Radio Observations of Merging Clusters in the Shapley Concentration

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Abstract. In this paper we present the first results of a radio survey at 22 cm in the central region of the Shapley Concentration, carried out with the Australia Telescope Compact Array. In order to study the effect of merging on the statistical properties of radio galaxies, and the relation between merging and the existence of relic and halo type radio sources, we observed the two complexes of merging clusters centered on A3528 and on A3558.

Our results show that the radio source counts in these regions, characterised by very high optical overdensity and major cluster mergers, do not differ from the background source counts. This suggests that the merging phenomenon does not influence the probability of a galaxy to become radio source.

Furthermore we investigated the possibility that the extended radio source J1324–3138 is a relic, applying the model recently proposed by Ensslin et al. (1998). Our analysis shows that the properties of J1324–3138 are consistent with the idea that the source is a relic located on the shock front between A3556 and a smaller group accreting onto the main cluster concentration.

Throughout this paper we will adopt \( H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

1. Introduction

Merging clusters are among the most energetic and common phenomena in the Universe, and the most natural way to explain the formation of rich clusters of galaxies within the cold dark matter scenario, which implies bottom-up hierarchy of structure formation. The expected peculiar velocities in merging clusters are of the order of \( 10^2 - 10^3 \text{ km s}^{-1} \). The merging process generates important perturbations in the intracluster medium (ICM), which leaves signatures in a wide range of frequencies, from X-ray energies to the radio band (see these proceedings). Numerical simulations demonstrate that merging drives efficient gas transfer to the central regions of clusters, which could trigger starburst or feed nuclear radio sources (Bekki 1999). In this paper we will concentrate on the relation between merging clusters and their radio emission properties.

The most important classes of merging-related radio sources are radio halos and relics. They are both characterised by diffuse extended emission on a scale up to the order of the megaparsec and have steep spectrum (\( \alpha \geq 1 \)) over a wide range of radio frequencies. Radio halos are typically found in the central regions of cluster galaxies, while the more elongated relics are usually located in peripheral cluster regions (Feretti & Giovannini 1996).

In order to study if and how cluster merging affects the properties of radio emission of galaxies, and to further investigate the relation between mergers and the formation of radio relics and radio halos (see also Feretti, Giovannini et al., Owen et al., these proceedings), it is important to carry out an extensive multifrequency study of merging clusters. With this aim in mind we have been carrying out a study in the optical and radio bands of the central region of the Shapley Concentration, the most remarkable example of cluster merging in the nearby Universe, located in the southern sky at approximately \( (\alpha_{2000} = 13^h 03^m 0\pm 0.05 \), \( \delta_{2000} = -29^\circ \), at an average distance \( <z> \sim 0.03 - 0.05 \).

In this paper we will present the first results emerging from a radio-optical analysis of the two main chains of rich clusters in the Shapley Concentration core, in particular, the A3558 complex and the A3528 complex, hereinafter A3528-C and A3558-C. We will briefly describe the observations and the data reduction, then we will show the radio source counts for both cluster complexes for comparison with the background source counts and we will comment on the results obtained. Finally we will discuss the astrophysical properties of the extended radio source J1324–3138, located in A3556 in the A3558 complex (Venturi et al. 1998) in the light of the model proposed by Ensslin et al. (1998) for the formation of relic sources in merging clusters.

2. The A3558 and A3528 cluster complexes

These two cluster complexes can be considered the dynamical centre of the Shapley Supercluster.
The **A3558** complex (Figure 1) is formed by the three ACO clusters A3556, A3558 and A3562 and by the two smaller groups SC 1327–312 and SC 1329–313 located between the cores of A3558 and A3562. 714 redshifts were obtained by the use of multifiber spectroscopic data in this region of the sky (Bardelli et al. 1994), confirming that A3558-C is a single physically connected structure, at a mean distance $<z> = 0.0483$, almost perpendicular to the line of sight. The physical connection and merging stage of all clusters in the chain is emphasised by the X–ray data (Bardelli et al. 1996, Ettori et al. 1997, Kull & Boehringer 1998), which shows that the distribution of the hot gas in this region remarkably follows the distribution of the optical galaxies. A detailed substructure analysis carried out by Bardelli et al. (1998) showed that the velocity distribution of the galaxies in the A3558 chain is very complex, with the existence of a large number of small groups, further evidence of its dynamical activity. We believe that A3558-C is an early stage cluster merger, after the first core-core encounter.

The **A3528** complex (Figure 2) is formed by the three ACO clusters A3528, A3530 and A3532 and it is located at an average distance $<z> = 0.0535$. X–ray data (Schindler 1996) show that A3528, the dominant cluster in this complex, is actually formed by two distinct groups, called for convenience A3528N and A3558S. The temperature distribution of the gas suggests that these two groups are in a pre-merging stage (Schindler 1996). The distance between the centres of A3530 and A3532 is much smaller than the Abell radius ($\sim 35''$ at this distance), and this is also evidence of strong interaction. A dynamical study of A3528-C, based on $\sim 600$ redshifts in this region is currently in progress (Bardelli et al. in preparation).

### 3. The 22 cm radio survey

#### 3.1. Observations and data reduction

In order to pursue the aim of our project and study the global effects of merging on the radio emission properties of cluster galaxies and the relation between mergers and extended relic- and halo-type radio sources, we surveyed A3528-C and A3558-C with the Australia Telescope Compact Array (ATCA) simultaneously at 13 cm and 22 cm, with the two array configurations 1.5B and 6C for a total of 8 hours on each field. We will concentrate here on the 22 cm results. The resolution of our observations is $\sim 10'' \times 5''$. We carried out our observations with a 128 MHz bandwidth, and in order to minimise the effects of bandwidth smearing in our large fields of view we fully exploited the spectral line mode correlation of the ATCA using 32 channels. The data were reduced with the MIRIAD package (Sault, Teuben & Wright 1995) and the image analysis was carried out in AIPS. For further details on the observations and data reduction see Venturi et al. 1997, 1999a and 1999b. In order to completely cover the sky region occupied by both complexes we also analysed archive data at the same wavelength and with comparable resolution (array 1.5C, 2 hours on each field).

The area surveyed in our observations is 1.04 deg$^2$ and 3.25 deg$^2$ for A3528-C and A3558-C respectively. The noise in our final images ranges from 70 $\mu$Jy/beam to 0.2 mJy/beam therefore we placed a conservative detection limit of 5$\sigma$ for those fields with highest noise and considered reliable detections all sources with $S_{22\text{ cm}} \geq 1$ mJy.

#### 3.2. Results and optical identifications

The results of our survey are reported in Table 1, where we give the total number of detected radio sources (Col. 2), the number and fraction of radio sources with optical counterpart (Col. 3) and the number and fraction of Shapley radio galaxies (Col. 4).

Table 1. Results of the 22 cm Survey

| Complex | N(radio) | N(ID) | N(Shapley) |
|---------|---------|-------|------------|
| A3528   | 152     | 40(26%) | 12(8%)     |
| A3558   | 263     | 69(26%) | 28(11%)    |

Among the 12 Shapley radio galaxies in A3528-C, six exhibit extended morphology, which is a fraction of 50%. In A3558-C only 4/28 of the Shapley radio galaxies are extended, i.e. $\sim 14\%$ (see Venturi et al. 1999b for further details on the A3558 complex). Figure 3 and 4 show...
the distribution of optical galaxies (dots) in A3528-C and A3558-C respectively, with the location of the radio galaxies superimposed (crosses).

The six extended radio galaxies in A3528-C are all located in the central regions of the clusters (Reid, Hunstead & Pierre 1998), in particular five of them are in the centre of A3528N and A3528S (J1254−2900, J1254−2901, J1254−2904, J1254−2913 and J1254−2916) and the sixth (J1257−3021) is coincident with the dominant dumb-bell galaxy in A3532 (see also Gregorini et al. 1994). A3528-C seems more active than A3558-C at radio wavelengths, and this could be related to its earlier merging stage. The relation between the properties of the extended radio galaxies in A3528-C and the merging stage will be studied and discussed in a future work (Venturi et al. in preparation).

The distribution of the extended galaxies in A3558-C is remarkably different. Two of them, i.e. J1324−3138 and J1333−3144, are located in the central region of A3556 and A3562 respectively (Venturi et al. 1999a), while the remaining two, J1322−3146 and J1335−3153, are located respectively at the extreme western and eastern end of the whole chain (see Venturi et al. 1997 and Venturi et al. 1999a).

### 3.3. Radio Source Counts

In order to test if the galaxy overdensity and the cluster merger in the Shapley Concentration core reflect in an overdensity in the number of radio sources, we computed the radio source counts in both complexes and compared...
our results to the background source counts (Prandoni 1997).

Our statistical analysis was carried out using a complete subsample of all radio sources detected in A3528-C and A3558-C. This was necessary to account for sensitivity losses due to the primary beam attenuation. For the present investigation we selected all sources with \( S \geq 2 \) mJy within a radius of 17.5 arcmin from the centre of the respective field. At such distance the primary beam attenuation of the ATCA at 22 cm is reduced by a factor of two, therefore sources with a flux density \( S \geq 2 \) mJy are seen as sources with \( S \geq 1 \) mJy before the correction. At the distance of the Shapley Concentration this reflects into a lower limit on the radio power \( \log P_{22\text{cm}} = 21.7 \).

The final sample of radio sources used for our statistical investigation includes 55 and 144 source for A3528-C and A3558-C.

Our results are shown in Figures 5 and 6 respectively for A3528-C and for A3558-C. The line drawn in each plot represents the radio source counts for the background. The errors in each flux bin are poissonian.

As it is clear from Figures 5 and 6, the distribution of the source counts in the Shapley Concentration core remarkably follows that of the background. We remind the reader that our sample is complete only down to 2 mJy, and the source counts in the first two bins, lower than the background in both complexes, reflect our incompleteness in the range 1 - 2 mJy. A KS test shows that for both complexes the source count distribution is the same as the background with a 99% confidence level.

Our result indicates that even in a remarkably overdense region as the Shapley Concentration core, the radio source counts are dominated by background sources. This implies that the extreme cluster merger in the Shapley Concentration has no effect on the source counts. Furthermore we can conclude that cluster merging does not seem to appreciably increase the probability of a single galaxy to become a radio source over a wide range of radio power.

4. J1324−3138: a radio relic in A3556?
It has been recently proposed (Ensslin et al. 1998, Ensslin these proceedings) that relic radio sources, trace shock fronts induced by the formation of large scale structure through cluster mergers and group accretion. Such shock fronts would give rise to electron reacceleration through magnetic field compression, therefore “old” emission from radio galaxies, faded away because of particle energy losses, would be “revived” during the passage though the shock. Under this hypothesis the properties of relics and the cluster gas temperature and pressure would depend on the accretion shock parameters, such as the shock radius \( r_s \) and the velocity of the infalling matter \( V_z \). Their model is able to account for the properties of most relics known thus far.

The extended radio galaxy J1324−3138 is located in A3556 (see Figures 1 and 7), one of the ACO clusters in A3558-C and it was studied in detail in Venturi et al. (1997). The radio galaxy is located at a projected distance
Fig. 7. Color optical image of the centre of A3556 with superimposed radio emission at 22 cm. J1324−3138 is the extended source on the top right. The centre of A3556 is coincident with the cD galaxy at the centre of the image.

of ∼ 2.5 arcmin from the centre of A3556. Its most important properties can be summarised as follows:

(a) low brightness tailed radio morphology without jets and with indication of a very faint nucleus. The source is associated with a 15.6 mag cluster galaxy belonging to a secondary group in A3556, with σ ∼ 222 km s\(^{-1}\) with respect from the main component in A3556. Its projected size is ∼ 182 × 15 kpc.

(b) steep spectrum, with α\(_{4.9\text{GHz}}\) ∼ 1.3;

(c) no polarisation, with a limit on the fractional polarisation m < 5% up to 4.9 GHz;

(d) low equipartition magnetic field \(B_{\text{eq}}\) and non-thermal pressure \(P_{\text{nt}}\), in particular \(B_{\text{eq}} = 1.6\ \mu\text{G}\) and \(P_{\text{nt}} = 1.5 \times 10^{-13}\ \text{dyn cm}^{-2}\);

(e) age \(t \sim 10^8\) yrs.

All these properties led us to the conclusion that J1324−3138 is a remnant of a tailed radio galaxy.

Given the similarity between this source and the few relics known up to date, we compared the observed properties of this source and of the gas in A3556 to the predictions made by Ensslin et al. (1998) in order to consider the possibility that J1324−3138 is a relic source located on the accretion shock front between the centre of A3556 and the secondary group visible in the galaxy velocity distribution for A3556 (Bardelli et al. 1998). Using the formulas given in Ensslin et al. we obtained for J1324−3138 a shock radius \(r_{\text{s}} \sim 1\ \text{Mpc}\), a viewing angle \(\delta \sim 5^\circ\) (defined as the angle between the line of sight and the line connecting the source and the cluster centre), and a compression ratio \(R = 2.9\). In Table 2 we give the results of the comparison between the source properties and the model.

In Table 2 \(P_2/P_1\) is the pressure ratio inside and outside the shock front and \(\sigma\) is the velocity dispersion of the group, related to the temperature ratio inside and outside the shock front. The observed values for \(V_s\) and \(\sigma\) are derived from the optical data in Bardelli et al. (1998).

The agreement between the predicted and observed critical parameters in Ensslin model is very good. This analysis suggests that the source is located within a small angle from the cluster centre, and the group it belongs to is accreting onto A3556. The viewing angle \(\delta\) has a 180° uncertainty, and the model does not allow us to predict if the source is located in front or behind the main cluster condensation. Also, if the source is aligned with the shock front, the derived geometry suggests that it is almost in the plane of the sky, so projection effects in its total size are negligible. This could be a problem, since the dimensions reported in the literature for the other known relics are considerably larger (see Feretti & Giovannini 1996), however with the increasing number of relic sources being found (these proceedings) the distribution of linear sizes for this type of sources may be reconsidered in the future.

The existence of an optical counterpart indicates that the stage of nuclear activity, responsible for the production of the relativistic electrons and magnetic field now “revived” by the shock, is fairly recent. J1324−3138 could represent the first stage of a relic radio source.

A similar multifrequency (radio, spectroscopic, X–ray) analysis for all extended sources in the Shapley Concentration core is currently in progress.

5. Summary and conclusions

We have surveyed the two chains of merging clusters centered on A3528 and A2558 located in the central region of the Shapley Concentration at 22 cm with the Australia Telescope Compact Array in order to investigate the effects of merging on their radio emission properties of clusters. Furthermore we have applied the model proposed by Ensslin et al. (1998) for the formation of relics to the extended source J1324−3138, located in A3556, in the A3558 complex.

We can summarise our results as follows:

(a) We detected 152 radio sources in A3528-C and 263 radio sources in A3558-C above the flux detection limit \(S \geq 1\ \text{mJy}\). The number of Shapley radio galaxies is respectively 12 (8%) and 28 (11%). In A3528-C we found 6/12 extended radio galaxies, corresponding to a remarkable fraction of 50%. In A3558-C we found 4/28 extended radio galaxies, i.e. ∼ 14%.

### Table 2. Comparison with the model

| Parameter          | Predicted | Observed |
|--------------------|-----------|----------|
| \(V_s\) (km s\(^{-1}\)) | ∼ 900     | 936      |
| \(P_2/P_1\)        | 9.3       | ∼ 5      |
| Polarisation       | no pol.   | < 5%     |
| \(\sigma\) (km s\(^{-1}\)) | 217       | 222      |
(b) The high optical galaxy density in the cluster merging environment of the Shapley Concentration does not affect the radio source counts, which are consistent with the background source counts. This suggests that merging does not influence the probability of galaxies to become radio sources.

(c) The properties of J1324−3138 are consistent with the idea that it is a relic source located on the shock front between the centre of A3556 and the infalling secondary group where its optical counterpart is located. The viewing angle between the line of sight and the normal to the shock front is $\delta \sim 5^\circ$ and the source lies almost in the plane of the sky.

Acknowledgements. We wish to thank the organisers for the very fruitful and successful workshop.

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