Research Paper

MWA and ASKAP observations of atypical radio-halo–hosting galaxy clusters: Abell 141 and Abell 3404

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Abstract

We report on the detection of a giant radio halo in the cluster Abell 3404 as well as confirmation of the radio halo observed in Abell 141 (with linear extents ~ 770 kpc and ~ 850 kpc, respectively). We use the Murchison Widefield Array (MWA), the Australian Square Kilometre Array Pathfinder (ASKAP), and the Australia Telescope Compact Array (ATCA) to characterise the emission and intervening radio sources from ~ 100–1000 MHz; power law models are fit to the spectral energy distributions with spectral indices $\alpha_{110} = -1.66 \pm 0.07$ and $\alpha_{88} = -1.06 \pm 0.09$ for the radio halos in Abell 3404 and Abell 141, respectively. We find strong correlation between radio and X-ray surface brightness for Abell 3404 but little correlation for Abell 141. We note each cluster has an atypical morphology for a radio-halo–hosting cluster, with Abell 141 having been previously reported to be in a pre-merging state, and Abell 3404 is largely relaxed with only minor evidence for a disturbed morphology. We find that the radio halo powers are consistent with the current radio halo sample and $P_{\nu} \sim M$ scaling relations, but note that the radio halo in Abell 3404 is an ultra-steep–spectrum radio halo (USSRH) and, as with other USSRHs lies slightly below the best-fit $P_{1.4} \sim M$ relation. We find that an updated scaling relation is consistent with previous results and shifting the frequency to 150 MHz does not significantly alter the best-fit relations with a sample of 86 radio halos. We suggest that the USSRH halo in Abell 3404 represents the faint class of radio halos that will be found in clusters undergoing weak mergers.

Keywords: galaxies: clusters: individual: (Abell 141, Abell 3404) – large-scale structure of the Universe – radio continuum: general – X-rays: galaxies: clusters

1. Introduction

Galaxy clusters represent ideal laboratories for investigating large-scale structure formation. As the largest virialized systems in the Universe, galaxy clusters are located at the nodes of the Cosmic Web and are assembled through hierarchical structure formation (Peebles, 1980); accretion of matter from filaments and mergers between clusters releases energy into the intra-cluster medium (ICM) to be transferred into various non-thermal processes (see e.g. Sarazin, 2002; Keshet et al., 2004; Brunetti & Jones, 2014). Resultant shocks and turbulence in the ICM are thought to energise electrons to emit synchrotron radio emission over large scales with steep power law spectra ($\alpha \approx -1$); see e.g. Brunetti et al. 2008; Brunetti & Jones 2014; van Weeren et al. 2019) in the micro-Gauss–level magnetic fields permeating the clusters (see e.g. Clarke et al., 2001; Brüggen et al., 2012, and Donnert et al. 2018 for a recent review).

The observed radio emission from ICM-based turbulence and shocks can be broken down into four main categories, with somewhat blurred lines between definitions (see e.g. Kempner et al., 2004; van Weeren et al., 2019, for taxonomic discussion). Megaparsec–scale radio relics are found in the low-density environments of cluster outskirts (e.g. in Abell 3667, Johnston-Hollitt 2003; CIZA J2242.8+5301, van Weeren et al. 2010; PSZ1 G096.89+24.17 de Gasperin et al. 2014; SPT-CL J2032–5627, Duchesne et al. 2021a)—shocks in the ICM are thought to energise electrons via diffusive-shock acceleration (DSA and related processes, e.g. Blandford & Eichler 1987) and relics have been observed to align with shocks detected via X-ray temperature and surface brightness discontinuities (e.g. Mazzotta et al., 2011; Akamatsu et al., 2015; Eckert et al., 2016). Smaller-scale (≤ 400 kpc) relic sources called radio relics are thought to be the revived corpses of ancient, lobed radio galaxies, with the radio plasma re-energised by adiabatic compression via small-scale ICM turbulence and shocks (Enßlin & Gopal-Krishna, 2001, furthermore, see Slee et al. 2001; de Gasperin et al. 2015 for examples) or gentle re-energisation of radio plasma from single (de Gasperin et al., 2017) or multiple electron populations (Hodgson et al., 2021). Phoenices are typically located closer to the cluster centre, and feature steeper spectra, with steepening beyond ~ 1 GHz. Mini-halos are smaller (≤ 400 kpc), centrally-located, steep-spectrum patches of diffuse emission often found surrounding a radio-loud active galactic nucleus (AGN) associated with the brightest cluster galaxy (BCG). These sources are predominantly found in relaxed cool-core clusters, thought to form through the inner sloshing of the ICM gas, with seed electrons fuelled by the embedded AGN (see e.g. Giacintucci et al., 2017, 2019). Finally, giant radio halos are found in the centres of massive, merging clusters and are thought to also form through ICM turbulence generated by the merger process (e.g. in Abell 2255,
Harris et al. 1980; 1E 0657–56, Liang et al. 2000; Abell 2163, Feretti et al. 2001; Abell 523, Giovannini et al. 2011). It has been suggested that mini-halos may transition into giant radio halos during mergers: the emitting cosmic ray electrons of mini-halos being transported throughout the cluster volume and re-accelerated via ICM turbulence (Brunetti & Jones, 2014). Observations suggest radio halos are transient phenomena—Donnert et al. (2013) showed that the range of spectral and morphological shapes seen in observed halos can, in part, be attributed to when they occur during a merger.

Historically, radio halo detections have been uncommon in clusters and the number of sources has, until recently, remained low. This was due in part to observational biases and limitations; many historic surveys were performed at 1.4 GHz, missing steep-spectrum emission only visible at lower frequencies. With the current generation of radio telescopes, telescope upgrades, increases in sensitivity, and low-frequency operation are helping to reveal a new population of radio halos (e.g. Duchesne et al., 2021b; Cassano et al., 2019; HyeongHan et al., 2020; Wilber et al., 2020; Di Gennaro et al., 2020; Hoefl et al., 2020; van Weeren et al., 2020; Knowles et al., 2021; Hodgson et al., 2021) and to clarify the nature of previously detected systems (e.g. Botteon et al., 2020c; Bonafede et al., 2020).

In this paper we present new observations of two clusters with candidate radio halo emission, originally detected in MWA data, now followed-up with the Australia Telescope Compact Array (ATCA; Frater et al., 1992), the Australian Square Kilometre Array Pathfinder (ASKAP; Hotan et al., 2021), and the recently upgraded Murchison Widefield Array (Tingay et al., 2013) in its new “phase 2” extended baseline configuration (Wayth et al., 2018, hereafter “MWA-2”). In this work we assume a flat Λ cold dark matter cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\OmegaM = 0.3$, and $\Omega_\Lambda = 1 - \OmegaM$.

1.1. Abell 141

During a search for diffuse, non-thermal emission in a selection of galaxy clusters within a large MWA image at 168 MHz covering the Epoch of Reionization 0-hour field (EoR0; Offringa et al., 2016), Duchesne et al. (2021b) reported the detection of a giant radio halo in the massive, merging galaxy cluster Abell 141 (Abell, 1958; Abell et al., 1989). Using the Giant Metrewave Radio Telescope (GMRT), Venturi et al. (2007) reported the non-detection of a radio halo in Abell 141 at 610 MHz. Using the low resolution MWA data and the GMRT limit, Duchesne et al. (2021b) reported a spectral index limit of $\alpha_{610 \text{ MHz}} < -2.1$, making it one of the steepest-spectrum radio halo detected to date, tied with the radio halo in Abell 521 ($\alpha_{500 \text{ MHz}} < -2.1$; Brunetti et al. 2008). Caglar (2018) investigated the X-ray properties of the cluster, which show both a bi-modal X-ray distribution as well as a bi-modal optical distribution (Dahle et al., 2002). The cluster is also detected in Planck Sunyaev–Zel’dovich (PSZ) surveys as PSZ2 G175.69–85.98 (Planck Collaboration et al., 2016a) and is reported to have an SZ-derived mass of $5.67_{-0.40}^{+0.36} \times 10^{14}$ $\Msun$. The cluster is reported to have a redshift of $0.23$ (Struble & Rood, 1999) where 1 arcmin corresponds to 221 kpc in scale. We show an updated composite image of Abell 141 in Fig. 1 with data described in Section 2.3 and 2.4.

1.2. Abell 3404

Abell 3404 was found to host unclassified extended emission permeating the cluster in GaLactic and Extragalactic All-sky MWA (GLEAM; Wayth et al., 2015; Hurley-Walker et al., 2017) data at 200 MHz from a search for diffuse cluster emission within clusters from the Meta-Catalogue of X-ray detected galaxy Clusters (MCXC; Piffaretti et al., 2011). Although the emission is elongated, typical of the morphologies of radio relics, its location at the centre of cluster suggested a halo-type source. The low resolution of the GLEAM data resulted in significant blending of the extended emission with nearby point sources and made it impossible to confirm its nature. Shakouri et al. (2016) investigated the cluster using the Australia Telescope Compact Array (ATCA; Frater et al., 1992) as part of the ATCA REXCESS 3 Diffuse Emission Survey (ARDES), though they found no evidence of a radio halo or other diffuse radio source. In advance of this publication, Brüggen et al. (2021) noted the detection of diffuse emission in Abell 3404 on the edge of a widefield observation of the cluster system Abell 3391-95 but leave the detailed characterisation to this work. The cluster has an SZ-derived mass of $7.96_{-0.21}^{+0.23} \times 10^{14}$ $\Msun$ and redshift $z = 0.1644$ (Planck Collaboration et al., 2016a). At the cluster redshift 1 arcmin corresponds to 170 kpc in scale. A composite image of Abell 3404 is shown in Fig. 2.

3Representative XMM-Newton Cluster Structure Survey (Böhringer et al., 2007).
for ionosphere-related astrometric shifts using fits_warp.py https://github.com/nhurleywalker/fits_warp and finally corrected for residual primary beam errors and flux scale errors with flux_warp https://gitlab.com/Sunmish/flux_warp to ensure a common flux scaling across snapshots. The snapshots are then co-added, weighted by the square of the primary beam response and local noise.

We make a number of image sets for multiple purposes: a) using an image weighting with a ‘Briggs’ robustness parameter of 0.0 for a maximum resolution image, b) robust = +2.0, and c) robust = +1.0 with an additional 120 arcsec Gaussian taper applied to produce a more common sensitivity between the five frequencies and to enhance the low surface-brightness emission in individual snapshots further. We find that, because of the slight difference in inner $u$–$v$ sampling between the five frequencies (see Appendix A, Figs. 11(i)–(v) and 12(i)–(v)) the 88- and 118-MHz images do not require additional tapering, though for Abell 3404 we find we can use the robust = +2.0 images for flux density measurement without additional confusion.

Fig. 3(i) and 3(ii) show the $3\sigma_{\text{rms}}$ contours of the robust = +2.0, 118-MHz image and the robust = 0.0, 216-MHz image of Abell 141, respectively. Similarly, Fig. 4(i) shows the $3\sigma_{\text{rms}}$ contour of the robust = +2.0, 118-MHz image of Abell 3404 and Fig. 4(ii) shows the $3\sigma_{\text{rms}}$ contour of the robust = 0.0, 216-MHz image.

2.1.2. Measuring dirty flux density

Snapshot imaging results in residual dirty flux (i.e. emission that has not been deconvolved by the CLEAN algorithm) that becomes significant in final stacked images as the CLEANing depth is set in the individual snapshot images. Using multiscale CLEAN can mitigate this somewhat as the root-mean-square (rms) noise on larger scales allows CLEANing of large structures below the point-source CLEAN depth. The result is measurement of residual dirty flux, which 1) has a point spread function (PSF) that differs from the restoring beam and 2) the dirty flux may be reduced or increased compared to the equivalent CLEAN flux due to complex PSF sidelobe interactions. We assume that the PSF difference is small—i.e. the fitted restoring beam is an accurate representation of the PSF. To test the difference in measured dirty to CLEAN flux density, we simulate 2-d circular Gaussian sources in all snapshots with an arbitrary $S = 1 \text{ Jy}$ with varying full-width at half maximum (FWHM) sizes, ranging from 5$''$ to 575$''$ in 30$''$ intervals and measure the integrated flux density in the dirty and CLEANed maps. We find that the ratios of measured $S_{p,\text{dirty}}/S_{p,\text{CLEAN}}$ (peak) and $S_{\text{dirty}}/S_{\text{CLEAN}}$ (integrated) decrease down to ~0.5–0.6 for structures up to 10 arcmin for the Abell 3404 data, but increase by only a few per cent for Abell 141. We show the robust = +2.0 results in Fig. 5.

To correct for this, we create separate CLEAN component model and residual stacked images to match the restored stacked image. When measuring $S$ for real sources, we use the restored image to guide the integration region, but sum the CLEAN model and add the integrated residuals with a correction factor applied to the residual flux density determined by the size of the emission region.

### 2. Data & methods

New data presented in this work are described in the following sections. A summary of observations used in this work and described in this section is presented in Table 1. We also provide representative plots of the $u$–$v$ coverage for all datasets in Appendix A.

2.1. MWA

2.1.1. Data processing

Both Abell 141 and Abell 3404 were observed with the MWA-2 as part of a follow-up of candidate radio halos and relics detected with the GLEAM survey. The observations covered five frequency bands (of 30-MHz bandwidth): 88, 118, 154, 185, and 216-MHz. Observation details are presented in Table 1. The MWA data are processed following Duchesne et al. (2020). Briefly, MWA data are observed in a 2-minute snapshot observing mode, with each 2-minute snapshot calibrated and imaged independently and stacked in the image plane at the end.

We use in-field calibration on a global sky model generated from the GLEAM, NVSS, and SUMSS catalogues (where survey coverage is available) using the Mitchcal algorithm (see Offringa et al., 2016). The calibrated data are then imaged using WSClean (Offringa et al., 2014; Offringa & Smirnov, 2017) to perform amplitude and phase self-calibration before imaging again to a lower threshold (i.e. CLEANing more deeply). After initial primary beam correction using the most recent Full-Embedded Element model (Sokolowski et al., 2017) these CLEANed images are then corrected

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**Figure 2.** Composite image of Abell 3404. Background optical data are from the SuperCOSMOS Sky Survey (Hambly et al., 2001a,b,c). Radio and X-ray data overlaid as in Fig. 1. The linear scale is at the redshift of the cluster.
Table 1 Details of the radio observations of Abell 141 and Abell 3404.

| Telescope       | \( \nu_c \) \(^a\) (MHz) | \( \Delta \nu \) \(^b\) (MHz) | \( \theta_{\text{max}} \) \(^c\) (arcmin) | \( \tau \) \(^d\) (min) | Dates                  |
|-----------------|--------------------------|-----------------|-----------------|-----------------|------------------------|
| Abell 141       |                          |                 |                 |                 |                        |
| MWA-2           | 88                       | 30              | 60              | 64              | 2017 Nov 03,04, Dec 22, 2018 Jan 06 |
| MWA-2           | 118                      | 30              | 60              | 68              | 2017 Nov 03,04, Dec 22, 2018 Jan 06 |
| MWA-2           | 154                      | 30              | 60              | 64              | 2017 Nov 03,04, Dec 22, 2018 Jan 06 |
| MWA-2           | 185                      | 30              | 60              | 62              | 2017 Nov 03,04, Dec 22, 2018 Jan 06 |
| MWA-2           | 216                      | 30              | 60              | 60              | 2017 Nov 03,04, Dec 22, 2018 Jan 06 |
| ASKAP           | 943                      | 288             | 49              | 2145            | 2020 Apr 03,04, Jul 03,04, Nov 28 |
| ATCA (CABB)     | 2100                     | 1500 \(^e\)     | 5.7             | 928             | 2015 May 05,10,15,16   |
| Abell 3404      |                          |                 |                 |                 |                        |
| MWA-2           | 88                       | 30              | 60              | 58              | 2018 Jan 10, Feb 18,21, Mar 04,13 |
| MWA-2           | 118                      | 30              | 60              | 42              | 2018 Jan 10, Feb 18, Mar 04,13 |
| MWA-2           | 154                      | 30              | 60              | 58              | 2018 Jan 10, Feb 18,21, Mar 04,13 |
| MWA-2           | 185                      | 30              | 60              | 42              | 2018 Jan 10, Feb 18,21, Mar 13 |
| MWA-2           | 216                      | 30              | 60              | 38              | 2018 Jan 10, Feb 18,21, Mar 13 |
| ASKAP           | 1013                     | 288             | 35              | 689             | 2019 Mar 22             |
| ATCA (pre-CABB) | 1344                     | 128             | 35              | 374             | 2007 Jun 10–16, Jul 26,28–30, Aug 02 |
| ATCA (pre-CABB) | 1432                     | 128             | 35              | 374             | 2007 Jun 10–16, Jul 26,28–30, Aug 02 |
| ATCA (CABB)     | 2100                     | 1400 \(^e\)     | 25              | 103             | 2013 Jun 21–23         |

\(^a\) Central observing frequency.

\(^b\) Observation bandwidth.

\(^c\) Maximum angular scale observation is sensitive to at the respective central frequency with a \(u–v\) limit employed during imaging.

\(^d\) Total observing time.

\(^e\) Originally a 2049 MHz band, significant RFI flagging reduces the usable bandwidth.

The correction factor is determined by the convolved source size and estimated from the nearest simulated ratio of \(S_{\text{dirty}}/S_{\text{CLEAN}}\).

2.2. ATCA

Abell 3404 was observed with both the Compact Array Broadband Backend (CABB; Wilson et al., 2011) and the ATCA correlator prior to the CABB installation (hereafter “pre-CABB”, Project Codes C1683 and C2837; Johnston-Hollitt et al., 2007, 2013). The observation details are listed in Table 1, though note for both the CABB and pre-CABB observations Abell 3404 was observed in a “\(u–v\) cuts” mode at a range of hour-angles, but not filling in the \(u–v\) plane significantly. The pre-CABB and CABB data have different phase centres, and the lower end of the CABB data are flagged due to RFI so the two data sets are imaged independently. Abell 141 was observed with the CABB (Project Code C2915; Shimwel et al., 2015), though two configurations were used: 1.5C and 6A, with maximum/minimum baselines of 4500/77 and 5939/337 m, respectively.

Calibration for all ATCA data follows standard data reduction procedures using miriad (Sault et al., 1995). Bandpass and absolute flux calibration is performed using the standard ATCA centremetre calibrator, PKS B1934-638, and appropriate secondary calibrators bracket the source observations, used for complex gain and phase calibration. We perform two rounds of self-calibration on each dataset, using WSClean to create initial CLEAN component models and the Common Astronomy Software Applications (CASA; McMullin et al., 2007) task, gaincal, to solve for phase-only gain solutions on successively shorter intervals (i.e. 120 s and 30 s). Additionally, final imaging for the Abell 3404 data removes the longest baselines formed with antenna 6 to achieve a more well-behaved point spread function. Imaging for all datasets is otherwise similar, utilising a ‘Briggs’ robustness parameter of 0.0, and splitting the full CABB bands into smaller subbands. Note that significant RFI flagging occurs in the 16-cm band for the ATCA data and the final usable band for CABB observations is \(\sim 1.5\) GHz and is split into subbands of \(\Delta \nu = 300\) MHz for discrete source measurements.

Fig. 3(ii) shows the robust = 0.0 full-band 2.2-GHz ATCA map for Abell 141 convolved to 18 arcsec. Fig. 4(ii) shows the similar 2.4-GHz full-band map for Abell 3404.

2.3. ASKAP

ASKAP operates between 700–1800 MHz and features a Phased Array Feed (PAF; DeBoer et al., 2009; Hotan et al., 2014; McConnell et al., 2016) allowing the creation of 36 independent primary beams which can be arranged in a number of different footprints to create large \(7^\circ \times 7^\circ\) mosaics in “6 by 6” primary beam footprints. ASKAP has recently been used to complete some observations for early science and survey projects (e.g. the Evolutionary Map of the Universe, EMU; Norris et al., 2011). Abell 3404 and Abell 141 feature in early
We follow a similar self-calibration process to the ATCA data, and the ASKAP Scheduling Block (SB)8275 (Harvey-Smith et al., 2017) pipeline uses daily observations of PKS B1934-638 for bandpass calibration, with each of the 36 beams being calibrated independently. Additionally, the data are averaged to 1 MHz/10 s spectral/temporal resolution. The full bandwidth for each observation is 288 MHz. We summarize additional observation details in Table 1.

### 2.3.1. ASKAP—Abell 3404

The ASKAP Scheduling Block (SB)8275 (Harvey-Smith et al., 2018) has two overlapping beams containing Abell 3404 (beam 17 and 23) with a central observing frequency of \(\nu_c = 1013.5\) MHz. We follow a similar self-calibration process to the ATCA data described in Section 2.2, though this calibration does not reduce the well-known, but not currently understood artefacts that appear around bright sources at a \(\sim 1\) per cent level. For the two beams containing Abell 3404, these artefacts are negligible and do not interfere with the cluster. Imaging is performed using WSClean, and we image by splitting the data into 4 subbands of \(\Delta\nu = 72\) MHz, jointly CLEANing in the fullband multi-frequency synthesis (MFS) image. Imaging for these data is done by first masking the diffuse emission within the cluster region, ensuring all discrete sources are included in the CLEAN process. The initial image weighting is robust = +0.5, which we found to be most accurate for modelling the discrete cluster sources. The second image set we produce are the re-imaged residuals convolved with a 25 arcsec beam to highlight diffuse cluster emission. Finally, we re-image the residuals with an additional 35 arcsec taper in 3 subbands of \(\Delta\nu = 96\) MHz.

For each image set, we linearly mosaic beams 17 and 23, applying a correction for primary beam attenuation assuming a 2-dimensional Gaussian model that scales with \(1.091/D\) (A. Hotan, priv. comms.) with \(D = 12\) m the diameter of the ASKAP dishes. For quality assurance we compare the spectral energy distribution (SED) of a nearby, bright test source measured by the MWA-2, ATCA, and additional survey data and find that the ASKAP data follow the expected flux density. Additionally, we find an astrometric offset of \(\Delta\delta_{J2000} \sim -0.0055\), which we correct in the image World Coordinate System (WCS) metadata. Fig. 4(i) shows the ASKAP full-band robust = +0.5 image with the source-subtracted 35 arcsec tapered image as contours.
2.3.2. ASKAP–Abell 141

Abell 141 is present on the edge of a beam (23) in a number of ASKAP observations. After an initial round of imaging with all available observations we find most of the observations contain significant radial artefacts crossing the cluster from a nearby bright source which is unable to be removed via direction-independent calibration. We find the SB12704, SB15191, and SB18925 observations do not show significant artefacts and combine those observations for further joint imaging. We opted to self-calibrate the data, generating a combined, jointly-deconvolved model image of the three datasets then self-calibrating each dataset individually based on the combined model. Initial imaging was carried out similarly to the Abell 3404 data, masking the cluster diffuse emission. The difference in this imaging process is we use a robust weighting scheme, which for these observations provided a better model of the cluster discrete sources. Additionally, we find that since the diffuse emission is much fainter than in Abell 3404, and because the cluster lies further from the primary beam centre, we only consider the fullband re-imaged residual visibilities rather than the subbands produced while CLEANing. As there is only a single primary beam, mosaicking is not required, however, a primary beam correction is applied. Because the source lies to the edge of the beam, we compare the ASKAP flux densities of sources across the image to extrapolated flux densities derived from the ATCA subband images and the catalogue used for MWA-2 flux scaling (independently, see Duchesne et al. 2020 for details of the calibration catalogue). For comparison with the MWA catalogue, the data are first convolved to a common resolution. We find the flux densities of sources do not deviate beyond ∼10 per cent. We find no discernible astrometric offset for these data.

The full-band, robust = +0.25 image is shown in Fig. 3(i) with the source-subtracted, 45 arcsec robust = +0.25 image as contours in Fig. 3(i) and the background in Fig. 3(ii).

2.4. Chandra

Both clusters have been observed with the Advanced CDD Imaging Spectrometer (ACIS-I) on the Chandra X-ray observatory. We obtain both datasets (Abell 141: Obs. ID 9410, PI: Smith, 19.91 ks; Abell 3404: Obs. ID 15301, PI: Murray, 9.96 ks) from the Chandra data archive and use the CIAO software suite (v4.12, with CALDB v4.9.1; Fruscione et al., 2006) to process the data following standard Chandra data reduction procedures, using the task

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**Notes:**

8SB9602, SB9649, SB9910, SB10463, SB12704, SB15191, SB18925; Murphy et al., 2019, as part of a gravitational wave follow-up programme, with an average of 8–10 h per observation with similar u–v tracks.

9Calibration database.
3.1. Abell 141

The central, diffuse radio emission in Abell 141 has a slightly elongated morphology as seen in the source-subtracted ASKAP data, with an extension towards the southeast becoming a distinct peripheral component (yellow, dashed box in Fig. 6(i)). The radio emission fills the volume between two X-ray sub-clusters, and extends into the northern sub-cluster. Excluding the peripheral source, we measure the size of the central diffuse emission in Abell 141 from N–S and E–W within \( 2\sigma_{\text{rms}} \) contours finding deconvolved dimensions of 4.2 arcmin and 3.7 arcmin, respectively, corresponding to a linear size of 910 kpc and 790 kpc. We will consider the mean linear extent to be 850 kpc. Additionally, the SE peripheral component has a maximum projected extent of 2.6 arcmin, corresponding to 550 kpc.

3.1.2. Abell 3404

The central diffuse emission in Abell 3404 is also elongated and we similarly see peripheral extended components that may not be associated with the central diffuse source—these are most prominent in the 25 arcsec source-subtracted ASKAP image (contours in Fig. 6(ii), indicated by yellow, dashed rectangles). The peak of the central radio emission is co-located with the X-ray peak, and the radio emission generally fills the X-ray-emitting area. The size of the central diffuse source is measured in the ASKAP source-subtracted, 35 arcsec tapered image within \( 2\sigma_{\text{rms}} \) contours as above, finding angular sizes in the N–S and E–W directions of 5.3 arcmin and 3.9 arcmin, respectively, corresponding to linear sizes of 900 kpc and 660 kpc. We note that the the N–S direction is influenced by additional peripheral components, though it is not clear if these are part of the central emission or not (further discussed in Section 3.4.3). For the estimate of the size the SE component—which is more distinct—is not included. We again will consider the mean linear extent of 770 kpc in the following sections. The NE peripheral component is found to have a maximum projected size of 1.7 arcmin (270 kpc) and the SW component is found to be 1.5 arcmin (230 kpc) in extent.

3.2. Radio spectral properties

3.2.1. Flux densities

Fig. 3(i) and 4(i) also show relevant discrete sources that are projected onto the clusters within the MWA-2 emission. For the ASKAP data these were subtracted in the visibilities using CLEAN component models (Section 2.3), but in the MWA data their contribution is subtracted from the integrated flux density measurement after extrapolation from their measured SEDs. The central diffuse emission in Abell 3404 from 185–216 MHz is only barely detected above a \( 3\sigma_{\text{rms}} \) significance in the MWA-2 data, with generally poorer image qualities and lack of detection in individual snapshots. As we cannot guarantee significant enough flux is recovered in these images, we opt not to provide measurements for Abell 3404 in the 185- and 216-MHz MWA-2 images. We instead measure the source using the 200-MHz GLEAM image. For Abell 141, we use all MWA-2 bands and re-measure the source in the 169-MHz EoR-0 image (Offringa et al., 2016) and the 200-MHz GLEAM image. We find the 169-MHz measurement is lower than reported by Duchesne et al. (2021b) largely due to additional discrete source-subtraction.

Table 2 shows the fitted power law properties of the discrete sources in each cluster. We measure the flux density of the peripheral

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Figure 5. Comparison of dirty and CLEANed flux densities in the robust +2.0 MWA-2 images as a function of source FWHM for simulated Gaussian sources. Note that individual snapshot \( S_{\text{dirty}}/S_{\text{CLEAN}} \) ratios are shown as transparent grey lines with the mean value plotted as a solid red line, and a shaded region corresponding to the standard deviation between snapshots.

chandra_repro to generate the level-2 event file. From this we generate count and exposure-corrected flux images using the task fluximage applying 1 arcsec binning for the full energy band ([0.5–7] keV). We use wavdetect to identify point-like sources in the images and remove them, finally creating images in the [0.5–2] keV band. For Abell 141, as there is an AGN at the centre of the northern sub-cluster that is subtracted, we fill in the removed component using the task dmfilth. Additional smoothing with a \( \sigma = 6 \) arcsec 2-dimensional Gaussian kernel is applied to the exposure-corrected image, using the task aconvolve. The [0.5–2] keV exposure-corrected, smoothed, and source-subtracted Chandra images are shown in Fig. 6 for each cluster.

3. Results & discussion

3.1. Morphology

The ASKAP and MWA-2 data show clear evidence of central diffuse emission and additional extended peripheral structures in Abell 141 and Abell 3404 (see Fig. 3(i), 4(i), 6(i), and 6(ii)), not necessarily associated with any particular radio galaxy, though it is unclear if these components are associated with the central diffuse sources. No diffuse radio emission is detected in the ATCA data for either cluster (Fig. 3(ii) and Fig. 4(ii)). We show the exposure-corrected, smoothed X-ray maps in Fig. 6 to highlight the morphology of the clusters and the co-location of the radio emission.

3.1.1. Abell 141

The central, diffuse radio emission in Abell 141 has a slightly elongated morphology as seen in the source-subtracted ASKAP

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diffuse sources in Abell 141 and Abell 3404 in the full-band, 25 arcsec ASKAP image, though are unable to provide a spectral index estimate. Individual flux density measurements of the diffuse sources are provided in Table 3, indicating the contributions from discrete sources that are subtracted from the total integrated flux density in the process. The peripheral components in each cluster contribute to the diffuse source measurements as we cannot subtract them from the MWA data and we only provide measurements of the peripheral sources in the full-band ASKAP images. Relevant details of images used for flux density measurements are also provided in Table 3.

3.2.2. Diffuse source spectral indices

The central diffuse radio sources can be described by a simple power law between 88 and 943 MHz for Abell 141 and 88 and 1110 MHz for Abell 3404. Fig. 7 plots the measured data as well as the best-fit power law models. The spectral index for the central diffuse source in Abell 3404 ($\alpha_{10^{13} \text{MHz}} = -1.66 \pm 0.07$) pushes it into the “ultra-steep spectrum radio halo” category (defined by $\alpha < -1.5$, USSRH; Cassano et al., 2013). We find that the central emission in Abell 141 has a flatter spectrum than reported by Duchesne et al. (2021b), though this is in part due to the subtraction of three discrete sources with steep spectra. We report all derived source properties in Table 4, including source linear size, spectral index, and extrapolated monochromatic power at 1.4 and 0.15 GHz.

![Figure 6](image6.png)

**Figure 6.** Exposure-corrected, smoothed, point source-subtracted [0.5–2] keV Chandra maps with source-subtracted ASKAP contours overlaid. (i) Abell 141: ASKAP contours as in Fig. 3(i), but without the $2\sigma_{\text{rms}}$ contour. (ii) Abell 3404: ASKAP contours are the source-subtracted without tapering, but convolved with a 25 arcsec beam (hence, slightly higher resolution than the tapered, source-subtracted map). In (i) the yellow, dashed box indicates the peripheral diffuse source. In (ii) we show the regions within which we extract radio and X-ray surface brightness profiles (yellow sectors) and indicate extended radio components in those profiles (yellow, dashed rectangles) that may indicate radio shocks discussed in Section 3.4.3. The magenta lines indicate the edge of the ACIS-I field-of-view.

![Figure 7](image7.png)

**Figure 7.** SEDs of the diffuse emission in Abell 141 and Abell 3404. The lines are power law fits, with 95 per cent confidence intervals represented by the shaded regions. Upper limits are represented by arrows. The fits are extrapolated to ATCA frequencies for ease of comparing to ATCA limits.
3.2.3. Limits on high frequency non-detections

To investigate the non-detections in ATCA data, we obtain upper limits by injecting simulated radio halos into the visibility data. We assume an azimuthally averaged brightness distribution described by Orrú et al. (2007, but see also Murgia et al. 2009; Bonafede et al. 2017), of the form

$$I(r) = I_0 e^{-r/r_c} \quad [\text{Jy arcsec}^{-2}],$$

(1)

with $I_0$ the peak brightness, the e-folding radius $r_c = f/R_H$, and $R_H$ the radio halo radius. A median value of $f$ is found to be 2.6 by Bonafede et al. (2017, based on radio halo samples described by Cassano et al. 2007; Murgia et al. 2009). For the purpose of determining limits, we use the calibrated GMRT data presented by Venturi et al. (2007, 2008) of Abell 141, recalculating the limit for consistency with the current method.

To determine the initial halo brightness and spectrum, we use the brightness from the ASKAP data and spectral index reported by Cassano et al. 2007; Murgia et al. 2009). For the purpose of determining limits, we use the calibrated GMRT data presented by Venturi et al. (2007, 2008) of Abell 141, recalculating the limit for consistency with the current method.

| Source  | $\alpha$   | $\Delta\nu$  |
|---------|------------|--------------|
|         |            | (MHz)        |
| Abell 141 |            |              |
| A       | $-1.09 \pm 0.07$ | 216–2674     |
| B       | $-1.44 \pm 0.05$ | 147–2674     |
| C       | $-1.07 \pm 0.07$ | 147–2674     |
| D       | $+1.18 \pm 0.09$ | 943–3000     |

| Abell 3404 |            |              |
| A       | $-0.49 \pm 0.11$ | 216–1388     |
| B       | $-0.35 \pm 0.10$ | 216–1388     |
| C       | $-1.02 \pm 0.14$ | 185–1121     |
| D       | $-0.67 \pm 0.18$ | 185–2424     |
| E       | $-0.65 \pm 0.08$ | 216–2424     |
| F       | -           |              |
| G       | -1          | 905–1121     |

* Frequency range over which source is modelled.
* Fit with a curved power law model.
* Source could not be modelled, but is not distinguishable from "E" in MWA data.
* No uncertainty is given as the SED is only over the ASKAP subbands and we do not quantify the internal flux scale uncertainty across the band.

3.3. Radio–X-ray correlation

Radio halo brightness ($I_R$) is often observed to correlate with the X-ray surface brightness ($I_X$) of the ICM ($I_R \propto I_X^k$; Govoni et al. 2001). Radio halos are typically observed with a sub-linear slope (e.g. Giacintucci et al., 2005; Rajpurohit et al., 2018; Hoang et al., 2019a; Botteon et al., 2020c; Rajpurohit et al., 2021; Bruno et al., 2021); conversely mini-halos have been found to have super-linear slopes (Ignesi et al., 2020). We use the exposure-corrected, source-subtracted, smoothed $[0.5–2]$ keV Chandra data along with the

Note this value is calculated from the reported limit to the luminosity at 610 MHz, requiring an assumption on the spectral index of $-1.3$, though the index does not appreciably change the power calculation here.
low-resolution, source-subtracted ASKAP images to perform a similar analysis for Abell 141 and Abell 3404.

Following a procedure described by Ignesti et al. (2020), we construct grids across the diffuse emission with cell sizes corresponding to the ASKAP beam major axis. For Abell 141 this is 49”, corresponding to 178 kpc and for Abell 3404 this is 44”, corresponding to 124 kpc. We fit the data as \( \log_{10}(I_\nu) = k \log_{10}(I_X) + C \) using the BCES method \(^{11}\) with an orthogonal regression. Fig. 8 shows the results for (i) Abell 141 and (ii) Abell 3404. For both, we separate out the contribution from the peripheral components, with each grid shown on the inset for each figure. Abell 3404 shows strong correlation (with Spearman rank-order correlation coefficient, \( \rho = 0.89 \)), and we find a sub-linear trend with \( k = 0.53 \pm 0.04 \).

\(^{11}\)Bivariate Correlated Errors and intrinsic Scatter: Akritas & Bershady (1996).
While many halos have been found with $k \geq 0.6$ (e.g. Govoni et al., 2001; Botteon et al., 2020c; Rajpurohit et al., 2021), we note the steep-spectrum radio halo in MACS J1149.5+2223 is found to have $k \leq 0.6$ (Bruno et al., 2021). The SW peripheral component (blue points, Fig. (ii)) appears unassociated whereas the NE component follows the correlation tightly. For the fit the NE component is included. For Abell 141, we find no significant correlation ($p = 0.31$). This may indicate a mixture of emission components, though Shimwell et al. (2014) notes, in reference to the Bullet Cluster radio halo showing a similar lack of correlation, this may be due to the halo occurring during a specific stage of a complex merger.

### 3.4. Cluster dynamics and source classification

#### 3.4.1. Abell 141—pre-merger?

The dynamic nature of Abell 141 has been studied extensively by Dahle et al. (2002, in optical) and Caglar (2018, hereafter C18, in X-ray). Dahle et al. (2002) and C18 find that the bi-modal distribution (as seen in the X-ray in Fig. 6(i)) represents two subclusters (labelled A141N and A141S by C18) which have not completed a core-crossing—i.e., the cluster is likely in a pre-merging state. C18 report that X-ray-emitting gas between the two subclusters features a hotspot, which may imply the presence of a shock or shocks. We note that the central diffuse radio emission coincides more with the A141N subcluster, but extends into the region between the subclusters. Most radio halos have been detected in clusters that are in a merging or dynamic state (see e.g. Cassano et al., 2013), with three examples in the literature of likely pre-merger subclusters: Abell 399–401 (Mur gia et al., 2010), MACS J0416.1–2403 (Ogorean et al., 2015), and Abell 1758N–S (Botteon et al., 2018). We note in the cases of Abell 399–401 and Abell 1758N–S each subcluster in the corresponding mergers clearly host their own radio halos whereas we do not detect two distinct radio halos in the A141N and A141S subclusters. The emission may represent a bridge between the subclusters rather than a traditional giant radio halo (see Govoni et al., 2019; Botteon et al., 2020a; Hoeft et al., 2020; Bonafede et al., 2021), though due to the resolution of our data we cannot confirm bridge emission distinct from the radio emission that permeates A141N.

A radio relic? Some radio relics have been found to be collocated with shocks detected via X-ray emission (e.g. Bourdin et al., 2013; Akamatsu et al., 2015; Eckert et al., 2016; Di Gennaro et al., 2019). Assuming the central region temperature jump in the X-ray corresponds to a shock, C18 derive a Mach number of $M_X = 1.69^{+0.41}_{-0.37}$. If we consider that a radio shock traces the same shock structure, and that DSA on a pool of thermal electrons triggers the emission (see e.g. Blandford & Eichler, 1987), a corresponding radio Mach number can be calculated from

$$M_R = \sqrt{\frac{2\alpha_{\text{inj}} - 3}{2\alpha_{\text{inj}} + 1}},$$

assuming that $\alpha = \alpha_{\text{inj}} - 0.5$, with $\alpha_{\text{inj}}$ the synchrotron injection spectrum index. We find $M_R = 5.9 \pm 0.9$, inconsistent with the X-ray–derived Mach number. This does not necessarily rule out the possibility of the source being a radio shock, as discussed by van Weeren et al. (2016, 2017) (but see also Hoang et al., 2019b; Lee et al., 2020), a discrepancy in Mach numbers may indicate that the thermal pool electrons are not seed electrons for the emission—i.e., pre-accelerated fossil electrons may be accelerated by the DSA process. In this case the injection spectrum may resemble the observed emission spectrum (van Weeren et al., 2016) with $\alpha = \alpha_{\text{inj}}$ and $M_R = 2.1 \pm 0.2$, in agreement with $M_X$. Assuming seed electrons for radio relics originate as fossil electrons rather than

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**Figure 8.** Radio–X-ray point-to-point correlation for (i) Abell 141 and (ii) Abell 3404. Upper limits correspond to cells where $I_X < 2\sigma_{\text{rms}}$. The black, dashed line is the best-fitting line with a 95 per cent confidence interval shaded in cyan. The insets show the Chandra X-ray maps with the source-subtracted ASKAP image overlaid as contours as in Fig. 6(i) and Fig. 4(i) for Abell 141 and Abell 3404, respectively. The cyan boxes on the insets show the cells within which surface brightnesses are calculated, and the red and blue cells indicate the locations of the peripheral components.
thermal pool electrons also alleviates the acceleration efficiency problem for some relics with X-ray detected shocks (see Botteon et al., 2020b, and references therein). Additionally, simulations show radio galaxies in cluster environments can supply fossil electrons for re-acceleration (Vazza et al., 2021). A difference in Mach number may also arise from the X-ray and radio emission preferentially tracing different shocks along a line of sight (see e.g. van Weeren et al., 2016; Rajpurohit et al., 2020, and references therein) or may arise due to turbulence near the shock front (Domínguez-Fernández et al., 2021).

The present data (including lack of polarimetry) do not allow us to rule out a radio relic or radio bridge interpretation, or a combination thereof. We consider the source a radio halo because the observed physical characteristics—including its morphology, location, and SED—are consistent with a radio halo classification.

### 3.4.2. Abell 3404—dynamics

Fig. 6(ii) shows the exposure-corrected, smoothed, and point-source subtracted [0.5–2] keV Chandra map for Abell 3404, where the X-ray emission is slightly elongated. We note that using XMM-Newton data Pratt et al. (2009) consider the cluster as non-cool gas, but also not morphologically disturbed based on its centroid shift, $w$ (Poole et al., 2006, but see also Mohr et al. 1993), which gives an indication of the dynamic state of the cluster. We repeat the calculation for the present Chandra data, using proffit (Eckert et al., 2011), subtracting a fitted background of $I_B = (1.41 \pm 0.05) \times 10^{-3}$ ph cm$^{-2}$ s$^{-1}$ arcmin$^{-2}$, finding $w = 0.039$ within $R_{500} = 1280$ kpc (Pratt et al., 2009), smaller than the expected $w > 0.075$ for a disturbed system of this radius. We note that the radio halo detected in Abell S1063 (Xie et al., 2020) is similarly detected in a cluster that is considered morphologically relaxed based on this definition.

We also calculate the concentration parameter, $c_{100/500}$ (and $c_{40/400}$; Santos et al. 2008), defined via

$$c_{r_1/r_2} = \frac{I_X(r < r_1 \text{ kpc})}{I_X(r < r_2 \text{ kpc})},$$

with $I_X$ the X-ray surface brightness. We find $c_{100/500} = 0.24$ which, in combination with the centroid shift within 500 kpc ($w_{500}$ kpc = 0.039) places the cluster just outside of the halo-hosting quadrant of the $c_{100/500} - w_{500}$ plane shown by Cassano et al. (2010)—no halos appear in clusters with $c_{100/500} > 0.2$. We also find $c_{40/400} = 0.062$, consistent with non-cool–core clusters (Santos et al., 2008). The ambiguity of the X-ray morphological parameters point towards a low-energy/weak merger or a late stage in the merger. For example, a merger between low velocity subclusters or a high mass-ratio between subclusters may result in low-energy mergers. Given the cluster’s SZ-derived mass of $7.96^{+0.22}_{-0.21} \times 10^{14}$ $M_{\odot}$ (Planck Collaboration et al., 2016b) we can infer the presence of a massive subcluster prior to the merger. Such scenarios are expected to generate USSRHs (Brunetti et al., 2008) as observed here.

### 3.4.3. Abell 3404—radio and X-ray shocks?

Fig. 6(ii) shows two extended diffuse emission regions (indicated with dashed, yellow rectangles) either side of the cluster center.

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**Figure 9.** Radio and background-subtracted X-ray surface brightness profile for sectors shown in Fig. 6(ii) for Abell 3404. The radio ordinate clips at $2\sigma_{rms}$. The dashed-red vertical line is at location of the discontinuity in the northern profile.

We do not have sufficient fidelity in the ASKAP subband data to investigate the spectral properties or to remove the northern component from the radio halo measurement, though for the purpose of this section we consider the possibility that the two extended structures represent radio shocks.

We investigate that possibility by extracting X-ray and radio surface brightness (SB) profiles along the directions of the relic-like sources (extracted regions shown as yellow sectors in Fig. 6(ii)). For the X-ray data, we use proffit, masking the point sources indicated in Fig. 6(ii) with yellow circles. The X-ray SB profiles are binned ensuring each bin is $\geq 10\sigma$ and $\geq 7\sigma$ for the north and south profiles, respectively. The radio SB profile is extracted using in-house Python code fluxtools.py. The extracted profiles in each direction are shown in Fig. 9. We find candidate discontinuities in the X-ray SB profile. We fit standard broken power law models, representing an electron density discontinuity either side of a putative shock (see e.g. Owers et al., 2009; Eckert et al., 2016):

$$\rho(r) = \begin{cases} C r^{-\Gamma_m} & \text{if } r < r_{\text{break}} \\ C n_{\text{out}}^{-\Gamma_m} r^{-\Gamma_{\text{out}}} & \text{otherwise} \end{cases},$$

with $\Gamma$ the power law indices either side of the discontinuity, $j = n_{\text{out}}/n_{\text{in}}$ the density jump, and $C$ a normalisation factor, and the SB profile is $\rho(r)$ integrated along the line of sight. For the southern profile we find $\Gamma_{\text{sout}} \sim 1$, indicating no evidence for a discontinuity. For the northern profile we obtain $\Gamma_{\text{nout}} = 1.11^{+0.09}_{-0.10}$. The radio source occurs $\sim 1$ arcmin ($\sim 170$ kpc) from the X-ray discontinuity; in the case of a relic associated with a shock the observed discontinuity in the X-ray profile occurs directly after the relic source (and a hard edge may be seen in the radio map), therefore the northern peripheral radio source is unlikely to be a relic.
with the exception of the halo in ACT-CL J0528.8-3927 reported by Knowles et al. (2021) as its small size and coincidence with a radio-bright BCG suggests a mini-halo. For consistency, cluster masses are obtained from PSZ measurements where available (Planck Collaboration et al., 2016c, with some masses obtained from the South Pole Telescope; Song et al. 2012; Reichardt et al. 2013), and only clusters with an SZ-derived mass are used. Note all radio halos are scaled to 1.4 and 0.15 GHz with either a measured spectral index or using the full sample mean, \( \langle \alpha \rangle = -1.4 \pm 0.2 \), following

\[
P_{\nu_1} = \frac{4\pi D_L(z)^2}{(1+z)^{1+\alpha}} S_{\nu_{\text{obs}}} \left( \frac{\nu_1}{\nu_{\text{obs}}} \right)^{\alpha} \quad \text{[W Hz\(^{-1}\]},}
\]

where \( \nu_{\text{obs}} \) is the closest observed frequency, \( \nu_1 \in \{0.15, 1.4\} \), and \( D_L \) is the luminosity distance of the cluster. We do not distinguish between normal giant radio halos and ultra-steep spectrum radio halos defined by \( \alpha < -1.5 \) (USSRH) (e.g. Brunetti et al. 2008; C13). We note that integrated flux densities measured by vW20 are integrated from a fitted exponential profile (Eq. 1) rather than measured directly from the maps and may be generally larger than those measured via integration directly from the pixel sum, especially for low-SNR halos.

We fit the radio halo sample assuming a scaling relation at \( \nu = 1.4 \) GHz and \( \nu = 0.15 \) GHz with a function of the form

\[
\log_{10}(P_{\nu}) = B \times \log_{10}(M_{500}) + A \quad \text{using the BCES method with an orthogonal regression. For comparison with C13 and vW20 we shift their fitted relations to the relevant frequencies via}
\]

\[
\log_{10}(P_{\nu}) = B \log_{10}(M_{500}) + A - \langle \alpha \rangle \log_{10} \left( \frac{\nu_2}{\nu_1} \right),
\]

where \( \nu_2 \) is the frequency at which the original scaling relation is fit and with \( P_{\nu_1} = P_{\nu_2}(\nu_1/\nu_2)^{\langle \alpha \rangle} \). Fig. 10 shows the \( P_{1.4-M_{500}} \) (10(i)) and \( P_{0.15-M_{500}} \) (10(ii)) planes with the relevant fits and aforementioned data. Best-fit values for the scaling relation for various methods are shown in Table 5 for comparison with other works.

The updated position of the radio halo in Abell 141 on both the \( P_{1.4-M_{500}} \) and \( P_{0.15-M_{500}} \) planes is in agreement with the fitted relations, and the halo in Abell 3404 lies below the \( P_{1.4-M_{500}} \) relation consistent with the general population of USSRHs (Cassano et al., 2013; Cuciti et al., 2021), but is closer to the fitted \( P_{0.15-M_{500}} \) relation. We note also that if the halo in Abell 141 was only associated with the A141N subcluster \( \text{14} \) the halo’s position on both \( P_{\nu-M_{500}} \) relations would be significantly above the best fitting lines. With a sample size of 86 we find (orthogonal) scaling relations consistent with C13 and vW20 at both frequencies within respective uncertainties, but note some deviation from the fit reported by vW20 at 0.15 GHz. Naturally, scaling radio halo powers to frequencies beyond which they are measured introduces additional uncertainties. We also find that the \( P_{\nu_1} \) relation is the most consistent method (albeit shallower than for orthogonal), with results from vW20 (\( B = 3.84 \pm 0.69 \)) and Cuciti et al. (2021) (\( B = 3.26 \pm 0.74 \)) for their ‘statistical’ sample with USSRHs with both vW20 and Cuciti et al. (2021) employing smaller, specific samples.

C13 find that inclusion of USSRHs steepens the scaling relation at 1.4 GHz and vW20 find generally steeper relations at 0.15 GHz

### Table 5 Fitted values for the \( P_{\nu-M_{500}} \) scaling relations for various methods.

| Method      | \( B \)   | \( \sigma_B \) | \( A \)   | \( \sigma_A \) |
|-------------|-----------|---------------|-----------|---------------|
| \( P_{1.4-M_{500}} \) | | | | |
| Orthogonal | 3.21 | 0.39 | -23.4 | 5.8 |
| Bisector   | 5.75 | 0.93 | -61.0 | 13.8 |
| \( P_{0.15-M_{500}} \) | | | | |
| Orthogonal | 3.15 | 0.41 | -21.2 | 6.0 |
| Bisector   | 4.76 | 0.93 | -45.0 | 13.8 |

3.5. Radio halo \( P_{\nu-M_{500}} \) scaling relations

Despite a somewhat atypical X-ray morphology of each cluster, based on the available data we classify both central diffuse radio sources as giant radio halos (for Abell 141, consistent with the classification from Duchesne et al. 2021b). Both Abell 141 and Abell 3404 have similar masses, and their constituent radio halos have similar sizes and brightness at \( \sim 1 \) GHz, however, due to the difference in their SEDs their 1.4- and 0.15-GHz monochromatic luminosities differ by around a factor of two.

Scaling relationships between radio halo power and various (related) cluster properties have been found (see e.g. Liang et al., 2000; Brunetti et al., 2007; Basu, 2012), somewhat explained physically by turbulent (re-)acceleration models for halo formation (Cassano et al., 2013, hereafter C13). A key finding by Brunetti et al. (2009, but see also Cassano et al., 2010, 2013) is the bi-modality to the sample of halo-hosting clusters, where morphologically disturbed (i.e., likely merging) clusters host radio halos, and most relaxed, X-ray–luminous, and massive clusters without halos have upper limits to radio halo power well below the empirical scaling relations.

Recent updates to the power–mass (\( P_{\nu-M_{500}} \)) relation (Cassano et al., 2013; Martinez Aviles et al., 2016; Duchesne et al., 2021b; van Weeren et al., 2020; Cuciti et al., 2021) find results largely consistent within reported uncertainties. We update this relation at \( \nu = 1.4 \) GHz and \( \nu = 0.15 \) GHz following van Weeren et al. (2020, hereafter vW20). For this work, we incorporate the compiled literature sample of halos reported by C13 and Martinez Aviles et al. (2016), halos in Abell S1121 and Abell 2811 reported by Duchesne et al. (2021b), and new halos reported in the literature from 2017 (Parekh et al., 2017; Wilber et al., 2018; Cassano et al., 2019; Birzan et al., 2019; Xie et al., 2020; HyeongHan et al., 2020; Giovannini et al., 2020; Wilber et al., 2020; Hoeft et al., 2020; Hoang et al., 2021; Di Gennaro et al., 2020; van Weeren et al., 2020; Raja et al., 2020; Knowles et al., 2021; Raja et al., 2021), with the exception of the halo in ACT-CL J0528.8-3927 reported by Knowles et al. (2021) as its small size and coincidence with a radio-bright BCG suggests a mini-halo. For consistency, cluster masses are obtained from PSZ measurements where available.
We have confirmed the detection of centrally-located diffuse, steep-spectrum cluster radio emission in Abell 141, and ultra-steep spectrum emission in Abell 3404. We have presented new observations from the MWA-2, ASKAP, and ATCA of the clusters, with the central diffuse sources detected with the MWA-2 and ASKAP. We conclude that these central diffuse radio sources can be described as giant radio halos with linear extents of ~ 850 kpc and ~ 770 kpc, for Abell 141 and Abell 3404, respectively. We find that each source has an SED that can be fitted with a normal power law model, with spectral indices of $\alpha_{88}^{943} = -1.06 \pm 0.09$ and $\alpha_{88}^{1110} = -1.66 \pm 0.07$ for Abell 141 and Abell 3404, respectively, making the radio halo in Abell 3404 the first reported USSRH detected with ASKAP. We find no evidence of these sources in pre-CABB and CABB ATCA data, though find the $\alpha$-$v$ coverage for the observations preclude detection of the radio halos assuming an exponential brightness profile described by the derived spectral index and the measured size and peak brightness in the ASKAP images. Additional peripheral components are detected along with the main central halos, though only for the SW peripheral source in Abell 3404 do we confirm this is not associated with the central halo. No shocks are detected at the locations of the peripheral components in Abell 3404 and they are unlikely to be relics. These peripheral components may be background/foreground radio galaxies, phoenices, or other extended sources and we do not classify them here.

We discuss the morphological properties of the two clusters based on their X-ray emission using Chandra data, noting that Abell 141 has previously been found to likely be in a pre-merging state, prior to core passage of the sub clusters. Conversely, we find that the dynamic status of Abell 3404 is likely to be in a more relaxed state, either in the late stage of a merger or a low-energy merger. The radio–X-ray surface brightness correlation is explored for each cluster, finding strong correlation for Abell 3404 but no significant correlation for Abell 141. Some of these properties make them atypical for most radio-halo–hosting clusters, though we find that the radio halos are located in the expected places on the $P$–$M$ scaling relations at both 1.4 and 0.15 GHz, given their respective spectral properties and cluster masses (considering Abell 141 a single cluster system). We fit the $P_{1.4}$–$M_{500}$ and $P_{0.15}$–$M_{500}$ scaling relations with the current sample of radio halos, finding results for radio halos detected around 0.15 GHz (and presumably generally steeper in spectrum). In Equation 6 we re-scale the scaling relation with an assumed mean $\langle \alpha \rangle$, where real observations at lower of higher frequencies may bias the sample selection towards steeper or flatter spectrum sources, respectively, finding opposed slopes to the $P_{0.15}$–$M_{500}$ relation. Uncertainties are still too significant to confirm this as discussed by vW20.

The concordance between these results and those in the recent literature demonstrates that we are now reaching sufficient sample sizes to have confidence in the scaling relation values. While it has recently been suggested there is little evolution of magnetic field strength as a function of redshift in galaxy clusters and hence a redshift dependence in the power-mass scaling relations are not expected (Di Gennaro et al., 2020), an outstanding question remains regarding if there is a difference in the relations for halos and USSRHs which may be expected from differences in their underlying physics. Yet larger samples of halos, expected in the near future, will allow this to be probed.

4. Summary

We have confirmed the detection of centrally-located diffuse, steep-spectrum cluster radio emission in Abell 141, and ultra-steep spectrum emission in Abell 3404. We have presented new observations from the MWA-2, ASKAP, and ATCA of the clusters, with the central diffuse sources detected with the MWA-2 and ASKAP. We conclude that these central diffuse radio sources can be described as giant radio halos with linear extents of ~ 850 kpc and ~ 770 kpc, for Abell 141 and Abell 3404, respectively. We find that each source has an SED that can be fitted with a normal power law model, with spectral indices of $\alpha_{88}^{943} = -1.06 \pm 0.09$ and $\alpha_{88}^{1110} = -1.66 \pm 0.07$ for Abell 141 and Abell 3404, respectively, making the radio halo in Abell 3404 the first reported USSRH detected with ASKAP. We find no evidence of these sources in pre-CABB and CABB ATCA data, though find the $\alpha$–$v$ coverage for the observations preclude detection of the radio halos assuming an exponential brightness profile described by the derived spectral index and the measured size and peak brightness in the ASKAP images. Additional peripheral components are detected along with the main central halos, though only for the SW peripheral source in Abell 3404 do we confirm this is not associated with the central halo. No shocks are detected at the locations of the peripheral components in Abell 3404 and they are unlikely to be relics. These peripheral components may be background/foreground radio galaxies, phoenices, or other extended sources and we do not classify them here.

We discuss the morphological properties of the two clusters based on their X-ray emission using Chandra data, noting that Abell 141 has previously been found to likely be in a pre-merging state, prior to core passage of the sub clusters. Conversely, we find that the dynamic status of Abell 3404 is likely to be in a more relaxed state, either in the late stage of a merger or a low-energy merger. The radio–X-ray surface brightness correlation is explored for each cluster, finding strong correlation for Abell 3404 but no significant correlation for Abell 141. Some of these properties make them atypical for most radio-halo–hosting clusters, though we find that the radio halos are located in the expected places on the $P$–$M$ scaling relations at both 1.4 and 0.15 GHz, given their respective spectral properties and cluster masses (considering Abell 141 a single cluster system). We fit the $P_{1.4}$–$M_{500}$ and $P_{0.15}$–$M_{500}$ scaling relations with the current sample of radio halos, finding results...
consistent with the literature suggesting that we are now converging with a high precision on these relations.

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A. $u$–$v$ coverage plots

Fig. 11(i)–11(viii) shows $u$–$v$ coverage (in $\lambda$, from $-3000\lambda$ to $3000\lambda$) for the Abell 141 data used in this work, excluding MWA-1 data. Similarly Fig. 12(i)–12(ix) show the $u$–$v$ coverage for observations of Abell 3404. We include these plots to highlight the coverage offered by both the MWA and ASKAP in comparison to ATCA and GMRT.
Figure 11. $u$–$v$ coverage plots for Abell 141 data. Axes are centered on zero and range from $-3000 \lambda$ to $3000 \lambda$. Note that the MWA-2 data are of single 2-min snapshots, representative of the snapshot observations. The true $u$–$v$ coverage is slightly more filled in. The observation used for the ASKAP example is SB15191.
Figure 12. $u$–$v$ coverage plots for Abell 3404 data. Axes are centered on zero and range from $-3000 \lambda$ to $3000 \lambda$. 