Diffuse galaxy cluster emission at 168 MHz within the Murchison Widefield Array Epoch of Reionization 0-hour field

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ABSTRACT
We detect and characterise extended, diffuse radio emission from galaxy clusters at 168 MHz within the Epoch of Reionization 0-hour field; a 45° × 45° region of the southern sky centred on R.A. = 0°, decl. = −27°. We detect 31 diffuse radio sources; 3 of which are newly detected haloes in Abell 0141, Abell 2811, and Abell S1121; 2 newly detected relics in Abell 0033 and Abell 2751; 5 new halo candidates and a further 5 new relic candidates. Further, we detect a new phoenix candidate in Abell 2556 as well as 2 candidate dead radio galaxies at the centres of Abell 0122 and Abell S1136 likely associated with the brightest cluster galaxies. Beyond this we find 2 clusters with unclassifiable, diffuse steep-spectrum emission as well as a candidate double relic system associated with RXC J2351.0-1934. We present measured source properties such as their integrated flux densities, spectral indices, and sizes where possible. We find several of the diffuse sources to be ultra-steep including the halo in Abell 0141 which has $\alpha \lesssim -2.1 \pm 0.1$ making it one of the steepest halos known. Finally, we compare our sample of haloes with previously detected haloes and revisit established scaling relations of the radio halo power ($P_{1.4}$) with the cluster X-ray luminosity ($L_X$) and mass ($M_{500}$). We find consistent fitting parameters for assumed power law relationships, and find that the $P_{1.4}$–$L_X$ has less raw scatter than the corresponding $P_{1.4}$–$M_{500}$ despite inhomogeneous $L_X$ measurements. These scaling relation properties are consistent with a sample of only non-cool core clusters hosting radio haloes.

Key words: radio continuum: general – galaxies: clusters: general – radiation mechanisms: non-thermal – galaxies: clusters: individual: (Abell 0033, Abell 0141, Abell 2811, Abell S1121, Abell 2751, Abell 2556, Abell S1136, Abell 0122, RXC J2351.0-1934)

1 INTRODUCTION
Clusters of galaxies are among the largest structures in the Universe. Understanding how clusters form and their dynamics is key to understanding how the Universe behaves on some of the largest scales. Galaxy clusters are thought to form in the hierarchical model, where galaxies eventually clump together during sometimes intense merger events (Peebles 1980). The clusters themselves are primarily dark matter, diffuse gas that makes up the intra-cluster medium (ICM), and the galaxies for which they are named. Galaxy clusters are found to host magnetic fields on the order of 0.1–1 µG (Clarke et al. 2001; Johnston-Hollitt 2003; Bonafede et al. 2010). The magnetic fields in clusters give rise to radio synchrotron emission; relativistic electrons accelerated by the magnetic fields with Lorentz factors of $\gamma > 1000$, where the spectral energy distribution (SED) of the emission gives insight into the ages of electron populations and the possible shock-driven re-acceleration from merger events (see Feretti et al. 2012; Brunetti & Jones 2014, for reviews). The steep spectral indices $^{1}$ of such synchrotron emission

$^{1}$ The spectral index $\alpha$ is defined through $S_\nu \propto \nu^{-\alpha}$ for flux density $S_\nu$ at frequency $\nu$. 

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means that to detect the faintest non-thermal diffuse cluster emission low-frequency radio telescopes are required, such as the southern Murchison Wide-field Array (MWA; Tingay et al. 2013) operating at 80–300 MHz or the northern LOw Frequency ARray (LOFAR; van Haarlem et al. 2013) which operates within the frequency bands 10–90 MHz and 110–250 MHz. As radio telescopes become more sensitive, more of this steep-spectrum diffuse emission is expected to be found (Cassano et al. 2012a; Johnston-Hollitt 2017).

Diffuse synchrotron emission comes in two main classes: cluster haloes and relics. Cluster relics can be broken down further into two types: kpc-scale phoenices and megaparsec-scale relics. Radio phoenices are kpc-scale relics that are thought to be the remnants of ancient radio galaxies whose active galactic nuclei (AGN) have become dormant while the electrons from the lobes slowly diffuse into the surrounding ICM (Komissarov & Gubanov 1994). These are usually found near the cluster centre. Megaparsec-scale relics (hereafter relics) are thought to trace shocks through the ICM during and after massive merger events. These are found on the periphery of clusters, usually aligned with the major merger axis and can come in adjacent pairs of so-called double relics (e.g. Abell 3667; Johnston-Hollitt 2003, Abell 3376; Bagchi et al. 2006, PSZ1 G108.18-11.53; de Gasperin et al. 2015). For both types of relics the electrons must go through some re-acceleration process albeit on vastly different scales. These processes are thought to be through turbulence and shocks typically resulting in an elongated or arc-like morphology. The key distinction between the two types of emission is their size and spectral properties. The kpc-scale phoenices are small enough that they do not require cluster-wide shocks or turbulence as so may display an SED of simple electron ageing, whereas the Mpc-scale cluster relics would require such shocks potentially displaying more complex SEDs indicative of re-acceleration of an older electron population.

Haloes also come in two main types: mini-haloes and cluster haloes. Mini-haloes are associated with strong active galactic nuclei (AGN), often the central dominant (cD) galaxy within the core of the cluster, and are smaller in extent though are otherwise morphologically similar to cluster haloes (for a recent review see Bravi et al. 2016). Cluster haloes are centrally located within the cluster, morphologically regular, and are often found to coincide with the X-ray emitting plasma of the ICM. Haloes do not normally show any significant fractional polarisation however this is likely a limitation of the resolution of current-generation radio interferometers (Govoni et al. 2013). The mechanism that generates these radio haloes is still under investigation. The primary, re-acceleration model of halo generation suggests the synchrotron emission occurs after electrons are re-accelerated through merger-driven turbulence in the magnetised ICM (see e.g. Brunetti et al. 2001; Buote 2001; Petrosian 2001; Petrosian & East 2008; Cassano et al. 2012b). An alternate model is that of hadronic origin (see e.g. Denison 1980; Dolag & Enßlin 2000). In this secondary model, electrons are generated as secondary products of collisions between cosmic ray protons and ICM protons. Pions, a product in these proton-proton collisions, produce the electrons that will be accelerated by magnetic fields, as well as γ-rays. This model not only requires γ-ray emission from clusters, but also that all galaxy clusters host radio haloes. The synchrotron emission from electrons produced through these proton-proton collisions will be significantly weaker than that seen through re-acceleration via turbulence (Blasi & Colafrancesco 1999). So far only upper limits for γ-ray emission have been presented (Prokhorov & Churazov 2014), and with current generation radio telescopes, the necessary sensitivity to detect haloes generated through the secondary model only has not been reached. The primary and secondary models are not mutually exclusive, and there has been work to combine the two models (e.g. Brunetti & Blasi 2005; Brunetti & Lazarian 2011, 2016). The primary model is observationally supported by the fact that only clusters with strong X-ray emitting cores are known to have radio haloes. However radio halo detection had been biased toward those clusters hosting highly X-ray luminous plasma as these are the clusters often targeted (e.g. Giovannini et al. 1999; Venturi et al. 2007, 2008; Kale et al. 2013, 2015). Only recently have surveys been conducted to search for diffuse cluster emission without preselecting clusters based solely on their X-ray luminosities. For example, Bernardi et al. (2016) select clusters based on mass, and Shakkouri et al. (2016) survey clusters over a wide range of X-ray luminosities.

Given the comparative rarity of diffuse cluster emission detection, we wish to perform larger surveys to properly ascertain the incidence and nature of these types of radio emission. In this paper we present the results of one such survey using deep 45° × 45° image produced by the MWA as part of the MWA Epoch of Reionization (EoR) project (Bowman et al. 2013; Offringa et al. 2016). This study forms the pilot for a larger search for diffuse cluster emission (Johnston-Hollitt et al. in prep.) using the recently released GaLactic and Extragalactic All-sky MWA survey (GLEAM; Wayth et al. 2015), which covers the entire southern sky below a declination of +25° and covers the frequency range 72–231 MHz. In the following sections we discuss the image and the process involved in searching for diffuse cluster emission.

This paper unless otherwise stated assumes a flat ΛCDM cosmology with $H_0 = 68\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$.

## 2 THE SEARCH FOR DIFFUSE CLUSTER EMISSION

### 2.1 The Epoch of Reionization 0-hour field

As part of the MWA EoR project Offringa et al. (2016) present a 45° × 45° image centred on $(\alpha_{2000}, \delta_{2000}) = (00\,\text{h} 00\,\text{min}, –27\,\text{deg})$, at a frequency of 168 MHz called the EoR0 field. This image is obtained from 45 hours of integration and has a resolution of 2.3 arcmin. The EoR0 field is the deepest, confusion limited image made with the MWA. In addition to the overall sensitivity, the MWA boasts a large number of short baselines, giving it an unprecedented low surface brightness imaging capability. Fig. 1 shows the number of baselines smaller than a given separation for the MWA. In particular, the large number of short ($\leq 60$ m) baselines makes the MWA a powerful tool to investigate extended, diffuse emission, as the shorter baselines of an interferometric telescope provide sensitivity to large-scale structure. Data collection, reduction, and imaging for the field used here is explained in detail in Offringa et al. Whilst the primary
purpose of the EoR0 field is the study of EoR, the image itself is incredibly sensitive, reaching near the centre of the image down to \(-3.2\,\text{mJy beam}^{-1}\) and increasing out towards the edges and in particular corners up to \(-100\,\text{mJy beam}^{-1}\). This surface brightness sensitivity makes the EoR0 field useful in the search for steep spectrum cluster haloes and relics. The R.A. and decl. range used here is as follows: \((-337.48^\circ \leq \alpha_{2000} \leq 22.49^\circ)\) and \((-44.69^\circ \leq \delta_{2000} \leq -08.61^\circ)\), which is chosen to cut out the most significant noise in the corners and edges of the image.

2.2 Catalogues of galaxy clusters

Within the EoR0 field we searched for diffuse emission within a \(-2\,\text{Mpc}\) radius around clusters within the following catalogues: Abell revised North, South, and Supplementary (Abell et al. 1989, hereafter ACO, but see also Abell 1958) catalogues with 5250 clusters; the Meta-Catalogue of X-ray detected Clusters of galaxies (Piffaretti et al. 2011, hereafter MCXC), with 1743 clusters; the Planck X-ray detected Clusters of galaxies (Piffaretti et al. 2011, hereafter PSZ1), with 1227 clusters. Between the three catalogues there is significant overlap, but within the region encompassed by the EoR0 field, and excluding those clusters that lie too far to the edge of the image, this constitutes 668 unique clusters, 505 unique to ACO, 70 unique to MCXC, and 19 unique to PSZ1, with 24 clusters present in all three catalogues. Fig. 2 shows the distribution of ACO, PSZ1, and MCXC clusters within the EoR0 field, showing also their redshifts where available.

All clusters are checked systematically for diffuse cluster emission except 217 clusters in the ACO catalogue without a redshift. For clusters without a redshift we are unable to determine the projected linear distance from the cluster centre, which makes determining if emission is part of the cluster difficult if not at a the centre. Whilst this does not pose much problem for haloes, we also consider that ACO clusters without a redshift are unlikely to have auxiliary data in the form of cluster mass, X-ray luminosities, or information on cluster members. We do note, however, that a subset of the PSZ1 cluster do not have a measured redshift though they are searched regardless as they have auxiliary measured properties. Further, cluster emission serendipitously found in clusters not part of the aforementioned catalogues is investigated when noticed.

2.3 Source detection and measurement

2.3.1 Manual source-finding: eyeballing galaxy clusters

While source-finding algorithms exist and are put to good use to produce point-source catalogues, automated source-finding can miss the extended, low surface brightness haloes and relics within clusters. Therefore the EoR0 field is searched by eye for diffuse emission. Auxiliary radio data exists in the form of the following sky surveys: the NRAO VLA Sky Survey \(^2\) (NVSS; Condon et al. 1998), the Sydney University Molonglo Sky Survey (SUMSS; Bock et al. 1999; Mauch et al. 2003), the TFIR GMRT Sky Survey \(^3\) (alter-

\(^2\) National Radio Astronomy Observatory Very Large Array Sky Survey

\(^3\) Tata Institute of Fundamental Research Giant Metrewave Radio Telescope Sky Survey.
nate data release, TGSS; Intema et al. 2016), and the VLA Large Sky Survey redux (VLSSr; Lane et al. 2014). These surveys and their salient properties are summarised in Table 1. Beyond radio surveys, we use the RÖntgen SATellite (ROSAT; Trümper 1984) All-Sky Survey (RASS; Voges et al. 1999); the Digitized Sky Survey (DSS2), as well as archival Chandra data with the Advanced CCD Imaging Spectrometer (ACIS) instrument and XMM-Newton data with the European Photon Imaging Camera (EPIC) instrument, where available. For a small selection of clusters, we utilise deep (> 30 ks exposure) X-ray images from the Representative XMM-Newton Cluster Structure Survey (REXCESS; Böhringer et al. 2007; Pratt et al. 2009).

To determine the nature of detected emission, we look for the following:

(i) high-frequency counterparts (1.4 GHz and 843 MHz),
(ii) low-frequency counterparts (147.5 and 74 MHz),
(iii) optical identifications, and
(iv) X-ray emission coincident with centrally located radio emission.

(i) and (ii) are used as an easy method of checking if we are looking at blended point sources. (i) gives a quick insight into the spectral index of the source, with significant high frequency emission, at least comparably to 168 MHz, a flat spectral index is present which is very uncharacteristic of diffuse cluster emission, (iii) is important as cluster haloes and relics are not associated with an optically visible galaxy, though in the case of cluster haloes there is expected to be a concentration of optically visible galaxies as the halo should be centrally located. If an optically visible galaxy is found at the peak of the diffuse emission or between two lobes, then the likelihood is that of extended, disturbed, or otherwise normal lobes of a radio galaxy. (iv) allows us to confidently classify centrally located diffuse emission as a cluster halo or relic. In particular, Chandra or XMM-Newton observations are detailed enough to provide the position and any elongation of the X-ray emission relative to any centrally located diffuse radio emission. With these points forming the foundations of our search, we eyeballed the subset of clusters described in Sec. 2.2 and noted emission that would fall into the category of either halo or relic. Once these objects are found, we wish to look at their spectral properties, including their integrated flux densities over the entire surface of the emission and the associated SED and spectral indices.

2.3.2 Noise

The EoR0 field is a large image that has greatly varying rms noise throughout. However, corners of the image feature heavy noise due to the primary beam null. Offringa et al. (2016) use BANE 4, a tool that is packaged with the source-finding software, AEGEAN (Hancock et al. 2012), to estimate noise throughout the EoR0 field. The mean noise level is calculated to be $3.2 \pm 0.6 \text{ mJy beam}^{-1}$ for the central 10° of the image. Large-scale diffuse structure of Galactic origin is seen streaking the image which leads to non-constant background signal affecting rms noise calculations. In regions with no Galactic emission the rms can be seen to be as low as $\sim 2 \text{ mJy beam}^{-1}$.

It is also vital to carefully estimate local noise in any ancillary data used at the position of any emission as we are looking at objects that often have emission at or barely above the $3\sigma_{\text{rms}}$ level at 168 MHz. Table 1 gives the lower estimate of the rms for each of the surveys, however, as discussed above, this varies significantly over the EoR0 field. For the NVSS and TGSS surveys, to obtain local rms values we simply consult the catalogues (Condon et al. 1998; Intema et al. 2016) and use the local rms noise of the nearest catalogue source. In the case of SUMSS, since no local rms is given in its catalogue (Murphy et al. 2007), we inspect each image and give an estimate of the rms which is usually on the order of 2–4 mJy beam$^{-1}$, depending quite strongly on whether there is a bright source in the field creating significant imaging artefacts. For the VLSSr images, we use 100–500 mJy beam$^{-1}$, again depending on the individual images.

2.3.3 Flux densities

The software that generated the EoR0 field did not, at the time, calculate a correct synthesized beam. As a result, the integrated flux densities across the field will be inconsistent with other radio data. We find that the integrated flux density measurements of the EoR0 field differed by a systematic factor of approximately 30 per cent when compared to the nearly equivalent 162–170 MHz band in the recently released GLEAM survey which is tied to the Baars flux scale (Baars et al. 1977). Fig. 3 shows this discrepancy. Bright point sources are measured with AEGEAN on both the EoR0 field and the 162–170 MHz band, within the central 5 degrees of the EoR0 field. Only sources that fit the following criteria are compared:

(i) $0.1 \leq S_\nu \leq 10 \text{ Jy},$
(ii) $(ab)/(B_{\text{maj}}B_{\text{min}}) < 1.5,$
(iii) sources in each image are within 5 arcsec of each other,

where $a$ and $b$ are the semi-major and semi-minor axes of the

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4 https://github.com/PaulHancock/Aegean/wiki/BANE

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Table 1. Existing sky surveys used as auxiliary data to the EoR0 field.

| Survey     | Frequency (MHz) | Declination (J2000,°) | Resolution $^a$ (arcsec × arcsec) | $\sigma_{\text{rms}}$ (mJy beam$^{-1}$) |
|------------|----------------|-----------------------|-----------------------------------|----------------------------------------|
| EoR0 field | 108            | $-44.69 \leq \delta \leq -08.61$ | $158 \times 158$ | $\geq 2.3$ |
| NVSS       | 1400           | $\geq -40$            | $45 \times 45$ | $\geq 0.45$ |
| SUMSS      | 843            | $\leq -30$            | $-2.2(45 \times 45)$ | $\geq 2$ |
| TGSS       | 147.5          | $\geq -53$            | $-1.5(25 \times 25)$ | $\sim 3.5$ |
| VLSSr      | 74             | $\geq -30$            | $75 \times 75$ | $\geq 100$ |

$^a$ At $\sigma_{J2000} = -27^\circ$. 

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MNRA 000, 1–35 (2017)
fitted ellipses, and $B_{\text{maj}}$, $B_{\text{min}}$ are the semi-major and semi-minor axes of the beam as given in the header of the image which may introduce non-point sources, though we use this only as a test to see the integrated flux density discrepancy. No sources were detected in this region above 3.5 Jy. Uncertainties are only applied to the flux densities in the 162–170 MHz GLEAM band, though are the quadrature sum of all uncertainties applicable – i.e. the uncertainty in the fitting by AEGEAN and the flux density scale uncertainties inherent to GLEAM and the EoR0 field. The fitting is a weighted least-squares fit, with resulting equation, however we do not use this scale for calibration.

To scale the integrated flux densities in the EoR0 field we choose six reasonably bright (2–6 Jy) unresolved sources, exhibiting no side-lobe structure and no blending with nearby sources. Fig. 4 shows the six calibrators with predicted 168 MHz flux density against measured flux density. From the resultant fit we find a factor 0.69 ± 0.05 to be used for calibration of measured integrated flux densities, and this calibration is used through the remainder of this paper. We note that the synthesized beam of the 162-170 MHz GLEAM image would be nearly identical to that expected of the EoR0 field.

Flux densities of sources are either calculated by purpose-built PYTHON code or simply using AEGEAN if sources are blended, as the aforementioned PYTHON code does not fit sources, and assumes each source is discrete. Both methods measure the source flux densities down to the 2.6σ$_{\text{rms}}$ level so as to include as much real contribution from the faint sources as possible (e.g. Kapinska et al. 2017, but see also Hales et al. 2012). We do not use AEGEAN for all sources as AEGEAN is intended as a point-source–finder, and will give the best results measuring such sources. Each flux measurement has an uncertainty, $\sigma_{S_{\nu}}$, calculated as

$$\sigma_{S_{\nu}} = (0.05 \times S_{\nu})^2 + (0.05 \times S_{\nu})^2 + (\sigma_{\text{rms}} \sqrt{N_{\text{beam}}})^2 \text{ [Jy]}.$$  

where $N_{\text{beam}}$ is the number of beams crossing the extended source. The first term in Eq. 1 is an additional uncertainty added due to flux density scaling in the EoR0 field as described in Section 4.1 of Offringa et al. (2016), the second term is the additional uncertainty in rescaling the integrated flux density measurements, and the third term is a standard error given to flux density measurements of extended sources.

### 2.3.4 Spectral indices and source sizes

Spectral indices of sources are calculated in one of two ways, depending on the number of available measurements. The first method involves approximating a straight line between two flux density measurements at different frequencies, e.g. 168 and 1400 MHz, which gives an estimation of the spectral characteristics in that frequency range. A more robust method requires measurements at more than two frequencies. In these cases the spectral index is estimated by weighted least squares fitting to the flux and frequency data in logarithm space, hence fitting a power law to the spectra. We follow fitting recipes present in Hogg et al. (2010), and extend these to be unbiased in estimating the uncertainty in the fitting parameters (see Wolberg 2006, pp. 50–51 and references therein). While the spectral energy distribution of many astronomical sources (see e.g. Jaffe & Perola 1973,
are not typically well described by a simple power law, over the frequency range here (74–1400 MHz) haloes and relics tend not to show any turnovers or breaks typically do not deviate from the assumed power law except in rare instances (e.g. the relic in Abell 2443 which has a break near 325 MHz reported by Cohen & Clarke 2011).

In parts of this work we estimate limits to flux densities where none is seen in an image. In particular, we use this for estimating 1.4 GHz and 147.5 MHz limits when 168 MHz emission has no counterpart in the NVSS or TGSS survey images, respectively. These are used then to impose limits on the spectral indices. For such sources, we estimate the source area at 168 MHz, which is a function of the MWA beam at $B_{\text{maj}} \approx 2.3$ arcmin, and attempt to correct for the difference in beam sizes between the VLA (NVSS), GMRT (TGSS), and MWA (EoR0) by naively taking the ratios of $B_{\text{maj}}$ and correcting the area based on this ratio. The limit is then

$$S_{\text{lim}} = \sigma_{\text{rms}} f A_{168} \times \frac{4 \ln 2}{\pi B_{\text{maj}} B_{\text{min}}} \text{[Jy]},$$

(2)

where $f = B_{\text{maj}} / B_{\text{maj.168}}$ and $A_{168}$ is the source area measured at 168 MHz.

The in-house Python code used also calculates the largest angular scale (LAS) of a source by comparing the angular separation between boundary pixels of a source. This is only possible for sources that are discrete and show no blending. For such sources, we estimate an angular size by making an assumption on how far the diffuse source blends into any nearby point sources. The size characterisation is important to determine if the detection is truly extended. For a non-blended source to be considered extended in this work it must have an LAS that is greater than $1.5 B_{\text{maj}}$, where $B_{\text{maj}} \approx 2.3$ arcmin, which is approximately the expected $B_{\text{maj}}$ of the EoR0 field.

3 RESULTS

3.1 Diffuse cluster emission at 168 MHz

Here we present the diffuse emission detected in the EoR0 field from the ACO, PSZ1, and MCXC catalogues. We detect 34 objects of interest, of which 29 are likely relics, phoenices, or haloes associated with 25 clusters. The detection rate for such emission within the EoR0 field is $\sim 6.4$ per cent, which on average is lower than previous surveys, (e.g. $\sim 32$ per cent: Venturi et al. 2007, 2008, $\sim 17$ per cent: Bernardi et al. 2016, $\sim 12$ per cent: Shakouri et al. 2016), however as mentioned, previous surveys target the most massive, and X-ray luminous clusters. Included are previously detected relics in Abell 0013, Abell 0085, and Abell 2744 (Slee & Reynolds 1984; Slee et al. 2001; Govoni et al. 2001), phoenices in Abell 0133 and Abell 4038 (Slee & Reynolds 1984; Slee & Roy 1998; Slee et al. 2001), haloes in Abell 2744 and MACS J2243.3-0935 (Govoni et al. 2001; Cantwell et al. 2016), as well as the large, ambiguous emission seen in Abell 0133 (Randall et al. 2010). Included are also 5 radio galaxies on first pass thought to be possible relic, phoenix, or halo candidates. For the purpose of distinguishing between relics and phoenices, we place a limit of 400 kpc as a maximum size of phoenix.

Where emission scale approaches this size we look at the spectral index and location, where a linear size approaching 400 kpc with ultra-steep spectral indices ($\alpha < -1.5$, Kempner et al. 2004) and a location closer to the cluster’s centre would be suggestive of phoenices rather than relics. Table 2 summarises the results of the diffuse emission search. Following this, Section 3.2 describes each cluster along with the diffuse emission detected within it. Images featuring optical DSS2 backgrounds are three-colour images with red, green, and blue corresponding to infrared, red, and blue respectively unless otherwise stated.
Table 2. List of diffuse emission presented in this paper. The order here is that of Section 3.2. Columns: (1) cluster or object name, (2) cluster redshifts, rounded to a standard three decimal places for clarity (precise redshifts are given in Section 3.2 upon discussion of each cluster), (3) classification (H: radio halo; R: radio relic; P: radio phoenix; RG: individual or blended radio galaxy; U: undecided – requires further information; C: candidate object), (4) new detections shown as a checkmark and previously detected objects shown as a cross, (5) and (6) flux weighted average right ascension and declination of the emission, or peak flux density position if using AREGAN, (7) 168 MHz flux density, (8) spectral index, (9) largest angular size, which should be taken with an added uncertainty of half a beamwidth (~2.3/2 arcmin) due to measuring boundary pixels and limitations of resolution, (10) largest linear size at cluster reddish, and (11) detection threshold for flux density measurements and detection. At or above 3σ₁₆₈, except in the case of MACS J2243.3-0935, which is approximately 2σ₁₆₈.

| Cluster          | Redshift | Type | New | α₂₀₀₀ | δ₂₀₀₀ | S₁₆₈ (mJy) | α₁₆₈  | LAS  | LLS  | Det. threshold (mJy beam⁻¹) |
|------------------|----------|------|-----|-------|-------|------------|-------|-----|-----|-----------------------------|
| Abell 0013        | 0.094    | R    | ×   | 003.37 | -19.50 | 1850 ± 132 | α₁₆₈  = -1.96 ± 0.08 | 6.7  | 750 | 7  |
| Abell 0022        | 0.142    | cH or cR | ✓ | 005.16 | -25.66 |            |       |      |     | 9  |
| Abell 0033        | 0.234    | RG or R  | ✓ | 006.89 | -19.54 | 25.5 ± 4.6 | -8.1(±1.4) ≤ α₁₄₇₅ ≤ -0.48(±0.09) | 6.72 | 1570 | 6.9 |
| Abell 0085        | 0.055    | R    | ×   | 010.38 | -09.37 | 9385 ± 987 | α₃₀₀  = -1.85 ± 0.03 | 7.1  | 470 | 72 |
| Abell 0122        | 0.113    | RG   | ✓   | 014.35 | -26.29 | 329 ± 25  | α₃₀₀  ≤ -1.52 ± 0.04 | 4.9  | 620 | 12 |
| Abell 0133        | 0.057    | P    | ×   | 015.67 | -21.87 |            |       |      |     | 15 |
| Abell 0141        | 0.230    | H    | ✓   | 016.39 | -24.64 | 110 ± 11  | α₁₆₈  ≤ -2.1 ± 0.1 | 5.51 | 1250 | 10 |
| Abell 2496        | 0.122    | cR   | ✓   | 342.72 | -16.45 | 561 ± 42  | α₁₆₈  = -1.26 ± 0.02 | -4.8 | -650 | 15 |
| Abell 2556        | 0.087    | cP   | ✓   | 348.30 | -21.47 | 29.3 ± 5.5 | α₁₆₈  = -1.22 ± 0.14 | 3.33 | 336 | 10 |
| Abell 2680        | 0.177    | cH   | ✓   | 059.13 | -21.04 | 23 ± 8   | α₃₀₀  ≤ 1.2 ± 0.2 | -3.2 | -600 | 7  |
| Abell 2693        | 0.173    | cH   | ✓   | 000.56 | -19.55 | 49.6 ± 6.0 | α₃₀₀  ≤ -0.88 ± 0.06 | 3.75 | 681 | 6.9 |
| Abell 2721        | 0.114    | cR   | ✓   | 001.56 | -34.73 | 54 ± 14  | α₃₀₀  ≤ -0.96 ± 0.12 | -4.1 | 460 | 10 |
| Abell 2744        | 0.307    | R    | ×   | 003.58 | -30.39 | 550 ± 51 | α₁₆₈  ≠ -1.11 ± 0.04 | -7.27 | -2030 | 10 |
| Abell 2751        | 0.107    | R    | ✓   | 004.23 | -31.39 | 324.9 ± 61.4 | -       | -   | -   | 7  |
| APMCC 039         | 0.082    | RG   | ✓   | 004.46 | -31.31 | 60.3 ± 7.7 | 0.28(±0.09) ≤ α₁₄₇₅ ≤ -0.43(±0.06) | 8.816 | 840.8 | 7  |
| Abell 2798        | 0.105    | cR   | ✓   | 009.41 | -28.51 | 110.3 ± 9.4 | α₁₆₈  = -1.18 ± 0.08 | 4.84 | 575 | 7  |
| Abell 2811        | 0.108    | H    | ✓   | 010.54 | -28.53 | 80.7 ± 16.5 | α₃₀₀  ≤ -1.5 ± 0.1 | -4.13 | -502 | 7  |
| Abell 4038        | 0.028    | P    | ×   | 356.92 | -28.15 | 4875 ± 249 | -       | -   | -   | 20 |
| GMBCG J357.91841-08.97978 | 0.108 | cH | ✓ | 012.33 | -29.51 | 32.3 ± 4.5 | α₁₆₈  ≤ -1.3 ± 0.1 | 4.19 | 511 | 7  |
| Abell 50084       | 0.110    | U    | ✓   | 348.27 | -23.14 | 184 ± 20  | α₁₆₈  = -1.00 ± 0.15 | -4.3 | -1300 | 15 |
| Abell 51099       | 0.358    | H    | ✓   | 351.31 | -41.21 | 154 ± 48  | α₁₆₈  ≤ -2.8 ± 0.17 | -2.8 | -670 | 10 |
| Abell 51121       | 0.063    | U    | ✓   | 354.08 | -31.61 | 586 ± 46  | α₁₆₈  ≤ -2.8 ± 0.17 | -2.8 | -670 | 10 |
| PSZ1 G307.55-77.87 | 0.453 | cH | ✓ | 011.58 | -39.21 | 19 ± 19  | α₁₆₈  ≤ -1.4 ± 0.1 | -3.64 | -1200 | 15 |
| RXC J3251.0-1945 | 0.248    | cR   | ✓   | 357.76 | -19.94 | 87 ± 17   | α₃₀₀  ≤ -1.4 ± 0.1 | -2.8 | -670 | 10 |
| RXC J3251.0-1945 (A) | 0.248 | cR | ✓ | 357.87 | -19.99 | 56.9 ± 8.6 | α₃₀₀  ≤ -1.23 ± 0.07 | 6.25 | 1500 | 10 |
| RXC J3251.0-1945 (B) | 0.248 | cR | ✓ | 357.59 | -19.81 | 147 ± 13 | α₃₀₀  ≤ -1.68 ± 0.04 | 5.87 | 1410 | 10 |
| MACS J2243.3-0935 | 0.447 | H | × | 340.86 | -09.59 | 83 ± 36 | α₃₀₀  ≤ -1.6 ± 0.4 | -2.8 | -1000 | 60 |
| GMBCG J357.91841-08.97978 | 0.394 | cH | ✓ | 357.91 | -08.98 | 128 ± 20 | α₃₀₀  ≤ -1.62 ± 0.10 | - | - | 10 |
| Abell S1063      | 0.348    | RG   | ✓   | 342.19 | -44.51 | 265 ± 38 | α₃₀₀  ≤ -1.36 ± 0.11 | -5.5 | -1670 | 50 |

- Reported by Slee & Reynolds (1984).
- Assuming a redshift of z = 0.2395.
- Assuming a redshift of z = 0.3850.
- Assuming a redshift of z = 0.4530.
- Reported by Cantwell et al. (2016).
- We consider GMBCG J357.91841-08.97978 and WHL J235151.0-0.085929 to be the same cluster.
- The emission is comprised of blended radio sources, all likely radio galaxies.
3.2 Individual galaxy clusters

3.2.1 Abell 0013

The cluster Abell 0013 (MCXC J0013.6-1930; PSZ1 G072.48-78.46) has mass $M_{\text{YZ,500}} = 2.79^{+0.36}_{-0.38} \times 10^{14}$ M$_\odot$ (PSZ1), a redshift of $z = 0.0940$, and X-ray luminosity $L_{500} = 1.23633 \times 10^{47}$ W (MCXC). Slee & Reynolds (1984) report the detection of a steep-spectrum radio relic after 1.465 GHz and 4.885 GHz VLA imaging. Slee et al. (2001) provide further VLA observations at 1.425 GHz of the emission to show its filamentary structure. The left panel of Fig. 5 shows an RGB image with MWA, NVSS, and TGSS contours overlaid. The steep spectrum relic is recovered in the MWA image, labelled as ‘A’ in the figure, and extends beyond what is expected due to the difference in resolution. The flux density at 168 MHz is measured to be $S_{\text{168}} = 1.850^{+0.132}_{-0.125}$ Jy, with an LAS of 6.7 arcmin and largest linear scale (LLS) at the cluster’s redshift of 750 kpc. Within the NVSS catalogue the source is split into two components: NVSS J001332-193003 and NVSS J001326-192950. These sources are reported to have flux densities of 10.7 ± 2.1 mJy and 18.0 ± 2.0 mJy respectively (Condon et al. 1998). With comparison to Fig. 2 of Slee et al. (2001) we conclude that both of these NVSS sources are a single source and so add them to arrive at a flux density of $S_{1.4} = 28.7 \pm 4.1$ mJy for the emission. We calculate a spectral index between the 1.4 GHz and 168 MHz measurements as $\alpha_{1.465} = -1.96 \pm 0.08$. Such a steep spectral index, along with apparent proximity to the cluster’s core is suggestive of a radio phoenix, however at the projected size of 750 kpc this becomes too large for small-scale turbulence to re-accelerate electrons. This size is indicative of a radio relic. It is entirely possible the relic is further on the periphery, only appearing close to the centre due to projection effects. Slee et al. (2001) report the spectral index between 1.465 GHz and 1.385 GHz to be $\alpha_{1.385} = -4.4 \pm 0.4$. Due to the resolution of the these observations, it is likely the relic has not been detected in its entirety, resulting in flux being resolved out of the VLA images and resulting in an overly steep spectral index. Slee et al. provide high resolution 1.4 GHz analyses of the relic, showing the structure that is traced by the TSGSS and NVSS emission as in the left panel of Fig. 5. They consider the possibility of the diffuse emission being old lobes of one of the optically visible cluster members near the core. They identify the most probable host as the brightest cluster galaxies (BCG) 2MASX J00133401-1929017 and 2MASX J00133853-1930007 with redshifts $z = 0.099272 \pm 0.000217$ and $z = 0.090529 \pm 0.000157$ (Quintana & Ramirez 1995) respectively.

The right panel of Fig. 5 shows exposure corrected, smoothed XMM-Newton data (Obs. ID 0201900301, PI Börhringer), which were taken and reduced as part of the REXCESS survey (Börhringer et al. 2007; Pratt et al. 2009). The 168 MHz radio emission extends far beyond the X-ray emission, however it is likely the bulk of the halo sits coincident with the X-ray peak, but is blending with DUKST 473-042, which has a spectroscopic redshift of $z = 0.63821 \pm 0.00050$ (Ratliffe et al. 1998) and is seen in the centre of the field. We cannot unambiguously classify the extended emission as either a candidate halo, relic, or both, if not the extended emission from a radio galaxy. We suggest follow-up observations at a higher resolution to disentangle the point sources from the diffuse radio emission.

3.2.2 Abell 0022

The cluster Abell 0022 (MCXC J0020.7-2542; PSZ1 G042.77-82.97) has a redshift of $z = 0.142352 \pm 0.000327$ (Pinbloot et al. 2006), mass $M_{\text{YZ,500}} = 4.56^{+0.42}_{-0.44} \times 10^{14}$ M$_\odot$ (PSZ1), and X-ray luminosity $L_{500} = 2.87245 \times 10^{47}$ W (MCXC). The cluster features extremely diffuse, faint emission that appears to permeate the cluster. Fig. 6 shows the emission extending from the centre of the cluster northward. Although we see from the NVSS and TGSS data that the MWA emission is coincident with three point sources: NVSS J002042-254239, associated with a member of the intervening galaxy triple DUKST 473-042; NVSS J002048-254437; and NVSS J002058-253957, emission associated with the cluster member 2MASX J00205811-2539516. The MWA data extends considerably further north reminiscent of the cluster halo in Abell 3888 (Shakouri et al. 2016). We do not obtain a flux density measurement for the extended emission as it blends into the emission from 2MASX J00205811-2539516, which has a flux density contribution that we are unable to subtract as there is neither significant emission seen at 1.4 GHz in the NVSS image, nor in the 147.5 MHz emission in the TGSS image.

XMM-Newton data is shown in the right panel of Fig. 6 (Obs. ID 0201900301, PI Börhringer), which were taken and reduced as part of the REXCESS survey (Börhringer et al. 2007; Pratt et al. 2009). The 168 MHz radio emission extends far beyond the X-ray emission, however it is likely the bulk of the halo sits coincident with the X-ray peak, but is blending with DUKST 473-042, which has a spectroscopic redshift of $z = 0.63821 \pm 0.00050$ (Ratliffe et al. 1998) and is seen in the centre of the field. We cannot unambiguously classify the extended emission as either a candidate halo, relic, or both, if not the extended emission from a radio galaxy. We suggest follow-up observations at a higher resolution to disentangle the point sources from the diffuse radio emission.

3.2.3 Abell 0033

Fig. 7 shows curious emission on the periphery of both Abell 0033 ($z = 0.28$, photometric; Leir & van den Bergh 1977) and WHL J002712.5-193045 ($z = 0.2395$, spectroscopic; Wen & Han 2013). The white circles in Fig. 7 have 1 Mpc radii about the cluster centres. The two clusters are separated by an angular distance of ~80 arcsec, and given the clear concentration of optical galaxies seen in the DSS2 images, they are likely the same cluster and we hereafter consider there to be only Abell 0033 at the redshift of $z = 0.2395$. The grey, dashed contour in Fig. 7 is at the 2$\sigma_{\text{rms}}$ level to indicate the possibility of the two objects, Obj. A and B,
being a single piece of extended emission on the cluster periphery. If this is the case, the entire structure has a flux density of $S_{168} = 25.5 \pm 4.6 \text{ mJy}$, and an LLS is 6.72 arcmin which translates to an LLS of 1570 kpc at $z = 0.2395$. Both the NVSS and TGSS surveys do not show significant emission within the area of the 168 MHz emission. From this we provide upper limits on the 1.4 GHz and 147.5 MHz flux densities of $S_{1.4} \leq 10 \text{ mJy}$ and $S_{147.5} \leq 73 \text{ mJy}$. This gives a limit on the spectral index between 147.5 MHz and 1.4 GHz of $-8.1(\pm1.4) \leq \alpha_{147.5} \leq -0.44(\pm0.09)$, assuming a simple power law to the SED. This range of spectral indices is consistent with either typical radio galaxies of $\alpha = -0.8$ (Condon 1992), the steep spectrum cluster relics (e.g. de Gasperin et al. 2014), or even the dying radio galaxies often found within clusters (e.g. Murgia et al. 2011) and so is not definitive for classification purposes.

Upon inspection of the optical data, two possible optical IDs are found and highlighted with boxes in Fig. 7. There is an optically visible source reported in the USNO-A2.0 catalogue, USNO-A2.0 0675-00178746, sitting between A and B. The RGB image of Fig. 7 shows significant reddening of this optical source, consistent with a high redshift. The shape of the emission is then reminiscent of the lobes of a radio galaxy and the overall morphology is similar to the dead radio galaxy associated with NGC 1534 recently discovered by the MWA (Hurley-Walker et al. 2015), with faint lobes and steep spectral indices as ancient remnants of old episodes of AGN activity. However, Obj. A has an optically visible galaxy, GALEXASC J002737.37-192909.3, near its centre and so could be associated with it. In this case, Obj. B is unlikely to be associated with Obj. A and may be a cluster radio relic. We offer these possibilities as the origins of this emission, but cannot classify the emission definitively. Note that the LLS presented in Table 2 assumes Obj. A and B are a single source and associated with the cluster with a redshift of $z = 0.2395$.

### 3.2.4 Abell 0085

Abell 0085 (MCXC J0041.8-0918; PSZ1 G115.20-72.07) has a redshift of $z = 0.055061 \pm 0.000340$ (Oegerle & Hill 2001) with mass $M_{300} = 4.90_{-0.22}^{+0.21} \times 10^{14} \text{ M}_\odot$ (PSZ1) and X-ray luminosity $L_{500} = 5.100085 \times 10^{43} \text{ W}$ (MCXC). Slee & Reynolds (1984) report the detection of a phoenix offset from the cluster centre, and Giovannini & Feretti (2000) provide follow-up 300 MHz imaging with the VLA and ascertain an LLS for the source of 386 kpc (corrected for this cosmology). 168 MHz emission coincides with the previously detected phoenix (Obj. A in Fig. 8), and has an approximate LLS of 470 kpc. With this size we hereafter refer to the source as a relic. To obtain the flux density of the relic in Abell 0085 we use aEGEAN with a seedclip of 3 and floodclip of 2 and find $S_{168} = 9.385 \pm 0.957 \text{ Jy}$. 1.4 GHz emission from the NVSS traces the relic as described by Slee et al. (2001) The TGSS shows 147.5 MHz emission beyond that of the NVSS despite similar resolutions with an extended structure to the southeast, tracing the emission at 300 MHz shown by Giovannini & Feretti. This extension is also encompassed by the 168 MHz emission. We do not use the 1.4 GHz flux density from the NVSS as a large portion of the relic is undetected. Rather, we use the 147.5 MHz TGSS image and measure a flux density of $S_{147.5} = 10.21 \pm 0.07 \text{ Jy}$. We use the 300 MHz measurement of $S_{300} = 2.739 \text{ Jy}$ (Giovannini & Feretti 2000) though include a 10 per cent uncertainty as no uncertainty is quoted by Giovannini & Feretti. Thus, we calculate...
Figure 6. Diffuse emission within Abell 0022. Left: RGB image with contours overlaid as follows: EoR0, white, beginning at 7 mJy beam$^{-1}$ increasing by a factor of $\sqrt{2}$; NVSS, red, beginning at 1.5 mJy beam$^{-1}$ increasing by a factor of 2; TGSS, medium purple, beginning at 21 mJy beam$^{-1}$ also increasing by a factor of 2. The dashed circle is centred on the cluster with a radius of 1 Mpc. Right: X-ray image from the REXCESS survey with EoR0 contours overlaid as in the left panel along with X-ray contours increasing with a factor of 2 in black.

Figure 7. Candidate relic on the periphery of Abell 0033. The background is an RGB image with contours overlaid as follows: EoR0, white, $3\sigma_{\text{rms}}$ beginning at 6.9 mJy beam$^{-1}$ increasing by a factor of $\sqrt{2}$ and grey, dashed, $2\sigma_{\text{rms}}$ at 4.6 mJy beam$^{-1}$; NVSS, red, beginning at 1.5 mJy beam$^{-1}$ increasing by a factor of 2. No TGSS emission is seen above the $3\sigma_{\text{rms}}$ level of 25.8 mJy beam$^{-1}$. The dashed circle is centre on the position of Abell 0033 and the dotted circled is centred on WHL J002712.5-193045, both with radii Mpc at the reported redshifts. They are suspected to be the same cluster (see main text). The boxes indicate possible optical IDs for the diffuse emission.

3.2.5 Abell 0122

Abell 0122 (MCXC J0057.4-2616), with a redshift of $z = 0.113478$ (Zaritsky et al. 2006), mass $M_{\text{X, 500}} = 1.7267 \times 10^{14} \, M_{\odot}$, and X-ray luminosity $L_{\text{400}} = 0.861163 \times 10^{47} \, \text{W (MCXC)}$, features a strong diffuse source at its centre. This candidate radio halo has a flux density of $S_{168} = 329 \pm 25 \, \text{mJy}$ with an LAS of 4.9 arcmin. At the redshift of the cluster the emission has a projected LLS of 620 kpc. There is no significant 1.4 GHz emission seen with the NVSS survey, though the 147.5 MHz TGSS data shows extended emission. The TGSS ADR1 catalogue splits this into two distinct sources with its higher $7\sigma_{\text{rms}}$ cutoff for source detections, compared to Fig 9 which has TGSS contours at the $3\sigma_{\text{rms}}$ level typically a spectral index of $\alpha_{147.5} = -1.85 \pm 0.03$, though note that the TGSS image is likely missing flux due to resolution and missing baselines, which suggests the relic may have an even steeper spectral index.

The radio source to the southeast of the relic (Obj. B in Fig. 8) has extended 168 MHz emission beyond the source seen in the NVSS which is likely associated with the galaxy SDSS J004150.17-092547.4. The TGSS 147.5 MHz data shows two distinct sources within this extended, steep-spectrum emission. The right panel of Fig. 8 shows a zoomed-in view of Obj. B, with MWA contours overlaid on exposure corrected, smoothed XMM-Newton data (Obs. ID 0723802201, PI de Plaa). Obj. B features an extension to the bulk of the X-ray emitting plasma at the cluster’s core. Kempner et al. (2002) suggest that this extension of X-ray emission, along with the complex of radio sources Obj. B, is representative of subcluster asymmetrically merging with the main cluster of Abell 0085.

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Figure 8. Abell 0085. Left: The background is an RGB image with contours overlaid as follows: EoR0, white, beginning at 49.7 mJy beam$^{-1}$ increasing by a factor of $\sqrt{2}$; NVSS, red, beginning at 1.5 mJy beam$^{-1}$ increasing by a factor of 2; TGSS, medium purple, beginning at 9.6 mJy beam$^{-1}$ also increasing by factor of 2. Right: Exposure corrected, smoothed XMM-Newton image with EoR0 contours overlaid as in the left panel. Note that the right panel has a smaller field of view and is centred to show the subcluster “A”. Both panels show the linear scale at the cluster’s redshift.

Figure 9. Steep-spectrum emission at the centre of Abell 0122. Left: The background is an RGB image with contours overlaid as follows: EoR0, white, beginning at 12 mJy beam$^{-1}$ and increasing by a factor of $\sqrt{2}$; NVSS, red, beginning at 1.5 mJy and increasing by a factor of 2; TGSS, medium purple, beginning at 13.5 mJy also increasing by a factor of 2. The linear scale is at the cluster’s redshift. Right: Exposure corrected, smoothed XMM-Newton image with 168 MHz contours overlaid as in the left panel. The dashed circle is centred on Abell 0122, and has a radius of 1 Mpc.
the spectral index of \(X\text{MM-Newton}\) smoothed MHz (et al. 2006). However the 147.5 MHz plasma as is typical of cluster radio haloes and the location, GHz a 1.4 necessary for faint diffuse emission detections. We provide mJy beam image with contours overlaid as follows: EoR0, white, beginning at 15 mJy beam\(^{-1}\) increasing with a factor of \(\sqrt{2}\); NVSS, red, beginning at 1.5 mJy beam\(^{-1}\) and increasing with a factor of 2; TGSS, medium purple, 13.2 mJy beam\(^{-1}\) also increasing with a factor of 2. The linear scale is at the redshift of the cluster, and Obj. A is the diffuse emission of interest.

necessary for faint diffuse emission detections. We provide a 1.4 GHz flux limit of \(S_{1.4} \leq 13\) mJy and a corresponding spectral index of \(\alpha_{1400}^{168} \leq -1.52 \pm 0.04\).

The right panel of Fig: 9 shows exposure corrected, smoothed XMM-Newton data (Obs ID 0504160101, PI Sivanandam). The 168 MHz radio emission fills the X-ray plasma as is typical of cluster radio haloes and the location, steep spectral index, and X-ray emission are suggestive of an ultra-steep spectrum radio halo (USSRH; see e.g. Cassano et al. 2006). However the 147.5 MHz morphology appears to suggest a tailed radio galaxy, or other radio galaxy-related origin. The tailed radio galaxy origin is somewhat hampered by the lack of optical ID coincident with the peak of the 147.5 MHz emission. The BCG, 2MASX J00572288-2616528, lies offset from the peak by approximately 10 arcsec. Given the morphology, steep spectral index, and displacement of an optical host, there exists the possibility that the emission is that of an old, dead radio galaxy, likely associated with the BCG. Abell 0122 shows no evidence in the either X-ray emission or the optical density that would suggest the cluster is undergoing, or had undergone, a merger event. If the turbulent re-acceleration model is correct, a halo in this cluster of this power would be unusual. Given the morphology of the source in the TGSS image, we have classified this emission as a radio galaxy.

### 3.2.6 Abell 0133

Abell 0133 (MCXC J0102.7-2152; PSZ1 G149.55-84.16) has a redshift of \(z = 0.0562\) (Way et al. 1997), X-ray luminosity \(L_{\text{X,500}} = 1.46 \times 10^{57}\) W (MCXC), and mass \(M_{\text{YZ,500}} = 3.08^{+0.23}_{-0.24} \times 10^{14}\) M\(_{\odot}\) (PSZ1). The cluster has been studied extensively in X-ray (e.g. Reichert et al. 1981; Fujita et al. 2002, 2004) along with the multi-wavelength study by Randall et al. (2010) which all point towards the disturbed, dynamic nature of the cluster. Further, steep-spectrum radio emission in the form of a radio phoenix was detected by Slee & Reynolds (1984) ~30 arcsec from the cD, ESO 541-G013. Further high-resolution follow-up observations by Slee et al. (2001) showed filamentary structure to this phoenix. An important result of the X-ray studies show that the X-ray-emitting gas is disturbed, with the possibility of a weak shock creating a tongue-like feature pointing to the northwest (Fujita et al. 2004). This feature coincides with the phoenix reported by Slee & Reynolds (1984).

Fig. 10 shows the cluster centre with the emission of interest, with Obj. A a large, possible lobe, Obj. B the radio phoenix, and the orange square indicating the possible ID for double-lobe-like structure, along with Obj. C, an interesting knot. Randall et al. (2010) discuss the possibility of the entire structure representing a giant, background radio galaxy, with the core and host marked in Fig. 10. As part of this interpretation, the phoenix is thought to be a separate entity, most likely associated with the cluster. We consider an alternative explanation not covered by Randall et al. (2010) where the southern lobe A is in fact a relic. This explanation draws on deep radio observations of 1E 0657-56 (the Bullet Cluster; Liang et al. 2000, 2001; Shimwell et al. 2014, 2015; Srinivasan 2015). Liang et al. (2000) show low resolution radio imaging of the Bullet Cluster, and further X-ray observations provide high resolution imaging to show the directionality of the shock (Markovitch 2006) with clear diffuse emission located to the east of the west-ward X-ray shock. This piece of diffuse emission is considered a relic, created through back-shock of the massive, merging system (Shimwell et al. 2014). We consider the possibility that the extended filament between the northern B and southern A lobes in Abell 0133 is in fact of similar origin. We refer the reader to Figure 6 of Randall et al. (2010), which shows Chandra data overlaid with 1400 and 330 MHz radio data. This shows the potential relic sitting beyond the X-ray emission towards the periphery of the cluster, and the X-ray emission is disturbed which is consistent with many clusters found to host relics. This scenario would suggest that the southern lobe is a relic similar to the bulb portion of the relic in the Bullet Cluster. The locational difference between the possible relic in Abell 0133 and relic in the Bullet Cluster could be simple projection effects. Obj. C in Fig. 10 marks a knot in the filament, clear in the medium purple TGSS contours, and seen in Figure 5(d) of Randall et al. (2010). This has no optical ID so is not necessarily an unassociated point source. In the case of structure being that of a background giant radio galaxy (GRG), there is a requirement that extreme twisting of the core relative to the southern lobe must have occurred, or is in the process of occurring. Whilst such disjoint motion is seen in lobed radio galaxies (e.g. NGC 326: Fanti et al. 1977; Murgia et al. 2001), these galaxies with disturbed lobes typically reside within clusters, where the ICM plays a crucial role in shaping the jets through ram pressure as the galaxy core travels through or precesses within the medium. It may be that the structure is a GRG in a background cluster. The supposed optical host has a redshift of \(z = 0.2930\) (2MASX J01024529-
2154137: Owen et al. 1995; Slee et al. 2001; Randall et al. 2010), however there are no other available redshifts within ~2000 km s^{-1} of z = 0.2930 near 2MASX J01024529-2154137. We find that the 147.5 MHz TGSS contours in Fig. 10 show that the peak of this emission near the core of the GRG does not align with the proposed optical ID, marked with an orange square, though the 1.4 GHz NVSS contours do align well with 2MASX J01024529-2154137. GRGs are found independent of clusters, but the ICM is required for jets to be bent from the axis of the GRG which may be the case here.

We estimate the extent of the diffuse emission within both the relic and radio galaxy interpretations. If the emission is that of a radio galaxy, we find LAS to be 10.4 arcmin, which at z = 0.2930 corresponds to an LLS of 2.82 Mpc and at z = 0.0856 an LLS of 701 kpc. In the relic scenario, we consider the southern lobe to be a relic, and measure the east-west dimensions. The LAS is found to be 6.0 arcmin, which corresponds to an LLS of 405 kpc at the cluster’s redshift. As mentioned, the filament between the core and southern lobe would likely be part of this relic in this scenario, the size of which is difficult to estimate given any additional emission from the cD, the phoenix, as well as the intruding emission likely associated with 2MASX J01024529-2154137. We do not provide any further certainty on the nature of the emission, merely offer the alternate explanation of radio relic akin to that in the Bullet Cluster. In Table 2 we list the phoenix, as well as the ambiguous emission as both a relic and a radio galaxy.

3.2.7 Abell 0141

Abell 0141 (MCXC J0105.5-2439; PSZ1 G175.59-85.95) is a distant cluster with a redshift of z = 0.230 (Struble & Rood 1999). We present a hitherto undetected radio halo at its centre coinciding with the optical mass concentration. The mass and X-ray luminosity are $M_{\text{200}} = 4.49 \pm 0.73 \times 10^{14}$ M$_\odot$ (PSZ1) and $L_{\text{500}} = 5.160525 \times 10^{47}$ W (MCXC). The left panel of Fig. 11 shows the cluster with an RGB image as a background with the 168 MHz contours overlaid to illustrate the radio halo’s location relative to the cluster.

Previous searches for diffuse radio emission in this cluster includes a search by Venturi et al. (2007, 2008) as part of the GMRT Radio Halo Survey (GRHS), in which their 610 MHz images with $1\sigma \text{rms} = 90$ mJy beam$^{-1}$ did not detect anything resembling the emission seen at 168 MHz. They estimate an upper limit to the radio halo power at 610 MHz to be $P_{\text{610}} < 24.07$, which translates to a flux density of $S_{\text{610}} \leq 7.0$ mJy assuming a standard spectral index of $-1.3$. The cluster had been a curiosity due to the lack of a halo as the cluster is undergoing a merger. The right panel of Fig. 11 features a exposure corrected, smoothed XMM-Newton image (Obs. ID 0693010501, PI Zhang) of the cluster wherein the dynamic nature is clearly seen in the bi-modality of the X-ray plasma. Further, the optical concentration of galaxies trace the two X-ray peaks and the elongation of the X-ray emission and 168 MHz radio emission. Dahle et al. (2002) comment on the ill-defined optical centre, noting that the two optical density peaks occur ~2 arcmin apart, with elongation along the north-south axis as seen in the X-ray and radio emission. Thus this new, unambiguous detection of a radio halo in Abell 0141 supports the previous findings in the literature of the association of radio haloes in merging clusters.

The radio halo is measured to have a flux density of $S_{\text{168}} = 110 \pm 11$ mJy and an LLS of 5.51 arcmin, which translates to an LLS of 1.250 Mpc. This LLS puts the radio halo within the class of giant radio haloes (GRH) defined to be greater than 1000 kpc in extent. With the upper limit from Venturi et al. (2008) we conclude that the halo must have a spectral index $\alpha_{168} \geq 2.1 \pm 0.1$. This places the halo within Abell 0141 at least equal in steepness to the halo detected in Abell 0521, which has an average spectral index of $\alpha \approx 2.1$ (Brunetti et al. 2008).

3.2.8 Abell 2496

Abell 2496 (MCXC J2251.0-1624; PSZ1 G047.75-60.16) has a redshift of $z = 0.1221$, an X-ray luminosity of $L_{\text{500}} = 2.030655 \times 10^{43}$ W (MCXC), and mass $M_{\text{200}} = 2.98^{+0.41}_{-0.44} \times 10^{14}$ M$_\odot$ (PSZ1). Fig. 12 shows the centre of the cluster with diffuse emission with an irregular morphology. Assuming that this emission is a single source and that any embedded galaxies do not show significant radio emission, the 168 MHz flux density is measured to be $S_{\text{168}} = 561 \pm 42$ mJy, with an estimated LAS of ~4.8 arcmin translating to an LLS at the cluster’s redshift of ~650 kpc. The radio source is part of the NVSS catalogue as NVSS J225055-162721 from which we obtain the 1.4 GHz flux density of $S_{\text{1.4 GHz}} = 37.7 \pm 2.0$ mJy (Condon et al. 1998). We obtain flux densities from the TGSS and VLSSR catalogues for sources at the position of the halo of $S_{\text{147 MHz}} = 659.4 \pm 67.0$ mJy (Intema et al. 2016) and $S_{\text{3 GHz}} = 1.34 \pm 0.25$ Jy (Lane et al.). With these and our 168 MHz measurement we obtain a spectral index across the frequency range 74–1400 MHz of $\alpha = -1.26 \pm 0.02$. This is consistent with typical cluster halo spectral indices (Peretti et al. 2012), however it is clear the 168 MHz flux density is being measured over a larger area, as well as including more sources, than the 147.5 MHz TGSS and 1.4 GHz NVSS measurements. This is clearly seen in Fig. 12 where there is much more emission to the north of the source, which may be unassociated and is not incorporated in the TGSS and NVSS catalogue values. The emission, while seen in the TGSS and NVSS contours at 3$\sigma_{\text{rms}}$, is not measured for the respective catalogues. Further, due to the higher resolution of the TGSS images, 147.5 MHz flux density measurements of extended emission may be under-estimated due to resolving out flux on larger spatial scales. This has less of an effect in the NVSS images. We note that the TGSS ADR1 has flux density discrepancies, where variations of more than ten per cent are seen within certain parts of the survey. This does not affect all regions within the survey, and in the case of Abell 2496 the flux density in this region does not vary by more than five per cent from the equivalent 151 MHz flux density obtained from the GLEAM survey, present in GLEAM extragalactic catalogue (GLEAM EGC; Hurley-Walker et al. 2017), so we consider the TGSS measurement as accurate on the spatial scales it samples. The bulk of the radio emission is offset from the X-ray emission seen with the exposure corrected, smoothed XMM-Newton data in the

5 http://tgssadr.strw.leidenuniv.nl/doku.php?id=knownproblems
The slight extension of the 168 MHz emission along with the patchy 1.4 GHz NVSS and 147.5 MHz TGSS at the peak of the X-ray may suggest a particularly faint or small halo at the center of the cluster, perhaps a mini-halo.

3.2.9 Abell 2556 and Abell 2554

Fig. 13 shows the two clusters Abell 2556 (MCXC J2313.0-2137) and Abell 2554 (MCXC J2312.3-2130; PSZ1 G041.51-66.77) which have centres within 13 arcmin of each other, but have redshifts of $z = 0.0871$ and $z = 0.1108$ (Caretta et al. 2002) respectively. Their respective masses are similar being $M_{500} = 2.4758 \times 10^{14} M_\odot$ (MCXC) and $M_{500} = 3.05^{+0.37}_{-0.39} \times 10^{14} M_\odot$ (PSZ1). Abell 2556 has an X-ray luminosity of $L_{500} = 1.509152 \times 10^{47}$ W (MCXC). To the north of Abell 2556, 1 Mpc from its centre (east of Abell 2554, over 1 Mpc) an elongated diffuse source is seen, labelled “A” in Fig. 13, with flux densities $S_{168} = 29.3 \pm 5.5$ mJy (this work) and $S_{1400} = 2.2 \pm 0.5$ mJy (Condon et al. 1998). From these we obtain a steep spectral index of $\alpha_{168} = -1.22 \pm 0.14$. The LAS of the source is 3.3 arcmin which suggests an LLS of 336 kpc at $z = 0.0871$ or 416 kpc at $z = 0.1108$. The size of the emission does not suggest a radio relic. With no visible optical galaxy at the centre of the emission, lack of significant elongation, size, and steep spectral index suggest a radio phoenix. However, we note that radio phoenices are more often found towards cluster centres but this would be consistent with the spectral index, where phoenices closer to the centre become much steeper.

3.2.10 Abell 2680

Abell 2680 has a photometric redshift of $z = 0.1771$ (Wen & Han 2013). Fig. 14 shows a patch of steep-spectrum emission at the centre of the cluster, where both the TGSS and NVSS surveys show no counterparts (Obj. A). The emission may be slightly elongated east-west, though this apparent elongation may just be the result of blending with the eastern sources. The steep-spectrum emission blends with the eastern NVSS sources: NVSS J235647-210352 and NVSS J235656-210326. The eastern-most source, NVSS J235656-210326, has a counterpart in the TGSS however the other source does not and so no spectral index can be calculated thus we do not predict a 168 MHz flux density for the source. We make an approximate measurement of the flux density yielding $S_{168} = 22.8 \pm 8.0$ mJy, where the uncertainty is given by Eq. 1 with an additional contribution to account for the slight blending to the east. We estimate a 1.4 GHz upper limit of 1.8 mJy to provide an upper limit to the spectral index between 168–1400 MHz, $\alpha_{168} \leq -1.2 \pm 0.2$. The LAS is estimated to be $\sim 3.2$ arcmin, which at $z = 0.1771$ suggests a projected LLS of 600 kpc. The physical extent of the source and coincidence with the cluster centre core suggests a cluster halo. This particular case requires observations at different resolutions to determine if the source is actually extended.

3.2.11 Abell 2693

Abell 2693 has a photometric redshift of $z = 0.173$ (Coziol et al. 2009) and hosts a candidate radio halo at its centre. The candidate halo, marked A in Fig. 15, has an LAS of 3.75 arcmin and an LLS at the cluster’s redshift of 681 kpc.
The location of the halo traces the optical galaxies. We measure the 168 MHz flux density to be $S_{168} = 49.6 \pm 6.0$ mJy. From the lack of 1.4 GHz emission in the NVSS, we estimate an upper limit to the 1.4 GHz flux density to be $S_{1.4} \leq 7.7$ mJy which imposes an upper limit on the spectral index of $\alpha_{168} = -0.88 \pm 0.06$. This limit on the spectral index is in no way conclusive of the classification of radio halo. However, the location, and size suggest that it may be a halo, and we classify this emission as a candidate halo.

To the west of the cluster there is an elongated steep-spectrum source marked B in Fig. 15. If the entirety of Obj. B is a single object, then there is a spectral gradient across the source, with a steeper spectral index towards the north-east. It is unlikely this is a cluster relic associated with Abell 2093 as it sits at ~2.5 Mpc from the cluster centre and has the morphology of a head-tail (HT) radio galaxy.

$\alpha_{168}$

\begin{equation}
\alpha = -\frac{\log S_{168}}{\log 168}\end{equation}

(Shakouri et al. 2016). Given that Abell 2721 was one of the more disturbed clusters in the ARDES sample, the lack of radio halo in the ATCA imaging was previously noted and an upper limit to the 1.4 GHz flux density is provided by (Shakouri et al. submitted): $S_{1.4} \leq 7$ mJy. We estimate the LLS of the diffuse emission to be ~460 kpc. As the source is blended with the two nearby sources, NVSS J000553-344434 and NVSS J000614-344730 to the west and south respectively, we use AEGEAN to measure the flux density. AEGEAN is able to separate the three sources, and returns a flux density of the diffuse source of $S_{168} = 54 \pm 14$ mJy. The other sources a measured to have flux densities of 234 ± 23 mJy and 276 ± 27 mJy for NVSS J000553-344434 and NVSS J000614-344730 respectively. We use the 168 MHz flux density with the ATCA 1.4 GHz limit to place a limit on the spectral index of $\alpha \leq -0.96 \pm 0.12$.

3.2.12 Abell 2721

Fig. 16 shows Abell 2721 (MCXC J0006.0-3443; PSZ1 G352.35-77.66) which has a redshift of $z = 0.114412 \pm 0.000334$ (Zaritsky et al. 2006) with mass $M_{200} = 3.77^{+0.35}_{-0.37} \times 10^{14} M_\odot$ (PSZ1) and X-ray luminosity $L_{200} = 1.809494 \times 10^{37}$W (MCXC). Diffuse radio emission is seen at 168 MHz offset to the east of the cluster centre (Obj. A in Fig. 16). No emission is detected at 1.4 GHz in NVSS, 843 MHz in SUMSS, or 147.5 MHz in TGSS above their respective ~3σ levels. The lack of emission seen in NVSS or SUMSS suggests a steep spectral index, however the lack of emission in TGSS is likely due to lack of sensitivity.

As part of the ATCA REXCESS Diffuse Emission Survey (ARDES), deep 1.4 and 2.1 GHz imaging of the cluster was obtained with the ATCA, finding no evidence of a halo

The right panel of Fig. 16 shows the REXCESS X-ray data overlaid with MWA contours. We see that the X-ray emission sits at the centre of the cluster, whereas the diffuse emission seen only at 168 MHz is offset towards the east. While there is the possibility that this is a cluster halo, elongated along the E-W direction and partially obscured by the emission from NVSS J000553-344434, it is more likely that this is a radio relic akin to the relics seen in Abell 0013 or Abell 0085. This candidate relic may be projected onto the centre of the cluster, and its reasonably flat spectral index compared to other relics would be consistent with a younger, more centrally located source in the early stages of propagation. Hence because of its offset and size, and in the absence of any available polarimetry, we classify this new diffuse emission as a candidate radio relic.

Figure 12. Diffuse emission within Abell 2496. Left: The background is an RGB image with contours overlaid as follows: EoR0, white, beginning at 15 mJy beam$^{-1}$ increasing by a factor of $\sqrt{2}$; NVSS, red, beginning at 1.5 mJy beam$^{-1}$ increasing by a factor of 2. Right: Exposure corrected, smoothed XMM-Newton data with 168 MHz contours overlaid as in the left panel. The dashed, white circle is centred on the MCXC coordinates with radius of 1 Mpc.
Figure 13. Diffuse emission, Obj. A, in Abell 2556. The background image is an RGB image with contours overlaid as follows: EoR0, white, beginning at 10 mJy beam$^{-1}$ and increasing by a factor of 2; NVSS, red, beginning at 1.5 mJy beam$^{-1}$ and increasing by a factor of 2; TGSS, medium purple, beginning at 13.4 mJy beam$^{-1}$ also increasing by a factor of 2. The dashed circle is centred on Abell 2556 and the dotted circle on Abell 2554, each with radii of 1 Mpc.

Figure 14. Abell 2680 with a candidate halo marked with an "A". The background image is an RGB image with contours overlaid as follows: EoR0, white, beginning at 7 mJy beam$^{-1}$ and increasing by a factor of 2; NVSS, red, beginning at 1.5 mJy beam$^{-1}$ and increasing by a factor of 2; TGSS, medium purple, beginning at 11.1 mJy beam$^{-1}$ also increasing by a factor of 2. The dashed circle represents is at a 1 Mpc radius about the cluster centre.

Figure 15. Candidate radio halo A and steep-spectrum source B within and nearby Abell 2693. The background is an RGB image with contours overlaid as follows: EoR0, white, beginning at 10 mJy beam$^{-1}$ and increasing by a factor of 2; NVSS, red, beginning at 1.5 mJy beam$^{-1}$ and increasing by a factor of 2; TGSS, medium purple, beginning at 12 mJy beam$^{-1}$ also increasing by a factor of 2. The dashed circle is centred on the cluster and has a 1 Mpc radius.

3.2.13 Abell 2744

Abell 2744 (MCXC J0014.3-3022; PSZ1 G009.02-81.22) is a distant massive X-ray luminous cluster ($M_{X,Z,S00} = 7.3614 \times 10^{15} M_\odot$ (PSZ1), $z = 0.3066$, and $L_{200} = 11.818114 \times 10^{47}$ W (MCXC)) and is a Hubble Frontier Fields cluster (Lotz et al. 2014) showing gravitational lensing of the high-redshift background galaxies (see Castellano et al. 2016, for a catalogue of lensed galaxies with redshift and magnification data). Fig. 17 shows Abell 2744 with both a centrally located giant radio halo (GRH, defined to have an LLS > 1 Mpc) and a mega-parsec scale radio relic on its northeast periphery (Govoni et al. 2001). Both of these objects are seen in the EoR0 field at 168 MHz, as is expected with such steep-spectrum sources, blending together along that northeast edge of the cluster. As seen in Fig. 17, the giant radio halo fills the entire cluster out to 1 Mpc having an approximate LLS of 2.03 Mpc (LAS of $\sim$7.27") and the relic with an LLS on the order 1.60 Mpc (LAS $\sim$5.72 arcmin).

We use AEGEAN to measure the integrated flux densities of the halo and relic. AEGEAN detects the two as a single source and fits two components – one for each the halo and relic – which give integrated fluxes of $S^{\text{halo}}_{168} = 550\pm51$ mJy and $S^{\text{rel}}_{168} = 237 \pm 24$ mJy. Venturi et al. (2013) obtain 325 MHz measurements using the GMRT, and use those along with re-reduced 1.4 GHz data from the VLA to estimate spectral indices of $\alpha_{\text{halo}} = -1.11 \pm 0.04$ and $\alpha_{\text{rel}} = -1.19 \pm 0.04$ for the halo and relic respectively. We use the 168 MHz flux density measurements along with those present in Venturi et al. to obtain spectral indices of $\alpha_{\text{halo}} = -1.11 \pm 0.04$ and $\alpha_{\text{rel}} = -1.19 \pm 0.04$ for the halo and relic. There is little deviation and spectral indices
calculated here agree to within the associated uncertainties, however the measurements by Venturi et al. (2013) exclude the bridge emission as well as at least one embedded point source, which are not excluded in these measurements.

3.2.14 Abell 2751 and APMCC 039

Abell 2751 (MCXC J00163.3-3121, \( L_{400} = 0.495174 \times 10^{37} \) W from MCXC) and APMCC 039 have an angular separation of 17.7 arcmin and redshifts of \( z = 0.107 \) (Struble & Rood 1999) and \( z = 0.082 \) (Dalton et al. 1997) respectively. However we note that the redshift for APMCC 039 is photometric, and so we compare the redshifts of the surrounding galaxies to check for the possibility that the two clusters may be interacting. Fig. 18 shows the two clusters, with the dashed and dotted circles indicating 1 Mpc radii about the cluster centres at their reported redshifts. The small orange squares indicate galaxies with redshifts in the range 0.1–0.114, which is \( c\zeta \approx 2000 \) km s\(^{-1}\) around the redshift of Abell 2751. There are no galaxies in the vicinity at the reported redshift of APMCC 039. It is clear from Fig. 18 that the two clusters host galaxies of similar redshifts and due to their angular separation are likely interacting.

We detect a new candidate relic to the east of Abell 2751 (Obj. A in Fig. 18), blending with the point source NVSS J001648-312223. As the relic sits ~1 Mpc from both Abell 2751 and APMCC039, it may be associated with either cluster. In the case where the clusters are interacting, the relic sits at the intersection point between them. The relic itself is part of the NVSS catalogue as NVSS J001655-312258. The 168 MHz emission appears to simply be an extended radio tail extending from NVSS J001648-312223, however the 147.5 MHz TGSS emission is resolved enough to show that the relic emission is not associated with the point source. Fig. 18 shows the emission around these clusters with an RGB image which does not show an obvious optical ID associated with the relic emission. The combined total flux density of the point source and relic is measured to be \( S_{\text{tot}} = 843.1 \pm 60.7 \) mJy. We obtain the following flux densities for NVSS J001648-312223 from catalogues: \( S_{1.4} = 55.0 \pm 2.1 \) mJy (Condon et al. 1998), \( S_{43} = 91.4 \pm 3.2 \) mJy (Murphy et al. 2007), \( S_{147.5} = 365.3 \pm 37.3 \) mJy (Intema et al. 2016), and \( S_{94} = 1360 \pm 270 \) mJy (Lane et al. 2014). Due to uncertainty in the TGSS ADR1 flux density scale in certain regions of the sky, we do not use the 147.5 MHz flux density for sources in this region. We assume a standard power law and fit these measurements to obtain a spectral index \( \alpha = -1.07 \pm 0.02 \) which we use to predict the 168 MHz flux density as \( S_{168} = 518.2 \pm 9.4 \) mJy. The flux density of the relic is then estimated to be \( S_{\text{relic}} \approx 324.9 \pm 61.4 \) mJy.

To the north of APMCC 039 is the radio source NVSS J001804-311824 (Obj. B in Fig. 18), which at 1.4 GHz in the NVSS appears as a discrete point source with a flux density of \( S_{1.4} = 4.0 \pm 0.6 \) mJy (Condon et al. 1998). The EoR0 field however shows emission extended far beyond this source, appearing as a faint tail to this possible radio galaxy. The entire emission is measured to have a 168 MHz flux density of \( S_{168} = 60.3 \pm 7.7 \) mJy and an LAS of 8.816 arcmin which at the reported redshift of APMCC 039 translates to an LLS of 840.8 kpc, or 1066 kpc at the redshift of Abell 2751. If we take the catalogue 1.4 GHz flux density to be a lower limit to the flux, we can estimate an upper limit to the flux density across the entire source to be \( S_{1.4} \leq 24.0 \pm 0.6 \) mJy. We determine limits to the spectral index to be \( -1.28(\pm 0.09) \leq \alpha_{1400} \leq -0.43(\pm 0.06) \). This range covers normal radio galaxies, flat-spectrum sources,
and X-ray luminosity $L_{500} = 2.734146 \times 10^{37}$ W (MCXC), and mass $M_{500} = 3.67^{+0.35}_{-0.37} \times 10^{14}$ $M_\odot$ (PSZ1). The left panel of Fig. 20 shows the cluster and RGB image overlaid with MWA, NVSS, and TGSS contours. At the centre of the cluster we make a new detection of a faint radio halo (Obj. A). The cluster has been studied previously within the context of galactic haloes and the enrichment of the ICM (e.g. Sivanandam et al. 2009) with particular focus on the BCG, 2MASX J00420892-2832087. Further, as part of the XMM-Newton survey of the soft X-ray background Henley & Shelton (2013) consider this emission a galactic halo. However, Sivanandam et al. note that the surrounding X-ray emission is offset from the BCG by 27 arcsec (~55 kpc), which suggests that the clusters is in a dynamic, merging state and that the low-frequency radio emission seen in Fig. 20 is a cluster halo not associated with the BCG. This is seen in the right panel of Fig. 20, which shows exposure corrected, smoothed XMM-Newton data (Obs. ID 040520101, PI Sivanandam). The XMM-Newton image also reveals a slight N-S elongation of the X-ray plasma, further hinting at a dynamical state.

This radio halo is on the order of 4.13 arcmin, which translates to ~502 kpc at the cluster’s redshift, however the surrounding sources make it difficult to properly ascertain its true size. We measure a flux density of the halo region with AEGEAN, which fits a Gaussian component to the halo, separating it out from the nearby sources it blends with, obtaining $S_{168} = 80.7 \pm 16.5$ mJy. Considering the lack of detection in the NVSS image, we estimate an upper limit to the 1.4 GHz flux density of 3.1 mJy which yields an upper limit to the spectral index of $\alpha^{1400}_{168} \leq -1.5 \pm 0.1$. This would place the emission within the realm of the ultra-steep spectrum haloes.

### 3.2.16 Abell 2811

The cluster Abell 2811 (MCXC J0042.1-2832; PSZ1 G357.94-87.52) has a redshift of $z = 0.107908 \pm 0.000500$ (Zaritsky et al. 2006), an X-ray luminosity $L_{500} = 2.734146 \times 10^{37}$ W (MCXC), and mass $M_{500} = 3.67^{+0.35}_{-0.37} \times 10^{14}$ $M_\odot$ (PSZ1). The left panel of Fig. 20 shows the cluster and RGB image overlaid with MWA, NVSS, and TGSS contours. At the centre of the cluster we make a new detection of a faint radio halo (Obj. A). The cluster has been studied previously within the context of galactic haloes and the enrichment of the ICM (e.g. Sivanandam et al. 2009) with particular focus on the BCG, 2MASX J00420892-2832087. Further, as part of the XMM-Newton survey of the soft X-ray background Henley & Shelton (2013) consider this emission a galactic halo. However, Sivanandam et al. note that the surrounding X-ray emission is offset from the BCG by 27 arcsec (~55 kpc), which suggests that the clusters is in a dynamic, merging state and that the low-frequency radio emission seen in Fig. 20 is a cluster halo not associated with the BCG. This is seen in the right panel of Fig. 20, which shows exposure corrected, smoothed XMM-Newton data (Obs. ID 040520101, PI Sivanandam). The XMM-Newton image also reveals a slight N-S elongation of the X-ray plasma, further hinting at a dynamical state.

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### 3.2.17 Abell 4038

Abell 4038 (MCXC J2347.7-2808) has a redshift of $z = 0.028190 \pm 0.000550$ (Sanders et al. 2011), mass $M_{500} = 2.033 \times 10^{14} M_\odot$ (MCXC), and X-ray luminosity $L_{500} = 1.299501 \times 10^{37}$ W (MCXC), Slee & Reynolds (1984) report a steep-spectrum source (Obj. B and C in Fig. 21) near the cluster centre without an optically visible host galaxy. Slee & Roy (1998) and Slee et al. (2001) then provide follow-up analyses of this steep-spectrum source and consider it a radio relic (defined as a radio phoenix here). As with Abell 0085 the 168 MHz emission extends beyond the emission seen with the NVSS and TGSS. The emission of the phoenix blends with the radio emission from IC 5358 and 2MASX J23474209-2807335 (Obj. A in Fig. 21). Kale & Dwarkanath (2012) present a multi-frequency study of the phoenix with the GMRT, combining literature data with their 150, 240, 606, and 1288 MHz data to subtract the interloping sources. We use results from their observations, as well as additional data from the NVSS at 1.4 GHz (Condon et al. 1998) and at 29.9 MHz from Slee et al. (2001; but see also Finlay & Jones 1973), to estimate the 168 MHz contributions from IC 5358 and 2MASX J23474209-2807335...
Figure 18. A candidate relic and a faint radio galaxy, near Abell 2751 and APMCC 039, marked as A and B. The background is an RGB image with contours overlaid as follows: EoR0, white, beginning at 7 mJy beam\(^{-1}\) and increasing by a factor of \(\sqrt{2}\); NVSS, red, beginning at 1.5 mJy beam\(^{-1}\) and increasing by a factor of 2; TGSS, medium purple, beginning at 13.5 mJy beam\(^{-1}\) also increasing by a factor of 2. The dashed circle is centred on Abell 2751 and the dotted on APMCC 039, each with radii of 1 Mpc.

Figure 19. Candidate radio relic within Abell 2798. The background is an RGB image with contours overlaid as follows: EoR0, white, beginning at 7 mJy beam\(^{-1}\) increasing by a factor of \(\sqrt{2}\); NVSS, red, beginning at 1.5 mJy beam\(^{-1}\) increasing by a factor of 2; TGSS, medium purple, beginning at 13.8 mJy beam\(^{-1}\) also increasing by a factor of 2.

Abell S0084 (MCXC J0049.4-2931) has a redshift of \(z = 0.108041 \pm 0.000400\) (Zaritsky et al. 2006) and X-ray luminosity \(L_{500} = 1.438047 \times 10^{37}\) W (MCXC). We detect diffuse radio emission at the cluster centre (Fig. 22). The cluster was part of the ARDES sample of Shakouri et al. (2016) though no diffuse emission was detected at the centre of the cluster. From ATCA imaging at 1.4 GHz Shakouri et al. obtain an rms noise of 313 \(\mu\)Jy beam\(^{-1}\) from which we estimate an upper limit to the 1.4 GHz flux density to be \(S_{1.4} \leq 2.2\) mJy (Shakouri et al. submitted). The centroid of the emission is offset from the cluster centre by 63 arcsec and has an LAS of 4.19 arcmin, which at the cluster’s redshift is an LLS of 511 kpc. The flux density is measured to be \(S_{168} = 32.3 \pm 4.5\) mJy. The 147.5 MHz emission is not suggestive of a point source and the lack of detection by Shakouri et al. (2016) suggests a steep spectral index. With the 1.4 GHz upper limit, we estimate an upper limit on the spectral index, \(\alpha_{1400}^{168} \leq -1.3 \pm 0.1\).

The right panel of Fig. 22 shows the REXCESS X-ray data with MWA contours overlaid. There is no cavity present in the X-ray data to suggest that the emission could be the lobes of an AGN and thus likely associated with the cluster itself. Further, Abell S0084 is not a cool core cluster (Pratt et al. 2009) and so we do not suspect this emission is a mini-halo. Given that the radio emission sits offset from the X-ray peak by \(-100\) kpc and that the X-ray plasma appears undisturbed, we only tentatively classify this as a candidate steep spectrum radio halo, though note that the emission may be from a centrally located radio galaxy, possibly dying or otherwise of old age.

as 80.6 ± 1.0 and 12.4 ± 0.4 mJy, respectively. We measure the combined total flux to be 4.87 ± 0.249 Jy and arrive at \(S_{168} = 4.782 \pm 0.249\) Jy for the phoenix.

3.2.18 Abell S0084
Figure 20. Radio halo within Abell 2811, marked with an “A”. Left: The background is an RGB image with contours overlaid as follows: EoR0, white, beginning at 7 mJy beam$^{-1}$ and increasing by a factor of $\sqrt{2}$; NVSS, red, beginning at 1.5 mJy beam$^{-1}$ and increasing by a factor of 2; TGSS, medium purple, beginning at 12.6 mJy beam$^{-1}$ also increasing by a factor of 2. Right: XMM-Newton EPIC image of Abell 2811 with the 168 MHz contours overlaid as in the left panel. In both panels the linear scale is at the redshift of the cluster.

Figure 21. The centre of Abell 4038. The background is an RGB image with contours overlaid as follows: EoR0, white, beginning at 20 mJy beam$^{-1}$ and increasing with a factor of $\sqrt{2}$; NVSS, red, beginning at 1.5 mJy beam$^{-1}$ and increasing with a factor of 2; TGSS, medium purple, beginning at 20 mJy beam$^{-1}$ also increasing with a factor of 2. Marked objects are described in the text.

3.2.19 Abell S1099

Abell S1099 is reported to have a redshift of $z = 0.110400$ (Caretta et al. 2002). Fig. 23 shows the RGB image with MWA, NVSS, and TGSS contours overlaid. The cluster hosts extended, diffuse emission with steep spectral index, perhaps associated with one of the BCGs, 2MASX J23130574-2308369 ($z = 0.108575$; Caretta et al. 2004), which coincides with the peak of the emission at 168 MHz. We measure the 168 MHz to be $S_{168} = 184 \pm 20$ mJy, where the uncertainty includes a term to account for the slight blending towards the northwestern source, NVSS J231317-230513. Further, Obj. A in Fig 23 appears to be an embedded point source, catalogued as NVSS J231255-230959 (Condon et al. 1998), which is not accounted for. We see that the 1.4 GHz emission is patchy and use the MIRIAD task CONVOL to convolve the NVSS image to the 108.87 arcsec x 108.87 arcsec of the EoR0 field to measure the emission. This yields $S_{1.4} = 22.3 \pm 6.4$ mJy, where the uncertainty incorporates the embedded source and the blending with NVSS J231317-230513. We calculate a spectral index of $\alpha_{1400}^{168} = -1.00 \pm 0.15$ which does not suggest a centrally located cluster relic, though is consistent with the flatter-spectrum haloes or peripheral relics. It is not clear where the cluster centre lies as galaxies with redshifts within $cz \approx 2000$ km s$^{-1}$ of the cluster’s redshift do not appear to concentrate in any region in particular within the cluster volume. With no auxiliary X-ray data beyond RASS we are unable to determine if the emission is that of a cluster halo. The morphology, and apparent steep spectral index are suggestive of a halo, but the BCG at the centre of the emission and the lack of clear cluster centre casts doubt towards this classification.

3.2.20 Abell S1121

Abell S1121 (PSZ1 G348.92-67.38) is reported by Coziol et al. (2009) to have a redshift of $z = 0.190431$ though Liu...
et al. (2015) report a redshift of $z = 0.3580$ for this system. Assuming $z = 0.3580$ as used by PSZ1 the cluster has a mass of $M_{200} = 7.05_{-0.61}^{+0.64} \times 10^{14} M_\odot$ (PSZ1). We detect a new radio halo, with extended 168 MHz emission located at the cluster centre, with little-to-no SUMSS or TGSS counterparts at 843 and 147.5 MHz. There is a bright source to the north of the cluster that in SUMSS is creating artefacts streaking across the SUMSS image for this region. However, it is also important to note that Abell S1121 lies near the edge of the EoR0 field and is in an area of the image with higher noise, hence the 15 mJy beam$^{-1}$ contours in Fig. 24. The left panel of Fig. 24 shows galaxies with available redshifts in the range $cz \approx 2000$ km s$^{-1}$ around the reported redshifts, with the orange circles associated with $z \approx 0.190431$ and the orange boxes associated with $z = 0.3580$. Given the location and numbers of each galaxy distribution, we consider the emission (and the cluster) to be at the redshift reported by Liu et al. (2015), $z = 0.3580$. There is likely a separate, intervening system along the line-of-sight that Coziol et al. (2009) are measuring.

The right panel of Fig. 24 shows archival Chandra data (Obs. ID 13405, PI Garmire, exposure time 8.94 ks, 0.1–13.1 keV). This X-ray emitting plasma is situated in the core of the cluster, however it has directionality, with morphology like a cone similar to the Bullet Cluster. This type of morphology suggests cluster dynamics often coincident with radio haloes. The main component of the diffuse 168 MHz emission coincides with this X-ray core. There are two point sources blended with the diffuse emission: SUMSS J232506-411339 and SUMSS J232457-411542. For SUMSS J232506-411339 we use the SUMSS catalogue measurement of $S_{443} = 24.3 \pm 3.0$ mJy (Murphy et al. 2007) and assume a spectral index of $\alpha = -0.8 \pm 0.2$ to predict a 168 MHz flux density of $S_{168} = 88 \pm 31$ mJy. Similarly, for SUMSS J232457-
The diffuse emission is a double source, catalogued as NVSS J233603-313431. We use the catalogue measurement of $S_{168} = 11.6 \pm 2.1$ mJy (Murphy et al. 2007), also assuming a spectral index of $\alpha = -0.8 \pm 0.2$, to predict $S_{168} = 42 \pm 16$ mJy. The total flux of the emission is measured to be $S_{168} = 284 \pm 32$ mJy. From this we estimate the flux density of the diffuse component to be $S_{168} = 154 \pm 48$ mJy. However, we have previously seen that extrapolating from poorly sampled SEDs – let alone using an assumed spectral index – does not always produce good results.

We estimate the LAS of the diffuse region of the emission to be $\sim 3.3$ arcmin which translates to an LLS of $\sim 1300$ kpc at $z = 0.358$. Given the location, size, coincidence with X-ray emission, approximate 168 MHz flux density, and the fact that Abell S1121 is a reasonably massive cluster, we classify the newly detected emission as a giant radio halo.

### 3.2.21 Abell S1136

Abell S1136 (MCXC J2336.2-3136) has a redshift of $z = 0.0625$ (Schwope et al. 2000), X-ray luminosity $L_{500} = 5.040007 \times 10^{37}$ W, and mass $M_{X,500} = 1.2886 \times 10^{14}$ $M_\odot$ (MCXC). Fig. 25 shows the centre of the cluster with an elongated piece of diffuse radio emission appearing strongly at 168 MHz, with a patchy counterpart in the TGSS survey at 147.5 MHz. There is no corresponding 1.4 GHz or 843 MHz emission seen in the NVSS or SUMSS surveys. This implies a steep spectral index. The source to the west of the diffuse emission is a double source, catalogued as NVSS J233603-313431. We use AEGEAN once again, and see the diffuse source split into two distinct components. The total flux density of the diffuse source is then measured to be $S_{168} = 586 \pm 46$ mJy.

The RASS broad-band 0.1–2.4 keV image does not show particularly strong X-ray emission at the centre, and the RGB image (Fig. 25) shows the optical concentration of galaxies at the centre is offset towards the west of the bulk of the 168 MHz emission. The elongation is north-south, with an almost bent double-lobed structure, and has an LAS of $\sim 7.2$ arcmin which translates to an LLS of $\sim 530$ kpc. While the emission could be classified as a cluster halo, alternate explanations are those of cluster relic intervening along the line-of-sight towards the cluster, or a dead radio galaxy likely having a previous association with the BCG, ESO 470-G020. Without polarisation data and higher resolution imaging we do not classify this emission here.

### 3.2.22 PSZ1 G307.55-77.87

PSZ1 G307.55-77.87 has a photometric redshift of $z = 0.4530$ (Planck Collaboration et al. 2014) with a mass of $M_{Y_{2},500} = 5.69_{-0.82}^{+0.82} \times 10^{14}$ $M_\odot$ (PSZ1). Fig. 26 shows diffuse emission towards the cluster periphery. The nearby point source is LCRS B004346.8-393051 which has a redshift of $z = 0.155664 \pm 0.000450$ (Shectman et al. 1996) and is not associated with the cluster, though it may be the source of the diffuse emission within the context of a tail or lobe of a radio galaxy.

In the case that the emission is a cluster relic, we estimate the 168 MHz flux density by estimating the 168 MHz flux density of the LCRS source. The LCRS source has 1.4 GHz flux density of $S_{1.4,500} = 7.8 \pm 0.5$ mJy (Condon et al. 1998) and 843 MHz flux density of $S_{843,500} = 11.1 \pm 1.0$ mJy (Murphy et al. 2007) which give a spectral index for the...
LCRS source of $\alpha_{1400} = -0.696 \pm 0.218$. Extrapolating from this and $S_{1400}^\text{LCRS}$ yields $S_{168}^\text{LCRS} = 34.4 \pm 16.2 \text{ mJy}$. The total emission of the possible relic and the LCRS source is measured to be $S_{168}^\text{tot} = 53.3 \pm 10.3 \text{ mJy}$. This implies a flux density of $S_{168} = 19 \pm 19 \text{ mJy}$ for the relic. Given the uncertainty there is not anything further we can say about the SED of the emission. We estimate an LAS of $\sim 3.64 \text{ arcmin}$ and a corresponding LLS of $\sim 1260 \text{ kpc}$ at the cluster’s redshift. Thus, the emission is likely one of: a radio galaxy and lobe or tail, not associated with the cluster but with LCRS B004346.8-393051, a faint point source coincident with the cluster periphery, or a cluster relic. In Table 2 we present measured properties assuming a relic associated with the cluster.

3.2.23 RXC J2351.0-1954

RXC J2351.0-1954 (PSZ1 G057.09-74.45) has a redshift of $z = 0.247700 \pm 0.000190$, a mass $M_{200} = 5.60^{+0.59}_{-0.62} \times 10^{14} \text{ M}_\odot$ (PSZ1), and X-ray luminosity $L_X = (4.33 \pm 0.84) \times 10^{47} \text{ W}$ (Chon & Böhringer 2012). The left panel of Fig. 27 shows the cluster and surrounding field, and the right panel shows the central region of the cluster. The dashed circle is at 1 Mpc radius and centred on (h) = (357.7703, −19.9132). In the left panel of Fig. 27 two steep-spectrum, diffuse sources are located to the southeast (Obj. A) and northwest (Obj. B). The right panel of the same figure shows a zoomed-in view of the cluster centre.

Obj. A and B have similarities with double relics on the periphery of merging clusters. Obj. A is $\sim 8.35 \text{ arcmin} (-2 \text{ Mpc})$ from the cluster centre and Obj. B is $\sim 11.8 \text{ arcmin} (-2.8 \text{ Mpc})$. Neither A nor B have an obvious ID visible in the blue, red, or IR bands from the DSS2. The flux densities of the sources are measured to be $S_{168}^\text{A} = 56.9 \pm 8.6 \text{ mJy}$ and $S_{168}^\text{B} = 147 \pm 13 \text{ mJy}$. Neither source appears in the NVSS data at 1.4 GHz so we place upper limits on the 1.4 GHz flux densities of $S_{168}^\text{A} \leq 4.22$ and $S_{168}^\text{B} \leq 4.7 \text{ mJy}$ places upper limits on the spectral indices of $\alpha_{168}^{1-4.4} \leq -1.23 \pm 0.07$ and $\alpha_{168}^{1-4.4} \leq -1.68 \pm 0.04$. Obj. B shows 147.5 MHz emission in the TGSS image above $3\sigma_{\text{rms}}$ but is not part of the TGSS ADR1 catalogue as it is not detected above $7\sigma_{\text{rms}}$. Further, emission from Obj. B is likely resolved out of the TGSS image due to its higher resolution than the MWA. Obj. A shows the elongated, bent shape that is typical of cluster relics. Obj. B shows a more regular morphology at 168 MHz in the EoR0, though shows elongation similar to a radio galaxy in the TGSS data. While the spectral indices and the elongated, bent morphology of Obj. A maybe suggest a double relic system, the distance from the centre, especially in the case of Obj. B, somewhat oppose this idea. We consider the possibility that the radio source between the two would-be relics, APMUKS(BJ) B234816.36-201016.8 (with no redshift data available, Obj. D in the left panel of Fig. 27), may be a radio galaxy that produced these, old and now disassociated, lobes from a past episode of activity. From flux densities presented in the NVSS and TGSS catalogues (Condon et al. 1998; Intema et al. 2016) we calculate the spectral index of APMUKS(BJ) B234816.36-201016.8 to be $\alpha_{147}^{142} = -0.50 \pm 0.06$. In this scenario it is likely the axis of the old AGN jets is angled such that the northwestern lobe, Obj. B, is closer than Obj. A, as the greater surface brightness of Obj. B would...
Figure 27. RXC J2351.0-1954. Left: RGB image with contours overlaid as follows: EoR0, white, beginning at 10 mJy beam$^{-1}$ and increasing with a factor of $\sqrt{2}$; NVSS, red, beginning at 1.5 mJy beam$^{-1}$ and increasing with a factor of 2; TGSS, medium purple, beginning at 13.8 mJy beam$^{-1}$ also increasing with a factor of 2. The dashed circle is centred on the cluster coordinates with a radius of 1 Mpc. “A” and “B” mark candidate relics, “C” a candidate halo, and “D” and “E” radio galaxies discussed in the text. Right: A smaller field of view of the left panel using the DSS2 red band only, with a small orange circle to denote the cluster’s coordinates given by Chon & Böhringer (2012), a small light-blue circle to denote the coordinates given by PSZ1, and orange squares to show galaxies with spectroscopic redshifts in the region.

Table 3. 168 MHz flux densities and spectral indices calculated for blended sources near RXC J2351.0-1954.

| Source | $S_{168}$ (mJy) | $\alpha_{1400}$ |
|--------|----------------|----------------|
| APMUKS(BJ) B234816.36-201016.8 (D) | 78.6 ± 10.7 | -0.50 ± 0.06 |
| NVSS J235053-195715 (E) | 56.5 ± 7.9 | -0.59 ± 0.06 |
| Central diffuse emission (C) | 87 ± 17 | ≤ -1.4 ± 0.1 |

suggest Doppler beaming due to the northwestern jet being pointed, in part, towards us. A flat spectrum is indicative of a radio galaxy that has recently started its central engine. We cannot rule out this scenario without a redshift of APMUKS(BJ) B234816.36-201016.8, such that we could estimate the separation of the lobes from the core both in linear extent and in time. If APMUKS(BJ) B234816.36-201016.8 is a member of RXC J2351.0-1945, then at this point the lobes are so disassociated that distinguishing between true relics and relic AGN emission would be difficult thus we have considered them candidate double relics here.

The right panel of Fig. 27 shows the cluster centre, with the small, orange circle indicating the central coordinates provided by Chon & Böhringer (2012). Coordinates provided by Planck Collaboration et al. (2015a) lie to the southeast, shown by a light-blue circle in the right panel of Fig. 27. The red-band DSS2 image shows an optical concentration of galaxies coinciding with 168 MHz radio emission extending from the point source NVSS J235053-195715. The orange squares indicate the positions of galaxies with spectroscopic redshifts, at the approximate redshift of the cluster and reported by Chon & Böhringer (2012). We assume that the centre of the cluster is traced by the optically visible galaxies, which does not coincide with coordinates from Chon & Böhringer. To better define the cluster centre we produce Fig 28, which shows the isodensity map generated from 2972 galaxies within half a degree of the cluster’s reported centre, obtained from the SuperCOSMOS Sky Sur-
vy (Hambly et al. 2001a,b,c). The contour map was made using a grid of 150 kpc cells (at the redshift of the cluster) and then smoothed via a Gaussian kernel with standard deviation of 250 kpc. The density peak at $\alpha_{2000} = 357.756$ and $\delta_{2000} = -19.945$ is about 2 arcmin from the reported centre of the cluster. We consider these peak-density coordinates as the cluster centre, which still disagree with the coordinates provided by PSZ1 of $(\alpha_{2000}, \delta_{2000}) = (357.78108, -19.98114)$.

The 168 MHz emission enveloping those galaxies at the optical centre of the cluster is likely a cluster halo (Obj. C in the left panel of Fig. 27), with the lack of significant 1.4 GHz NVSS emission implying a steep-spectrum source. We estimate the flux density of this diffuse emission by subtracting the extrapolated flux densities of the two blended sources, APMUKS(BJ) B234816.36-201016.8 and NVSS J235053-195715 (Obj. D and E in the left panel of Fig. 27, respectively), using 1.4 GHz and 147.5 MHz flux density measurements from the NVSS and TGSS catalogues respectively (Condon et al. 1998; Interna et al. 2016). The spectral indices and extrapolated 168 MHz flux densities are presented in Table 3. The diffuse source is estimated to have a flux density of $S_{168} = 87 \pm 17$ mJy. From the lack of 1.4 GHz emission in the NVSS image above $3\sigma_{\text{rms}}$ we estimate an upper limit of $S_{1.4} \leq 4.3$ mJy resulting in an upper limit of $S_{168}$ for the spectral index. We estimate the LAS to be $\sim 2.8$ arcmin, though note that the emission likely bleeds into the point source NVSS J235053-195715 and so is likely an underestimate. This translates to an LLS of $\sim 670$ kpc at the redshift of the cluster. No significant emission is seen in the RASS broad band image, however due to the cluster’s redshift this is not surprising. Without supplementary archival Chandra or XMM-Newton data it is difficult to definitively classify this emission, nevertheless, given the strong association of the emission with the optical density peak, we consider this a newly detected candidate radio halo.

### 3.2.24 MACS J2243.3-0935

Cantwell et al. (2016) report the detection of a radio halo in the merging cluster MACS J2243.3-0935 (MCCX J2243.3-0935; PSZ1 G056.94-55.06), detected using the Karoo Array Telescope-7 telescope and GMRT. The cluster has a redshift of $z = 0.447$ (Ebeling et al. 2010), mass $M_{\text{YZ},500} = 10.07^{+0.58}_{-0.60} \times 10^{14} M_{\odot}$ (PSZ1), and X-ray luminosity $L_{\text{X},500} = 15.200000 \times 10^{37}$ W (MCXC). Fig. 29 shows the MWA contours overlaid on the RGB image. MACS J2243.3-0935 is near the edge of the EoR0 field and so the region within which it resides features heavy noise. Because of this, the detection is tentative, with the emission barely showing above $2\sigma_{\text{rms}}$. Fig. 29 shows the cluster with $2\sigma_{\text{rms}}$ contours to emphasise this. At this level we measure the 168 MHz flux density to be $S_{168} = 81 \pm 36$ mJy, with an LAS of $\sim 2.8$ arcmin and a corresponding LLS of $\sim 1$ Mpc. With the 610 MHz flux density measured by Cantwell et al. (2016) we obtain a spectral index of $\alpha_{168} = -1.6 \pm 0.4$. However, these results should be taken with caution due to the noise in this region of the EoR0 field. In particular, the source size is not sufficient to consider this extended and without the previous detection at 610 and 1826 MHz by Cantwell et al. (2016) of the halo we would not consider this detection sufficient to consider the emission as real and extended.

Figure 29. MACS J2243.3-0935 with radio halo. The background is an RGB image with contours overlaid as follows: EoR0, white, beginning at 60 mJy beam$^{-1}$ increasing by a factor of $\sqrt{2}$; NVSS, red, beginning at 1.5 mJy beam$^{-1}$ increasing by a factor of 2; TGSS, medium purple, beginning at 10.2 mJy beam$^{-1}$ also increasing by a factor of 2. The dashed circle is centred on the cluster with a radius of 1 Mpc.

#### 3.2.25 GMBCG J357.91841-08.97978 and WHL J235151.0-085929

WHL J235151.0-085929 (PSZ1 G082.31-67.01), a distant cluster with a redshift of $z = 0.3939$ (Wen et al. 2012) and mass $M_{\text{YZ},500} = 5.90^{+0.78}_{-0.80} \times 10^{14} M_{\odot}$ (PSZ1). Fig. 30 shows the cluster with an RGB (red, IR, blue) background and radio contours overlaid. Obj. A is a possible diffuse source on the cluster’s periphery. The cluster does not show significant X-ray emission in the RASS broad-band image. The location of the emission relative to the cluster centre and the lack of optical ID (see Fig. 30) are suggestive of a cluster relic. We note that source is point-like in the EoR0 field image, and that at this resolution – especially given the redshift of the cluster – there is an inherent uncertainty in whether the source is extended or not. The NVSS image shows a source that is extended in the north-south direction, beyond that of the beam which is circular. The source does not appear in the TGSS ADR1 catalogue due to their higher $\sigma_{\text{rms}}$ cut-off but is present in the NVSS catalogue, with 1.4 GHz flux density of $S_{1.4} = 4.1 \pm 0.6$ mJy (Condon et al. 1998). We use AEGEAN here to measure the flux density of the source to be $S_{168} = 128 \pm 20$ mJy. This, in conjunction with the 1.4 GHz measurement, is used to estimate a spectral index of $\alpha_{168} = -1.62 \pm 0.10$.

We note that the Gaussian Mixture Brightest Cluster Galaxy (GMBCG; Hao et al. 2010) catalogue reports a cluster at the centre of the emission: GMBCG J357.91841-08.97978, with a photometric redshift of $z = 0.4$. It is entirely likely that the emission resides within this cluster. If this is the case the steep spectral index and central location would imply a cluster halo. The two clusters, WHL
The dotted circle is centred on the cluster GMBCG J357.91841-08.97978, centres separated by J235151.0-085929 and GMBCG J357.91841-08.97978, have Figure 30. Diffuse emission on the periphery of WHL J235151.0-085929 or centre of GMBCG J357.91841-08.97978. The background is an RGB image with contours overlaid as follows: EoR0, white, beginning at 10 mJy beam$^{-1}$ increasing by a factor of $\sqrt{2}$; NVSS, red, beginning at 1.5 mJy beam$^{-1}$ increasing by a factor of 2; TGSS, medium purple, beginning at 11.7 mJy beam$^{-1}$ also increasing by a factor of 2. The dashed circle is centred on the PSZ1 coordinates of WHL J235151.0-085929 with radius 1 Mpc. The dotted circle is centred on the cluster GMBCG J357.91841-08.97978 with the same 1 Mpc radius.

J235151.0-085929 and GMBCG J357.91841-08.97978, have centres separated by ~2.7 arcmin which at $z = 0.3939$ is ~890 kpc. This separation in both angular distance and redshift would suggest either the clusters are interacting or that they are the same cluster. With this in mind we suggest that the emission is a candidate cluster halo, at a redshift of $z = 0.3939$, associated with the cluster GMBCG J357.91841-08.97978.

3.2.26 Abell S1063

Abell S1063 (MCXC J2248.7-4431; PSZ1 G349.46-59.90) is a Hubble Frontier Fields cluster and features heavy gravitational lensing of the distant optical galaxies (see e.g. Diego et al. 2016). The cluster has a redshift of $z = 0.3475$ (Bohringer et al. 2004) with mass $M_{200} = 11.41^{+0.43}_{-0.42}$ x 10$^{14}$ $M_\odot$ (PSZ1) and X-ray luminosity $L_{500} = 27.166569 \times 10^{47}$ W (MCXC). The cluster is near the Southern edge of the EoR0 field and so is more affected by noise. Despite this, above a 50 mJy beam$^{-1}$ level, a diffuse and elongated piece of emission is seen within the cluster. Exposure corrected, smoothed XMM-Newton data (Obs. ID 0504630101, PI Andersson) shows strong X-ray emission coinciding with the 168 MHz radio emission though their respective peaks lie offset to one another, with the X-ray peak situated at the position of the BCG (see Fig. 31). The X-ray emission can be seen to extend further northeast with the peak of the 168 MHz emission occurring in this same direction. The BCG, LCRS B224549.3-444744, with redshift $z = 0.347110 \pm 0.000250$ (Guzzo et al. 2009) is marked with a square in Fig. 31. Note that the MCXC, PSZ1, and ACO catalogues all report different coordinates for the cluster centre, and it is the MCXC coordinates that coincide with the cD, hence the MCXC coordinates are taken as the cluster centre (e.g. in Fig. 31).

The emission at 168 MHz has counterparts in the TGSS and SUMSS surveys. The morphology in the TGSS and SUMSS surveys is suggestive of a tailed radio galaxy, with the tail pointing into the cluster centre, however the peak of these TGSS and SUMSS emission does not show an optical ID for such a galaxy. The TGSS catalogue reports a source here with flux density $S_{168} = 155.5 \pm 16.5$ mJy and the SUMSS catalogue has a source with $S_{443} = 29.4 \pm 3.0$ mJy. However, the source lies in a region where the TGSS ADR1 flux densities are systematically low, and so we do not consider the 147.5 MHz flux density here. With the EoR0 field, a flux density (with a cut-off threshold of 50 mJy) of $S_{168} = 265 \pm 38$ is measured. We also obtain a LAS of ~5.5 arcmin and an LLS of ~1670 kpc. Taking the ratios of the logarithms of the 843 and 168 MHz flux densities yields a spectral index for the source of $\alpha_{843} = -1.36 \pm 0.11$. Due to the difference in resolution, it is likely this is an upper limit, where a not insignificant percentage of the 843 MHz integrated flux density may be resolved out. This will likely be the case with the TGSS measurement of the source also, though it is hard to be certain with the inherent flux density discrepancy that exists already with the TGSS ADR1 data.

The nature of the cluster (massive and X-ray luminous) would suggest a halo may be present, and the estimated spectral index of the emission agrees with this hypothesis. However, the morphology of the emission is more reflective of a HT galaxy with a blended point source possibly associated with the BCG, LCRS B224549.3-444744. The cluster has been observed with the ATCA in 2013 with the EW352 configuration (Project code C2837, PI M. Johnston-Hollitt) in a search of diffuse cluster emission from clusters in the South Pole Telescope survey (SPT: Song et al. 2012; Reichardt et al. 2013) though the data had not yielded unambiguous diffuse emission. We use these data in conjunction with observations in the 6A configuration (Project code C2585, PI R. Kale) obtained from the Australia Telescope

### Table 4. Properties of the ATCA observations of Abell S1063.

| Configuration | Date         | $t_{\text{scan}}$ (min) | Bandwidth (MHz) | $v_c$ (MHz) |
|---------------|--------------|------------------------|-----------------|-------------|
| EW352         | 18.20-22-06-2013 | 224                    | 2048            | 2100        |
| 6A            | 03.04-05-02-2012 | 543                    | 2048            | 2100        |

### Table 5. Sub-band properties for the ATCA observations of Abell S1063.

| Sub-band Centre frequency | Restoring beam (MHz) | $\sigma_{\text{rms}}$ (mJy beam$^{-1}$) |
|--------------------------|----------------------|--------------------------------------|
| 1332                     | 1384                 | 9.95 x 4.45, -3.1                     | 50                     |
| 1844                     | 1873                 | 7.57 x 3.89, 1.5                      | 21                     |
| 2356                     | 2349                 | 6.10 x 3.15, 0.0                      | 22                     |
| 2868                     | 2811                 | 5.13 x 2.74, -4.0                     | 26                     |
| Stacked                  | 2034                 | 9.95 x 4.45, -3.1                     | 18                     |
| a                        | 2251                 | 122.9 x 40.1, -17.7                   | 360                    |

*a Stacked after tapering sub-bands with a 60 arcsec Gaussian.
Figure 31. Abell S1063. Left: The background is an RGB image with contours overlaid as follows: EoR0, white, beginning at 50 mJy beam$^{-1}$ increasing by a factor of $\sqrt{2}$; SUMSS, red, beginning at 5 mJy beam$^{-1}$ increasing by a factor of 2; TGSS, medium purple, beginning at 7.8 mJy beam$^{-1}$ also increasing by a factor of 2. The white box indicates the BCG of the cluster. Right: Exposure corrected, smoothed XMM-Newton image with contours 168 MHz contours overlaid as in the left panel. The dashed circle in both panels is centred on the cluster (with coordinates from Piffaretti et al. 2011 – see text) and has a radius of 1 Mpc.

Figure 32. Abell S1063. Left: ATCA stacked image of the 1100–3100 MHz band centred on 2100 MHz overlaid with contours as follows: 168 MHz EoR0, black, beginning at 40 mJy beam$^{-1}$; 2100 MHz ATCA, red, beginning at 72 µJy beam$^{-1}$. The red ellipse in the top-right corner is the size of the synthesized beam. Right: Stacked ATCA image of the same band, but with a 60 arcsec Gaussian taper applied during the Fourier transform process. The EoR0 contours are as in the right panel, with ATCA contours in red, beginning at 1.08 mJy beam$^{-1}$. ATCA contours in both images are increasing with factors of 2 and the EoR0 contours increase with factors of $\sqrt{2}$. The linear scale is at the cluster’s redshift. The red ellipse in the bottom-left corner is the size of the synthesized beam.
Online Archive (ATOA) to fully explore the cluster’s emission in the frequency range 147.5–3100 MHz. Table 4 summarises the properties of the observations used in this work.

The reduction of ATCA data follows standard procedures of continuum data reduction with miriad. In the data processing, we first flagged and removed RFI. We flagged further the edge channels that are within the bandpass rolloff, as the filters on the correlator have an area of approximately 32 MHz on each side with lessened sensitivity. PKS B1934-638 was used as the bandpass and flux calibrator for both configurations, PKS B2326-477 was the phase calibrator for EW352 configuration and MRC 2117-614 was the phase calibrator for 6A configuration. The dataset was split into four sub-bands of 512 MHz width, approximately centred at 1332, 1844, 2356, and 2868 MHz. In the Briggs robust weighting scheme, natural weighting 0 is used in an attempt to enhance any low surface brightness, diffuse emission. The multi-frequency clean task mfclean is used for deconvolution using the Clark method. Each sub-band goes through two passes of amplitude and phase self-calibration using the task selselfcal. The first pass utilises a higher clip level of 50 mJy beam$^{-1}$ for the lower three bands and 10 mJy beam$^{-1}$ for the highest. The second pass uses a lower clip value of 1 mJy beam$^{-1}$. A single pass of mfclean is used between each round of self-calibration, where each self-calibration and clean stage uses previously generated clean model as a prior. Finally the sub-bands are convolved to the synthesized beam of the lowest frequency band and stacked using the task linmos, which performs linear mosaicing on a set of images. In this case, it is used to increase the signal-to-noise ratio in the final, stacked 2100 MHz image. This stacked image has an rms of 21 mJy beam$^{-1}$ at the centre, increasing out towards the edges of the image. Table 5 summarises the sub-band images, on which we perform measurements. Fig. 32 shows the stacked sub-bands convolved to the resolution of the 1332 MHz sub-band centred on approximately 2100 MHz (left panel) and the stacked image after tapering to 60 arcmin (right panel).

The core of the cluster features four radio sources detected in the ATCA images: The BCG of the cluster, LCRS B224549.3-444744, is detected in each band, along with the source SUMSS J224845-443025 (Obj. C and D). Additionally, the stacked ATCA image shows the a source to the west of the BCG, Obj. B, which is revealed to be a spiral galaxy in archival HST images (see e.g. Diego et al. 2016, their Figure 1). From the SUMSS and TGSS images it would appear that Obj. D is in fact the core of a HT galaxy, with Obj C its tail. However, upon inspection of the higher resolution ATCA images, we see that the tail is a discrete emission masquerading as an extended, steep spectrum cluster halo.

The high resolution ATCA images confirm that there are embedded point sources within the emission seen at 168 MHz in the EoR0 field. These sources trace the emission seen in SUMSS and the TGSS, though the previous notion that SUMSS J224845-443025 was a HT galaxy is dispelled. While a diffuse cluster halo may be present, it is – with the current data – rendered undetectable. Given that cluster may have recently gone through a merger (Gómez et al. 2012) and its high X-ray luminosity (equivalent to the Bullet Cluster, 1E 0657-56; see e.g. Liang et al. 2000; Markevitch 2006; Shimwell et al. 2014; Srinivasan 2015) it was expected that Abell S1063 might host a halo.

3.3 On the scaling relations of cluster radio haloes

3.3.1 The $P_{1.4}$–$L_X$ relation

There exists an empirical relation between the thermal and non-thermal emission of galaxy clusters traced by the synchrotron emission giving the radio halo 1.4 GHz power, $P_{1.4}$, and the thermal Bremsstrahlung X-ray emission giving the cluster X-ray luminosity, $L_X$. The $P_{1.4}$–$L_X$ scaling relations have been studied and added to as each new halo detection or halo survey is released (e.g. GRHS: I; Venturi et al. 2007 and II; Venturi et al. 2008, EGRHS $^\dagger$; I; Kale et al. 2013 and II; Kale et al. 2015, KAT-7 observations: Bernardi et al. 2016, ARDES: I; Shakouri et al. 2016 and II; Shakouri et al. submitted) in an attempt to improve understanding about how the thermal X-ray emitting plasma interacts with the synchrotron electron population and how these relations might be caused by the clusters’ often dynamical natures.

For those haloes in our sample with measured 168 MHz flux densities and X-ray luminosities, we extrapolate using an assumed spectral index of $\alpha = -1.3 \pm 0.2$ (e.g. Cassano et al. 2013 use $-1.3$ for haloes with no spectral index) to obtain the 1.4 GHz flux densities. We do not discriminate between ultra-stEEP spectrum and normal-spectrum radio haloes, as a number of the new detections presented here fall within the ultra-stEEP category when considering their spectral index limits. We then obtain the $k$-corrected 1.4 GHz radio power, $P_{1.4}$, (see Hogg 1999; Hogg et al. 2002) via

$$P_{1.4} = \frac{4\pi D_L^2(z)}{(1+z)^{\alpha}} S_{1.4} \left[ \text{W Hz}^{-1} \right],$$

with the luminosity distance, $D_L(z)$, at the cluster’s redshift, and associated error, $\sigma_{P_{1.4}}$,

$$\sigma_{P_{1.4}} = \frac{P_{1.4}}{S_{1.4}} \sqrt{\left(\frac{\ln (1+z) \sigma_\alpha}{\sigma_{S_{1.4}}} \right)^2 + \left(\sigma_{S_{1.4}}\right)^2} \left[ \text{W Hz}^{-1} \right].$$

Further, for radio haloes in our sample with spectral index limits we calculate upper limits to the $P_{1.4}$ values. Fig. 33 shows the 64 current literature halo detections with $L_X$ measurements along with the newly detected haloes in Abell 0141 and Abell 2811 and the newly detected candidate haloes in Abell S0084 and RXC J2351.0-1954. All

7 Adapted from https://github.com/rsnemmen/nemen/blob/master/nemen/stats.py
8 Extended GMRT Radio Halo Survey

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measurements without quoted uncertainties we assume a standard three per cent uncertainty to allow for BCES fitting (see text). The GHz spectral index limits calculated here, thus they are upper limits to the 1.4 GHz radio halo power. For X-ray luminosities and radio power measurements without quoted uncertainties we assume a standard three per cent uncertainty to allow for BCES fitting (see text). The mauve shaded region represents the 95 per cent confidence interval associated with the solid black BCES orthogonal fit made to all the data. The powder-blue region is the same for the dotted BCES orthogonal fit presented by Cassano et al. (2013), and the aqua region is the for the dashed BCES orthogonal fit by Shakouri et al. (submitted). The halo associated with the cluster CL 0217+70 has been included. Note that radio power is computed here assuming a flat ΛCDM cosmology, with $H_0 = 70\, \text{km s}^{-1}\, \text{Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$, as compared to the rest of Section 3 which uses $H_0 = 68\, \text{km s}^{-1}\, \text{Mpc}^{-1}$.

![Figure 33. The $P_{1.4}$-$L_X$ scaling relation updated with the halo detections in this paper. Error bars have been omitted for the sake of clarity. The black unfilled circles are haloes from the literature, drawing from the same sample as Shakouri et al. (2016) with the addition of the haloes detected in Triangulum Australis (Scalise et al. 2015), MACS J2243.3-0935 (Cantwell et al. 2016), ACT-CL J0256.5+0006 (Knowles et al. 2016), and PSZ1 G285.0-23.7 (Martinez Aviles et al. 2016). The green, filled circles are new halo detections from this paper, with assumed spectral indices of $\alpha = -1.3 \pm 0.2$. The dark-purple, filled circles are the same new halo detections but with the spectral index limits calculated here, thus they are upper limits to the 1.4 GHz radio halo power. For X-ray luminosities and radio power measurements without quoted uncertainties we assume a standard three per cent uncertainty to allow for BCES fitting (see text). The mauve shaded region represents the 95 per cent confidence interval associated with the solid black BCES orthogonal fit made to all the data. The powder-blue region is the same for the dotted BCES orthogonal fit presented by Cassano et al. (2013), and the aqua region is the for the dashed BCES orthogonal fit by Shakouri et al. (submitted). The halo associated with the cluster CL 0217+70 has been included. Note that radio power is computed here assuming a flat ΛCDM cosmology, with $H_0 = 70\, \text{km s}^{-1}\, \text{Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$, as compared to the rest of Section 3 which uses $H_0 = 68\, \text{km s}^{-1}\, \text{Mpc}^{-1}$.

64 literature radio haloes are included by Shakouri et al. (submitted) in their scaling relation analysis, and all but four (Triangulum Australis, MACS J2243.3-0935, ACT-CL J0256.5+0006, PSZ1 G285.0-23.7) of the previous literature detections are included by Shakouri et al. (2016) in their scaling relation plots. For Triangulum Australis we use $L_X[0.1-2.4\, \text{keV}] = (4.83 \pm 0.12) \times 10^{44} \, \text{erg s}^{-1}$ (Zhao et al. 2013), and for PSZ1 G285.0-23.7 we use $L_X[0.1-2.4\, \text{keV}] = (16.91 \pm 0.27) \times 10^{44} \, \text{erg s}^{-1}$ (Planck Collaboration et al. 2011). The cluster Abell 1213 has been removed from our sample as we do not consider this emission to be that of a cluster halo. The diffuse emission detected in Abell 1213 has an LLS of ~250 kpc (LAS of ~4.3 arcmin), and is asymmetric. It is more likely a radio phoenix within our classification scheme, or possibly a mini-halo. Further, as a point of difference from values presented by Shakouri et al. (2016), for Abell 0523 we use the X-ray luminosity estimated by Girardi et al. (2016) of $3.44 \times 10^{44} \, \text{erg s}^{-1}$ compared to $1.07 \times 10^{44} \, \text{erg s}^{-1}$ reported by Ebeling et al. (1998).

For $L_X$ and $P_{1.4}$ measurements without quoted uncertainties we attribute a standard three per cent error, which is approximately the mean value of the reported uncertainties, such that we can utilise the Bivariate Correlated Errors and intrinsic Scatter (BCES) linear regression method (Akritas & Bershady 1996) to determine the best-fitting parameters to the data. We use the Python code BCES, a utilisation of which is shown by Nemmen et al. (2012). Table 6 summarises the best-fitting parameters for each of the BCES methods. Fig. 33 shows the best-fitting line (solid black) of the BCES orthogonal method, with the mauve, shaded region the 95 per cent confidence levels for that fit. The fit shown in Fig. 33 uses the assumed $\alpha = -1.3 \pm 0.2$ rather than the upper limits calculated. We also estimate the raw scatter, $\sigma_{\text{raw}}$, in the data via the error-weighted orthogonal distances to the best-fitting regression line via (e.g. Pratt et al. 2009; Cassano et al. 2013)

$$\sigma_{\text{raw}}^2 = \frac{(N/N - 2)}{\sum_{i=1}^{N} 1/\sigma_i^2} \sum_{i=1}^{N} \frac{1}{\sigma_i^2} (Y_i - aX_i - b),$$

where $N$ is the sample size, $\sigma_i^2 = \sigma_Y^2 + \sigma_X^2 + \sigma_{\text{raw}}^2$ for uncertainties $\sigma_Y$, $\sigma_X$, in $Y$, $X$, and fitting parameters $a$, $b$.

We find that the equivalent BCES orthogonal fits from Cassano et al. (2013) and Shakouri et al. (submitted) are consistent within the uncertainties of the data, however the raw scatter for equivalent fits has increased with the increase in sample size. New haloes and halo candidates from this work lie where expected. The halo within Abell S0084 is...
hosted by the second least X-ray luminous cluster in the sample, surpassed only by CL 0217+70; its location on the $P_{1.4}-L_X$ diagram expected for the cluster's X-ray luminosity assuming the spectral index is close to $-1.3$. Such a low-luminosity, low-power detection was expected of the MWA due to its sensitivity to weak, steep-spectrum emission. However, we would also expect to find more ultra-steep spectrum halo candidates, given the frequency of 168 MHz used here. Only one halo in our sample clearly fits this definition: the candidate halo within GMBCG J357.91841-08.97978 with $\alpha_{168} = -1.61 \pm 0.10$. This cluster, however, does not have a measured X-ray luminosity, nor significant emission seen in the soft-band RASS image, thus is not included in the present analysis.

There is a single halo that lies far beyond the rest of the sample, residing in the under-luminous cluster CL 0217+70, detected via its radio emission (Brown et al. 2011). The cluster is somewhat unique in its detection via radio emission, but also in that it features both a halo and a pair of relics. Its nature as under-luminous in the 0.1–2.4 keV X-ray band may be an effect of an uncertain redshift, though we have included the halo assuming the redshift is correct. Table 6 includes BCES best-fitting parameters for the four BCES methods, both including and excluding CL 0217+70. We see that the raw scatter ($\sigma_{\text{raw}}$) of the data is lower when excluding CL 0217+70, and that the overall fits tend to be steeper.

### 3.3.2 The $P_{1.4}$–$M_{500}$ relation

We also update the known $P_{1.4}$–$M_{500}$ scaling relation (e.g. Cassano et al. 2013, Shakouri et al. submitted) similarly. We draw again from the same sample of haloes of Shakouri et al. (2016, submitted) with the exception of the following clusters: Abell 1213 as this is not likely a halo; CL 0217+70, CL 1446+26, Abell 0339, Abell 1550, due to lack of $M_{500}$ value; we do not use Abell 0851 as mass estimates through various methods vary from $4.4 \times 10^{14} M_\odot$ (Martinet et al. 2016) to $12.5 \times 10^{14} M_\odot$ (Hoekstra et al. 2015); we do not use MACS J0416.1-2403 as the mass estimate is via X-ray proxy; we do not use Abell 0523 as the mass estimate from Umetsu et al. (2014) is via weak lensing methods; and we do not use Abell 0800 as the only available mass is that given as part of the MCXC which uses X-ray luminosity as the mass proxy compared to the Compton parameter, $y_{SB}$, as used by PSZ1. As the underlying scaling relations for mass estimates via X-ray and SZ effect select for different cluster samples, mass estimates may differ hence we use only mass estimates via SZ as this provides a larger sample. For the remaining clusters, mass estimates are taken from PSZ1. We also add the newly detected haloes in Abell S1121 and Abell 0141, and the candidate haloes in Abell 2811, Abell S0084, RXC J2351.0-1954, and GMBCG J357.91841-08.97978, as well as the recent detections in Triangulum Australis, MACS J2243.5-0935, ACT-CL J0256.5+0006, and PSZ1 C285.0-23.7.

Fig. 34 shows the updated scaling relation. We use the BCES method again to determine best-fitting parameters to the data. Table 6 summarises the best-fitting parameters for the four BCES methods for both the $P_{1.4}$–$L_X$ and the $P_{1.4}$–$M_{500}$ relation. Fig. 34 shows the BCES orthogonal fit along with the equivalent BCES orthogonal fits by Cassano et al. (2013) and Shakouri et al. (submitted). We use a total of 64 haloes in this analysis (including those from this work), and Cassano et al. (2013) use 25. Despite this difference in sample size, we see identical best-fitting parameters for the BCES orthogonal method.

### 3.3.3 A comparison of the scaling relations

Despite the equivalence in best-fitting parameters between this work and Cassano et al. (2013), we measure higher raw scatter for each fitting type. This is likely owed to the larger sample size for each relation. However, the $P_{1.4}$–$L_X$ scaling relation features lower scatter for each fitting method than the $P_{1.4}$–$M_{500}$ relation. We note that with the homogeneity of mass measurements by PSZ1 and the inhomogeneous $L_X$ measurements we should expect higher scatter in the $P_{1.4}$–$L_X$ relations.

Pratt et al. (2009) find, for a representative sample of clusters, that the X-ray luminosities show more scatter when cool core clusters are in the sample. Fig. 35 shows the $L_X$–$M_{500}$ relation for clusters hosting radio haloes. The solid, black fit with mauve 95 per cent confidence region is a BCES orthogonal fit to the cluster hosting haloes, whereas the dotted, black fit is the equivalent BCES orthogonal fit presented by Pratt et al. (2009) for the REXCESS sample of clusters, which comprises both cool and non-cool core clusters. This fit assumes a redshift of 0, whereas the dotted, black fit assumes a redshift of 1. These two fits sit atop one another, illustrating that redshift does not change the fits substantially. The only cluster in the halo sample to host a cool core is CL 1821+643 which features a giant radio halo with LLS of $\sim 1.1$ Mpc (Bonafede et al. 2014). The sample of clusters used by Pratt et al. (2009) feature $\sim 32$ per cent cool cores, which in the $L_X$–$T$ relation preferentially lie above the best-fitting parameters. With a significant lack of cool core clusters, we find best-fitting parameters to the $L_X$–$M_{500}$ relation that shows a similar slope (within the uncertainties to the BCES fitting) though the relation sits further down in X-ray luminosity, consistent with the sample consisting of only a single cool core cluster.

The lack of cool core clusters may explain the lower

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**Table 6.** Best-fitting parameters from the BCES fitting with different methods, where $\log_{10}(P_{1.4}) = a \log_{10}(X) + b$ for $X = L_X, M_{500}$. The raw scatter in the data, $\sigma_{\text{raw}}$, is computed for each fitting method.

| Method          | $a$     | $b$     | $\sigma_{\text{raw}}$ |
|-----------------|---------|---------|----------------------|
| $P_{1.4}$–$L_X$, excluding CL 0217+70 |         |         |                      |
| BCES(Y)         | $2.64 \pm 0.27$ | $-94.15 \pm 12.15$ | 0.50                  |
| BCES(Y)         | $1.46 \pm 0.16$ | $-41.16 \pm 7.22$  | 0.37                  |
| Bisector        | $1.91 \pm 0.12$ | $-61.57 \pm 5.15$  | 0.38                  |
| Orthogonal      | $2.38 \pm 0.21$ | $-82.29 \pm 9.56$  | 0.45                  |
| $P_{1.4}$–$L_X$, including CL 0217+70 |         |         |                      |
| BCES(Y)         | $2.51 \pm 0.27$ | $-88.25 \pm 11.98$ | 0.54                  |
| BCES(Y)         | $1.32 \pm 0.19$ | $-34.97 \pm 8.42$  | 0.39                  |
| Bisector        | $1.77 \pm 0.16$ | $-55.22 \pm 7.26$  | 0.41                  |
| Orthogonal      | $2.21 \pm 0.24$ | $-74.64 \pm 10.78$ | 0.47                  |

| Method          | $a$     | $b$     | $\sigma_{\text{raw}}$ |
|-----------------|---------|---------|----------------------|
| $P_{1.4}$–$M_{500}$ |         |         |                      |
| BCES(Y)         | $5.41 \pm 0.79$ | $-56.01 \pm 11.77$ | 0.61                  |
| BCES(Y)         | $2.90 \pm 0.28$ | $-18.76 \pm 4.17$  | 0.46                  |
| Bisector        | $3.80 \pm 0.30$ | $-32.10 \pm 4.46$  | 0.48                  |
| Orthogonal      | $5.26 \pm 0.76$ | $-53.72 \pm 11.35$ | 0.60                  |
scatter in the $P_{1.4} - M_{500}$ relation compared to that in the $P_{1.4} - M_{500}$ relation, where we would otherwise expect a relation derived from homogeneous mass measurements to be more tightly constrained than that of inhomogeneous X-ray measurements. However, simulations show that there may be a transient boost to $L_X$ during the course of a cluster merger (Donnert et al. 2013), though it is not clear whether this will push the cluster above the $P_{1.4} - L_X$ relation or along it with a simultaneous increase to the radio halo power. Less scatter in the $P_{1.4} - L_X$ relation may suggest the latter, where transient boosts above the relation would otherwise increase the raw scatter.

However the largest contribution to raw scatter in the data (which exists for both $P_{1.4} - L_X$ and $P_{1.4} - M_{500}$ relations) will arise from inhomogeneous $P_{1.4}$ measurements. Radio flux densities are often measured on maps made with differing beam sizes and $u-v$ plane coverage. In the case of missing $u-v$ coverage, not all spatial scales are recovered which results in missing flux, yielding lower limits to integrated flux densities on the resulting maps. There is no steadfast rule for measuring the radio flux density from a map. In this work we used two methods: summing pixels that comprise a source and the use of AEGEAN to measure the flux density enclosed by a fitted ellipse. Other works use similar methods but also summing flux density within regions of various shapes. Finally, flux densities are not always measured at 1.4 GHz. Often as in this work – a lower-frequency integrated flux density is measured for the halo, and a corresponding 1.4 GHz flux density (hence, power) is extrapolated from a calculated or assumed spectral index. Spectral indices are often calculated with very few points along the SED, where it is usually assumed the SED is modelled by a simple power law. This may not be the case – at least for the entire range between the lowest frequency measurements (e.g. 150 MHz GMRT measurements) and the 1.4 GHz measurement that is extrapolated to. For haloes without a spectral index, it is typical to assume a spectral index of $-1.3$. This is not always accurate, as there are haloes with measured spectral indices below and above this value, e.g. the halo in Abell 2744 (Section 3.2.13) is measured to have $\alpha_{1400} = -1.11 \pm 0.04$, the halo in Abell 2811 (Section 3.2.16) has $\alpha_{1400} \leq -1.5 \pm 0.1$, or the candidate halo within GMBCG J357.91841-08.97978 (Section 3.2.25) with $\alpha_{1400} = -1.62 \pm 0.10$.

### 3.4 The detection rate of diffuse cluster emission within the EoR0 field

Here we examine the detection rate of radio haloes, relics, and phoenices within the EoR0 field and compare these to clusters in which no such emission is seen. For these comparisons we consider only those clusters within the MCXC and PSZ1 catalogue, as a majority of ACO clusters do not have available masses, and a significant portion do not have redshifts. Fig. 36 shows cluster mass against redshift. Up until recently it has only been possible to detect radio haloes and relics in nearby clusters, except in the most massive and luminous examples (e.g., Abell 2744). This plot effectively demonstrates the power of the MWA to detect diffuse cluster emission in the redshift range 0.02–0.5, with uniformly distributed masses and redshifts over this range from catalogue-selected clusters. Fig. 36 also shows that with such sensitivity we are now probing the diffuse emission in nearby X-ray-emitting low-mass clusters.

The two major limiting factors in the detection of such
Table 7. Clusters with diffuse emission and available mass measurements included in Fig. 36.

| Cluster          | $M_{500}$ ($\times 10^{14}$ $M_\odot$) | Type | Notes |
|------------------|------------------------------------------|------|-------|
| Abell 0013       | 2.79$^a$                                  | R    |       |
| Abell 0085       | 4.90$^a$                                  | R    |       |
| Abell 0133       | 3.08$^a$                                  | P    |       |
| Abell 0141       | 4.48$^a$                                  | H    |       |
| Abell 2556       | 2.47$^b$                                  | cP   |       |
| Abell 2721       | 3.77$^a$                                  | cR   |       |
| Abell 2744       | 9.56$^a$                                  | H,R  |       |
| Abell 2751       | 1.26$^b$                                  | R    |       |
| Abell 2798       | 1.31$^a$                                  | cR   |       |
| Abell 2811       | 3.67$^a$                                  | H    |       |
| Abell 4058       | 2.03$^b$                                  | P    |       |
| Abell S0084      | 2.36$^a$                                  | cH   |       |
| Abell S1121      | 7.05$^a$                                  | H    |       |
| RXC J2351.0–1934 | 5.60$^a$                                  | cH,cR,cR |       |
| MACS J2243.3–0935| 10.07$^a$                                 | H    |       |
| GMBCG J357.91841–09.97978 | 5.90$^a$ | cH |       |

a $M_{500}$ (Planck Collaboration et al. 2015a)
b $M_{500}$ (Piffaretti et al. 2011), truncated to two decimal places.

emission are the resolution and sensitivity of the telescope. The MWA as a low-frequency telescope is limited in its resolution by the maximum baseline at 2873.3 m. The EoR0 field in particular has a beam size of ~2.3 arcmin, which, when considering only resolution, means that the viable detection range for distant haloes is LLS$_{500}$–1000 kpc ($z_{\text{LS}}$). Beyond these redshifts, any potential haloes if detected become point sources as they appear the same angular size as the synthesized beam. The second issue is sensitivity; the EoR0 field reaches a sensitivity of approximately 2.3 mJy beam$^{-1}$ in the best regions of the image. The lowest theoretical sensitivity of the Phase I MWA is approximately 1.7 mJy beam$^{-1}$ (Franzen et al. 2016). However the sensitivity here is not the limiting factor in detecting high-redshift haloes. For the redshift range $z = 0.22–0.67$, a halo the size of the beam could theoretically be detected with 1.4 GHz power in the range of $P_{1.4}(z = 0.22–0.67) \geq 0.3–2 \times 10^{23}$ WHz$^{-1}$. This entire range falls below the what is typically seen of cluster haloes (e.g. Cassano et al. 2013; Kale et al. 2015; Shakouri et al. 2016). The solid, black line in Fig. 36 shows the theoretical limit for detecting 1 Mpc radio haloes given the $P_{1.4}-M_{500}$ relation found in Section 3.3.2 and assuming a spectral index in of $\sim -1.3$. We see that haloes detected as part of this work lie above this limit, as expected, but note that relics are not bound by the same limit.

The somewhat uniform distribution of detections shown Fig. 36 is not surprising given the approximate limits above, and with the sensitivity and resolution of the EoR0 field, the entire redshift space covered by the PSZ1 and MCXC catalogues are available for halo detection.

### 4 CONCLUSIONS

In this paper we have presented diffuse cluster emission detected by the MWA at 168 MHz within the EoR0 field. This includes the detection of 10 haloes, 10 relics, and 3 phoenices, of which 8 are new haloes, 7 are new relics, and 1 is a new phoenix, or candidates of each. In particular, we detect a halo associated with the cluster Abell 0141 which is undergoing a merger as suggested by the bi-modality of its optical density and X-ray--emitting plasma. This halo appears to be ultra-steep with $a_{168} \leq 2.1 \pm 0.1$. Such ultra-steep haloes are predicted to be found in low frequency surveys (Cassano et al. 2012b) and their detection is suggestive of the validity of current halo acceleration models. Along with these objects, we have also detected 6 objects that may be haloes, relics, phoenices, or relic AGN emission from ancient radio galaxies. In the case of Abell S1063 we obtain archival ATCA imaging to determine the nature of the emission and find blended point sources with no trace of diffuse cluster emission. Where possible we measure 168 MHz flux densities, estimate angular and linear sizes, and estimate spectral indices or spectral index limits based on non-detections at 1.4 GHz in the NVSS.

With these new halo detections, we update the known $P_{1.4}-L_X$ and $P_{1.4}-M_{500}$ scaling relations of radio halo power with cluster X-ray luminosity and mass. We show that with that with an increase in sample size we are seeing the same, or similar to within the fitting uncertainties, best-fitting parameters estimated via the BCES orthogonal method. We see less scatter in the $P_{1.4}-L_X$, suggesting a lack of cool cores.
in the halo sample. We see an increase in raw scatter with the increase in sample size and suggest this is due to inhomogeneous measurements of the 1.4 GHz radio halo power. Finally, with these new detections we examine the incidence rate of such emission, finding that the MWA is beginning to see emission with little bias beyond what is present in the catalogues the clusters are drawn from.

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This research made use of astropy, a community-developed core python package for Astronomy (Astropy Collaboration, 2013), along with aplpy, an open-source plotting package for python hosted at http://aplpy.github.com. This research has made use of the VizieR catalogue access tool, CDS, Strasbourg, France. The original description of the VizieR service was published in A&AS 143, 23. This research also made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The Digitized Sky Surveys were produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the

Figure 36. Cluster mass against redshift for clusters within the MCXC and PSZ1 catalogues. The filled points are those using the PSZ1 $M_{500}$ measurements and unfilled points are those using the MCXC $M_{500}$ measurements. Where clusters appear in both catalogues we use the PSZ1 $M_{500}$ measurements. The coloured lines indicate the limit at which a 1 Mpc halo can be detected given the $P_{1.4-M_{500}}$ scaling relation in Section 3.3 assuming a sensitivity of 2.3 mJy beam$^{-1}$, beam size of 2.3 arcmin, and spectral indices $\{-1.1, -1.2, -1.3, -1.4, -1.5, -1.7, -1.8\}$, where a lower spectral index requires a lower mass cluster. No haloes are detected below this limit. Table 7 provides details of the clusters with detected diffuse emission included here. References for redshifts: Abell et al. (1989), Dalton et al. (1994), Alonso et al. (1999), Batuski et al. (1999), de Propris et al. (1999), Jones & Forman (1999), Struble & Rood (1999), Caretta et al. (2002), Zaritsky et al. (2006), Coziol et al. (2009), Wen et al. (2010), Piffaretti et al. (2011), Williamson et al. (2011), Chon & Böhringer (2012), Mahajan et al. (2012), Hicks et al. (2013), Pearson & Batuski (2013), Wen & Han (2013), Planck Collaboration et al. (2014), Bleem et al. (2015), Liu et al. (2015), and Planck Collaboration et al. (2015b).
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