The Deep Diffuse Extragalactic Radio Sky at 1.75 GHz

T. Vernstrom\textsuperscript{1}, Ray P. Norris\textsuperscript{2}, Douglas Scott\textsuperscript{1}, J.V. Wall\textsuperscript{1}

\textsuperscript{1}Department of Physics and Astronomy, University of British Columbia, Vancouver, BC V6T 1Z1, Canada
\textsuperscript{2}Australia Telescope National Facility, PO Box 76, Epping NSW 1710, Australia

\textsuperscript{*} E-mail:tvern@phas.ubc.ca

\begin{abstract}
We present a study of diffuse extragalactic radio emission at 1.75 GHz from a portion of the ELAIS-S1 field observed with the Australia Telescope Compact Array. The resulting mosaic covers an area of 2.46 deg$^2$ with a beam size of 150 arcsec $\times$ 60 arcsec and instrumental noise $\langle \sigma_n \rangle = (52 \pm 5) \mu$Jy beam$^{-1}$. Using models of point-source emission obtained from the ATLAS survey, we subtracted the discrete emission in this field to a flux density of 150 $\mu$Jy beam$^{-1}$. Comparison of the source-subtracted probability distribution, or $P(D)$, with the predicted distribution from the noise and model of unsubtracted discrete emission, we find an excess of $(76 \pm 23) \mu$Jy beam$^{-1}$. We take this excess as an upper limit on any possible extended emission and constrain several models of extended emission source counts, assuming source sizes of 2 arcmin or less. The best-fitting models yield temperature contributions to the radio background from extended emission of $\bar{T}_b = (10 \pm 7)$ mK, giving an upper limit on the total background temperature at 1.75 GHz of $(73 \pm 10)$ mK. Further modelling shows that our data are inconsistent with the reported excess temperature found by the ARCADE 2 experiment of 55 mK at 3.3 GHz to a source-count limit of 1 $\mu$Jy. Our new data close a loop-hole in the previous constraints, because of the possibility of extended emission being resolved out at higher resolution. Additionally we looked at two WIMP dark matter source-count models, likewise finding them to be inconsistent with our data. We discuss general constraints on any predicted source count models from dark matter annihilation. Finally we report the derived integral source count at 1.4 GHz using the deepest discrete count determinations plus our new extended-emission limits, providing numbers that can be used for planning future ultra-deep radio surveys.

\textbf{Key words:} radio continuum: galaxies – diffuse radiation – methods: statistical – galaxies: haloes, clusters
\end{abstract}

1 INTRODUCTION

It is well known that the bulk of discrete radio sources, for frequencies near 1.4 GHz, is made up of either active galactic nuclei (AGN) or starburst galaxies. Their space distributions have been modelled via their luminosity functions to determine how they evolve with redshift. The number counts $dN/dS$, or the differential number of sources per steradian per flux density interval, have been accurately measured well into the sub-mJy region (Owen & Morrison 2008; Condon et al. 2012), as well as the contribution from these sources to the cosmic radio background (CRB). However, what is less well characterized is the extended larger-angular-scale emission associated with these galaxies or perhaps associated with groups or clusters of galaxies or with the cosmic web. There have been few surveys carried out for large angular scale extragalactic emission, and very few that also have high sensitivity. The most sensitive lower resolution survey yet published was by Subrahmanyan et al. (2010), which reached an rms of 85 $\mu$Jy beam$^{-1}$ with a 50 arcsec beam. This angular scale encompasses extended low-surface-brightness emission from individual galaxy haloes, as well as emission from the intra- and inter-cluster medium, features such as giant and mini radio haloes, radio relics, and diffuse emission from filaments and other structures in the inter-cluster medium (see e.g. Feretti et al. 2012).

It is unknown how much this large-scale emission may contribute to the cosmic radio background (CRB) temperature. This background at radio frequencies ($T_b$) is composed of emission from the cosmic microwave background (CMB), the contribution from the Milky Way, and the contribution from extragalactic sources; thus $T_b = T_{\text{CMB}} + T_{\text{Gal}} + T_{\text{source}}$. The CMB contribution has been measured to high accuracy and corresponds to 2.7255 K (Fixsen 2009). Recent estimates from the deep survey by Condon et al. (2012) and Vernstrom et al. (2014) hereafter V14 were made of the contribution from extragalactic sources using the Karl G. Jansky Very Large Array (VLA) at 3 GHz. They found the contribution from compact sources to be $T_{\text{source}} = 14$ mK at 3 GHz and
120 mK when scaling this result to 1.4 GHz. However, the beam size of the VLA at 3 GHz was 8 arcsec and the image was constructed from $uv$ weighting that filtered out scales much larger than the beam. Thus that survey would not have been sensitive to emission on larger scales.

Extended low-surface-brightness radio emission can be difficult to survey. Galactic- and cluster-scale emission can extend up to several arcminutes. Single-dish telescopes at radio frequencies have beams on much larger scales and are limited in their continuum sensitivity by systematic errors, while most interferometers are not ideal for measuring low surface brightness extended objects. The surface brightness sensitivity of an interferometer is limited by its spatial frequency coverage in the image domain, which is the Fourier transform of its coverage of the aperture plane, often referred to as its ‘$uv$ coverage’. For example, if an interferometer consists of antennas of diameter $D$, and the length of the shortest baseline is $b$, then the interferometer is generally insensitive to objects in the sky with angular size greater than $\frac{b}{D}$ radians. An interferometer with $D = 25$ m and $b = 1000$ m observing at 20 cm is therefore insensitive to astronomical objects with scale sizes greater than 0.7 arcmin. Mosaicing can recover spatial information $> \frac{b}{D}$ in size but nothing can recover information between $\frac{b}{D}$ and $\frac{b}{2D}$, as that has not been measured by the interferometer. Thus, not many deep extended emission surveys have been carried out at radio frequencies.

The issue of large-scale emission and the CRB has been of greater interest in the last few years, considering the results of ARCADE 2 (Fixsen et al. 2009, 2011). This balloon-borne experiment observed the sky at several radio frequencies, ranging from 3.3 to 100 GHz. It measured a background temperature at 3.3 GHz much higher than current estimates from extragalactic sources. (54 ± 6) mK compared with the $T_{\text{source}} \simeq 14$ mK of V14 [Singal et al. (2010)] proposed that the excess could be due to a new population of faint distant star-forming galaxies. V14 ruled out any new populations of discrete sources having peaks in the source count above 50 nJy.

For compact sources to be causing the excess emission seen by ARCADE 2, the additional sources would need to have number-count peaks at very faint flux densities. This could raise a problem with the far-IR to radio correlation (unless this correlation evolves with redshift), as well as conflict with limits to the overall number of galaxies.

However, the cause of the ARCADE 2 excess could be due to larger-scale emission (scales ranging from around 0.5 arcmin up to the 12” primary beam size of the ARCADE 2 experiment). It has been proposed that the emission could be caused by dark matter annihilation (Fornengo et al. 2011; Hooper et al. 2012; Yang et al. 2013; Fornengo et al. 2014), in which case it would trace the dark matter distribution of clusters of galaxies, with a characteristic scale size of arcmin. Other emission processes could include those normally seen from clusters, such as radio relics and haloes, or with diffuse synchrotron emission from the cosmic web [Brown 2011]. Such emission processes do not directly correlate with star formation and therefore could evade constraints from the far-IR radio correlation.

In this paper we use deep low-resolution radio observations from the Australia Telescope Compact Array (ATCA) to investigate the emission that might be present at larger angular scales and constrain how it might contribute to the CRB. In Section 2 we detail the radio observations, data reduction, and imaging process, as well as discussing the image noise properties. Section 3 describes the technique used to examine the data. In Section 4 we discuss our treatment of discrete point sources, our subtraction method, and the contribution from faint un-subtracted sources. We discuss issues of detecting extended emission at both high and low resolutions in Section 5. Section 6 details the models we use for investigating the extended or diffuse emission. Section 7 discusses the conversion from source count to background temperature, as well as the predicted background temperatures from ARCADE 2 at our image frequency. Section 8 presents the results of fitting our extended emission source count models to our new data and their contribution to the CRB, and as well as discussing models fit to the ARCADE 2 results. In Section 9 we discuss our findings, in particular what the results might mean in terms of astrophysical sources and the integrated source count at various frequencies. Finally, in Section 10 we present our current estimates of integral source counts for both discrete and extended source count models.

### Table 1. ATLAS ELAIS-S1 pointings.

| ATLAS | RA (HH:MM:SS.ss) | Dec (HH:MM:SS.ss) | $\sigma_n$ ($\mu$Jy beam$^{-1}$) |
|-------|-----------------|------------------|------------------------------|
| el1_1 | 00 : 32 : 03.55 | -43 : 44 : 51.24 | 53.7 ± 4.64 |
| el1_5 | 00 : 32 : 57.67 | -43 : 28 : 09.00 | 52.3 ± 2.66 |
| el1_6 | 00 : 33 : 50.79 | -43 : 44 : 57.36 | 57.0 ± 5.31 |
| el1_7 | 00 : 35 : 38.02 | -43 : 44 : 57.36 | 57.8 ± 3.18 |
| el1_8 | 00 : 34 : 44.40 | -43 : 28 : 11.88 | 58.1 ± 7.28 |
| el1_16 | 00 : 34 : 44.40 | -44 : 01 : 42.84 | 59.2 ± 6.51 |
| el1_17 | 00 : 32 : 57.67 | -44 : 01 : 42.84 | 50.8 ± 3.61 |

#### 2.1 Calibration and editing

The calibration, editing, and imaging were performed using the MIRIAD software package [Sault et al. 1995]. After several rounds of RFI flagging, the source J1934+638 was used for bandpass and flux density calibration. The source 0022−423 (IAU J0024+4202)

http://www.atnf.csiro.au/computing/software/miriad/
was observed for 2-minute intervals every 10 minutes and used to correct the gain phases. The task GPCAL was utilized to derive frequency-dependent gain solutions, solving for the gains of the upper and lower parts of the band separately.

Observations at this frequency are highly affected by radio frequency interference (RFI), most notably at the lowest frequencies. The task MIRFLAG was used for automated RFI flagging on the phase calibrator source and the target fields. This allowed us to flag the majority of interference, so that only a small amount of manual flagging was required. Each of the seven pointings was flagged individually for uv points above an amplitude threshold. The data were then split into two frequency bands (1.1 to 2.1 GHz and 2.1 to 3.1 GHz), and separated into individual data sets for each pointing. The last hour of time was not usable, since the source was setting, and for the the final four hours Antenna 1 was lost due to shadowing. In the end about 55 per cent of the data was flagged (i.e. not used) in the 1.1 to 2.1 GHz frequency band, and about 30 per cent in the 2.1 to 3.1 GHz band.

The following analysis is only carried out for the lower part of the CABB band (1.1 to 2.1 GHz) which, after flagging, ranged from 1.38 to 2.1 GHz, with a centre frequency of 1.75 GHz. This decision was made because it more closely matches the image frequency of the ATLAS survey. We planned to use the ATLAS point-source models to subtract discrete emission from our data. The spectral change of the primary beam going from the lower band to the upper band (2.1 to 3.1 GHz) is large, which makes accurate scaling of the point source models difficult and the output of the subtraction at the higher frequency less reliable. For this reason we do not believe the addition of the upper band would contribute additional meaningful information for our analysis.

2.2 Imaging

Imaging was first performed on the full uv data sets, primarily for the purposes of self-calibration of the data. However, the ultimate goal was to perform subtraction of the known point sources in the fields and re-image the source-subtracted data for further analysis. The subtraction process is discussed in more detail in Section 3.3.

The MIRIAD tasks INVERT, MFCLEAN, and RESTOR were used to create and clean the images. Due to the large frequency range covered, we used multi-frequency synthesis and deconvolution, or cleaning (MFCLEAN). MFCLEAN attempts to solve for a frequency dependent intensity, $I(\nu)$. Here

$$I(\nu) = I(\nu_0) \left(\frac{\nu}{\nu_0}\right)^{\alpha},$$

and solving for the partial derivative of the intensity with frequency gives the spectral index,

$$I(\nu_0)\alpha = \nu_0 \frac{\partial I}{\partial \nu} \bigg|_{\nu_0}.$$  

Thus by using MFCLEAN the resulting image has two planes, the intensity at the reference frequency and the intensity times the spectral index. This allows us to take advantage of the large bandwidth and solve for the frequency dependence of sources (though a high signal-to-noise ratio is usually required in order to produce a good measurement). That this process can be complicated by the changing primary beam size at the different frequencies. There should therefore be an additional term representing the spectral dependence of the primary beam; however, currently MFCLEAN only allows for fitting of one additional spectral term. Instead the primary beam frequency dependence was accounted for during the mosaicing process.

Each pointing was cleaned separately, initially down to a level of 600 $\mu$Jy beam$^{-1}$. At this stage we performed two rounds of phase-only self-calibration and one of amplitude and phase. The final images were cleaned down to 250 $\mu$Jy beam$^{-1}$. The resulting synthesized clean beam size is $150 \times 60$ arcsec, with a position angle of $6^\circ$, using Briggs weighting (Briggs 1995) and a robustness factor of 0.5. A mosaic of the seven pointings was made using LINMOS, and this is shown in Fig. 1 with each pointing having a primary beam full width at half maximum (FWHM) of roughly 27 arcmin; the final mosaic has a total area of approximately 2.46 deg$^2$.

2.3 Image noise

Obtaining a precise measure of the instrumental noise $\sigma_i$ is difficult, because with the large beam size the confusion rms $\sigma_c$ is expected to dominate over the instrumental noise. However, for our analysis goals an accurate measurement and characterization of the noise is required. We employed two different techniques in order to estimate the instrumental image noise. First we made measurements of the noise using the "jackknife" method. This involves taking two (approximately) equal halves of the data and creating separate images. Each of these images should have noise equal $\sigma_{\text{total}}$. By differencing the images and dividing by two, the noise of the combined image should be left, with all the signal subtracted out. Since the noise in each half adds in quadrature, then after the subtraction,

$$\sigma = \sqrt{\frac{\sigma_i^2 + \sigma_c^2}{2}} = \sqrt{\frac{(\sqrt{2}\sigma_{\text{total}})^2 + (\sqrt{2}\sigma_{\text{total}})^2}{2}} = \sigma_{\text{total}}.$$  

(3)

It can be challenging with interferometry to create images with equal halves of the data. Choosing two equal time chunks can introduce issues with different uv coverage between the two data sets. We therefore chose to create two images using the even and odd numbered spectral channels, which should give approximately half in each set. The images were cleaned in the same manner and then subtracted for each pointing. We measured the rms in the cleaned portion of the image and fit it with a Gaussian. This can be seen for two of the pointings in Fig. 2. The jackknife procedure yielded measurements of the instrumental noise of the individual pointings of 50–65 $\mu$Jy beam$^{-1}$.

As a check on this procedure we also used a second approach. The Stokes $V$ parameter measures circular polarization and is de-

---

2 In radio interferometry images the point spread function (PSF) resulting from the Fourier transform of the uv coverage and weighting functions is known as the ‘dirty’ synthesized beam. The dirty beam generally contains positive and negative sidelobes. The cleaning process finds bright peaks and stores them in a model as pixel flux densities known as the clean model. These model components are then convolved with the central Gaussian of the dirty beam, which is known as the ‘clean’ synthesized beam, and added back to the original image. This clean beam is free of sidelobes.

3 Uniform weighting of the uv data results usually in a better behaved synthesized beam, and smaller side lobes, but usually with higher noise. Natural weighting generally gives the best signal-to-noise ratio (though not in the confusion-limited case) but at the expense of an increased beam size. Briggs, or 'robust', weighting allows for weighting between the two options, doing so in an optimal sense (similar to Wiener optimization).
Figure 1. ELAIS-S1 mosaics. The top left panel shows the full area, with the seven pointings outlined and labelled at their centres. The top right panel is the final 1.75 GHz mosaic image. The bottom left panel shows the noise across the mosaic field, with contour levels at 46, 48, 78, 120, 190, 305, 480, 760, 1200, 1900, and 3000 $\mu$Jy beam$^{-1}$. The bottom right panel shows the image after subtraction of the ATLAS point sources.

Extragalactic radio sources generally have low levels of circular polarisation (Rayner et al. 2000) and so a Stokes $V$ image should have subtracted out all the signal, leaving only instrumental noise (similar to the jackknife, but performed in the $uv$ plane rather than the image plane). We therefore made Stokes $V$ images of all the pointings and again measured the rms and fitted Gaussians to the probability distributions. This yielded similar estimates of 55–65 $\mu$Jy beam$^{-1}$, as can also be seen in Fig. 2. For final values of $\sigma_n$ we averaged the measured and fitted values from the jackknife and Stokes $V$ for each pointing, and have listed them in Table 1. These values only account for instrument noise and do not include any additional noise contributions from the imaging process, such as uncleaned dirty beam sidelobes, artefacts from bright sources, or from sources out in the lobes of the primary beam (of which there are several).

For the final mosaic each pointing had a primary beam correction applied to it, raising the noise radially. LINMOS takes in the values of $\sigma_n$ for each pointing and combines pixels by weighting...
3 PROBABILITY OF DEFLECTION

The goal of this work is to examine larger-scale emission, to quantify it, and (if present) to determine what might be causing it. To do this we employ the method of probability of deflection, or $P(D)$ analysis, the 1-point function (e.g. Scheuer 1957; Condon 1974; Patanchon et al. 2009). This involves comparing observed and predicted histograms of the image to investigate the underlying source count. Starting from a source count model, a predicted $P(D)$ can be generated, convolved with noise, and then fit to the observed $P(D)$. A more detailed explanation of $P(D)$ analysis and derivation of the equations used can be found in the papers cited above or in V14 which we follow in detail. We briefly describe the steps here. Starting with a model for the source count, $dN/dS$, we compute $R(x)$ as the integral of the count divided by the beam function $B(\theta, \phi)$. $R(x)$ is the mean number of pixels per steradian having observed intensities between $x$ and $dx$, with $x \equiv SB(\theta, \phi)$, where $S$ is flux density. The predicted $P(D)$ is then computed from the Fourier transform of $R(x)$, such that

$$P(D) = \mathcal{F}^{-1}\left[\exp\left(\int_0^\infty R(x) \exp(i\omega x) \, dx - \int_0^\infty R(x) \, dx\right)\right].$$

An additional term can be added to account for image noise, as a multiplication in the Fourier domain.

In order to fit an accurate $P(D)$ with a source-count model in this way, the shape of the beam and the image noise must be well understood. Ordinarily one would use a Gaussian model of the synthesized clean beam in the calculation of the model $P(D)$, under the assumption that it is not significantly different from the dirty
synthesized beam. However, in our case, the dirty beam has fairly large sidelobes, and is not well approximated by the clean beam. This is shown in Fig. 4 with the full-sized beams and with a close up of the regions near the peaks. The peak sidelobes are at about the $\pm 0.1$ level. However, there are pronounced streaks in the outer regions, of amplitude around $\pm 0.02$, which, when convolved with a source of $S \approx 100 \mu Jy$, would create many pixel values in the $\mu Jy$ region. If only the clean beam was used in the calculation then a source count model with a large number of $\mu Jy$ sources would be fit, even if no such population of sources truly existed. Thus in all following $P(D)$ calculations we used the dirty beam for all sources below our cleaning limit of $S < 150 \mu Jy$, while for sources with $S > 150 \mu Jy$ the clean beam values were used.

### 4 DISCRETE SOURCES

The discrete source count is now known quite well, and has been shown to provide a very much lower background temperature than the one seen by ARCADE 2, down to at least 50 $\mu$Jy [V14]. In this paper we are therefore interested in more diffuse extended emission, which would be resolved out at higher resolution. In order to focus on this emission we first need to subtract out the known contribution from point source emission. We are only able to subtract out sources down to a certain flux density; therefore we must also consider any discrete emission that was not subtracted out.

#### 4.1 Source subtraction

We used the clean component models from the ATLAS survey third data release [Franzen et al. 2014, Banfield & et. al. 2014 in preparation] as point source models for subtraction, since the ATLAS resolution is significantly higher, at around 10 arcsec. It is not entirely clear what the median source size might be and how it changes with flux density, but we expect a value between 1 and 3 arcsec for typical galaxies in evolutionary models (e.g. Wilman et al. 2008). Thus the ATLAS resolution should be sufficient to measure all of the discrete or point source emission. The ATLAS point source models were split into two frequency bands: the lower frequencies from 1.30 to 1.48 GHz; and the higher frequencies from 1.63 to 1.80 GHz. For the subtraction we split our seven $uv$-data sets (for each pointing) into two equal frequency bands as well, 1.30 to 1.70 GHz and 1.70 to 2.10 GHz. The ATLAS images were made using multi-frequency deconvolution and thus contain estimates of the spectral indices of the clean components, which can be used to scale the flux density to different frequencies during subtraction. The task UVMODEL was used to subtract the appropriate pointing and frequency coverage clean model from each corresponding $uv$-data set; then the $uv$-data for each pointing were concatenated using the task UVGLUE (combining the lower and upper frequency parts for each pointing). An independent image was constructed from each pointing with a mosaic constructed subsequently.

The ATLAS survey has an rms sensitivity of 15 to 25 $\mu$Jy beam$^{-1}$ (depending on the pointing) and the models were cleaned.
down to a level of $150 \mu\text{Jy}$. Thus all point sources with $S > 150 \mu\text{Jy beam}^{-1}$ should have some fraction of their discrete emission subtracted out. There is some residual emission apparent around the brightest sources, which is visible in the bottom right panel of Fig. 4. We cannot say if this is due to some slight calibration or subtraction error, possible time variability of AGN sources, or if this represents a portion of the sources’ diffuse emission. Looking at the peak positions of the well defined objects in each of the images, the average residual is only 5 per cent of the peaks. The $P(D)$s for the central region of the mosaic images before and after source subtraction are presented in Fig. 5. This shows a clear decrease in the size of the positive source tail for the subtracted image.

When comparing our data to $P(D)$ predictions from source-count models we use the $P(D)$ of the source-subtracted mosaic image, including only pixels from regions where the noise due to the primary beam correction is not more than 1.5 times the lowest noise value. This is because the $P(D)$ calculation from a source-count model assumes a constant image noise. The noise is certainly inhomogeneous in our data. However, if we limit ourselves to a region where the change in the noise is small and create a noise-weighted histogram, simulations have shown that the effect on the $P(D)$ calculation is small. Using a weighting scheme described in [14] we calculate a mean noise in this area (approximately 0.61 deg$^2$) of $\sigma_n = (52 \pm 5) \mu\text{Jy beam}^{-1}$.

### 4.2 Counts and confusion

We need to estimate the contribution of discrete emission from sources that were not subtracted out. For sources below the clean threshold of the ATLAS models we take the discrete source count of [14] including sources up to $S = 150 \mu\text{Jy}$, which is measured via confusion analysis down to $S \approx 0.05 \mu\text{Jy}$ at 3 GHz. We scale this to 1.75 GHz according to $S \propto \nu^\alpha$, with $\alpha = -0.70 \pm 0.05$ being the mean spectral index of star-forming galaxies (Condon 1984). We found that slight variation in this spectral index produces no significant effect on the output.

For the bright residuals left over from the subtraction process the issue is not as straightforward. Even neglecting any errors in calibration or subtraction, the clean process which generated the models is highly non-linear. The clean components may only represent a fraction of the true flux density, which can vary by peak flux density and from point to point. We do not believe there to be extended emission brighter than approximately $150 \mu\text{Jy beam}^{-1}$ (as discussed in more detail in Section 5.1). To account for residuals brighter than this we counted all the peaks in the source-subtracted image brighter than $150 \mu\text{Jy beam}^{-1}$ that are associated with point sources in the image with no subtraction, and calculated a slope for their differential source count of $-2.50$.

Our model for the unsubtracted point source contribution is the scaled [14] source count up to $150 \mu\text{Jy}$ with a power law of slope $-2.50$ attached for sources up to $3 \mu\text{Jy}$ (the brightest residual in the fitting area). We compute the $P(D)$ from this count and convolve this $P(D)$ with a Gaussian of $\sigma_n = (52 \pm 5) \mu\text{Jy beam}^{-1}$. The noiseless and convolved $P(D)$ distributions are shown in Fig. 6. We measured the confusion noise $\sigma_c$, or width of the distribution, by first finding $D_1$ and $D_2$:

$$\sum_{D_1} P(D) = \sum_{\text{median}} P(D) = 0.34,$$

when normalised such that the sum over the $P(D)$ is 1. Then we take $\sigma_c = (D_2 - D_1)/2$. We do this since, in the Gaussian case, 68 per cent of the area is between $\pm 1\sigma$, and since, in the more realistic case, the long positive tail makes the variance of the full distribution a poor estimate of the width if the peak. The estimated width of the source-subtracted image $P(D)$ is $\sigma = 155 \mu\text{Jy beam}^{-1}$ with an uncertainty of $\pm 5 \mu\text{Jy beam}^{-1}$ measured from bootstrap resampling. For the discrete source model $P(D)$ we find a value of $\sigma_c = 125 \mu\text{Jy beam}^{-1}$. The $P(D)$ of this model convolved with Gaussian noise thus has an rms of $\sigma_{c\oplus n} = 135 \mu\text{Jy beam}^{-1}$.

This discrete model estimate should be treated with some caution. The result is dependent on the exact value of the noise used in the calculation and the exact shape of the unsubtracted discrete count contribution. The unsubtracted discrete count is based on a model which is dependent on the maximum flux density value for the point sources with no subtraction, as well as the power law used for the brighter sources. Taking these points into consideration we adopt an uncertainty of $\pm 10 \mu\text{Jy beam}^{-1}$ on the measure of $\sigma_c = 125$, yielding a measurement and uncertainty for the width of the noise convolved distribution of $\sigma_{c\oplus n} = (135 \pm 12) \mu\text{Jy beam}^{-1}$.

We want to know how different the model of unsubtracted discrete source emission is from the data. To do this we performed a bootstrap significance test. We randomly selected a subset of half the image pixels, generated random numbers from the noiseless model distribution and added varying amounts of Gaussian noise (to account for the uncertainty in the model). We then combined the real and model data into one set and drew two new subsets at random from the combined distribution. We compared the binned
real data to the binned model data, and the binned combined random sets to each other. We repeated this procedure 5000 times. This gives a distribution of the test statistic from the combined random samples of the null hypothesis (that the observed and model data come from the same population) and a distribution of the test statistic when comparing the ordered sets (the observed and model sets not combined). We computed three different test statistics: the Euclidean distance (the root-mean-square distance between the histograms), the Jeffries-Matusita distance (similar to the Euclidean distance but more sensitive to differences in small number bins), and a simple \(\chi^2\).

The results of the bootstrap test show an average excess width of \((76 \pm 23) \mu Jy \ beam^{-1}\). The exact significance of this excess varies depending on the test statistic. Regardless of which test statistic is used the data and model are statistically different with a minimum of 99.5 per cent confidence. This excess cannot be converted directly into a background temperature, however, as the conversion depends on the underlying source-count model responsible for the width (see Section 7 for more discussion on the temperature conversion).

Based on these tests, we conclude that there is more emission present than that from compact galaxies alone. However, due to the uncertainty in the source subtraction process, this excess and any resulting extended emission models are considered as upper limits on the extended emission present.

5 EXTENDED SOURCES

5.1 High resolution extended emission

Before attempting to model any extended emission in the ATCA data we consider how extended emission is detected at higher resolutions, comparing with the VLA data used by [V14] and the ATLAS ATCA high resolution images. The VLA 3-GHz beam used in [V14] had a FWHM of 8 arcsec, while the ATLAS beam was roughly 10 arcsec. We would like to know how emission on arcmin scales appears with these types of data, as a certain amount of emission present than that from compact galaxies alone. However, due to the uncertainty in the source subtraction process, this excess and any resulting extended emission models are considered as upper limits on the extended emission present.

From the simulated extended-size images we see that sources with total halo flux densities greater than approximately 150 \(\mu Jy\) would be visible in the VLA or ATLAS images. The top panel of Fig. 7 shows a cut-out of the simulation with just point source emission (left), point sources plus haloes of 30 arcsec diameter (middle), and point sources plus haloes of 60 arcsec diameter (right), all convolved with a 9 arcsec beam and with Gaussian noise of 2 \(\mu Jy\) beam\(^{-1}\) added. The total flux density of each the halo is equal to the point source flux density divided by 10. The bottom panel shows the \(P(D)\) distributions from the three images with the solid black line being for point sources only, the red dashed line point sources plus 30 arcsec haloes, and the blue dotted line point sources plus 60 arcsec haloes.

Figure 7. Simulation showing point source and extended emission at higher resolution. The top panels show a cut out of the simulation with just point source emission (left), point sources plus haloes of 30 arcsec diameter (middle), and point sources plus haloes of 60 arcsec diameter (right), all convolved with a 9 arcsec beam and with Gaussian noise of 2 \(\mu Jy\) beam\(^{-1}\) added. The total flux density of each the halo is equal to the point source flux density divided by 10. The bottom panel shows the \(P(D)\) distributions from the three images with the solid black line being for point sources only, the red dashed line point sources plus 30 arcsec haloes, and the blue dotted line point sources plus 60 arcsec haloes.
sources. This emission could be low surface brightness diffuse emission around individual galaxies, diffuse cluster emission, or something more exotic, such as emission from dark matter annihilation in halos. We use three source count models to investigate the possible excess (extended) emission. We follow the fitting procedure described in detail in V14. We use Monte Carlo Markov Chains (MCMC), employing the software package Cosmomc (Lewis & Bridle 2002) to minimize $\chi^2$ for each model. The three most negative bins from the image histogram were neglected in the calculation of $\chi^2$. This is because the data have a clearly non-Gaussian negative tail, due in part to the non-constant noise but also due to the areas of over subtraction, which produces an excess of negative points (see the bottom panel of Fig. 5). Tests on subsets of the data, and using different detailed approaches for subtracting bright sources, showed that these effects were restricted to the most negative bins, with the rest of the histogram being quite stable.

6.1 Discrete counts shift model

Using evolutionary models (e.g. Condon 1984, Hopkins et al. 2003), the source count can be broken into contributions from two populations, namely AGN and star-forming galaxies, as shown in Fig. 12. The simplest extended emission model assumes that each of these populations has a radio-emitting halo on arcmin scales, proportional to some fraction of the discrete flux density (or $S_{\text{discrete}} \times C$), separately for the two populations. The counts associated with this extended emission must then retain the shape, or slope, of the discrete counts for each population, but can be shifted in flux density. To estimate the extended counts that are consistent with our data we took the discrete counts for each population and simply applied a shift in $\log_{10}[S]$ separately. Thus,

$$\frac{dN(S_{\text{ext}})^{\text{AGN}}}{dS_{\text{ext}}} = \frac{dN([S_{\text{dis}}(C_1)])^{\text{AGN}}}{dS_{\text{dis}}(C_1)}$$

$$\frac{dN(S_{\text{ext}})^{\text{SB}}}{dS_{\text{ext}}} = \frac{dN([S_{\text{dis}}(C_2)])^{\text{SB}}}{dS_{\text{dis}}(C_2)},$$

where $C_{1,2}$ are constants that are varied to fit the counts. When combined with the unsubtracted discrete count and Gaussian noise, we can find the values that best fit the observed $P(D)$ distribution of our source-subtracted image. Figure 9 shows an example of this model with the two populations of discrete counts, each with shifts applied with $S^2$ normalization and with no normalization. This model will be referred to as Model 1.

6.2 Parabola model

We need to investigate the possibility of the extra emission being fit by a single new population. To do this we introduce a new population as a parabola in $\log_{10}[S^2dN/dS]$ in the form

$$S^2 \frac{dN(S)}{dS} = A(x - h)^2 + k.$$  

Here $x = \log_{10}[S]$ and $A$, $h$, and $k$ are all free parameters. The parameter $h$ is the peak position in $\log_{10}[S]$, $k$ is the amplitude or height of the peak, and $A$ (along with $k$) controls the width. We chose this model because it allows for a smooth curve, and since the discrete count populations are themselves crudely approximated by parabolas in $\log_{10}[S^2dN/dS]$. This model will be referred to as Model 2.
In the above equation \( k_B \) is the Boltzmann constant, and \( T_b \) is the sky temperature from all the sources brighter than \( S_{\text{min}} \). Equation (11) is also equivalent to
\[
\int_{S_{\text{min}}}^{\infty} S^2 \frac{dN}{dS} d\ln(S) = \frac{T_b e^2}{2 k_B \nu^2}.
\]

It is for this reason that it is convenient to show the source count weighted not by the Euclidean \( S^2/2 \) but by \( S^2 \), e.g. as in Fig. 9. This alternate weighting of \( S^2 dN/dS \) is proportional to the source count contribution to the background temperature per decade of flux density. With such a plot the source count must fall off at both ends to avoid over-predicting the background (i.e. violating Olbers paradox); hence the higher end must turn over at flux densities above those we have plotted. The discrete source count used by \( \mathcal{V}_{14} \) integrates (up to \( S = 900 \) Jy) to a background temperature at 1.75 GHz of \( T_{\text{dis}}(1.75 \text{ GHz}) = 63 \text{ mK} \).

7.2 ARCADE 2

The ARCADE 2 experiment measured a background temperature of \( (54 \pm 6) \text{ mK} \) at 3.3 GHz. Several fits are provided to their data which allow for scaling of the result to different frequencies. The initial fit provided in Seifert et al. (2009) is
\[
T_b = (1.06 \pm 0.11 \text{ K}) \left( \frac{\nu}{1 \text{ GHz}} \right)^{-2.56 \pm 0.04}.
\]

There is another fit, incorporating data from lower frequencies, given in Fixsen et al. (2011) as
\[
T_b = (24.1 \pm 2.1 \text{ K}) \left( \frac{\nu}{310 \text{ MHz}} \right)^{-2.59 \pm 0.036}.
\]

Using both of these fits we calculated the estimated background temperature at 1.75 GHz by taking the average from the two equations, and the highest and lowest values, and found \( T_{\text{dis}}(1.75 \text{ GHz}) = (265 \pm 45) \text{ mK} \), which corresponds to a total flux density, given our beam size, of 5600 \( \mu \text{Jy} \) beam\(^{-1}\).

In addition to fitting the data with no constraints, we also fit the models to see what kind of count shapes would be necessary to achieve the ARCADE 2 temperature. We fit the models as described above, only this time adding a prior requiring that the integrated temperature be in the range of 150 to 300 mK. This should show if there is any such source count model consistent with both ARCADE 2 and our data. These models are referred to as Model 1A (shifts), Model 2A (parabola), and Model 3A (nodes).

8 RESULTS

8.1 Summary of fitting results

Using the three models from Section 6, we (a) examined what model parameters best fit our new ATCA data, (b) calculated the resulting contribution to the background brightness temperature, and (c) modelled what would be necessary to achieve a background temperature consistent with ARCADE 2.

The results from Model 1 and Model 1A in Table 1 and results from fitting Model 2 and 2A in Table 4, and results from Model 3 and Model 3A are listed in Table 5. Each of these extended counts was added to the unsubtracted discrete count model (discrete source count fainter than subtraction limit plus a power law for subtraction residuals, discussed in Section 12) to compute the \( P(D) \) for each model. The \( P(D) \) models, convolved with Gaussian noise of 52 \( \mu \text{Jy} \)
beam$^{-1}$, are shown in Fig. 10 along with the $P(D)$ for the central region of our source-subtracted mosaic image.

Each step in the MCMC chains is another source count model; we integrated each of these models and calculated the background temperatures, using eq. (11), and plotted the temperature distributions in Fig. [11] The temperature distributions imply a mean temperature of $(10 \pm 7)$ mK. The resulting source count models are presented in Fig. [12] broken down by population and shown along with the discrete counts at 1.75 GHz.

### 8.2 Model uncertainties

We tried variations in the fitting method by first changing the fit statistic used ($\chi^2$ vs. log likelihood), which produced little change in the output; and second by trying different models. Instead of the parabola we also tried a Gaussian in $S^2 dN/dS$. The Gaussian model also produces a peak in roughly the same spot as the parabola, though the parameters were not as well constrained. All models tried resulted in best-fit parameters that yielded background temperature estimates for the extended emission in the range of $(20 \pm 10)$ mK.

We tested whether an incorrect estimate of the instrumental noise of $52 \pm 5 \mu$Jy beam$^{-1}$ could affect the results by re-fitting the models while allowing the noise to vary between 40 and $70 \mu$Jy beam$^{-1}$. This has little effect, except in the Model 3, as the faintest node is degenerate with the noise. Thus a higher noise would decrease the amplitude of the faintest node. Nevertheless, we conclude that our noise estimate cannot be underestimated enough to explain the excess $P(D)$ width.
Figure 12. $S^2$ normalized source counts at 1.75 GHz. The black lines are the same in all plots and are counts of discrete sources from the recent estimates by Vernstrom et. al [14] at 3 GHz, scaled to 1.75 GHz using $\alpha = -0.7$, while the coloured lines are the extended emission counts from model fitting. The count is broken into two populations, AGN and starbursts, based on evolutionary models, shown as the dotted and dashed lines, respectively, with the solid lines being the sum of all components. The top left panel shows Model 1 (blue lines), while the top right panel shows Model 1A (red lines). Note that the $S^2$ normalization makes it hard to see that the shifted populations have the same $\frac{dN}{ds}$ heights. The middle panels are Model 2 (left, purple lines) and Model 2A (right, green lines). The bottom panels are Model 3 (left, solid yellow line) and Model 3A (light blue solid line). The shaded regions are the 68 per cent confidence intervals.

Table 5. Best-fitting parameter results Model 3 and Model 3A.

| Parameter | Model 3 (unconstrained) | Model 3A (constrained) |
|-----------|-------------------------|------------------------|
| $\log_{10}[S]$ | $\log_{10}[\frac{dN}{ds}]$ | $\log_{10}[\frac{dN}{ds}]$ |
| $(\log_{10}[\mu Jy])$ | $(\log_{10}[\mu^{-1} Jy^{-1}])$ | $(\log_{10}[\mu^{-1} Jy^{-1}])$ |
| $-6.25$ | $15.01 \pm 1.26$ | $16.97 \pm 0.04$ |
| $-5.43$ | $13.06 \pm 0.74$ | $13.77 \pm 0.07$ |
| $-4.62$ | $11.04 \pm 0.62$ | $10.67 \pm 0.13$ |
| $-3.81$ | $8.50 \pm 0.76$ | $7.73 \pm 0.55$ |
| $-3.00$ | $6.04 \pm 0.92$ | $7.05 \pm 0.17$ |
| $T_b$ (mK) | $7.2_{-5.20}^{+14.0}$ | $159.6_{-12.6}^{+9.50}$ |
| $\sigma_c$ ($\mu Jy$ beam$^{-1}$) | $62.73$ | $78.12$ |
| $\chi^2$ ($N_{ dof} = 39$) | $75.3$ | $251.6$ |

8.3 ARCADE 2 fits

We refitted the models to explore what source counts would be necessary to yield background temperatures in the range predicted by ARCADE 2, and to assess how well those source counts fit our data. It is clear from Fig. [10] that shifting the two populations with the ARCADE 2 prior (Model 1A) is strongly inconsistent with our data. However, with Model 2A or Model 3A it is possible to obtain source count temperatures in the ARCADE 2 range and find a reasonable fit to our data. However, Fig. [12] shows that such a population would need to be extremely faint and numerous. The typical flux density of the peak of the parabola is three orders of magnitude below our instrumental and confusion noise limits. That region of the source count is nearly impossible to constrain with existing data. With Model 3A, the fitting routine makes the faintest node higher in amplitude, since changes to the counts that far below our instrumental and confusion noise limits. That population would need to be extremely faint and numerous. The typical flux density of the peak of the parabola is three orders of magnitude below our instrumental and confusion noise limits.

The two models are also difficult to interpret in terms of physical objects. Since these extended, faint, numerous objects would completely overlap on the sky, modelling them as discrete objects fails. Future work will examine whether a faint diffuse cosmic web structure could produce this emission.

We conclude that there are no source count models, to a depth of $1 \mu Jy$ and for source sizes of $2 \text{arcmin}$ or less, that are consistent with both our data and the ARCADE 2 background temperature.
Scaling our best-fitting discrete and extended source-count temperature (70 mK) to the ARCADE 2 frequency of 3.3 GHz via a spectral index of $-0.7$ gives only 13 mK, compared with the nearly 55 mK result from ARCADE 2. \cite{V14} has ruled out a new discrete population peaking brighter than 50 mJy. Combing that with our constraint on an extended population peaking above 1 mJy indicates that the ARCADE 2 result is highly unlikely to be due to extragalactic emission. Residual emission from subtraction of the Galactic component thus seems a more likely explanation for the excess seen by the ARCADE 2 experiment.

9 DISCUSSION

When unconstrained by the ARCADE results, we find Model 2 and Model 3 fit our data significantly better than Model 1 (an improved $\chi^2/\nu$). Model 3 fit our data significantly better than Model 1 (an improved $\chi^2/\nu$). When unconstrained by the ARCADE results, we find Model 2 and Model 3 fit our data significantly better than Model 1 (an improved $\chi^2/\nu$). Residual emission in clusters has only been observed in high mass clusters \cite{Riebe et al. 2013}.

The Deep Diffuse Extragalactic Radio Sky at 1.75 GHz

9.1 Sources of diffuse emission

Model 1, consisting of only shifts in the discrete counts, is considered here as an approximate representation of individual galaxy haloes. The best-fit results from this model should be considered only as upper limits for galactic haloes. This model on its own does not optimally fit the data. If there are other sources contributing to the measured $P(D)$, the fitting process would push the shifts artificially high in an attempt to make the model as consistent with the data as possible.

For any of the models, in order to be consistent with known constraints on the cosmic infrared background (CIB) the emission process(es) must not be linked directly to star formation rates. Moreover, as noted in Section 5.2, this technique can only constrain sources that are roughly 2 arcmin or smaller. Thus, these models are valid only for objects in that size range.

If we are to assume that Model 2 (middle right panel of Fig 12) represents astrophysical sources we need to determine how they compare to known objects. Making some simple assumptions, we can calculate possible luminosities and redshifts. We chose several redshifts for the peak of the parabola and calculated the $K$-corrected 1.4-GHz luminosity, assuming a spectral index of $\alpha = -0.7$. Then, assuming the objects all have the same intrinsic luminosity, we calculated the redshifts at which the counts have fallen to 50 per-cent of the peak. We did this for peak redshifts of $z = 0.25$, $0.5$, $1$, and $2$; the results are listed in Table 6.

It seems unlikely that this population could represent cluster emission from radio haloes or relics. The luminosity values for such objects given in \cite{Feretti et al. 2012} are in the range of $23 \leq \log_{10}[L_{1.4}] \leq 26$, several orders of magnitude larger than seen here. To date, we know of less than 100 clusters that host giant or mini radio haloes \cite{Feretti et al. 2012}. Extended radio emission in clusters has only been observed in high mass clusters ($\geq 10^{14} M_\odot$) at low redshift, and all with total 1.4 GHz flux densities in the 10s to 100s of mJy.

There could of course be similar objects (relics, haloes, etc.) in smaller mass groups at higher redshifts that are contributing. \cite{Nurmi et al. 2013}, using data from the SDSS survey, found that the majority of galaxies actually reside in intermediate mass groups, as opposed to large clusters. Stacking of subsamples of luminous X-ray clusters by \cite{Brown et al. 2011} found a signal of diffuse radio emission below the radio upper limits on individual clusters. It is possible that there are clusters or groups that are more “radio quiet”, below current detection thresholds.

\cite{Zandanel et al. 2014a} used a cosmological mock galaxy cluster catalogue, built from the MultiDark simulation \cite{Zandanel et al. 2014a}, to investigate radio loud and radio quiet halo populations. Their model, which assumes 10 per cent of clusters to have radio loud haloes, fits well (see figure 5 of \cite{Zandanel et al. 2014b}) with observed radio cluster data from the NVSS survey \cite{Giovannini et al. 1999}. The luminosity limit for the observed NVSS data is $\log_{10}[L_{1.4} (\text{W Hz}^{-1})] \approx 23.5$, while the simulation continues to a limit of $\log_{10}[L_{1.4} (\text{W Hz}^{-1})] \approx 20$

It is instructive to compare these simulated haloes with our ATCA data. Using the online database to access the simulation \cite{Riebe et al. 2013} used the 1.4 GHz halo simulation snapshots for $z = 0$, $0.1$, $0.5$, and $1$, scaling the luminosities slightly for each redshift snapshot to give the flux density that would be observed at 1.75 GHz. We computed a source count from these data, combined it with the unsubtracted discrete emission model and Gaussian noise to obtain a predicted $P(D)$. The source count and $P(D)$ are shown in Fig. 13. The source count from this model only adds an additional 1.5 mK to the radio background temperature.

The fit to the image $P(D)$ is not unreasonable, with this model adding only slight width to the distribution compared with the unsubtracted discrete model on its own. The source count would likely not decrease as significantly in the sub-mJy region if the simulation had data from redshifts higher than $z = 1$, and this would likely improve the fit. The $\chi^2$ is high mainly due to this model having a higher number of bright objects and thus over-predicting the tail of the distribution. However, some of these brighter haloes would be relatively nearby, hence larger on the sky and so potentially resolved out in our data (see Table 2).

The halo model has similar count amplitude to our best-fit for Model 3 around 1 mJy. This halo model then begins to fall off whereas the node model rises, this again could be due to the lack of high redshift objects. However, this shows that this type of halo model is not necessarily inconsistent with our phenomenological model. Assuming the model from \cite{Zandanel et al. 2014b} is a realistic extension of radio haloes to fainter luminosities, then it is possible for this these types of haloes to exist given our data. However, more deep observations of clusters are necessary to know if this model is accurate.

9.2 Dark matter constraints

It has been proposed that radio emission may result from models of WIMP dark matter. Dark matter particle annihilation in haloes releases energy as charged particles, which emit synchrotron radiation due to the magnetic field of the surrounding galaxy or galaxies. The predicted emission depends on the mass of the dark matter particle, and halo mass or density profile, as well as the strength of the magnetic field.

\cite{Fornengo et al. 2011} presented one dark matter model with two source count predictions, the first assuming all the halo...
substructures are resolved and the second assuming all the substructures are unresolved. The predicted source counts, shifted to 1.75 GHz, along with the discrete radio source count, are shown in the top panel of Fig. 14. Their best-fit model has a dark matter mass of 10 GeV, assuming annihilation or decay into leptons. We computed the predicted $P(D)$ for both models plus the unsubtracted discrete source contribution convolved with Gaussian noise of 52 μJy beam$^{-1}$ (black points).

Clearly these particular models are not consistent with our current radio data. Any other dark matter models would need reduced amplitude of the counts for flux densities greater than about 10 μJy. Models with the dark matter count amplitude as high as or higher than that from known radio sources for these brighter flux densities would overproduce the emission seen and are therefore ruled out. Any dark matter models consistent with our data and responsible for the ARCADE 2 emission would need to produce a large portion of the emission from the sub-μJy region, a region not constrained by our data. However, the required number counts would make such models unrelated to galactic haloes.

10 INTEGRAL COUNTS

Now that we have closed the loophole on extended emission, we can revisit source count constraints in general. It is important for future deep survey designs to have an accurate estimate of the expected number of source detections. To estimate this we can derive the integral source counts $N(> S)$, or the total number of sources with flux density greater than $S$ per unit area. Deep and accurate estimates of $N(> S)$ can provide useful information for surveys at a range of frequencies, with proper scaling; in the synchrotron-
Figure 15. Integrated source counts, or number of sources per square degree, at 1.4 GHz (top) and 1.75 GHz (bottom). The solid black lines are the discrete source count from V14, originally at 3 GHz, and scaled to 1.75 and 1.4 GHz using $\alpha = -0.7$. The green dotted lines are the discrete count plus Model 1. The red dot-dashed lines is the discrete count with the addition of Model 2. The blue dashed lines are the discrete source count with the addition of Model 3. The shaded grey areas represent 68 per cent confidence regions of the discrete count derived from V14. The upper right-hand panel shows a close up of the region marked by the solid rectangle in the upper left panel. The three points show the expected number of sources per square degree for the upcoming SKA and SKA pathfinder surveys based on their expected depths (the circle is SKA, the square is MeerKAT MIGHTEE and the all sky SKA, and the star is for the ASKAP EMU survey). The bottom panel (1.75 GHz) shows Model 1A, Model 2A, and Model 3A as orange dotted, magenta dot-dashed, and light blue dashed lines respectively (same models fit with the ARCADE 2 temperature prior).

dominated regime we should be able to extrapolate by a factor of a few in frequency.

This is of particular relevance to the Square Kilometre Array (SKA), and its pathfinders, ASKAP and MeerKAT, as well as the new planned deep VLA survey. The VLA Sky Survey (VLASS) is planning a 10 deg$^2$ to a depth of 1.5 $\mu$Jy at 1.4 GHz with a resolution of roughly 1 arcsec (Jarvis et al. 2014). The “Evolutionary Map of the Universe” (Norris et al. 2011) EMU continuum survey planned for ASKAP will survey the entire sky south of Dec $+30^\circ$ with a resolution of 10 arcsec at 1.4 GHz, and will also be sensitive to diffuse emission with a sensitivity at 1 arcmin scale similar to that reached in this paper. The deep survey with MeerKAT
and for the SKA will conduct an all-sky survey to an rms of $1$ square degrees with arcsec resolution. In the following decade, the models from the ATLAS survey, removing the discrete emission. This includes individual galaxy haloes from starburst or AGN galaxies, haloes from another population such as dwarf spheroidals (or something unknown), and possibly some contribution from clusters (or smaller mass groups) through emission structures such as radio relics and haloes.

Looking ahead to future deep surveys, we presented deep integral source counts at $1.4$ GHz from both discrete and extended emission models. These can be easily scaled to estimate deep counts at nearby frequencies.

The models used represent upper limits on the extended emission, and are valid for sources with angular size of approximately $2$ arcmin or less. Assuming the excess is truly from extended emission, rather than data artefacts, we discussed some possible sources for the extended emission. This includes individual galaxy haloes from starburst or AGN galaxies, haloes from another population such as dwarf spheroidals (or something unknown), and possibly some contribution from clusters (or smaller mass groups) through emission structures such as radio relics and haloes.

We showed an example of dark matter models from [Fornengo et al. (2011)] and found them to be inconsistent with our data. It is clear that for any WIMP dark matter model the resulting source count, for source sizes up to $2$ arcmin, must lie below the source count of current radio galaxies, at least for flux densities greater than around $10$ $\mu$Jy.

If there is a large number of faint diffuse sources causing additional radio background temperatures, as suggested by ARCADE 2, it is unlikely that the emission can be seen by current-generation telescopes. For further constraints, assuming a steep spectral index, the natural way to search for such sources would be with a similar resolution survey at a much lower frequency, e.g. $325$ or $610$ MHz. Although we have focused here entirely on the 1-point statistics (i.e. $P(D)$) a different approach would be to study the 2-point statistics of the radio sky. Measurements of the radio angular power spectrum could provide constraints on the smoothness of the radio background and statistically measure the clustering of the CRB over a range of angular scales.

ACKNOWLEDGMENTS

We acknowledge the support of the Natural Sciences and Engineering Research Council (NSERC) of Canada. The Australia Telescope Compact Array is part of the Australia Telescope National Facility which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO. The authors would like to thank Thomas Franzen and Julie Banfield for their hard work on the ATLAS data.
REFERENCES
Banfield J. K., et. al. 2014, in preparation
Briggs D. S., 1995, in American Astronomical Society Meeting Abstracts Vol. 27 of BAAS, High Fidelity Interferometric Imaging: Robust Weighting and NLDS Deconvolution. p. 112.02
Brown S., Emerick A., Rudnick L., Brunetti G., 2011, ApJ, 740, L28
Brown S. D., 2011, Journal of Astrophysics and Astronomy, 32, 577
Condon J. J., 1974, ApJ, 188, 279
Condon J. J., 1984, ApJ, 287, 461
Condon J. J., Cotton W. D., Fomalont E. B., Kellermann K. I., Miller N., Perley R. A., Scott D., Vernstrom T., Wall J. V., 2012, ApJ, 758, 23
Feretti L., Giovannini G., Govoni F., Murgia M., 2012, A&A Rev., 20, 54
Fixsen D. J., 2009, ApJ, 707, 916
Fixsen D. J., Kogut A., Levin S., Limon M., Lubin P., Mirel P., Seiffert M., Singal J., Wollack E., Villela T., Wuenhse C. A., 2009, preprint (arXiv:0901.0555)
Fixsen D. J., Kogut A., Levin S., Limon M., Lubin P., Mirel P., Seiffert M., Singal J., Wollack E., Villela T., Wuenhse C. A., 2011, ApJ, 734, 5
Fornengo N., Lineros R., Regis M., Taoso M., 2011, Physical Review Letters, 107, A261302
Fornengo N., Lineros R. A., Regis M., Taoso M., 2014, preprint (arXiv:1402.2218)
Franzen T. M. O., et al. 2014, in preparation
Giovannini G., Tordi M., Feretti L., 1999, New Astronomy, 4, 141
Hales C. A., Norris R. P., Gaensler B. M., Middelberg E., Chow K. E., Hopkins A. M., Huynh M. T., Lenc E., Mao M. Y., 2014, preprint (arXiv:1403.5307)
Hooper D., Belikov A. V., Jeltema T. E., Linden T., Profumo S., Slatyer T. R., 2012, Phys. Rev. D, 86, 103003
Hopkins A. M., Afonso J., Chan B., Cram L. E., Georgakakis A., Mobasheri B., 2003, AJ, 125, 465
Jarvis M. J., 2012, African Skies, 16, 44
Jarvis M. J., Bhatnagar S., Bruggen M., Ferrari C., Heywood I., Hardcastle M., Murphy E., Taylor R., Smirnov O., Simpson C., Smolcic V., Stil J., van der Heyden K., 2014, preprint (arXiv:1401.4018)
Lewis A., Bridle S., 2002, Phys. Rev. D, 66, 103511
Middelberg E., Norris R. P., Cornwell T. J., Voronkov M. A., Siana B. D., Boyle B. J., Ciliegi P., Jackson C. A., Huynh M. T., Berta S., Rubele S., Lonsdale C. J., Ivison R. J., Smail I., 2008, AJ, 135, 1276
Norris R. P., Afonso J., Appleton P. N., Boyle B. J., 2006, AJ, 132, 2409
Norris R. P., Hopkins A. M., Afonso J. e. a., 2011, PASA, 28, 215
Nurmi P., Heinämäki P., Sepp T., Tago E., Saar E., Gramann M., Einasto M., Tempel E., Einasto J., 2013, MNRAS, 436, 380
Oliver S., Rowan-Robinson M., Alexander D. M., Almaini O. e. a., 2000, MNRAS, 316, 749
Owen F. N., Morrison G. E., 2008, AJ, 136, 1889
Patanchon G., Ade P. A. R., Bock J. J., Chapin E. L., Devlin M. J., Dicker S. R., Griffin M., Gundersen J. O., Halpern M., Hargrave P., 2009, ApJ, 707, 1750
Planck Collaboration Ade P. A. R., Aghanim N., Alves M. I. R., Armitage-Caplan C., Arnaud M., Ashdown M., Atrio-Barandela F., Aumont J., Austel H., et al. 2013, ArXiv e-prints
Rayner D. P., Norris R. P., Sault R. J., 2000, MNRAS, 319, 484
Riebe K., Partl A. M., Enke H., Forero-Romero J., Gottlöber S., Klypin A., Lemson G., Prada F., Primack J. R., Steinmetz M., Turchaninov V., 2013, Astronomische Nachrichten, 334, 691
Sault R. J., Teuben P. J., Wright M. C. H., 1995, in Shaw R. A., Payne H. E., Hayes J. J. E., eds, Astronomical Data Analysis Software and Systems IV Vol. 77 of Astronomical Society of the Pacific Conference Series, A Retrospective View of MIRIAD. p. 433
Scheuer P. A. G., 1957, Proceedings of the Cambridge Philosophical Society, 53, 764
Seiffert M., Fixsen D. J., Kogut A., Levin S. M., Limon M., Lubin P. M., Mirel P., Singal J., Villela T., Wollack E., Wuenhse C. A., 2009, preprint (arXiv:0901.0559)
Singal J., Stawarz Ł., Lawrence A., Petrosian V., 2010, MNRAS, pp 1458–+
Subrahmanyan R., Ekers R. D., Saripalli L., Sadler E. M., 2010, MNRAS, 402, 2792
Vernstrom T., Scott D., Wall J. V., Condor J. J., Cotton W. D., Fomalont E. B., Kellermann K. I., Miller N., Perley R. A., 2014, MNRAS, 404, 2791
Wilman R. J., Miller L., Jarvis M. J., Mauch T., Levrier F., Abdalla F. B., Rawlings S., Klöckner H.-R., Obreschkow D., Oteau D., Young S., 2008, Monthly Notices of the Royal Astronomical Society, 388, 1335
Yang Y., Yang G., Huang X., Chen X., Lu T., Zong H., 2013, Phys. Rev. D, 87, 083519
Zandanel F., Pfrommer C., Prada F., 2014a, MNRAS, 438, 116
Zandanel F., Pfrommer C., Prada F., 2014b, MNRAS, 438, 124

This paper has been typeset from a PDF file prepared by the author.