'$ NW from the X-ray center of the cluster. The X-ray center coincides with the galaxy triplet VV 162, also classified as a dumb-bell (Gregorini et al. 1994). However, source C is clearly displaced from VV 162, and is elongated, with no obvious optical identification. Polarized flux is detected in the central region of source C at $\sim$ 7%. We discuss higher-resolution images of this source in Sect. 3.3.

We retrieved from the ROSAT archive the PSPC image of A548 of total exposure time 10.9 ks, and show the overlay of radio and X-ray images in Fig. 1. The centroid of the X-ray emission of A548b is consistent with the position of the dumbbell galaxy VV 162. The two relics A and B are at projected distances of $\sim$ 500 and $\sim$ 430 kpc from the cluster center and lie at the boundary of the X-ray brightness distribution but still well within one Abell radius ($R_A \sim 40'$ or 2 Mpc for the adopted cosmology). Source C is clearly displaced $\sim 1'$ ($\sim$50 kpc) due NW from the cluster center.

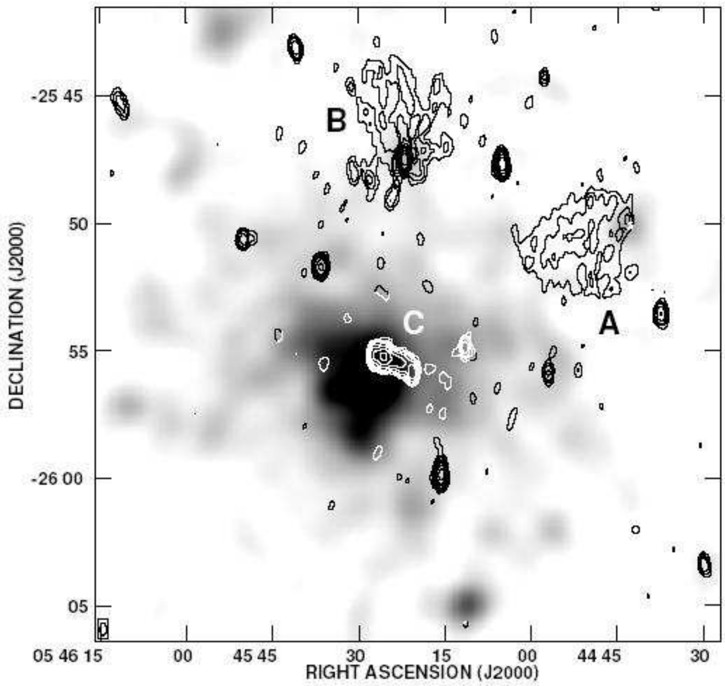

Fig. 1. Overlay of the radio image of A548b obtained at 1.4 GHz with the VLA C array at a resolution of $15'' \times 30''$ onto the cluster X-ray emission from ROSAT PSPC (grey-scale). Contour levels are 0.3, 0.6, 1, 2, 4, 8, 16, 32, 64 mJy/beam. The noise level is 0.09 mJy/beam. Diffuse radio sources are labeled A, B and C

3.2 High-resolution ATCA images

The two 1.4-GHz data sets from the ATCA were concatenated to produce a naturally weighted map of $25'' \times 8''$ resolution and a noise of 33 μJy/beam, covering the same area as the VLA map in Fig. 1. Similar images were made at 1.7 and 2.5 GHz, but with somewhat higher rms noise (52 and 41 μJy/beam) and a resolution of $12.5'' \times 4.2''$ at 2.5 GHz. The latter images, together with the VLA data at 1.4, 4.8 and 8.4 GHz, were used to obtain spectra for the discrete sources embedded within the relics.

The higher-resolution ATCA image (see Fig. 4 in Feretti et al. 2006) shows no sign of the smooth structure of relic A as seen in Fig. 1, but reveals five fairly compact sources within the relic area. They appear as peaks in the brightness contours of Fig. 1 and are present in the 1.7-GHz image, enabling estimates of their spectral indices. None of these sources coincide with galaxy or stellar images on the Digitized Sky Survey (DSS). The spectral indices of three sources are in a similar extreme range ($-6 < \alpha < -1.5$) as those reported by Slee et al. (2001) in four other relics, indicating they may be fine-structure peaks in the relic's emission.

The 1.4-GHz ATCA image shows that the strong source (PMN J0545−2547) in the southern part of relic B is surrounded on the western side by three diffuse patches associated with diffuse radio structure in Fig. 1. These patches do not appear to be associated with optical objects on the DSS, and our estimates for their spectral indices are compatible with them being the brightest peaks in the fine structure of relic B. The SE extension of relic B in Fig. 1 coincides with two faint elliptical galaxies, so it cannot be considered as part of the relic. PMN J0545−2547 is pointlike in our images at $\sim 1''$ resolution and is identified with the bright cluster galaxy PGC 17735 (J054522.1−254730), thus any connection to the

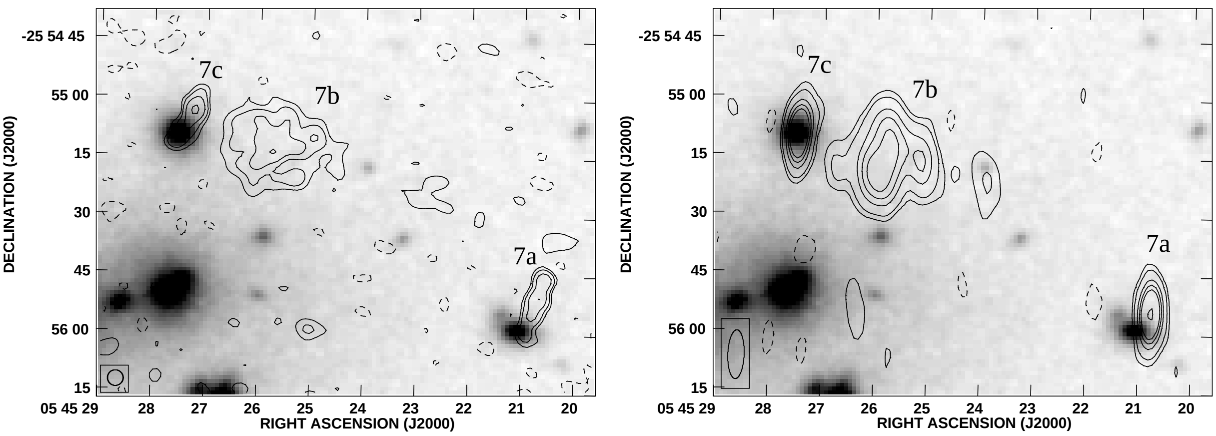

Fig. 2. Left: 1.4-GHz contours of the extended source C (also 7) obtained with the VLA in BnA configuration, at 4″ resolution and an rms noise level of 0.1 mJy/beam. Components 7a, 7b and 7c are discussed in the text. Right: 2.5-GHz ATCA image covering the same area as the left panel, at 4.2″ × 12.5″ resolution and rms noise of 0.075 mJy/beam. In both panels the grey-scale represents the optical R-band image taken from the DSS2

diffuse emission B is unlikely.

The strong compact source (NVSS J054504-254741) about midway between A and B (Fig. 1) coincides with PGC 17721 at z=0.0358, which might be the nucleus of a double-lobed radio galaxy, if its extended lobes were the diffuse sources A and B. However, our high-resolution VLA images at 5 and 8.5-GHz show it to be a double-lobed source of size $\sim 12''$ with a prominent nucleus, no clear jets and an overall orientation along PA$\sim 25°$, i.e. different from the PA connecting sources A and B ($\sim$60°). If sources A and B were the lobes of a single radio galaxy, the latter would have a total projected size of $\sim$ 650 kpc at z=0.04, and a total 1.4-GHz power of 3×10^{23} W Hz^{-1}, i.e. it would be among the largest sources for its power in the size-power diagram. For this reason and for its high-resolution structure, we consider PGC 17721 as unrelated to the diffuse sources A and B, and consider the diffuse features as relics.

3.3 Region C

In our higher-resolution 1.4-GHz VLA image (Fig. 2a) source C consists of three components, a central diffuse emission and two brighter and more compact spots at the outer extremes. These are marked in Fig. 2 as 7a, 7b and 7c, according to the nomenclature of Feretti et al. (2006). Components 7a and 7c are elongated in a radial direction with respect to the map pointing centre, thus at least part of their elongation is likely due to bandwidth smearing. The total flux density of this complex in Fig. 2a is only about 1/3 of that in the lower-resolution image, indicating the presence of unseen diffuse emission of lower brightness. We detect no sign of a radio source coincident with the brightest cluster galaxy VV 162 (the central and W component of which are seen at the lower left edge of the images in Fig. 2).

The same structure is visible in the 2.5-GHz image shown in Fig. 2b. The radio fluxes of component 7b at 1.4 and 2.5 GHz are seriously underestimated and no spectral index can be obtained. The more compact components 7a and 7c, have indices of −0.84 and +0.05, respectively. The total flux in the three components is well defined at all frequencies except 2.5 GHz, and yield a spectral index of $\alpha = -0.80 \pm 0.06$, which is more typical of a radio galaxy than a relic and would not support the idea that 7b, which contributes the major fraction of the total flux, is a relic of the usual type. Perhaps the most unusual of the trio is the flat-spectrum component 7c, associated with the cluster elliptical 2MASXi J0545274−255509. Component 7a is within $\sim 5''$ of another cluster member, probably unrelated to the radio source. Both the absence of an identification for 7b and its diffuse radio structure are at least consistent with its status as a radio relic, despite the relatively normal spectral index of the C complex. Source 7b may also be a very distant radio galaxy with an optical counterpart below the DSS plate limits, but we consider this unlikely because of the source's amorphous morphology, the lack of a compact nucleus and the missing flux at high resolution. Moreover, a rather large size, of about 500 kpc, would be derived for a radio galaxy at a redshift $\gtrsim 1$. Finally, we cannot exclude the possibility that source 7b is a lobe of either source 7a or 7c, however the lack of a symmetric lobe located on the opposite side of the presumed nucleus would lead to a quite unusual radio structure.

4 Discussion and Conclusions

The radio data presented in this paper provide clear evidence that both diffuse sources A and B are cluster relics. While they are typical of relics in that they show diffuse morphology, no connection to cluster galaxies, steep spectrum, and a high level of polarization, the relics in A548b are located at smaller distances from the cluster center than usually, unless they lie in the far front or back of the cluster. Their projected distance from the cluster centre (∼0.25 Abell radii) is similar to that of the relic in A85, discussed by Giovannini & Feretti (2000) and Slee et al. (2001) and modeled by Enßlin & Brüggen (2002). The presence of two radio relics makes the cluster A548b very peculiar in the radio domain. Moreover, this is the first cluster in which two relics are found on the same side of the cluster center. The two relics A and B show a roundish structure, and are about 300 kpc in size.

Spectral data on the relics A and B are very limited, with the only indication of $\alpha \sim -2$ based on the comparison of our L-band VLA images. The radio emission peaks in relic A have extremely high negative spectral indices between 1.4 GHz and 2.5 GHz, indicating that fine structure is present over the greater part of the relic. For relic B we can place an upper limit of $\alpha < -2$ on the brightest peak in the fine structure.

With the two relics located on the same side of the cluster center, they might form a "double-lobed" relic of a total size of 650 kpc, oriented roughly perpendicularly to the cluster radius, as found in giant relics in cluster peripheral regions (Giovannini & Feretti 2004). The magnetic field orientation we observe seems not aligned with the elongated structure, as expected and detected in relics, but the lack of Faraday rotation data precludes any conclusion. In Sect. 3.2 we also argue against the two relics being the outer lobes of PGC 17721.

The nature of source C is still very uncertain. It seems probable that the more compact components 7a and 7c are not physically related to the more extended 7b, although all lie in projection within ∼50 kpc of the X-ray centroid and the galaxy VV 162. The total fluxes give a normal spectral index indicative of a radio galaxy which should be much brighter than the DSS plate limits and lie well within its contours. Source C might contain the brightest radio sources in a distant cluster well beyond A548b. However, the amorphous morphology, the absence of an active nucleus, and the presence of very low surface brightness emission (see Sect. 3.3) are in favor of a diffuse nature for this complex, which we thus consider a relic candidate. Because of the flux missing in the high-resolution images, we expect the diffuse emission to extend further out of the structure labeled 7b, as traced in Figs. 2a and 2b.

Small-size relics, although with quite steep spectra, have been detected in A133 and A4038, located near, but not coincident with, the brightest cluster galaxy (BCG). For these sources, a connection to the activity of the BCG is not clear. If these diffuse sources were old lobes of a previous activity of the BCG, an almost symmetric double structure centered on the galaxy should be detected in most cases (see e.g. Giovannini & Feretti 2004).

Radio relics are detected in clusters both with and without a cooling flow, suggesting that even minor or off-axis mergers may play an important role in the external cluster regions. Theoretical models for the origin of relics propose that they are tracers of shock waves in merger events (Enßlin et al. 1998, Enßlin & Brüggen 2002). A fraction of the energy dissipated in shock waves can be transferred to relativistic particles. Accelerated relativistic electrons have short radiative lifetimes and should therefore produce the radio relic emission close to the current location of the shock waves.

The clusters of the A548 complex are likely in a state of interaction, thus the presence of relics in A548b confirms the association between relics and mergers. In this framework, the relics A and B would trace a shock wave in an outer cluster region, whereas the source C, if confirmed as a relic, would indicate a much more internal shock wave. In this respect, this cluster offers a unique scenario to investigate the evolution of a cluster merger. Future studies in the radio and X-ray domains will allow to detect the details of the merger process and shed more light on the connection between cluster mergers and the formation of radio relics.

Acknowledgments

We are indebted to B. Komberg for valuable comments. H.A. acknowledges support from CONACyT grant 40094-F. This research has made use of the NASA/IPAC Extragalactic Database (NED). We also made use of the database CATS (`http://cats.sao.ru` of the Special Astrophysical Observatory. The Compact Array is part of the Australia Telescope, which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

References

Condon J.J., Cotton W.D., Greisen E.W., et al. // 1998. AJ 115. 1693.
Davis D.S., Bird C.M., Mushotzky R.F., Odewahn S.C. // 1995. ApJ 440. 48.
Den Hartog R., Katgert P.// 1996. MNRAS 279. 349.
Enßlin T.A., Biermann P.L., Klein U., Kohle S. // 1998. A&A 332. 395.
Enßlin T.A., Brüggen M. // 2002. MNRAS 331. 1011.
Feretti L. // 2003. in *Texas in Tuscany.* XXI Symp. on Relativistic Astrophysics. eds. R. Bandiera. R. Maiolino. F. Mannucci. World Scientif. Publ. Singapore. P. 209.
Feretti L., Bacchi M., Slee O.B., Giovannini G., Govoni F., Andernach H., Tsarevsky G. // 2006. MNRAS. in press (astro-ph/0601572).
Giovannini G., Tordi M., Feretti L. // 1999. New Astronomy 4. 141.
Giovannini G., Feretti L. // 2000. New Astronomy 5. 335.
Giovannini G., Feretti L. // 2004. J. Korean Astron. Soc. 37. 323.
Gregorini L., de Ruiter H.R., Parma P., et al. // 1994. A&AS 106. 1.
Johnston-Hollitt M., Ekers R.D., Hunstead R.W. // 2003. IAUJD 10. 59.
Nikogossian E.H. // 2001. Ap 44. 23.
Slee O.B., Roy A.L., Murgia M., Andernach H., Ehle M. // 2001. AJ 122. 1172.
Smith R.J., Hudson M.J., Nelan J.E., et al. // 2004. AJ 128. 1558.