



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 and ~ 850 kpc, respectively). We use the Murchison Widefield Array, the Australian Square Kilometre Array Pathfinder, and the Australia Telescope Compact Array to characterise the emission and intervening radio sources from ~ 100 to 1 000 MHz; power law models are fit to the spectral energy distributions with spectral indices $\alpha_{88}^{1110} = -1.66 \pm 0.07$ and $\alpha_{88}^{943} = -1.06 \pm 0.09$ 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 that 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_ν - 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 $P_{1.4}$ - 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.

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1. Introduction

Galaxy clusters represent ideal laboratories for investigating large-scale structure formation. As the largest virialised 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 ($\alpha \lesssim -1^a$; 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; Brügggen 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).

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^a $S_\nu \propto \nu^\alpha$

Mega-parsec scale *radio relics*^b 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 ($\lesssim 400$ kpc) relic sources called *phoenixes* 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). Phoenixes are typically located closer to the cluster centre and feature steeper spectra, with steepening beyond ~ 1 GHz. *Mini-halos* are smaller ($\lesssim 400$ 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

^bAlso called *radio shocks*: van Weeren et al. (2019).

gas, with seed electrons fuelled by the embedded AGN (see e.g. Giacintucci et al., 2017; Giacintucci et al., 2019). Finally, *giant radio halos* ($\gtrsim 1$ Mpc) 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 that 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; Hoeft 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 Murchison Widefield Array (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 $H_0 = 70$ km s⁻¹ Mpc⁻¹, $\Omega_M = 0.3$, and $\Omega_\Lambda = 1 - \Omega_M$.

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-h 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 $\alpha_{168\text{ MHz}}^{610\text{ MHz}} < -2.1$, making it one of the steepest-spectrum radio halo detected to date, tied with the radio halo in Abell 521 ($\alpha_{240\text{ MHz}}^{610\text{ MHz}} \approx -2.1$; Brunetti et al., 2008). Caglar (2018) investigated the X-ray properties of the cluster, which show both a bi-modal X-ray distribution and 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 $5.67_{-0.40}^{+0.36} \times 10^{14} M_\odot$. 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 Figure 1 with data described in Sections 2.3 and 2.4.

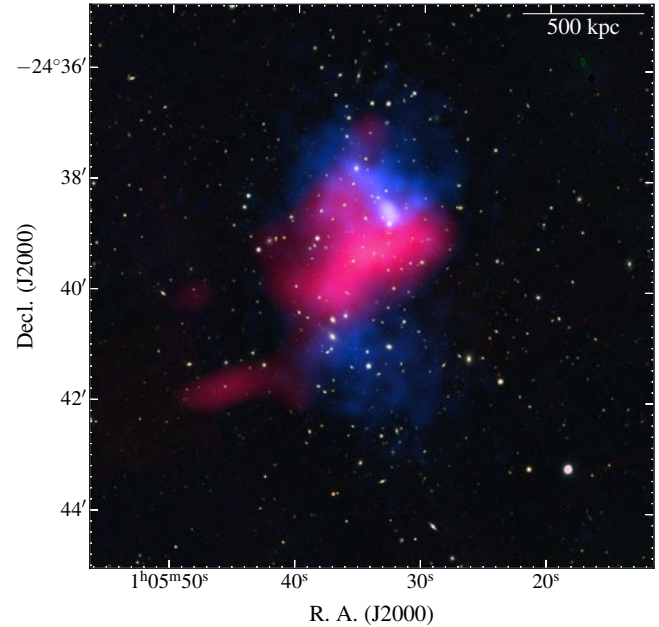


Figure 1. Composite image of Abell 141. Background optical data are from the Pan-STARRS survey, data release 1 (bands r, i, z ; Kaiser et al., 2010; Tonry et al., 2012) with *Chandra* (blue, Section 2.4) and source-subtracted ASKAP (red, Section 2.3) maps overlaid. The linear scale is at the redshift of the cluster.

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 the 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^c Diffuse Emission Survey (ARDES), though they found no evidence of a radio halo or other diffuse radio source. In advance of this publication, Brüggén 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 $7.96_{-0.21}^{+0.23} \times 10^{14} M_\odot$ 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 Figure 2.

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 data sets in Appendix, A.

^cRepresentative *XMM-Newton* Cluster Structure Survey (Böhringer et al., 2007).

Table 1. Details of the radio observations of Abell 141 and Abell 3404.

Telescope	ν_c^a (MHz)	$\Delta\nu^b$ (MHz)	θ_{\max}^c (arcmin)	τ^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

^aCentral observing frequency.^bObservation bandwidth.^cMaximum angular scale observation is sensitive to at the respective central frequency with a $u-v$ limit employed during imaging.^dTotal observing time.^eOriginally a 2049 MHz band, significant RFI flagging reduces the usable bandwidth.

2.1. MWA-2

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-min snapshot observing mode, with each 2-min 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 for ionosphere-related astrometric shifts using `fits_warp.py`^d (Hurley-Walker & Hancock, 2018) and finally corrected for residual primary beam errors and flux scale errors with `flux_warp`^e (Duchesne et al., 2020) to ensure a common

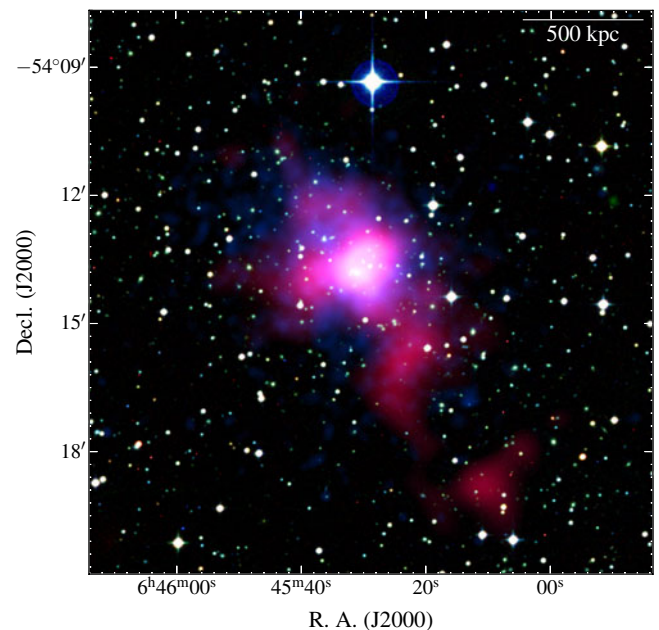
^dhttps://github.com/nhurleywalker/fits_warp^ehttps://gitlab.com/Sunmish/flux_warp

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 Figure 1. The linear scale is at the redshift of the cluster.

flux scaling across snapshots. The snapshots are then co-added, weighted by the square of the primary beam response and local noise.

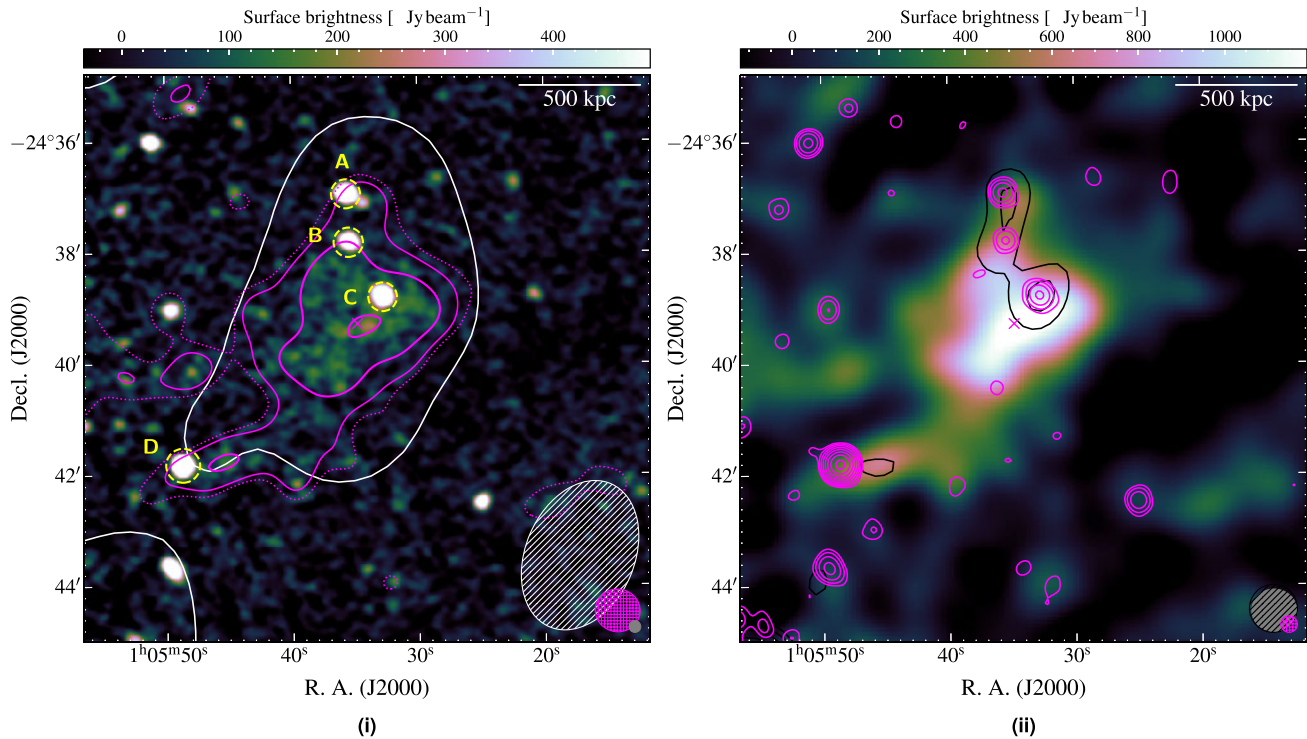


Figure 3. Abell 141 radio maps. (i) ASKAP, 943-MHz image at robust = +0.25. The overlaid contours are as follows: MWA-2, 118-MHz robust = +2.0 image, single white contour at $3\sigma_{\text{rms}}$ ($4.7 \text{ mJy beam}^{-1}$); ASKAP, 943-MHz source-subtracted image, solid magenta contours starting from $3\sigma_{\text{rms}}$ ($\sigma_{\text{rms}} = 0.105 \text{ mJy beam}^{-1}$), increasing with increments of 2 with a single dotted magenta contour at $2\sigma_{\text{rms}}$. Sources subtracted after SED modelling are labelled. (ii) ASKAP, 943-MHz source-subtracted image with contours as follows: MWA-2, 216-MHz robust = 0.0, black contours starting at $3\sigma_{\text{rms}}$ ($11.4 \text{ mJy beam}^{-1}$); ATCA full-band image at robust = 0.0, magenta contours starting at $3\sigma_{\text{rms}}$ ($\sigma_{\text{rms}} = 27 \mu\text{Jy beam}^{-1}$). For both figures, the resolution of each image is shown in the bottom right corner, with the grey ellipse corresponding to the background map. The linear scale in the top right is at the redshift of the cluster.

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, Figures 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.

Figure 3(i) and 3(ii) shows 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, Figure 4(i) shows the $3\sigma_{\text{rms}}$ contour of the robust = +2.0, 118-MHz image of Abell 3404, and Figure 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 arcsec to 575 arcsec in 30 arcsec intervals and measure the integrated flux density in the dirty and CLEANed maps. We find that the ratios of measured $S_{\text{p,dirty}}/S_{\text{p,CLEAN}}$ (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 Figure 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. 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

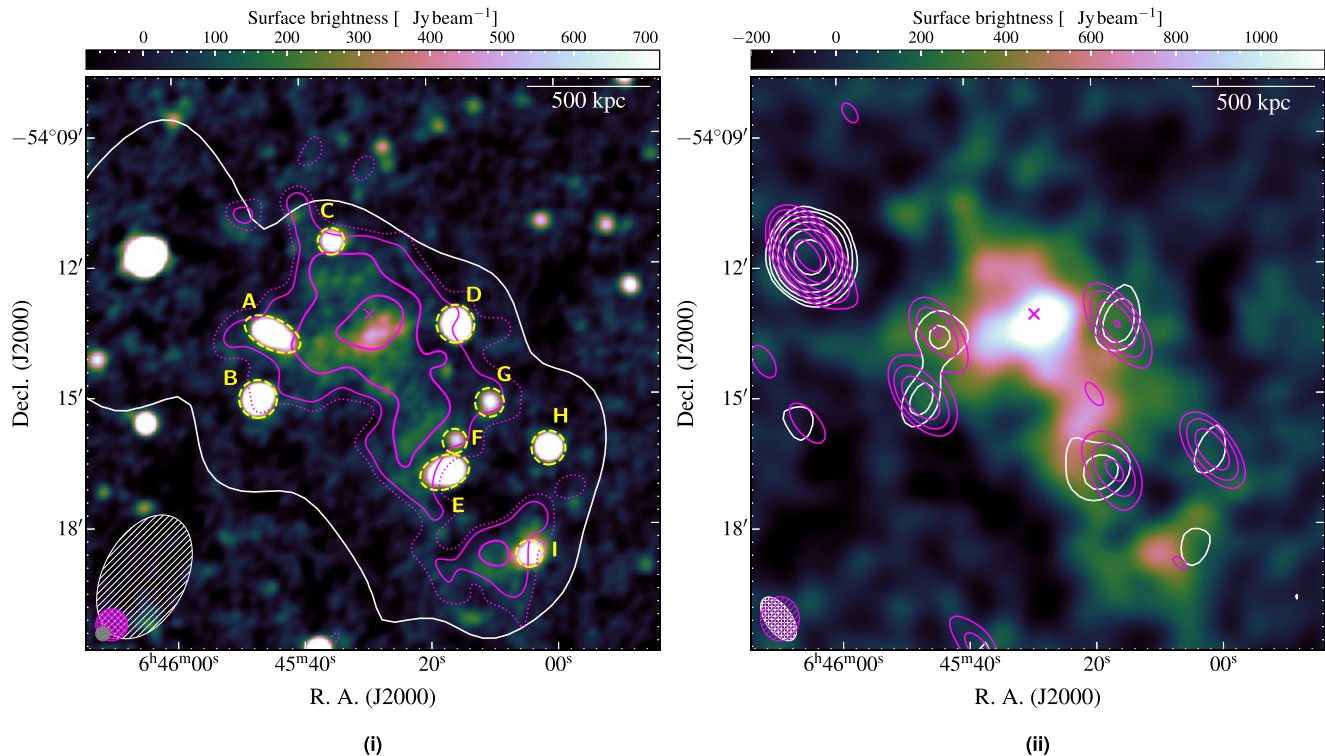


Figure 4. Abell 3404 radio maps. (i) ASKAP, 1013-MHz image at robust = +0.5. The overlaid contours are as follows: MWA-2, 118-MHz robust = +2.0, single white contour at $3\sigma_{\text{rms}}$ ($6.1 \text{ mJy beam}^{-1}$); ASKAP, 1013-MHz tapered source-subtracted image, solid magenta contours starting from $3\sigma_{\text{rms}}$ ($\sigma_{\text{rms}} = 0.84 \text{ mJy beam}^{-1}$), increasing with increments of 2 with a single dotted magenta contour at $2\sigma_{\text{rms}}$. Sources subtracted after SED modelling are labelled. (ii) ASKAP source-subtracted, tapered, with contours as follows: MWA-2, 216-MHz robust = 0.0 image, white contours starting at $3\sigma_{\text{rms}}$ ($\sigma_{\text{rms}} = 6.6 \text{ mJy beam}^{-1}$); ATCA, 2.4-GHz robust = 0.0 image, magenta contours starting at $3\sigma_{\text{rms}}$ ($\sigma_{\text{rms}} = 0.24 \text{ mJy beam}^{-1}$). The ellipses in the the lower left are as in Figure 3, and the linear scale is at the redshift of the cluster.

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 is 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 data set, 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 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 data sets 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 ~ 1.5 GHz and is split into subbands of $\Delta\nu = 300$ MHz for discrete source measurements.

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

2.3. ASKAP

ASKAP operates between 700 and 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 science observations; however, both Abell 141 and Abell 3404 sit towards the edges of primary beams. The ASKAP data are publicly available and are retrieved from the CSIRO^f ASKAP Science Data Archive (CASDA; Chapman et al., 2017). Prior to being made available through CASDA, the ASKAPsoft^g 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 summarise additional observation details in Table 1.

^fCommonwealth Scientific and Industrial Research Organisation

^g<https://www.atnf.csiro.au/computing/software/askapsoft/sdp/docs/current/pipelines/introduction.html>

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 $\sim 1\%$ 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 is 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 $1.09\lambda/D$ (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. Figure 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^h. 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 data sets then self-calibrating each data set 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 = +0.25 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 full-band 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

^hSB9602, SB9649, SB9910, SB10463, SB12704, SB15191, SB18912, 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.

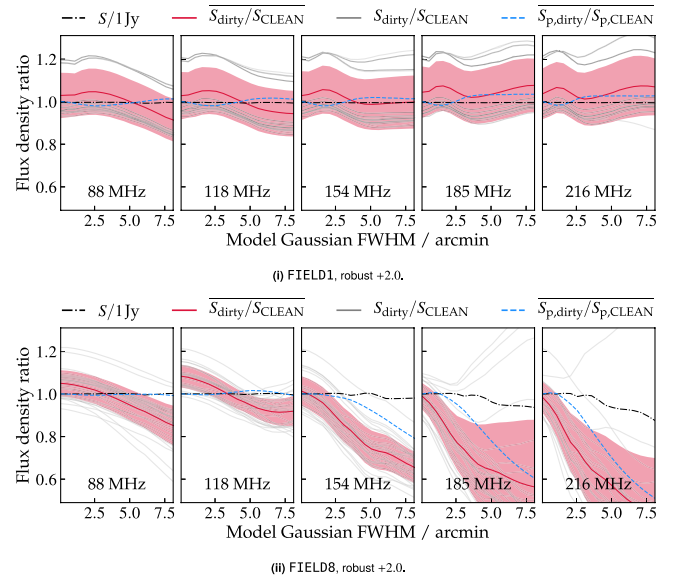


Figure 5. Comparison of dirty and CLEANed flux densities in the robust +2.0 MWA-2 images as a function of source FWHM for simulated Gaussian sources. Note that individual snapshot $S_{\text{dirty}}/S_{\text{CLEAN}}$ ratios are shown as transparent grey lines with the mean value plotted as a solid red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

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 $\sim 10\%$. We find no discernible astrometric offset for these data.

The full-band, robust = +0.25 image is shown in Figure 3(i) with the source-subtracted, 45 arcsec robust = +0.25 image as contours in Figure 3(i) and the background in Figure 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 data sets (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 CALDBⁱ v4.9.1; Fruscione *et al.*, 2006) to process the data following standard *Chandra* data reduction procedures, using the task `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 Figure 5 for each cluster.

ⁱCalibration database.

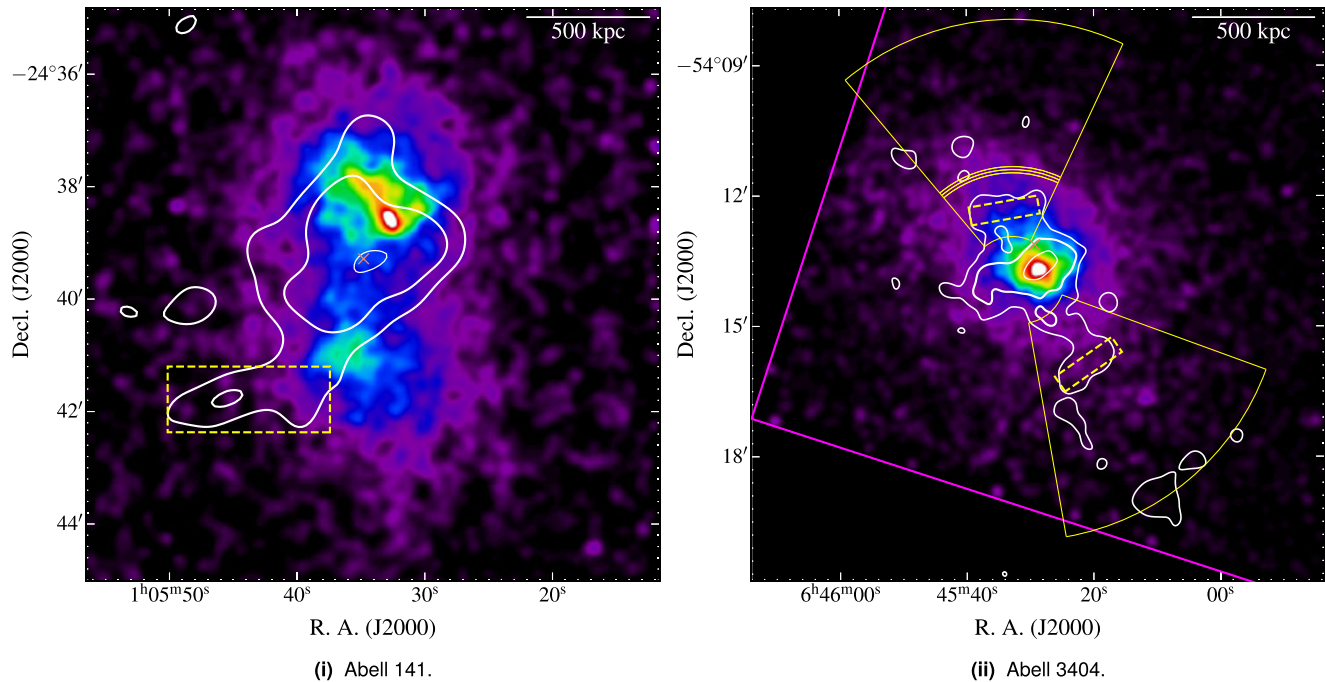


Figure 6. Exposure-corrected, smoothed, point source-subtracted [0.5–2] keV *Chandra* maps with source-subtracted ASKAP contours overlaid. (i) Abell 141: ASKAP contours as in Figure 3(i), but without the $2\sigma_{\text{rms}}$ contour. (ii) Abell 3404: ASKAP contours are the source-subtracted without 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.

3. Results and 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 Figures 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 clusters (Figures 3(ii) and 4(ii)). We show the exposure-corrected, smoothed X-ray maps in Figure 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 data, with an extension towards the southeast becoming a distinct peripheral component (yellow, dashed box in Figure 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 and 3.7 arcmin, respectively, corresponding to a linear size of 910 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 Figure 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 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

Figures 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,

Table 2. Discrete source SED properties for both clusters.

Source	α	$\Delta\nu^a$ (MHz)
Abell 141		
A	-1.09 ± 0.07	216–2 674
B ^b	-1.44 ± 0.05	147–2 674
C	-1.07 ± 0.07	147–2 674
D ^c	$+1.18 \pm 0.09$	943–3 000
Abell 3404		
A	-0.49 ± 0.11	216–1 388
B	-0.35 ± 0.10	216–1 388
C	-1.02 ± 0.14	185–1 121
D ^b	-0.67 ± 0.18	185–2 424
E	-0.65 ± 0.08	216–2 424
F ^d	–	–
G ^e	–1	905–1 121

^aFrequency range over which source is modelled.

^bFit with a curved power law model.

^cInverted spectrum.

^dSource could not be modelled, but is not distinguishable from ‘E’ in MWA data.

^eNo uncertainty is given as the SED is only over the ASKAP sub-bands, and we do not quantify the internal flux scale uncertainty across the band.

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 to 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 that 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 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 1 110 MHz for Abell 3404. Figure 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 ($\alpha_{88}^{1.013} = -1.66 \pm 0.07$) pushes

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.

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

$$I(r) = I_0 e^{-r/r_e} \quad [\text{Jy arcsec}^{-2}], \quad (1)$$

with I_0 the peak brightness, the e -folding radius $r_e = f/R_H$, 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); Venturi et al. (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 in Section 3.2.2. Additionally, we find values of f (Equation (1)) to be 2.0 and 1.9 that recover adequate model flux for the Abell 141 and Abell 3404 radio halos, respectively. We use WSClean to inject the simulated halo as a function of frequency into the relevant data sets. During imaging of the mock radio halo, we increase brightness by factors of $\sqrt{2}$ until a detection is made. Imaging is done as a two-part process: first, the model data are imaged alone and then imaged with the true calibrated data. The imaging of the model alone allows us to investigate the percentage of flux lost due to the u - v sampling. For Abell 141, we image both the ATCA and GMRT data with a 30 arcsec Gaussian taper applied to the visibilities to maximise the likelihood of detection. We find that the ATCA observation of Abell 141 only recovers $\sim 20\%$ of the model radio halo flux due to the lack of inner spacings limiting sensitivity on larger scales, with the GMRT observation recovering $\sim 60\%$. For Abell 3404, the flux recovered is $\sim 70\%$ and $\sim 90\%$ for the pre-CABB and CABB data, respectively. We use the same detection criterion as Bonafede et al. (2017): $D_{2\sigma_{\text{rms}}}^{\text{mock}} \geq R_H$, where $D_{2\sigma_{\text{rms}}}^{\text{mock}}$ is the diameter of the mock radio halo within $2\sigma_{\text{rms}}$ contours. As per Bonafede et al. (2017), we opt to consider the model radio halo flux density for the limit, as this is the flux density that would be required to make the detection. The resultant limits, along with new limits obtained for the GMRT data (Venturi et al., 2007; Venturi et al., 2008), are provided in Table 3, though are not used in fitting in Section 3.2.2.

We note that the limit found for the GMRT data of Abell 141 is higher than what is reported by Venturi et al. (2007); Venturi et al. (2008): $\sim 7 \text{ mJy}^{\dagger}$. This discrepancy is a result of, in part, the $\sim 60\%$ of flux lost to u - v sampling, and the difference in the modelled brightness profile, where Venturi et al. use optically thin concentric spheres (see also Brunetti et al., 2007). The remaining

[†]Note that 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.

Table 3. Flux density measurements and limits of the diffuse sources.

Instrument	Weighting	ν (MHz)	Resolution ("×")	$\langle\sigma_{\text{rms}}\rangle^{\text{a}}$ (mJy beam ⁻¹)	$S_{\text{c},\nu}^{\text{b}}$ (mJy)	S_{ν} (mJy)
Abell 141 radio halo (+ peripheral source)						
MWA-2	Robust 0.0	87.7	130 × 130	8.6	78 ± 28	182 ± 46
MWA-2	Robust +2.0	118.4	168 × 118	4.7	58 ± 16	135 ± 28
MWA-2	Robust +1.0, 120" taper	154.2	166 × 147	6.1	45 ± 8	75 ± 21
MWA ^c	Uniform	169.6	109 × 109	4.9	41 ± 6	80 ± 27
MWA-2	Robust +1.0, 120" taper	185.0	150 × 137	5.1	38 ± 5	66 ± 19
MWA	Robust -1.0	200.3	133 × 126	16.3	35 ± 4	79 ± 20
MWA-2	Robust +1.0, 120" taper	215.7	138 × 130	5.1	32 ± 3	65 ± 22
GMRT ^d	Natural, 30" taper	617.5	71 × 56	0.45	-	< 26 ^e
ASKAP	Robust +0.25, 45" taper	943.5	49 × 46	0.14	-	13.7 ± 1.9
ATCA	Robust 0.0, 45" taper	2 224.5	44 × 31	0.052	-	< 8.1 ^e
Abell 141 peripheral source (SE)						
ASKAP	Robust +0.25, 45" taper	943.5	49 × 46	0.15	-	1.7 ± 0.5
Abell 3404 radio halo (+ peripheral sources)						
MWA-2	Robust +2.0	87.7	242 × 157	24.7	130 ± 140	990 ± 190
MWA-2	Robust +2.0	118.4	183 × 114	10.4	120 ± 120	620 ± 140
MWA-2	Robust +2.0	154.2	137 × 86	4.7	100 ± 100	300 ± 110
MWA	Robust -1.0	200.3	147 × 134	8.3	90 ± 91	204 ± 99
ASKAP	Robust +0.5, 35" taper	917.5	36 × 36	0.15	-	18.9 ± 2.7
ASKAP	Robust +0.5, 35" taper	1 013.5	36 × 36	0.12	-	16.0 ± 2.3
ASKAP	Robust +0.5, 35" taper	1 109.5	36 × 36	0.16	-	14.9 ± 2.8
ATCA	Robust 0.0	1 388.0	98 × 38	0.15	-	< 21 ^e
ATCA	Robust 0.0	2 424.0	71 × 37	0.055	-	< 5.7 ^e
Abell 3404 peripheral source (NE)						
ASKAP	Robust +0.5	1 013.5	25 × 25	0.074	-	1.3 ± 0.3
Abell 3404 peripheral source (SW)						
ASKAP	Robust +0.5	1 013.5	25 × 25	0.065	-	1.4 ± 0.4

^aAverage rms noise within the measured source region.

^bConfusing source flux that is subtracted from initial measurement based on SEDs reported in Table 1.

^cEoR-0 field image (Offringa et al., 2016) as used by Duchesne et al. (2021b), re-measured with present integration region and source subtraction, including brightness scaling of 0.69.

^dData originally presented by Venturi et al. (2007).

^eLimit from mock radio halos as described in Section 3.2.3.

difference may be contributed from a different model geometry and spectrum and a bias that occurs when measuring the integrated flux density of low-SNR extended sources (Stroe et al., 2016, but see also Helfer et al., 2003).

Cuciti et al. (2018) perform a similar mock halo analysis for GMRT and Karl G. Jansky Very Large Array (JVLA) data to test flux recovery of incomplete u - ν sampling. An important note they make is that the recovered flux density fraction decreases as the mock halo brightness decreases. We note that the flux recovery fraction for our mock halos is based on the limits. Appendix, A shows representative u - ν coverage plots for the observations used in this work (MWA-2, ASKAP, ATCA, and GMRT). These plots highlight that inner u - ν sampling for the GMRT and ATCA (Abell 141) observations is lacking, whereas the MWA-2, ASKAP, and even the pre-CABB and CABB data for Abell 3404 have much

more densely sampled inner u - ν data. We note, however, that the smaller λ values become less populated towards the higher end of the MWA-2 band. We opt not to provide limits on the MWA-2 data between 185 and 216 MHz for Abell 3404 due to partial detection of the radio halo combined with significant confusion with discrete sources.

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 ($I_{\text{R}} \propto I_{\text{X}}^k$; 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., 2020; Rajpurohit et al., 2021; Bruno et al., 2021); conversely, mini-halos have been found to have

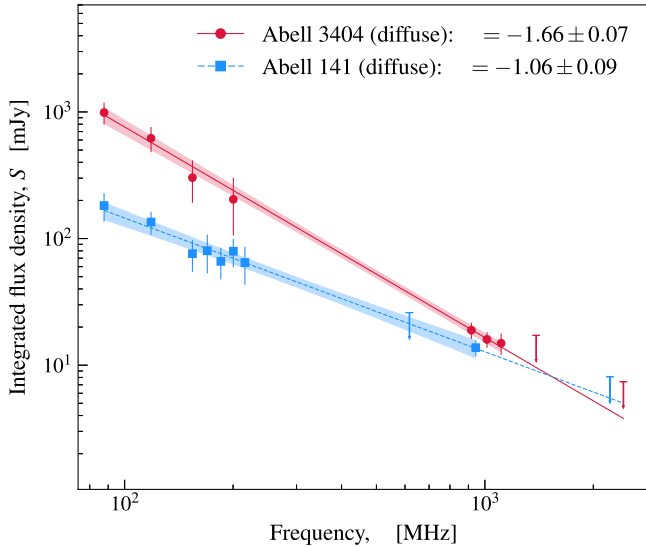


Figure 7. SEDs of the diffuse emission in Abell 141 and Abell 3404. The lines are power law fits, with 95% confidence intervals represented by the shaded regions. Upper limits are represented by arrows. The fits are extrapolated to ATCA frequencies for ease of comparing to ATCA limits.

Table 4. Derived radio halo properties.

Property	Abell 141	Abell 3404
Linear size (kpc)	850	770
α	-1.06 ± 0.09	-1.66 ± 0.07
$P_{1.4}$ (10^{23} W Hz $^{-1}$)	14.4 ± 2.0	8.6 ± 1.7
$P_{0.15}$ (10^{23} W Hz $^{-1}$)	164 ± 43	350 ± 70

super-linear slopes (Ignesti *et al.*, 2020). We use the exposure-corrected, source-subtracted, smoothed [0.5–2] keV *Chandra* data along with the 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 $\log_{10}(I_R) = k \log_{10}(I_X) + C$ using the BCES method^k with an orthogonal regression. Figure 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 $k = 0.53 \pm 0.04$. While many halos have been found with $k \gtrsim 0.6$ (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 $k \lesssim 0.6$ (Bruno *et al.*, 2021). The SW peripheral component (blue points, Figure (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 ($\rho = 0.31$). 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 Figure 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 reports 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 (Murgia *et al.*, 2010), MACS J0416.1–2403 (Ogrea *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 co-located 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 derives a Mach number of $\mathcal{M}_X = 1.69^{+0.41}_{-0.37}$. 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

$$\mathcal{M}_R = \sqrt{\frac{2\alpha_{\text{inj}} - 3}{2\alpha_{\text{inj}} + 1}}, \quad (2)$$

assuming that $\alpha = \alpha_{\text{inj}} - 0.5$, with α_{inj} the synchrotron injection spectrum index. We find $\mathcal{M}_R = 5.9 \pm 0.9$, 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); van Weeren *et al.* (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 $\mathcal{M}_R = 2.1 \pm 0.2$, in agreement with \mathcal{M}_X . Assuming seed electrons for radio relics originates as fossil electrons rather than 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.*,

^kBivariate Correlated Errors and intrinsic Scatter: Akritas & Bershady (1996).

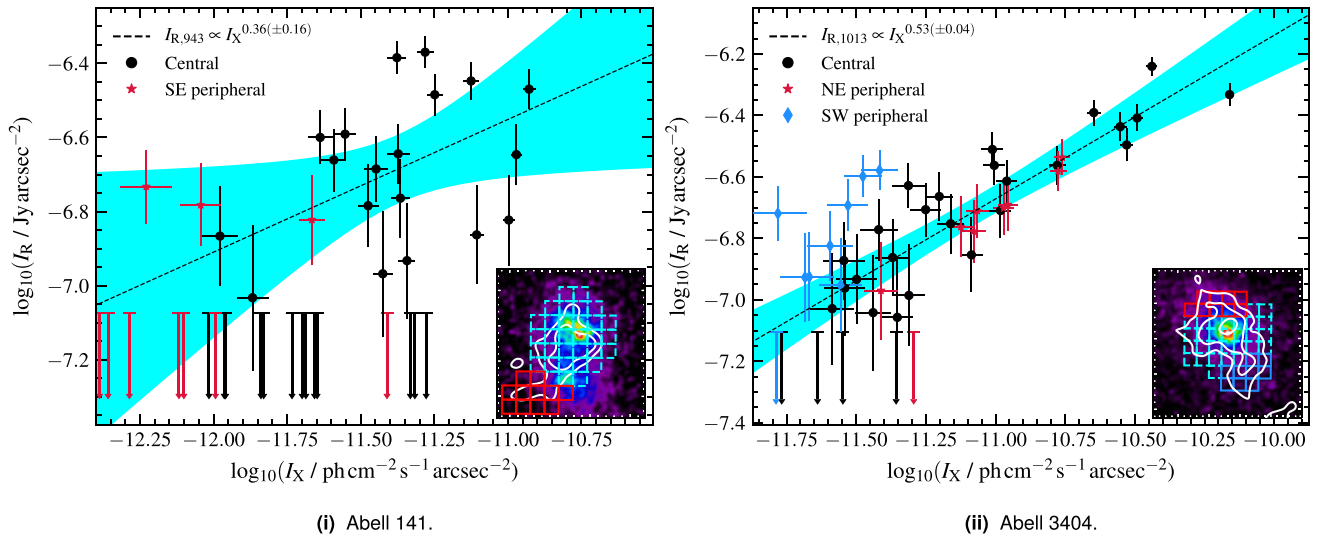


Figure 8. Radio–X-ray point-to-point correlation for (i) Abell 141 and (ii) Abell 3404. Upper limits correspond to cells where $I_R < 2\sigma_{rms}$. The black, dashed line is the best-fitting line with a 95% confidence interval shaded in cyan. The insets show the *Chandra* X-ray maps with the source-subtracted ASKAP image overlaid as contours as in Figures 6(i) and 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.

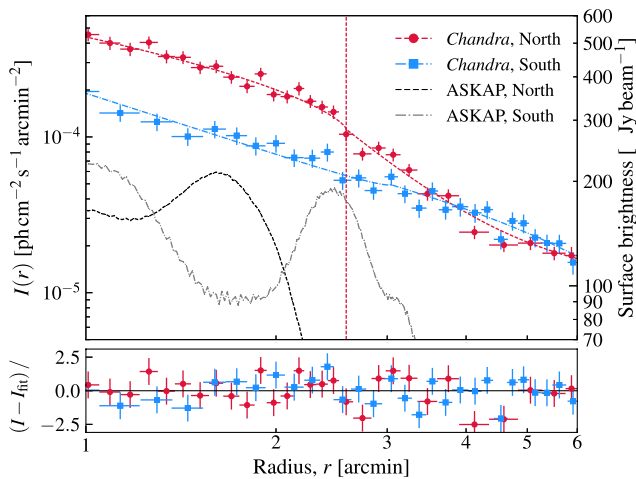


Figure 9. Radio and background-subtracted X-ray surface brightness profile for sectors shown in Figure 6(ii) for Abell 3404. The radio ordinate clips at $2\sigma_{rms}$. The dashed-red vertical line is at location of the discontinuity in the northern profile.

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

Figure 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 core 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*¹ (Eckert et al., 2011), subtracting a fitted background of $I_B = (1.41 \pm 0.05) \times 10^{-5}$ ph cm⁻² s⁻¹ arcmin⁻², finding $w = 0.039$ within $R_{500} = 1\,280$ 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

$$c_{r_1/r_2} = \frac{I_X(r < r_1 \text{ kpc})}{I_X(r < r_2 \text{ kpc})}, \quad (3)$$

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 ($w_{500 \text{ kpc}} = 0.039$), places the cluster just outside of the halo-hosting quadrant of the $c_{100/500} - w_{500 \text{ kpc}}$ 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 points 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 $7.96^{+0.23}_{-0.21} \times 10^{14} M_\odot$ (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.

¹<http://www.isdc.unige.ch/deckert/newsite/Proffit.html>

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

Figure 6(ii) shows two extended diffuse emission regions (indicated with dashed, yellow rectangles) either side of the cluster center. 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 Figure 6(ii)). For the X-ray data, we use `proffit`, masking the point sources indicated in Figure 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`^m. The extracted profiles in each direction are shown in Figure 8. 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):

$$\rho(r) = \begin{cases} Cr^{-\Gamma_{\text{in}}}, & \text{if } r < r_{\text{break}} \\ C \frac{n_{\text{out}}}{n_{\text{in}}} r^{-\Gamma_{\text{out}}}, & \text{otherwise} \end{cases}, \quad (4)$$

with Γ 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 $j_{\text{south}} \sim 1$, indicating no evidence for a discontinuity. For the northern profile, we obtain $j_{\text{north}} = 1.11_{-0.10}^{+0.09}$. The radio source occurs ~ 1 arcmin (~ 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 associated with a shock.

3.5. Radio halo P_{ν} – 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 ~ 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; Cassano et al., 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_{ν} – 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; Brzan 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 (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

$$P_{\nu_1} = \frac{4\pi D_L(z)^2}{(1+z)^{1+\alpha}} S_{\nu_{\text{obs}}} \left(\frac{\nu_1}{\nu_{\text{obs}}} \right)^{\alpha} \quad [\text{W Hz}^{-1}], \quad (5)$$

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

$$\log_{10}(P_{\nu_1}) = B \log_{10}(M_{500}) + A - \langle\alpha\rangle \log_{10} \left(\frac{\nu_2}{\nu_1} \right), \quad (6)$$

where ν_2 is the frequency at which the original scaling relation is fit and with $P_{\nu_1} = P_{\nu_2}(\nu_1/\nu_2)^{\langle\alpha\rangle}$. Figure 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 subclusterⁿ the halo’s position on both P_{ν} – M_{500} relations would be significantly above the best-fitting lines.

^m<https://gist.github.com/Sunmish/198ef88e1815d9ba66c0f3ef3b18f74c>

ⁿWith $M_{X,500} = (3.79 \pm 0.3) \times 10^{14} M_{\odot}$ C18.

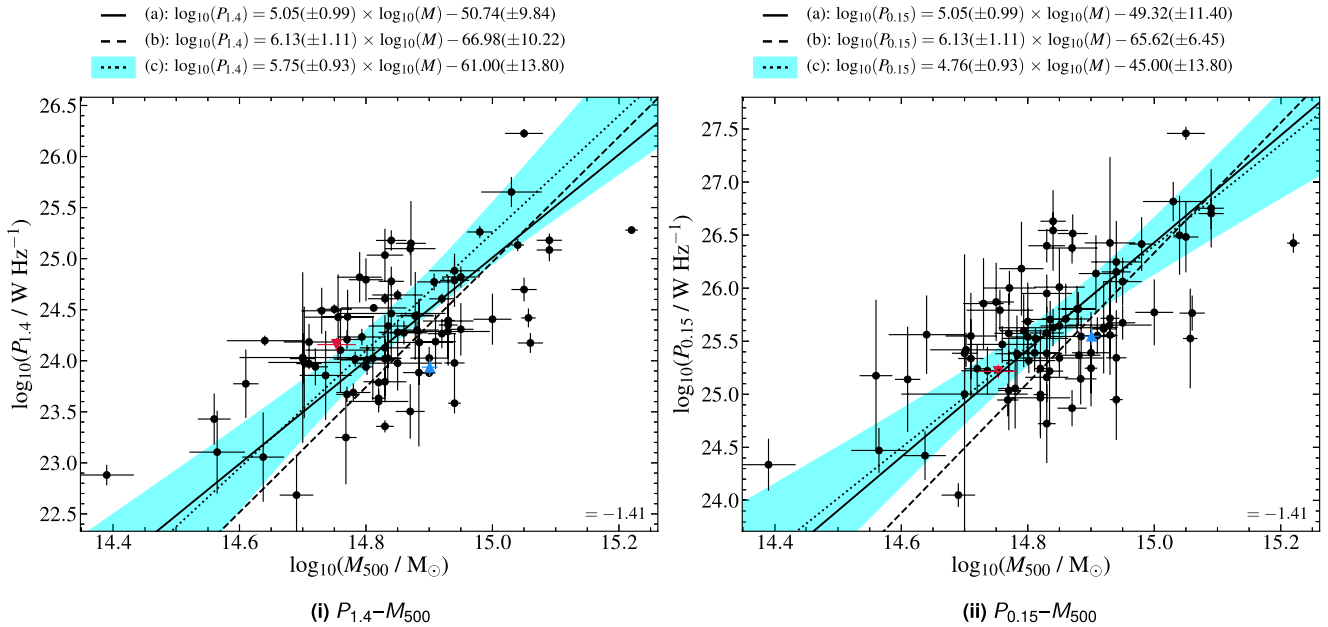


Figure 10. Radio halo $P_{1.4}$ - M_{500} relation (i) and $P_{0.15}$ - M_{500} relation (ii) with best-fitting orthogonal relations from (a) Cassano et al. (2013) (solid, black), (b) van Weeren et al. (2020) (dashed, black), and (c) this work (dotted, black). Halos are taken from the literature (as discussed in Section 3.5) with the addition of the halo in Abell 3404 (blue, upright triangle) and the updated values for Abell 141 (red, downward triangle), for a total of 86 halos. The shaded regions are 99.7% confidence intervals for fits from this work.

Table 5. Fitted values for the P_ν - M_{500} scaling relations for various methods.

Method	B	σ_B	A	σ_A
$P_{1.4}$ - M_{500}				
$P_{1.4} M_{500}$	3.21	0.39	-23.4	5.8
Orthogonal	5.75	0.93	-61.0	13.8
Bisector	4.17	0.46	-37.7	6.8
$P_{0.15}$ - M_{500}				
$P_{0.15} M_{500}$	3.15	0.41	-21.2	6.0
Orthogonal	4.76	0.93	-45.0	13.8
Bisector	3.84	0.50	-31.4	7.4

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 $P_\nu|M_{500}$ fitting^o 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 finds that inclusion of USSRHs steepens the scaling relation at 1.4 GHz, and vW20 finds generally steeper relations at 0.15 GHz 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 (α), where real observations at lower or higher frequencies may bias the sample selection towards steeper or flatter spectrum sources, respectively, finding opposed slopes to the P_ν - M_{500} relation. Uncertainties are still too significant to confirm this as discussed by vW20.

^o P_ν the dependent variable and M_{500} the independent variable.

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 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 u - 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, phoenixes, 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 subclusters. Conversely, we find that the dynamic status of Abell 3404 is likely to be in 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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Appendix A u - v coverage plots

Figure 11(i)–11(viii) shows u - v coverage (in λ , from -3000λ – 3000λ) for the Abell 141 data used in this work, excluding MWA-1

data. Similarly, Figure 12(i)–12(ix) shows 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.

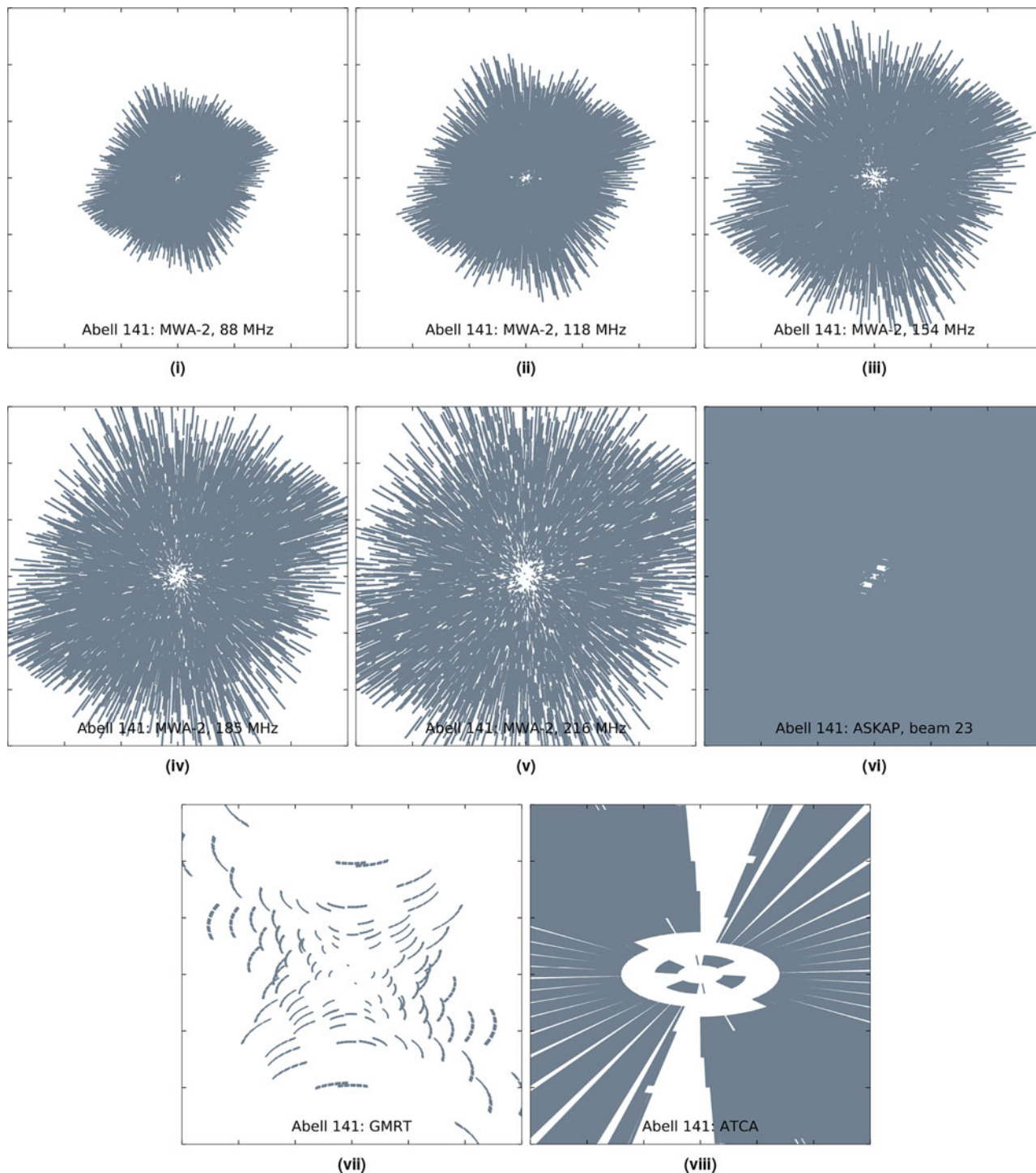


Figure 11. u - v coverage plots for Abell 141 data. Axes are centered on zero and range from -3000λ to 3000λ . Note that the MWA-2 data are of single 2-min snapshots, representative of the snapshot observations. The true u - v coverage is slightly more filled in. The observation used for the ASKAP example is SB15191.

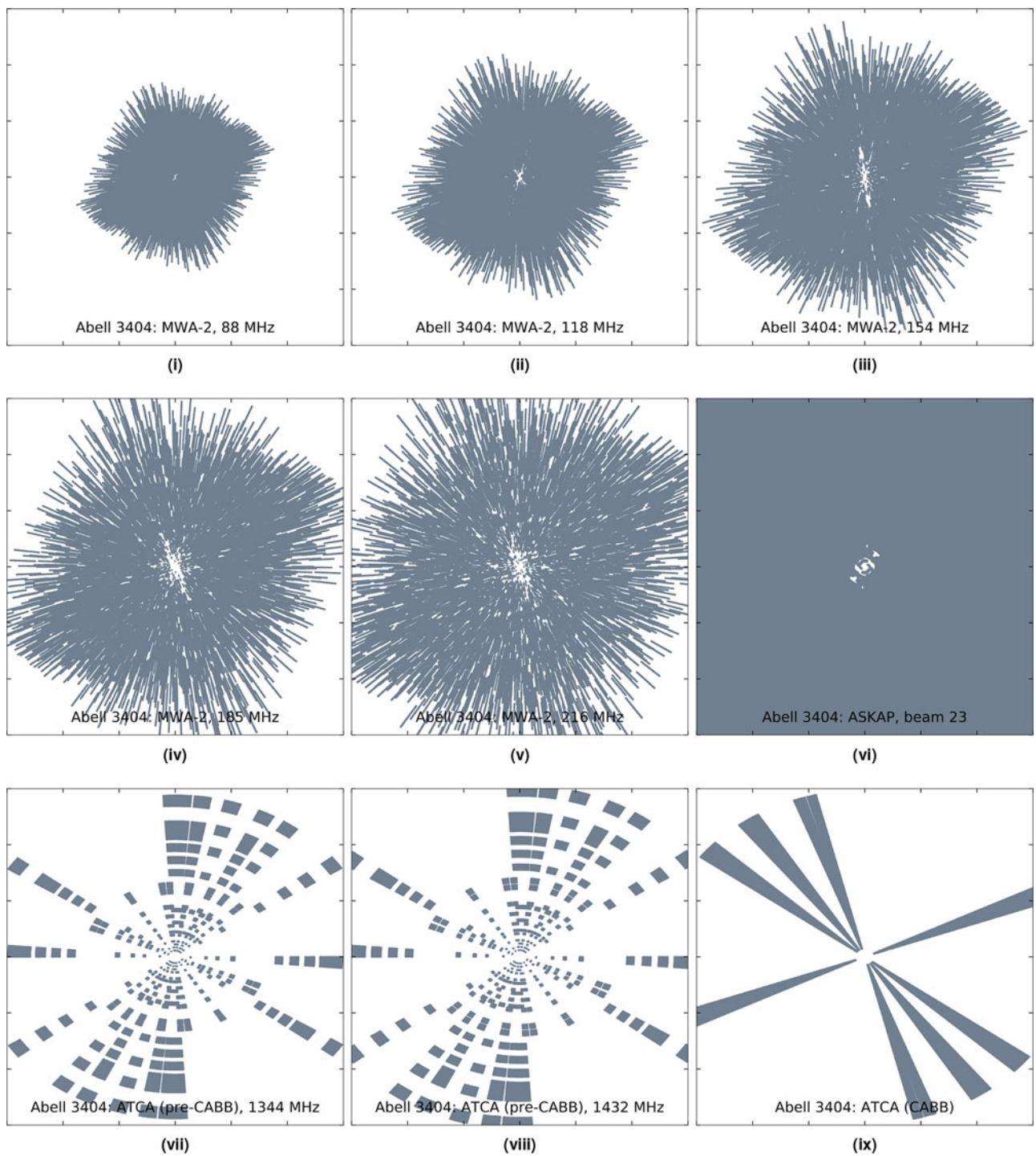


Figure 12. $u-v$ coverage plots for Abell 3404 data. Axes are centered on zero and range from -3000λ to 3000λ .