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Megahertz peaked-spectrum sources in the Boötes field I -
a route towards finding high-redshift AGN?

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ABSTRACT
We present a 324.5 MHz image of the NOAO Boötes field that was made using Very
Large Array (VLA) P-band observations. The image has a resolution of 5.6 × 5.1 arcsec,
a radius of 2.05° and a central noise of ∼ 0.2 mJy beam−1. Both the resolution and
noise of the image are an order of magnitude better than what was previously avail-
able at this frequency and will serve as a valuable addition to the already extensive
multiwavelength data that are available for this field. The final source catalogue con-
tains 1370 sources and has a median 325 to 1400 MHz spectral index of -0.72. Using a
radio colour-colour diagram of the unresolved sources in our catalogue, we identify 33
megahertz peaked-spectrum (MPS) sources. Based on the turnover frequency linear
size relation for the gigahertz peaked-spectrum (GPS) and compact steep-spectrum
(CSS) sources, we expect that the MPS sources that are compact on scales of tens
of milliarcseconds should be young radio loud active galactic nuclei at high (z > 2)
redshifts. Of the 33 MPS sources, we were able to determine redshifts for 24, with an
average redshift of 1.3. Given that five of the sources are at z > 2, that the four faint
sources for which we could not find redshifts are likely at even higher redshifts and
that we could only select sources that are compact on a scale of ∼ 5 arcsec, there is
encouraging evidence that the MPS method can be used to search for high-redshift
sources.

Key words: techniques: interferometric - catalogue - galaxies: active - high-redshift
- radio continuum: galaxies

1 INTRODUCTION
The National Optical Astronomy Observatory (NOAO)
deep wide-field survey Boötes field covers ∼ 9 deg2 in the
optical and near infrared B, R, I and K bands (Jannuzi & Dey 1999). In addition, the field has also been covered in
the X-ray (Murray et al. 2005; Kenter et al. 2005), ultra-
 violet (Martin et al. 2003, mid infrared (Eisenhardt et al.
2004; Martin et al. 2003) and radio: 3.1 GHz (Croft et al.
2013), 1.4 GHz (de Vries et al. 2002; Higdon et al. 2005),
153 MHz (Williams et al. 2013; Intema et al. 2011) and at
62 MHz, 46 MHz and 34 MHz by van Weeren et al. (2014).
Furthermore, the active galactic nuclei (AGN) and Galaxy
Evolution Survey (AGES; Kochanek et al. 2012) have mea-
sured redshifts for 23,745 galaxies and AGN in the field.

This extensive multiwavelength data set have in the past
been used to study, amongst other things: the properties
of galaxy groups (Vajgel et al. 2014), the spacial clustering
of quasars (Hickox et al. 2011), search for radio transients
(Bower et al. 2011), study the start formation rate in optical
obsured galaxies (Calanog et al. 2013) and study the com-
position of gas and dust in AGN (Usman et al. 2012). The
325 MHz observations of the field presented here will serve
as a valuable addition to the multiwavelength coverage of
the field and will, as shown in this paper, be used to study
these topics and more.

Supermassive black holes, which drive AGN, are be-
lieved to lie at the center of nearly every galaxy. They not
only grow with their host galaxy, but also shape and influ-
ence the galaxy and inter-galactic medium via feedback from
their relativistic jets. So, to understand galaxies and their
evolution we need to understand AGN evolution (eg. Fabian

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A critical key to this is identifying both young AGN and AGN at high-redshifts, something that is currently a great observational challenge.

While AGN have been found in optical surveys out to $z = 7.1$ (Mortlock et al. 2011), Ly-alpha absorption makes detecting them at $z > 6.5$ very difficult (Mortlock et al. 2011). On the one hand, the most powerful AGN in the radio, such as Cygnus A, are expected to have observed 1 GHz flux densities in the order of 15 mJy at $z = 8$, well within the capabilities of modern radio telescopes. Hence, not only should these sources be detectable in the radio, but radio also has the advantage that it is not obscured by dust which can hide sources at all redshifts from optical identification.

While large-scale radio surveys such as the Very Large Array (VLA) Faint Images of the Radio Sky at Twenty-Centimeters (FIRST) survey (White et al. 1997) can detect these sources, a method needs to be found to identify them based purely on their radio properties. Based on an observed correlation between redshift and spectral index (e.g. De Breuck et al. 2000), searches for high-redshift radio galaxies tend to focus on sources with ultra-steep spectral indices. While this method has proven successful in finding sources out to $z \sim 4$ (e.g. Jarvis et al. 2001; Cruz et al. 2006; De Breuck et al. 2006; Singh et al. 2014) found median redshifts of only $\sim 1.18$ and $\sim 1.57$ for their two selections of faint ultra-steep-spectrum (USS) sources, which is only slightly higher than the median redshifts of $\sim 0.99$ and $\sim 0.96$ for the non-USS sources in their samples. Moreover, the physical reason for why USS sources should be at higher redshifts than non-USS sources remains unclear (Miley & De Breuck 2008) and indeed recent deep observations of the Cosmological Evolution Survey (COSMOS) field with the VLA found no clear evidence that sources at higher redshift have steeper spectral indices (Smolčić et al. 2014). Finally, in a recent study using nine samples of radio sources, Ker et al. (2012) found that the fraction of $z > 2$ sources is not significantly higher in the sub-sample of USS sources compared to the full sample. Hence, finding a method with which high-redshift AGN can reliably be selected from radio images (the focus of this paper) is very important as it would allow us to search for them in existing large radio surveys such as FIRST, current and future LOFAR (Low-Frequency Array; van Haarlem et al. 2013) surveys such as the Multi-frequency Snapshot Sky Survey (MSSS) and in the future, the Square Kilometer Array (SKA), which might be able to detect these sources beyond redshift ten (Falcke et al. 2001).

High-frequency peaked (HFP), Gigahertz peaked-spectrum (GPS) and compact steep-spectrum (CSS) sources are thought to be the youngest and smallest AGN (O'Dea 1998; Murgia et al. 2002; Conway 2002). These sources are characterized by their peaked spectra and steep spectral indices ($\alpha$; where $\alpha$ is defined as $S \sim \nu^{-\alpha}$ with $S$ the spectral flux density at frequency $\nu$) above the spectral turnover. The HFP and GPS sources have rest-frame turnover frequencies above 1 GHz and linear (lobe to lobe) sizes smaller than $\sim 1$ kpc while the CSS sources typically turn over below 500 MHz and range in size from 1 kpc to 20 kpc. An evolutionary sequence is believed to exist from the HFP to the GPS sources and finally to the CSS sources (O'Dea 1998; Snellen et al. 2000; Tschager et al. 2003). Furthermore, it is likely that the CSS sources will evolve to eventually become the large FR I and FR II radio galaxies (Begelman 1996; Snellen et al. 2000; de Vries et al. 2002).

An empirical relation was found between the rest-frame turnover frequency $\nu_o$ and the linear size of nearby ($z \sim 1$) GPS and CSS source over three orders of magnitude (O'Dea 1998; Snellen et al. 2000). From the observed turnover frequency $\nu_o$, we can therefore estimate the linear size of a source by taking into account that $\nu_o = \nu_o(1+z)$, where $z$ is the redshift of the source. Using this, we can predict the source’s observed angular size, noting that in conventional cosmology ($\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$), a fixed-ruler will appear to first decrease in angular size moving from $z = 0$ to $z \sim 1$ before appearing to increase again beyond $z \sim 1$. We therefore expect a typical GPS source of 100 pc, with corresponding rest-frame turnover frequency of 2.7 GHz, to appear as a 25 mas source at $z = 10$ with an unusually low observed turnover frequency of 245 MHz. From these arguments, Falcke et al. (2004) proposed an, as of yet, untested method to find high-redshift AGN by searching for compact (on scales of tens of milliarcseconds) megahertz peaked-spectrum (MPS; turnover frequency below 1 GHz) sources.

It should be pointed out that, while our aim is to use the MPS method to search for high-redshift ($z > 2$) AGN, we expect that the method will also find young AGN at lower redshifts. For example, sources with a rest-frame turnover frequency of 1 GHz and corresponding size of 470 pc will have an observed turnover frequency of 325 MHz and angular size of 60 mas at $z = 2.1$. While this means that we do not expect all the MPS sources that are compact on a few hundred milliarcseconds to be at high redshifts, the sources that are not at high redshifts are still young AGN and are interesting in their own right since they help us understand how the AGN population evolves with redshift.

In this paper, we publish a 325 MHz source catalogue of the Boötes field that is at least an order of magnitude better in terms of both resolution and noise (see Table 2) than what was previously available for this field with the Westerbork Northern Sky Survey (WENSS; Rengelink et al. 1997). We also take the first steps towards using the MPS method to search for high-redshift AGN by identifying 33 MPS sources in the image and looking at their redshift distribution.

In Section 2, we describe the data reduction and imaging before describing source extraction, image quality and catalogue construction in Section 3. The spectral properties of the sources, selecting and discussing the MPS sources and the affect of selecting USS sources in different frequency ranges on the selected sample of USS sources is presented in Section 4. Finally, in Section 5, we summarize our results and discuss future work.

2 OBSERVATIONS AND DATA REDUCTION

The archival data set (project code AB0976) of the Boötes field was taken with the VLA on 22 November 2000, 12 December 2000, 2 January 2001 and 4 January 2001 and is summarized in Table 1. The observations were taken in
the P-band with the VLA in A configuration, using 27 antennae on every day except 4 January 2001 when only 26 antennae were available. The observations covered a single pointing in the Boötes field centered at RA 14:32:05.72 and DEC +34:16:47.5 using 3.3 s integrations with a total integration time on the field of 20 hours spread over the four days. The data were taken in spectral line mode with two intermediate frequencies (IFs) at 327.53 MHz and 321.53 MHz each with two polarizations (LL and RR). We will take the average frequency of 324.525 MHz of the two IFs as the representative frequency. Each IF was split into 16 channels of 394 KHz each, giving a bandwidth of 6.3 MHz per IF and total bandwidth of 12.6 MHz. Observations of the calibrator source 3C286, used for phase, amplitude and bandpass calibration, were irregularly interleaved between those of the source 3C286, used for phase, amplitude and bandpass calibration, were irregularly interleaved between those of the target field. Typically, 3C286 was observed for 2.5 minutes every 25 minutes.

The initial data reduction was done using the AIPS (Greisen 1990) software package. Data were flagged using both the automatic flagging task RFLAG and the manual flagging task TVFLG before and after calibration. After calibration, the calibrated data were imported into CASA for self-calibration, imaging and primary beam correction. Five rounds of phase only self-calibration were done, in which the solution interval was decreased from 20 to 1 min. During each round, a clean component model of the brightest sources in the field was derived from the previous best image and used as an input model. The final image of the field (the inner 1.2° of which is shown in Fig. 1) was made using 1.5 arcsec pixels, Brigg’s weighting with a robustness parameter of 0.0 and 128 w-projection planes. While the VLA P-band primary beam has a full-width half-maximum (FWHM) of 2.5°, the final image produced using CASA’s clean task was made with a diameter of 4.1° to increase the number of sources in the image. The image has a resolution of 5.6 × 5.1 arcsec and central noise of ∼ 0.2 mJy beam \(^{-1}\) increasing to ∼ 0.8 mJy beam \(^{-1}\) at the edge of the image after the flux correction has been applied (see Section 3.3).

### 3 IMAGE QUALITY AND CATALOGUE CONSTRUCTION

#### 3.1 Source Extraction

Source extraction was done using the PYBDSM source detection package\(^2\) PYBDSM works by identifying all pixels in the image that are above the pixel detection threshold and adding all of the surrounding pixels that are above the island detection threshold together to form islands of emission. Multiple Gaussians are then fitted to each island before grouping the Gaussians together into individual sources. We used the default values of three and five times the the local root mean square (rms) noise for the island and pixel thresholds respectively, where the local rms noise was calculated in a sliding box of 50 × 50 pixels that was moved across the image in steps of ten pixels.

For each source, the flux density reported is the sum of the flux densities of the Gaussians in the source, the flux density errors are the 1σ statistical errors calculated using the formula in Condon (1997). To determine the spectral properties of the sources and check the flux density scale of our image (hereafter referred to as the VLA-P image), all of the sources were matched to the 1.4 GHz FIRST, 1.4 GHz National Radio Astronomy Observatory (NRAO) VLA Sky Survey (NVSS; Condon et al. 1998), 1.38 GHz (de Vries et al. 2002, hereafter referred to as the deVries catalogue), 325 MHz WENSS and 153 MHz (Williams et al. 2013, hereafter referred to as the Williams catalogue) catalogues. A summary of the catalogues (including the VLA-P catalogue for comparison) is given in Table 2. Matching was done with the STILTS (Taylor 2006) software package using the task TSKYMATCH2. Using the central position of each source in the VLA-P catalogue and a search radius of half the FWHM of the catalogue with the lowest resolution, TSKYMATCH2 returned all sources in the matched catalogue separated by less than the search radius from the input sources.

Since our aim is to search for high-redshift AGN, which are expected to have linear sizes of at most a few hundred milliarcseconds, we matched the VLA-P sources to the catalogue with the highest resolution at each frequency. However, while FIRST has the highest resolution at 1.4 GHz, 562 sources could not be matched to a FIRST source because they were too faint to be detected in FIRST due to their steep spectral indices. Consequently, the VLA-P sources were also matched to the deVries catalogue, which, while having a lower resolution than FIRST (see Table 2), also has a significantly lower rms noise. Hence, 417 sources that could not be matched to a FIRST source could be matched to a source in the deVries catalogue.

In order to exclude confused sources and sources that are resolved in one of the catalogues, only one-to-one matches were accepted. In other words, if a source in the VLA-P catalogue was matched to two or more sources in another catalogue, or vice versa, the matches were rejected.

To exclude resolved sources, VLA-P sources with a major or minor axis greater than 10 arcsec were excluded from all further analysis. While the beam size in the VLA-P image is ∼ 6 arcsec, a value of 10 arcsec was used to accommodate the errors on the fitted major and minor axes of the

<table>
<thead>
<tr>
<th>Date</th>
<th>Start Time [UTC]</th>
<th>End Time [UTC]</th>
<th>TOS (^a) Boötes</th>
<th>TOS (^a) 3C286</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 Nov. 2000</td>
<td>12:06:59</td>
<td>20:02:56</td>
<td>255</td>
<td>42</td>
</tr>
<tr>
<td>12 Dec. 2000</td>
<td>12:17:30</td>
<td>20:14:00</td>
<td>280</td>
<td>34</td>
</tr>
</tbody>
</table>

Notes: \(^a\) The time on source (TOS).

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\(^2\) \url{http://casa.nrao.edu}

\(^3\) \url{http://dl.dropboxusercontent.com/u/1948170/html/index.html}
Figure 1. Inner 1.2° of the VLA-P image. The full image has a radius of 2.05°, a resolution of 5.6 × 5.1 arcsec and central noise of ∼ 0.2 mJy beam⁻¹.

Table 2. Catalogues matched to the VLA-P catalogue.

<table>
<thead>
<tr>
<th>Catalogue Name</th>
<th>Frequency [MHz]</th>
<th>Resolution [&quot;]</th>
<th>rms Noise ² [mJy beam⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIRST</td>
<td>1400</td>
<td>5.4 × 5.4</td>
<td>0.15</td>
</tr>
<tr>
<td>NVSS</td>
<td>1400</td>
<td>45 × 45</td>
<td>0.45</td>
</tr>
<tr>
<td>deVries</td>
<td>1380</td>
<td>13 × 27</td>
<td>0.03</td>
</tr>
<tr>
<td>VLA-P</td>
<td>325</td>
<td>5.6 × 5.1</td>
<td>0.2*</td>
</tr>
<tr>
<td>WENSS</td>
<td>325</td>
<td>54 × 54</td>
<td>3.6</td>
</tr>
<tr>
<td>Williams</td>
<td>153</td>
<td>25 × 25</td>
<td>2.0*</td>
</tr>
</tbody>
</table>

Notes: ² The values quoted are the typical catalogue noise except for the two marked with a ’*’, which are the noise at the center of the image.

3.3 Flux Density Scale

Since the central frequencies of both the VLA P-band and WENSS catalogues are 325 MHz, we matched the two catalogues so that we could check the absolute flux density scale and the primary beam correction. When doing this, only single isolated non-extended sources were used. Additionally, sources with a signal-to-noise ratio (SNR; defined as the peak flux density divided by the island rms) below ten
in either the VLA-P or WENSS catalogue were excluded from the analysis.

To check the flux density scale, the flux density ratio of the VLA-P with WENSS \( \frac{S_{\text{VLA-P}}}{S_{\text{WENSS}}} \) was plotted for each pair of matched sources as a function of the source SNR and the angle of the source with respect to the phase center in order to check for a potential irregular beam shape. In addition, the VLA-P flux density was also plotted as a function of the WENSS flux density for each pair of matched source. No trends were visible in any of these plots. Finally, the flux density was corrected using their distance from the phase center.

To correct for this offset, an exponential function of the form

\[
\frac{S_{\text{VLA-P}}}{S_{\text{WENSS}}} = k_1 + k_2 e^{k_3 r}
\]

was fitted to the data using a non-linear least squares fitting routine (shown as the solid line in Fig. 2), where each point was weighted by its error. In the function, \( k_1, k_2 \) and \( k_3 \) are constants with best-fit values of 1.00±0.03, 0.005±0.002 and 2.93 ± 0.19 respectively and \( r \) is the distance of the source from the phase center in degrees. The fitted function has a reduced chi-squared of 1.34, a value of 1.003 at \( r = 0^\circ \) and 1.22 at \( r = 1.25^\circ \), the FWHM of the VLA primary beam, increasing to 3.72 at the edge of the image. This shows that the flux density offset was only a significant problem outside the primary beam. Using Equation (1) and the condition

\[
\frac{S_{\text{corrected VLA-P}}}{S_{\text{WENSS}}} = k_1,
\]

all of the flux densities, flux density errors and rms values, were corrected using their distance from the phase center and the errors of the fitted parameters.

Fig. 3 shows a plot of the corrected VLA-P flux density as a function of the WENSS flux density for the sources used to check the flux density scale. As can be seen, the VLA-P flux densities agree well with those of WENSS. Since the mean of the corrected flux density ratios is 1.05, we conclude that no systematic offset between the VLA-P and WENSS flux densities remained after the flux density correction.

3.4 Catalogue Construction

A sample of the final catalogue is given in Table 3, the full catalogue containing 1370 sources is available from the CDS\(^4\). In the catalogue, the flux densities, peak flux densities and rms values have been corrected as described in Section 3.3. The columns in the table are: (1) Source name, (2,3) right ascension (RA) and uncertainty, (4,5) declination (DEC) and uncertainty, (6) integrated 342.5 MHz flux density and uncertainty, (7) peak 342.5 MHz intensity and uncertainty, (8,9) deconvolved major- and minor-axis, (10) position angle, (11) local rms noise, (12) number of Gaussians out of which the source is composed. In all cases, values that could not be calculated are indicated as ‘–‘. For sources composed of more than one Gaussian, the individual Gaussians are named alphabetically and given below the source.

4 RESULTS AND DISCUSSION

4.1 Spectral Properties

Two spectral indices, \( \alpha_{\text{low}} \) and \( \alpha_{\text{high}} \), were calculated for each source. The low frequency spectral index, \( \alpha_{\text{low}} \), was calculated between the Williams (153 MHz) and VLA-P (325 MHz) catalogues. The high frequency spectral index,
\( \alpha_{\text{high}} \), was calculated between the VLA-P (325 MHz) and FIRST (1400 MHz) catalogues unless the source could not be matched to a source in FIRST (for the reason explained in Section 3.2) but could be matched to a source in the deVries catalogue. In that case \( \alpha_{\text{high}} \) was calculated between the flux densities of the VLA-P (325 MHz) and deVries (1380 MHz) catalogues.

The \( \alpha_{\text{high}} \) values calculated using FIRST were found to have a median value of -0.72 and interquartile range from -0.91 to -0.52. These values are consistent with those found by Smolčič et al. (2014) and Owen et al. (2009) who made VLA-P-band images of the VLA COSMOS and Spitzer Wide-area InfraRed Extragalactic Survey (SWIRE) fields with similar sensitivity and resolutions as our image. This serves to further confirm our flux density scale. The median value and interquartile range for \( \alpha_{\text{low}} \) was found to be -0.56 and from -0.83 to -0.30. Considering that \( \alpha_{\text{high}} \) and \( \alpha_{\text{low}} \) have mean values of -0.685 ± 0.007 and -0.505 ± 0.033 respectively, it is clear that the spectral index flattens towards lower frequencies, as was reported by among others Williams et al. (2013) and van Weeren et al. (2014). This is possibly the result of spectral aging which results in the sources having a steeper spectrum a higher frequencies.

### 4.2 MPS Sources

To select the MPS sources, a colour-colour diagram (Fig. 4) was made by plotting \( \alpha_{\text{high}} \) against \( \alpha_{\text{low}} \) for the 198 sources which could be matched to both the Williams and either the FIRST or the deVries catalogues. In the figure, the sources in the bottom left and top right quadrants have, respectively, negative and positive spectral indices across the entire frequency range from 153 MHz to 1.4 GHz and contain 85 and 3 percent of the sources respectively. The remaining 12 percent of the sources lie in the bottom right and have convex (peaked) spectra. In order avoid confusion, error bars are not shown in the figure. As a guide it is noted that the median errors on the points are 0.1 and 0.43 for \( \alpha_{\text{high}} \) and \( \alpha_{\text{low}} \) respectively. It should be noted that from the size of the median errors, it is clear that the higher errors on \( \alpha_{\text{low}} \) are caused by higher flux density errors in the Williams catalogue compared to those in FIRST.

Since the MPS sources have a spectral peak below 1 GHz, we selected these sources to have \( \alpha_{\text{high}} < -0.5 \) and \( \alpha_{\text{high}} < 1.5 \alpha_{\text{low}} - 0.5 \) (the region below and to the right of the dotted line in Fig. 4). The selection criteria for \( \alpha_{\text{low}} \) was used in order to not only select the sources with a clear spectral peak, but also select the sources that flatten towards lower frequencies, which could be indicative of a turnover frequency below 153 MHz. While the selection criteria \( \alpha_{\text{high}} < 1.5 \alpha_{\text{low}} - 0.5 \) is somewhat arbitrary, it does ensure that \( \alpha_{\text{high}} \) is at least one and a half times \( \alpha_{\text{low}} \) for the sources that show a flattening in their spectra. In addition, this also removes the effect of the spectral index flattening towards lower frequencies (see Section 4.1) from the selection. In total, 33 MPS sources were selected and presented in Table 4. We note that when fitting Gaussians to the sources, pybdsm fit a single Gaussian to each of the 33 MPS sources. In the table, the columns correspond in name to the columns in Table 4 except for the following columns: (8) low frequency spectral index, (9) high frequency spectral index, (10) redshift calculated using the EAZY code, (11) redshift calculated using the LTR code (a description of how columns 10 and 11 were calculated are given below). While the low frequency spectral index was calculated between 153 MHz and 325 MHz, the high frequency spectral index was calculated between 325 MHz and 1400 MHz unless the value is marked with a ‘*’ in which case it was calculated between 325 MHz and 1380 MHz. Of the 33 sources in Table 4, 18 have spectra that flatten (\( \alpha_{\text{low}} \leq 0 \)) while the remaining 15 sources have peaked spectra. Due to the errors on the spectral indices, only two of the 15 sources might unambiguously be consistent with a peaked spectrum.

Photometric redshifts (\( z_{\text{phot}} \)) were determined for the MPS sources by identifying candidate counterparts in the NOAO Deep Wide-Field Survey (NDWFS; Jannuzi & Dey 1999) I-band images using either the FIRST position or, if the source could not be matched to a FIRST source, the VLA-P position. We then matched the I-band sources to, and extracted flux density measurements from, the point spread function matched photometric catalogues (Brown et al. 2007) which comprise fluxes from the following surveys: NDWFS (B, W, R, I and K bands), the Flamingos Extragalactic Survey (FLAMEX, J and Ks bands; Elston et al. 2006), the zBootes survey (z' band; Cool 2007), the Spitzer Deep Wide Field Survey (SDWFS, 3.6, 4.5, 5.8 and 8.0 micron images; Ashby et al. 2009), the Galaxy Evolution Explorer GR5 survey (GALEX, near- and far-ultraviolet bands; Morrissey et al. 2007) and the MIPS AGN and Galaxy Evolution Survey (MAGES, 24 micron images; Jannuzi et al. 2007).
Figure 4. Colour-colour diagram for sources with a one-to-one match to the Williams and either the FIRST or the deVries catalogues. In the plot, $\alpha_{\text{low}}$ was calculated between 153 MHz and 325 MHz while, $\alpha_{\text{high}}$ was calculated between 342.5 MHz and 1400 MHz for the sources marked as filled circles and between 342.5 MHz and 1380 MHz for sources marked as crosses. The dashed lines indicate spectral indices of zero and the MPS sources were selected from the region below and to the right of the dotted line. While error bars are not shown to avoid confusion, the median error bar size is illustrated at the bottom right of the figure.

Finally, the resulting spectral energy distribution (SED) was fitted for $z_{\text{phot}}$ using the LRT code from Assef et al. (2008) and EAZY code (Brammer et al. 2008) for comparison. A more detailed description of the matching and SED fitting of the sources in the field will be given in Williams et al. (in preparation).

In total, we were able to determine redshifts (given in Table 4) for 24 of the 33 sources. Of the nine sources without redshifts, five lie outside the multiwavelength coverage while the remaining four were too faint to be matched. Except for the two confused sources J143359+340421 and J143542+341321, each of which have two optical matches, and J142917+332626, the values output by the LRT and EAZY codes agree well with each other and range between 0.14 and 3.16. While the LRT code, which includes an empirical AGN SED template in the fitting and therefore fits AGN spectra better, gives a mean and median redshift of 1.3 and 1.0 respectively, the mean and median redshift output by the EAZY code is 1.4 and 1.1. On average, both the LRT and EAZY codes agree that the redshift of the flattening sources are 0.1 units higher than the peaked sources. Similarly, the median redshift of the flattening sources are 0.4 units higher than that of the peaked sources for the EAZY code, and 0.3 units higher for the LRT code. While the median redshift error of the EAZY code is 0.1 units for both the flattening and peaked sources, and could therefore explain the difference between the average redshifts, this does add weight to the argument that the flattening sources could peak towards lower frequencies and could therefore be at higher redshifts than the peaked sources.

Since our current selection allows sources with an observed turnover frequency of $\sim 325$ MHz to be selected, and these sources are expected to have a linear and angular size of $\sim 2.3$ kpc and $\sim 1.3$ arcsec respectively at $z = 0.1$, it is not surprising that our selection contains sources at low ($z < 1$) redshifts. It should however be pointed out that these sources are classic CSS sources and hence likely to be young AGN (O’Dea 1998; Murgia et al. 2002). Our expectation is that the high-redshift sources should all be compact on scales of tens of milliarcseconds, which is something that
we will test in our upcoming paper Coppejans et al. (in preparation), and appear as quasars at optical wavelengths (O’Dea 1998, 1999). What is encouraging is that both codes agree that five of the sources for which we have redshifts are at $z > 2$. Furthermore, given the correlation between optical magnitude and redshift for the host galaxies of sources with radio jets (O’Dea 1998, Rocca-Volmerange et al. 2004, Miley & De Breuck 2008), we expect that the four sources for which we could not find redshifts because they are too faint to be matched are likely at higher redshifts than the sources with known redshifts.

### 4.3 USS Sources

USS source have been selected using different spectral cuts and frequency ranges e.g., $\alpha_{\text{408 MHz}} < -1.1$ (Wieringa & Katgert 1992), $\alpha_{\text{151 MHz}} < -0.981$ (Blundell et al. 1998), $\alpha_{\text{141 MHz}} < -1.3$ (De Breuck et al. 2004), $\alpha_{\text{141 MHz}} < -1.0$ (Cruz et al. 2006), $\alpha_{\text{25 MHz}} < -1.0$ (Broderick et al. 2007) and $\alpha_{\text{25 MHz}} < -1.0$ (Singh et al. 2014). Defining USS sources as those with a spectral index steeper than -1.3, we find that only 4.2 percent of the sources for which $\alpha_{\text{high}}$ could be calculated can be classified as USS sources. Similarly, 4.9 percent of the sources for which $\alpha_{\text{low}}$ could be calculated can be classified as USS sources. This is once again consistent with both Smolčič et al. (2014) and Owen et al. (2009) who do not find a large population of USS sources in their samples.

Looking only at the sources in the colour-colour diagram (for which both $\alpha_{\text{high}}$ and $\alpha_{\text{low}}$ are available), we find that eight sources can be classified as USS based on their value for $\alpha_{\text{high}}$ and another seven based on their value of $\alpha_{\text{low}}$.
\( \alpha_{\text{low}} \). What is interesting is that only three sources have both \( \alpha_{\text{high}} \) and \( \alpha_{\text{low}} \) smaller than -1.3 and will appear in both selections. Hence, if we make two selections of USS sources, one based on \( \alpha_{\text{high}} \) and the other based on \( \alpha_{\text{low}} \), and take into account the error bars on the spectral indices, only 25\(^{\circ}\)\(2\) per cent of the sources in the combined selection appear in both of the individual selections. Changing the selection criteria for USS sources from a spectrum steeper than \(-1.3\) to a spectrum steeper than \(-1.0\), changes the number to selection criteria for USS sources from a spectrum steeper than \(-1.0\), appear in both of the individual selections. Changing the selection criteria for USS sources from a spectrum steeper than \(-1.3\) to a spectrum steeper than \(-1.0\), changes the number to 25\(^{\circ}\)\(2\) per cent. To check if these low values are because \( \alpha_{\text{low}} \) is on average 0.2 units higher than \( \alpha_{\text{high}} \) (see Section 4.1), we made new selections use a cut that is 0.2 units higher for \( \alpha_{\text{low}} \) than that of \( \alpha_{\text{high}} \). For both cases, the percentage of sources that appear in both selections were between two and five per cent lower than the values given above, indicating that the low percentages are not caused by spectral flattening at low frequencies. Hence, in our case, even when using the same spectral cut, selecting USS sources in different frequency ranges does not select the same group of sources and care should be taken when comparing different selections of USS sources.

5 SUMMARY AND FUTURE PROSPECTS

In this paper, we presented a 325 MHz VLA image of the NOAO Boötes field. Both the resolution and the noise of image are an order of magnitude better than what was previously available for the field at this frequency. Matching our sources to the FIRST, de Vries et al. (2002) and Williams et al. (2013) catalogues of the field we calculated spectral indices for the sources between 153 MHz and 325 MHz and between 325 MHz and 1.4 GHz. We then used the spectral indices to make a radio colour-colour diagram of the unconfused point sources.

In Section 4 we described an untested method of finding young and high-redshift AGN by selecting sources with a peaked spectrum in the megahertz frequency range, the megahertz peaked-spectrum (MPS) sources. Using our colour-colour diagram, we identified 33 MPS sources of which 15 have peaked and 18 have flattening spectra. Of the 33 MPS sources, we were able to determine redshift values for 24 ranging between 0.1 and 3.2. Considering that five of the sources are at \( z > 2 \), that we expect the sources that are compact on scales of tens of milliarcseconds to be at the highest redshifts while we could only select sources that are compact on a scale of \( \sim 5 \) arcsec and that the four sources which were too faint to be matched are likely at \( z > 3 \), there is encouraging evidence that the MPS method can be used to search for high-redshift sources. In the second paper in this series, Coppejans et al. (in preparation), we will take the next step in testing the MPS method by presenting observations of the sources with the European Very-long-baseline interferometry Network (EVN) to determine their angular sizes and combine that with our redshift estimates to test whether the sources at higher redshifts are compact on scales of tens of milliarcseconds as we expect.

At the moment, the greatest challenge to finding MPS sources is the lack of high resolution (\(< 10 \) arcsec) low noise (<1 mJy beam\(^{-1}\)) radio maps below 1 GHz. Since LOFAR will be able to make such maps in the near future and covers the frequency range between 30 and 240 MHz, it will be ideal for searching for MPS sources. As pointed out in Section 4.2 the large errors on the low frequency spectral indices are the result of large flux density errors in the 153 MHz Williams catalogue that was made using observations by the Giant Metrewave Radio Telescope (GMRT). Since it is expected that LOFAR will produce images with lower noise and higher resolution than what can be achieved with the GMRT at these frequencies, it will significantly improve the reliability with which MPS sources can be selected.

Finally, in Section 4.3 we found that selecting USS sources in different frequency ranges using the same spectral cut does not select the same group of sources and care should be taken when comparing different selections of USS sources.

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