The diffuse radio filament
in the merging system ZwCl 2341.1+0000

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ABSTRACT

Context. In some clusters of galaxies, a diffuse non-thermal emission is present, not obviously associated with any individual galaxy. These sources have been identified as relics, mini-halos, and halos according to their properties and position with respect to the cluster center. Moreover in a few cases have been reported the existence of a diffuse radio emission not identified with a cluster, but with a large scale filamentary region.

Aims. The aim of this work is to observe and discuss the diffuse radio emission present in the complex merging structure of galaxies ZwCl 2341.1+0000.

Methods. We have obtained VLA observations at 1.4 GHz to derive a deep radio image of the diffuse emission.

Results. Low resolution VLA images show a diffuse radio emission associated to the complex merging region with a largest size = 2.2 Mpc. In addition to the previously reported peripheral radio emission, classified as a double relic, diffuse emission is detected along the optical filament of galaxies.

Conclusions. The giant radio source discussed here shows that magnetic fields and relativistic particles are present also in filamentary structures. Possible alternate scenarios are: a giant radio halo in between two symmetric relics, or the merging of two clusters both hosting a central radio halo.

Key words. galaxies:cluster:non-thermal – Clusters: individual: ZwCl 2341.1+0000 – Cosmology: large-scale structure of the Universe

1. Introduction

Diffuse non-thermal radio sources with steep spectra have been found in a relatively large number of clusters of galaxies (see e.g. Giovannini et al. 2009 and references there in). These sources are not directly associated with the activity of individual galaxies and are related to physical properties of the whole galaxy. According to their properties and location they are commonly classified as Relics and Halos.

Relics have been found at the cluster peripheries and the most common interpretation is that they are related to the presence of shocks originated by cluster mergers. Halos are located in the central cluster regions and have always been found in clusters with evidence of merger activity, which plays an important role in particle re-acceleration providing the energy that powers these sources (Brunetti et al. 2009, Feretti & Giovannini 2008).

In addition some evidence has been found of the existence of non thermal emission on even larger scales. Bridges of radio emission have been observed in the regions between relics and halos in a few clusters, including Coma (Kim et al. 1989, Giovannini et al. 1990), A2255 (Feretti et al. 1997), and A2744 (Govoni et al. 2001). Diffuse emission have been found at large distance from A2255 (Pizzo et al. 2008), and A2256 (van Weeren et al. 2009a).

A convincing evidence of radio emission from a filament structure was reported by Bagchi et al. 2002 identified with the multi-Mpc scale filamentary network of galaxies in the ZwCl2341.1+0000 region at z = 0.27. The authors discuss the presence of large scale shocks originating in the accretion flows of intergalactic gas, inferred from the Mpc scale diffuse radio emission. van Weeren et al. 2009b presented GMRT observations at 610 MHz, 241 MHz and 157 MHz of this region, combined with X-ray and optical data. The radio images show two diffuse sources to the north and south of the cluster position which they classified as double radio relics. These relics are perpendicular to the X-ray axis which can be considered the merger axis. They are suggested to be due to outward travelling shocks caused by a major merger event. The distance between the two relics is \sim 2.2 Mpc.

We present here new low resolution VLA images of the diffuse radio emission at 1.4 GHz. Despite of the higher frequency, the better sensitivity to surface brightness allowed us to detect very extended diffuse radio emission, which spans along the optical filament. We discuss its nature and properties.

The intrinsic parameters quoted in this paper are computed for a $\Lambda$CDM cosmology with $H_0 = 71$ km s$^{-1}$Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$. At $z = 0.27$ the angular conversion factor is 4.1 kpc/".

2. Radio images

The ZwCl2341.1+0000 region was observed for 6 hrs with the VLA at 1.4 GHz in the D configuration on July 24 2008, at two different pointings: RA=23h43m40s DEC=+00°20′00″, and RA=23h43m50s DEC=+00°14′00″, to avoid high primary
beam attenuation and bandwidth smearing. Each field was observed for 3 hrs, and we moved the pointing center every half hour to obtain a better uv-coverage. Calibration and imaging were performed with the NRAO Astronomical Image Processing System (AIPS). The sources 3C48, 3C138 and 2316+040 were used as primary flux-density calibrator, absolute reference for the electric vector polarization angle and phase calibrator respectively. Several cycles of self-calibration were applied in order to remove residual phase and gain variations. Images of the total intensity (Stokes I) as well as of the Stokes parameters U and Q were produced for the two pointings separately following the common procedures: Fourier-Transform, Clean, and Restore. The images resulting from the two pointings were finally combined together using the AIPS task LTESS. We then derived images of the polarized intensity \( P = \sqrt{U^2 + Q^2} \), corrected for the positive bias, and of the polarization angle \( \Psi = \arctan(U/Q) \). Calibration errors are of the order of 5%.

2.1. Total intensity radio emission

In Fig. 1, we show the final image obtained with natural weights. The diffuse emission is easily visible even if a large number of discrete sources are present. To obtain the image of the diffuse source, and measure its flux, we subtracted unrelated discrete sources in the uv plane. To this aim, we produced high resolution images with uniform weight (ROBUST = -5), after cutting baselines shorter than 2K\( \lambda \). In these images only discrete sources are present, whereas the extended diffuse emission is resolved out (see Fig. 2 left panel).

Discrete sources present in our images are in agreement with the list of unrelated sources found by van Weeren et al. 2009b using GMRT data at lower frequencies, but at higher resolution. A comparison between GMRT flux densities at 610 MHz and at 1.4 GHz, taking into account the different angular resolution and uv-coverage, gives spectral indexes in the range 0.8 - 1.5, expected from extra-galactic radio sources (for the strongest subtracted source (A) \( \alpha_{0.4-1.4} = 1.2 \)). Clean components were subtracted from the uv data. With the new data sets we produced low resolution images to enhance the low brightness extended emission. Final images were combined and corrected for the primary beam attenuation. The final combined, and primary beam corrected image is shown in the right panel of Fig. 2. In this image, the radio emission is continuous, and the gap between the northern and southern regions visible in Fig. 1 is no longer present, clearly because of a positive noise in this area, enhanced by the slightly larger beam.

2.2. Polarized emission

We investigated the presence of polarized emission from the radio diffuse emission. We produced Stokes Q and U low resolution images. The discrete sources were subtracted as explained above for the total intensity image. We derived the polarization angle image and the polarization intensity image without imposing any cut. From the polarization intensity image we derived the fractional polarization image, and we considered as valid pixels those whose signal-to-noise ratio was \( > 3 \). This cut is done in order to get rid of possible spurious polarization. The resulting image is shown in Fig. 3. We can gather that there is a detection of polarization in the northern and southern components, as well as in the central region.

3. Results

In the final image, obtained after the subtraction of discrete sources, an extended emission is detected, which is consistent with the result of Bagchi et al. 2002. Owing to the better sensitivity of our image, the diffuse source is well defined. The radio morphology is elongated, clearly following the distribution of the optical galaxies and of the X-ray emission, shown by van Weeren et al. 2009b. We note that the regions of highest brightness are coincident with the two relics presented by van Weeren et al. 2009b. In the central region, we detect a low surface brightness emission, at the level of 0.4 – 0.6 mJy/beam (corresponding to \( ~7 \times 10^{-5} \) mJy/arcsec\(^2\)), which could be detected at 610 MHz with a 15'' beam only if the spectral index \( \alpha_{1.2}^{+} \) is steeper than 2.5 - 3.

The total size of the diffuse emission is \( \sim 2.2 \) Mpc. The measured total flux at 1.4 GHz is 28.5 mJy, corresponding to a radio power \( P_{1.4} = 23.66 \) W/Hz. The radio emission is irregular and decreases from the two bright outer regions toward the cluster center. A plateau of radio emission, at the level of about 0.6 mJy/beam is present at the location of the southernmost X-ray peak, detected by Chandra and published in Fig. 1 of van Weeren et al. 2009b.

We detect polarized emission from large areas of the diffuse radio source, both from the outer and the central regions. The polarized flux is more prominent in the eastern side of the extended source. Once the discrete sources have been subtracted, the total polarized flux is \( \sim 2.4 \) mJy. The polarized percentage in the northern and in the southern bright regions is \( \sim 15\% \) and \( 8\% \) respectively, while the mean fractional polarization in the central region is \( \sim 11\% \). The polarization vectors are very regular and oriented toward the NE-SW direction in the northern source region. In the other regions they follow the eastern edge of the total intensity emission still showing some level of ordering.

From present images and following the detailed discussion by Bagchi et al. 2002 and van Weeren et al. 2009b, we ruled out...
4. Discussion

Radio emission of very low brightness is detected in the ZwCl2341.1+0000 complex, owing to the high sensitivity to surface brightness of the present observations. The data reported in this paper indicate the existence of diffuse radio emission along the whole optical filament, as first reported by Bagchi et al. 2002, in addition to the bright radio regions located at the outer source boundary, where van Weeren et al. 2009b suggested the existence of two relics. The low angular resolution of the present data does not allow us to separate the the radio emission of these features from the rest of the diffuse emission.

The most obvious interpretation is, as suggested by Bagchi et al. 2002, that this region is witnessing the process of a large scale structure formation, where cosmic shocks originated by a complex multiple merger are able to accelerate particles and amplify seed magnetic fields. The large-scale radio emission would originate from large-scale shocks and possibly turbulence, and the identification of single radio source components as relics, would be problematic. The existence of significant polarized emission image can be easily explained in this scenario. The shocks connected to large scale filaments are indeed expected to compress the magnetic field, allowing the detection of polarized emission also at such low resolution. Furthermore, we note that the lower gas density of filaments with respect to clusters would cause less depolarization, and internal Faraday rotation, that could explain the ordered features revealed by the polarization image. The high fractional polarization in the eastern side could be related to the direction and dynamics of the merging process.

An alternate possibility could be that the extended emission in this cluster actually consists of two peripheral relics and a central radio halo, as in the clusters A1758 (Giovannini et al. 2009) and RXCJ1314.4-2515 (Feretti et al. 2005; Venturi et al. 2007). In this scenario, shocks originated in the merging processes of this complex structure could give origin to the peripheral...
relics, while a large scale turbulence at the cluster center as enhanced by X-ray data (van Weeren et al. 2009b) could give origin to the central halo. Although it is not obvious to separate in ZwCl1234.1+0000 the relic and halo emission, we estimate that the radio halo size is ~ 4' (~ 1 Mpc) with a flux density ~ 10 mJy (log P_{1.4} = 23.2 W/Hz), and the Northern and Southern relics have a flux density ~ 5 mJy and 13 mJy, respectively. The spectral index of the two relics between 1.4 GHz and 610 MHz, estimated from the present data and those by van Weeren et al. 2009b is ~ 1.2 (for both relics). This value is higher with respect to α_{1.4} = 0.49 and 0.76 for the N and S relics respectively reported by van Weeren et al. 2009b. Although this may be due to a genuine flattening at low frequency, we note that because of different UV coverages and sensitivities, it is not possible to derive firm conclusions about the spectral index properties.

From the image presented in this paper, we derive that the central radio halo is likely to show a quite irregular structure, however its radio size and power are in good agreement with the correlation between radio power and size reported by Giovannini et al. 2009. Also the two possible relics are peculiar, indeed their shape is not regular and elongated as in typical relics like 1253+275 in the Coma cluster (Giovannini et al. 1991) or the double relics in A3376 (Bagchi et al. 2005), and A3667 (Röttgering et al. 1997). However, exceptions are known in the literature as the relics in A1664 (Govoni et al., 2001), and A548b (Feretti et al. 2006). The presence of polarized emission in the two relics is in favour of this scenario, whereas the detection of polarization in the central halo would be against it. Indeed, radio halos are typically unpolarized, with upper limits of the order of few percent. The only two cases known so far where polarized emission has been detected from radio halos are the cluster Abell 2255 (Govoni et al. 2005) and MACS J0717+3745 (Bonafede et al. 2009).

As a third possibility, we wish to remember the case of two halos found for the first time in the double cluster system A399/A401 (Murgia et al. 2009). These two clusters are probably in a pre-merging phase: the X-ray excess, the slight temperature increase in the region between the two clusters, and the relatively high metallicity of the hot IGM in the same region are evidence of a physical link between this pair of clusters (Murgia et al. 2009 and references there in). In this scenario, we may interpret the complex radio emission in ZwCl1234.1+0000 as an evolved case of two clusters, both hosting a radio halo. During the ongoing merger process, the two radio halos would appear as brighter diffuse radio emitting regions, connected by a faint radio bridge, which could originate from the cluster interaction as in the bridge in the Coma cluster (Kim et al. 1989). After the merger, the two clusters would eventually create a giant radio halo. A major concern about this scenario is that from the optical isodensity contours presented by van Weeren et al. 2009b in the brightest radio emitting regions there is no evidence of a galaxy overdensity which is the expected signature of the two merging clusters. Furthermore, the detected polarization flux could not obviously be reconciled with this scenario.

5. Conclusions

Diffuse radio emission identified with the ZwCl1234.1+0000 complex is detected along the whole filament of galaxies, in agreement with the results of Bagchi et al. 2002. We confirm that the regions of highest radio brightness are located at the outer source boundary, where van Weeren et al. 2009b suggested the presence of two relics. The angular resolution of the present data does not allow us to separate the radio emission of the various features. We suggest three possible scenarios:

1. The cluster is the site of cosmic shocks originated by the multiple mergers during the large scale structure formation, as proposed by Bagchi et al. 2002. In this case, the radio emission would be related to the galaxy filament as a whole. The polarized emission image could be easily reconciled with this scenario, as the shocks connected to large scale filaments are expected to compress the magnetic field to a high degree of ordering.

2. The diffuse radio emission could consist of a central radio halo and two opposite radio relics, as found in A1756 or RXCJ1314.4-2515. Despite of the irregular structure of the central halo, its size and power would be consistent with the correlation between radio power and size reported by Giovannini et al. 2009. The structure of the two relics is different from that of typical elongated relics, however some other cases of irregular relics are found in the literature (A1664, A548b). The fractional polarization detected in the diffuse source is consistent with the polarization of relics, whereas the radio halos are generally unpolarized (but see A2255 and MACS J0717+3745).

3. The complex structure could derive from a double cluster, hosting two radio halos, similar to the cluster system A399/A401 (Murgia et al. 2009), but at a later stage of merging, therefore the system has developed a radio bridge between the two interacting clusters. The presence of polarized flux cannot be easily reconciled with this scenario, as radio halos are generally unpolarized. Moreover, from the optical isodensity contours presented by van Weeren et al. 2009b, in the brightest radio emitting regions there is no evidence of a galaxy overdensity which is the expected signature of the two merging clusters.

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