Into the depths: the radio hunt for the youngest and most distant AGN

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The present can only be understood in light of the past. The local Universe – galaxies, stars, black holes, active galactic nuclei (AGN), the intergalactic and interstellar medium etc. – as we see it today has been evolving for about 13.8 billion years. The only way to therefore understand the local Universe is by understanding how it has evolved over the last 13.8 billion years. This task is both made easier and harder by the speed of light being finite. As a result of this, the further away an object is from us the longer it will take for its light to reach us, and the older the light will be when it reaches us. This means that when we look at the Universe, we are looking back in time. The good thing about this is that it allows us to see how the Universe looked at different times, allowing us to study how and why it evolved. The problem is that when imaging the sky at any frequency, there are both nearby and very distant sources in the images. We therefore need to find ways to distinguish between them. In this thesis I investigate ways to find the most distant sources in radio images. A by-product of the megahertz peaked-spectrum (MPS) method of finding distant sources (a description of the method is given in Section 1.2) is that it not only finds very distant sources but also finds sources that are likely young at all ages of the universe. While these sources might not be the most distant sources in the Universe, they are still extremely important as they help us to understand how sources at a given age of the universe evolve.

The remainder of this chapter is structured as follow: in Section 1.1 I will explain what an AGN is and discuss the aspects of AGN that are relevant to this thesis. Additional reasons why distant sources are important and the methods that are used to identify them in radio data are discussed in Section 1.2. Finally, in Section 1.3 a brief guide to the thesis is presented.

Before continuing with the discussion of what an AGN is, I will first introduce the concept of redshift as it is needed in the following discussion. In astronomy, cosmological distances are measured in redshift, with redshift zero being the present day. Because the Universe is expanding, for a source at redshift $z$, radiation that is emitted at a rest frame frequency of $\nu_r$ will be redshifted to an observed frequency of $\nu_o$, where $\nu_r = (1 + z)\nu_o$. For a source at redshift one, or $z = 1$, the light was emitted when the Universe was approximately 43% of its current age. In Chapters 2 and 3 I will look at sources that are at $z \lesssim 3$, when the Universe was older than about 16% of its current age, before discussing sources that are between redshift 4.5 and 6.2 in Chapters 4 and 5, when the Universe was between $\sim 7$ and $\sim 10\%$ of its current age.
1.1 Active galactic nuclei

As mentioned already, the aim of this section is to discuss the aspects of AGN that are relevant to this thesis. For a detailed review of AGN readers are referred to Alloin [2006] and Beckmann & Shrader [2012]. AGN are powered by the accretion of material from accretion disks onto supermassive black holes (SMBHs) at the centers of galaxies. Since it is believed that there is a SMBH at the center of every galaxy [Magorrian et al., 1998; Kormendy & Ho, 2013], every galaxy has the potential to host an AGN. During accretion, a fraction of the material can be ejected into two collimated outflows, or jets, perpendicular to the accretion disk. AGN are extremely luminous at all wavelengths, and their jets often grow to be significantly larger than their host galaxy. As the material in the jet moves outward, it runs into slower moving material in the jet itself, the interstellar medium and, eventually, the intergalactic medium. This shocks and heats the gas, forming hotspots along the jet axis and lobes at the ends of the jets. An example radio image of the AGN Cygnus A is shown in Fig. 1.1. In the image, the core (which contains the accretion disk and SMBH), jets, hotspots and lobes of the AGN are labeled. The interaction of the jet with the interstellar and intergalactic medium can, for example, quench or trigger star formation in the galaxy [e.g. Best et al., 2005; Miley & De Breuck, 2008]. This process whereby the AGN influences its host galaxy, is known as feedback [e.g. Fabian, 2012; Morganti et al., 2013].

In the literature, AGN are grouped into a large number of different classes (see for example [Urry & Padovani, 1995; Netzer, 2015]). The classification of a specific AGN often depends on the wavelength at which it is observed and the orientation of its jet with respect to our line of sight. The radio classifications of AGN that are relevant for this thesis are discussed later in this section and in the following chapters. Across all wavelengths AGN are divided into two main classes: blazars and off-axis sources. The difference between these two classes is in terms of their orientation with respect to the observer. In blazars, the jet axis lies within a small angle of the
observers (our) line of sight. Consequently, as the emission from one of the jets is directed towards
the observer and the material in the jet moves at relativistic speeds, the jet pointing towards the
observer appears very bright because of Doppler boosting. In contrast the emission from the jet
pointing away from the observer is decreased by Doppler de-boosting. In off-axis sources, the
jet axis is not pointed towards the observer. In these sources we are therefore, to some degree,
observing the jet edge on.

1.1.1 The radio spectra of AGN

In my thesis I investigate ways to find the youngest and most distant AGN using their sizes and
radio spectra. In this section I therefore review the radio spectra of AGN. AGN emit at radio
frequencies via synchrotron emission from relativistic electrons spiraling around magnetic fields.
Assuming a constant magnetic field and a power law distribution of electron energies, optically
thin synchrotron emission in AGN has a typical spectral index ($\alpha$; defined as $S \propto \nu^\alpha$, where $S$

is the flux density at frequency $\nu$) around -0.7. This results in the flux density increasing towards
lower observing frequencies. However, the flux density can not continue to increase indefinitely.
At lower frequencies, the jet and lobes will become optically thick and the spectrum will turn over
with the flux density decreasing towards lower frequencies. This turnover is caused by synchrotron
self-absorption, in which the synchrotron photons are re-absorbed by the electrons that emitted
them before they can escape from the area of emission. It is worth noting that while the turnover
is primarily caused by synchrotron self-absorption, evidence exists that in at least some sources
free-free absorption outside the area of emission (jets) also contributes [e.g. Orienti, 2016, and
references therein]. An example spectrum of the source J0906+6930, which is discussed in detail
in Section 5.4.3.2, is shown in Fig. 1.2. In the figure the optically thin, optically thick and turnover
regions of the spectrum are clearly visible on the right, left and center, respectively.

There are two classes of radio AGN that have flat radio spectra ($-0.5 < \alpha < 0.5$): blazars
and the compact (unresolved) cores of AGN in which the lobes have been resolved out by the
observations. Blazars are known to be extremely variable in the radio on time scales from days to
years and have flat time averaged spectra [e.g. Ciaramella et al., 2004; Worsley et al., 2006]. The
compact cores of AGN, have flat spectra at MHz and GHz frequencies [e.g. Massaro et al., 2013b].
While this could be caused by a flat distribution of electron energies, it is usually attributed to
multiple compact regions of emission in the unresolved core [e.g. Blandford & Königl, 1979; Falcke
& Biermann, 1995; Peterson, 1997]. As each region has a slightly different peak frequency, the
sum of the spectra of all of the regions results in a flat overall spectrum. Both the blazars and the
compact cores of AGN in which the lobes have been resolved out are referred to as flat-spectrum
radio quasars$^1$ (FSRQ). Depending on the frequency range and resolution of an observation, AGN,
therefore, typically have steep ($\alpha < -0.5$), flat ($-0.5 < \alpha < 0.5$) or peaked spectra.

I will now discuss the spectral classification of the peaked sources as they are critical to all of
the chapters in the thesis. Based on the location of the peak, peaked sources are grouped into one
of the following classes: compact steep-spectrum (CSS), MPS, gigahertz peaked-spectrum (GPS)
or high-frequency peaked (HFP) sources. The CSS, MPS, GPS and HFP sources have observed
peaked frequencies of $\nu_{0,p} < 0.5$, $\nu_{0,p} < 1$, $1 < \nu_{0,p} < 5$ and $\nu_{0,p} > 5$ GHz, respectively. For the

$^1$ A quasar, or quasi-stellar radio source, is an optically unresolved radio source.
Figure 1.2: Example spectrum of the peaked source J0906+6930 that is discussed in Section 5.4.3.2. J0906+6930 is at $z = 5.47$, flux densities from very long baseline interferometry (VLBI) observations are shown as filled grey symbols and the solid line shows a linear least-squares fit to the non-VLBI flux densities.
1.1 Active galactic nuclei

nearby (z ∼ 1) peaked sources, an empirical relation, shown in Fig. 1.3, was found over three orders of magnitude between their rest frame peak frequencies (ν_{r,p}) and the linear sizes of the source [O’Dea, 1998; Snellen et al., 2000; Orienti & Dallacasa, 2014]. This relation shows that the spectrum of sources with smaller physical sizes transition from optically thin to optically thick at higher frequencies (photon energies) than sources with larger physical sizes. Based on this, an evolutionary sequence is believed to exist from the HFP, to the GPS, to the CSS sources [O’Dea, 1998; Snellen et al., 2000; Tschager et al., 2003]. The CSS sources, which are the largest peaked sources, have typical sizes between 1 and 20 kpc, which is significantly smaller than the giant FR I and FR II radio galaxies\(^2\), the largest of which has a projected linear size of ∼ 4.7 Mpc [Machalski et al., 2008]. Based on similarities between their host galaxies and evidence from their expected luminosity evolution, it is likely that at least some of the CSS sources evolve into FR I and FR II sources [Fanaroff & Riley, 1974; Begelman, 1996; Snellen et al., 2000; De Vries et al., 2002b].

1.1.2 Young or confined?

As mentioned previously, the peaked sources all have linear sizes smaller than ∼ 20 kpc, and are therefore often smaller than their host galaxies\(^3\). There are three possibilities for why the peaked sources are small. First, it could be that the sources are large, but we observe them to be small because of projection effects. Using the linear size distribution of the sources and the probability of observing a source at any given angle, Fanti et al. [1990] showed that this is not the case. Secondly as a young jet moves outward through its host galaxy, it will ram into the interstellar medium. If the interstellar medium is dense enough, it is possible that the jet can be stopped, or the jet advance speed significantly reduced. This is known as confinement. The third possibility is that the jet is small because the AGN is young, the youth scenario. It should be noted that AGN go through phases of activity when the SMBH is launching, and not launching, a jet [e.g. Brienza et al., 2016]. The youth scenario does not imply that this is the first time that the SMBH is launching jets, only that the jet is young in the current phase of activity.

If the peaked sources are confined, we would expect the interstellar medium in these sources to be, on average, denser than that of the large FR II sources. However, no evidence has been found for this [Fanti et al., 1995a, 2000; Siemiginowska et al., 2005]. One piece of evidence that does support confinement is the number of asymmetric GPS and CSS sources. In about 50% of the sources the lobe closest to the core is brighter than the lobe farther away [Orienti, 2016]. This likely indicates that one side of the jet is interacting with a denser interstellar medium compared to the other side, which enhances the synchrotron emission from it [Orienti, 2016]. Despite this evidence for confinement, based on age estimates from their spectra [Murgia et al., 1999, 2002; Murgia, 2003; Nagai et al., 2006] and measuring lobe expansion speeds [Conway, 2002; Polatidis & Conway, 2003; Polatidis, 2009; Giroletti & Polatidis, 2009], the peaked sources are generally accepted to be young (≲ 10^5 years) AGN rather than being confined [O’Dea, 1998; Fanti, 2009; Orienti, 2016].

\(^2\)For this thesis, all that the reader needs to know about the FR I and FR II sources are that they are the largest radio AGN. Interested readers are referred to Alloin [2006] and Beckmann & Shrader [2012] for a review of FR I and FR II sources.

\(^3\)For reference, the diameter of the Milky Way is roughly 31 kpc.
Figure 1.3: The turnover frequency–linear size relation. The figure is reproduced from Orienti & Dallacasa [2014] using the information in table 5 of the publication. The sources for which the authors only have an upper limit for the turnover frequency are indicated as downward triangles.
1.2 Searching for high-redshift AGN in the radio

In this section I will first discuss more reasons why high-redshift sources are important that have not already been mentioned, before briefly outline the methods with which high-redshift sources are identified in radio data. Note that these methods are discussed in detail in upcoming chapters, consequently this section only serves as a brief introduction.

1.2.1 The importance of high-redshift sources

There are a number of reasons why high-redshift sources are important that have not yet been mentioned. Note that this section is not intended as a complete review. The aim is rather to give the reader a taste of some of the many different reasons.

As mentioned already one of the main reasons why high-redshift sources are important are that they allow us to study how the Universe evolved. One specific topic of study is understanding why AGN activity peaks around redshift two [e.g. Peterson, 1997; Wolf, 2005]. A second topic is the reason for the correlation between the masses of SMBHs and the stellar masses in the bulges of their host galaxies [e.g. Magorrian et al., 1998; Kormendy & Ho, 2013]. Another correlation has also been found between the mass of SMBHs and the velocity dispersion of the stars in the galactic bulges of their host galaxies [e.g. Gebhardt et al., 2000; Ferrarese & Merritt, 2000]. Since SMBHs are believed to have formed in the early Universe [e.g. Mortlock et al., 2011], the only way to study the reasons for these correlations and the observed peak in AGN activity is by studying high redshift AGN. The two aforementioned correlations also illustrate that SMBHs and their host galaxies evolve together and that galaxy evolution cannot be understood without understanding the evolution of the SMBHs at their centers. In this respect, observations of AGN at high-redshifts provide constraints on accretion onto the SMBHs and thereby their growth rate [e.g. Wyithe & Loeb, 2012; Page et al., 2014].

High-redshift sources are also important as they serve as illuminating background objects in 21-cm absorption studies which are used to study the evolution of neutral hydrogen in the intergalactic medium [e.g. Pritchard & Loeb, 2012]. Similarly, these sources can be used to study the magnetic field properties of the intergalactic medium between us and them [e.g. O'Sullivan et al., 2011]. In addition, by studying the magnetic fields of high-redshift sources it is possible to study how they evolve and their influence on galaxy evolution [e.g. Hammond et al., 2012; Farnes et al., 2014]. Finally, high-redshift sources are used to test the predictions of cosmological models. For example, very long baseline interferometry (VLBI) observations of these sources have been used to test the apparent proper motion–redshift and angular size–redshift relations [e.g. Kellermann et al., 1999; Gurvits et al., 1999].

1.2.2 Methods of identifying high-redshift sources in radio data

When imaging the sky at any frequency, astronomers face the problem that each image has sources at all distances, both near and far. Consequently, when searching for high-redshift sources, ways need to be found to distinguish the high-redshift sources from the nearby sources. While optical searches have been successful in finding sources 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; Becker et al.,...
In addition, dust obscuration will prevent sources at all redshifts from being detected. Unlike optical light, radio waves have the advantage that it does not suffer from dust obscuration [e.g. Osmer, 2004]. Radio searches therefore have the potential to detect more sources and sources at higher redshifts than optical searches. There is, however, only one (rather large) problem, how do you identify the high-redshift sources in radio data? This problem is specifically relevant as current radio arrays are being upgraded and new ones are coming on line such as the Meer Karoo Array Telescope (MeerKAT), the Low-Frequency Array (LOFAR), the Square Kilometer Array (SKA), the upgraded Giant Metrewave Radio Telescope (uGMRT), the upgraded Karl G. Jansky Very Large Array (VLA) and others. These instruments can, or will be able to, detect an unprecedented number of sources out to extremely high redshifts. For example the GMRT and VLA have already detected sources at \( z = 5.8 \) and 6.2, respectively (see Chapter 5), and the SKA is predicted to be able to detect sources out to \( z = 10 \) [Falcke et al., 2004].

There were two ways of identifying high-redshift sources in radio data: the ultra-steep-spectrum (USS) and the MPS method. This former method relies on an observed correlation between spectral index and redshift, with sources that have steeper spectra being at higher redshifts [e.g. Whitfield, 1957; Laing & Peacock, 1980; De Breuck et al., 2000]. In Chapters 2 and 5 this method and its successes and problems are discussed. For now it is sufficient to note that the USS method has been successful in finding sources out to \( z > 4 \) [e.g. van Breugel et al., 1999; Jarvis et al., 2001; Kopylov et al., 2006], but it has also faced criticism. The main points of criticism have been that no explanation exists for the correlation between spectral index and redshift [Miley & De Breuck, 2008; Verkhodanov & Khabibullina, 2010; Singh et al., 2014] and that a number of authors have failed to reproduce the correlation [e.g. Ker et al., 2012; Singh et al., 2014; Smolčić et al., 2014].

Falcke et al. [2004] proposed another method to find high-redshift sources, which is discussed in detail in Chapters 2 and 5. The idea behind this method is that there are two different groups of sources that have spectral peaks below 1 GHz. The first is the CSS sources that, because of their low redshifts, have observed and rest frame peak frequencies that are nearly the same. The second group contains GPS and HFP sources that are at higher redshifts than the CSS sources, which results in their peak frequencies being redshifted to values below 1 GHz. Since these sources are at higher redshifts than the CSS sources and, from the turnover frequency–linear size relation, have smaller physical sizes than the CSS sources, it should be possible to distinguish the high-redshift sources from the CSS sources based on their smaller angular sizes. This method, the MPS method, was untested at the start of this thesis. An important point to mention is that while the high-redshift sources are expected to have smaller angular sizes than the local sources, they are not expected to have infinitely small angular sizes, as you might expect to happen if a sources with a fixed linear size is moved further and further away from an observer. Instead, conventional cosmology (\( \Omega_m = 0.3, \Omega_\Lambda = 0.7, H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1} \)) predicts that the angular size of the source will decrease from \( z = 0 \) to \( z \sim 1 \) before increase again beyond \( z \sim 1 \). This relation is illustrated graphically for three sources with fixed linear sizes of 0.1 kpc, 1 kpc and 10 kpc in Fig. 1.4.

\(^4\)It should be noted that optical spectroscopy is still required to determine redshifts for the candidate high-redshift sources identified in the radio.
1.3 This Thesis

In this thesis I study ways of identifying high-redshift sources in radio images and discuss their properties. In Chapter 2, I describe the MPS method of finding high-redshift sources. Combining my new 325 MHz image of the Boötes field with existing radio maps at 150 MHz and 1.4 GHz, I identify 33 MPS sources and study their redshift distribution. I also discuss the effect of selecting USS sources over different frequency ranges. In Chapter 3, I continue my study of the MPS sources in the Boötes field with 1.7 GHz European VLBI Network (EVN) observations of the sources. With these observations I study the nature of the MPS sources.

Very few $z > 4.5$ sources are known, and even less have been observed with VLBI. In Chapter 4, I present observations of ten $z > 4.5$ sources with the EVN at 1.7 and 5 GHz, thereby increasing the number of $z > 4.5$ sources that have been observed with VLBI by 50% from 20 to 30 sources. Combining my observations with those from the literature I discuss the 1.4 GHz variability, VLBI spectra, Doppler boosting and the origin of the radio emission for the $z > 4.5$ VLBI sources. Using new multi-frequency GMRT observations and observations from the literature, I construct broad-band radio spectra of all 30 $z > 4.5$ VLBI sources in Chapter 5. I then use the spectral classification to check how many of the sources the USS and MPS methods would have selected, and the implications of these numbers. Finally in the Summary & Conclusion I present a conclusion to the thesis.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Angular size plotted as a function of redshift for a 0.1 kpc (red), 1 kpc (blue) and 10 kpc (green) source.}
\end{figure}
Chapter 2

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

Rocco Coppejans, David Cseh, Wendy L. Williams, Sjoert van Velzen and Heino Falcke


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 available 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 contains 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.


Chapter 2 : Megahertz peaked-spectrum sources in the Boötes field

2.1 Introduction

The National Optical Astronomy Observatory (NOAO) deep wide-field survey Boötes field covers \( \sim 9 \text{ deg}^2 \) 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], ultraviolet [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., 2002a; 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 measured 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 obscured galaxies [Calanog et al., 2013] and study the composition 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 believed to lie at the center of nearly every galaxy. They not only grow with their host galaxy, but also shape and influence 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, 2012]. 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; Becker et al., 2001]. On the other 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 [eg. 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 \( z \sim 4 \) [eg. 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 Multifrequency 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., 2004].

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 \( S \propto \nu^\alpha \) 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., 2002b].

An empirical relation was found between the rest-frame turnover frequency \( \nu_r \) 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 \( \nu_r = \nu_o(1 + z) \), where \( z \) is the redshift of the source. Using this, we can predict the source’s observed angular size, noting that in conventional cosmology \((\Omega_m = 0.3, \Omega_\Lambda = 0.7, H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1})\), 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\(^1\) of the Boötes field that is at least an order of magnitude better in terms of both resolution and noise (see Table 2.2) than what was

\(^1\)Available in electronic format from the CDS at http://cdsarc.u-strasbg.fr/
Chapter 2: Megahertz peaked-spectrum sources in the Boötes field

Table 2.1: Summary of observations.

<table>
<thead>
<tr>
<th>Date</th>
<th>Start Time [UTC]</th>
<th>End Time [UTC]</th>
<th>TOS Boötes [min]</th>
<th>TOS 3C286 [min]</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).

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 2.2 we describe the data reduction and imaging before describing source extraction, image quality and catalogue construction in Section 2.3. 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 2.4. Finally, in Section 2.5 we summarize our results and discuss future work.

2.2 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 2.1. 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 3.3s 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 327.53MHz and 321.53MHz each with two polarizations (LL and RR). We will take the average frequency of 324.525MHz of the two IFs as the representative frequency. Each IF was split into 16 channels of 394KHz each, giving a bandwidth of 6.3MHz per IF and total bandwidth of 12.6MHz. Observations of the calibrator source 3C286, used for phase, amplitude and bandpass calibration, were irregularly interleaved between those of the target field. Typically, 3C286 was observed for 2.5minutes every 25minutes.

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\(^2\) for self-calibration, imaging and primary beam correction. Five rounds of phase only self-calibration was done, in which the solution interval was decreased from 20 to 1min. During each round, a clean component model of the brightest sources in the field was derived from the previous best

\(^2\)http://casa.nrao.edu
image and used as an input model. The final image of the field (the inner 1.2° of which is shown in Fig. 2.1) was made using 1.5 arcsec pixels, Briggs’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 2.3.3).

2.3 Image Quality and Catalogue Construction

2.3.1 Source Extraction

Source extraction was done using the PYBDSM source detection package³. 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 $1\sigma$ statistical errors calculated using the formula in Condon [1997] and the source position is the the centroid of the Gaussians. In total 1377 sources made up of 1586 Gaussians were recovered from the image. After visual inspection, seven sources were rejected because they were found to be artefacts near bright sources. Of the remaining 1370 sources, 1251 were fit by a single Gaussian.

### 2.3.2 Source Matching

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., 2002a, 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 2.2. Matching was done with the stilts [Taylor, 2006] software package using the task tskymatch2. Using the central position of each sources 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 2.2), 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 $\sim 6$ arcsec, a value of 10 arcsec was used to accommodate the errors on the fitted major and minor axes of the faint sources. Similarly, VLA-P sources that were matched to a source with a major or minor axis greater than 7 arcsec in FIRST or matched to a sources that is flagged as being extended in WENSS were excluded. In total 283 resolved sources were excluded. Matching to multiple
## 2.3 Image Quality and Catalogue Construction

### Table 2.2: Catalogues matched to the VLA-P catalogue.

<table>
<thead>
<tr>
<th>Catalogue Name</th>
<th>Frequency [MHz]</th>
<th>Resolution [′′]</th>
<th>rms Noise [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:** a 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.

catalogues at the same frequency (FIRST, deVries and NVSS), we exclude 323 variable sources by removing sources that showed a flux density difference of more than 20 per cent in any two of the catalogues. Since NVSS’s resolution is about eight times lower than that of FIRST, this also ensures that none of the sources have extended structure that is resolved out in one of the higher resolution catalogues. Finally, all of the matches were visually inspected to check for potential incorrect matches. This resulted in 18 matches to 13 VLA-P sources being rejected.

### 2.3.3 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 ratio was plotted as a function of the distance of the source from the VLA-P phase center (shown in Fig. 2.2). From the figure it is clear that sources further from the phase center (specifically those beyond the primary beam) had a larger flux density ratio, indicating that the flux densities at the edge of the VLA-P image were over estimated. This problem was likely caused by an error in the model of the VLA P-band primary beam that *casa* used to do the primary beam correction.

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

\[
\frac{S_{\text{VLA-P}}}{S_{\text{WENSS}}} = k_1 + k_2 e^{k_3 r}
\] (2.1)
Chapter 2: Megahertz peaked-spectrum sources in the Boötes field

Figure 2.2: The uncorrected flux density ratio ($S_{\text{VLA-P}} S_{\text{WENSS}}^{-1}$) plotted as a function of the distance from the phase center for the sources used to check the flux density scale. The dashed line shows the function $y = 1$ while the solid line is the function fitted to the data to correct for the VLA-P flux density offset. The function has a value of 1.0 at the phase center, increasing to 3.72 at the edge of the image.
was fitted to the data using a non-linear least squares fitting routine (shown as the solid line in Fig. 2.2), 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 \( 1.00 \pm 0.03, 0.005 \pm 0.002 \) and \( 2.93 \pm 0.19 \) 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 2.1 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. 2.3 shows a plot of the corrected VLA-P flux densities as a function of the WENSS flux densities 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.

### 2.3.4 Catalogue Construction

A sample of the final catalogue is given in Table 2.3, 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 2.3.3. 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.

\(^4\text{http://cdsarc.u-strasbg.fr/}\)
Figure 2.3: Log-log 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. The line $y = x$ was added as a guide.
Table 2.3: Example entries of the online catalogue.

<table>
<thead>
<tr>
<th>Source ID</th>
<th>RA</th>
<th>$\sigma_{\text{RA}}$</th>
<th>DEC</th>
<th>$\sigma_{\text{DEC}}$</th>
<th>$S_i$</th>
<th>$S_p$</th>
<th>$a$</th>
<th>$b$</th>
<th>$\phi$</th>
<th>rms</th>
<th>$N_{\text{Gauss}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>J143821+340235</td>
<td>219.5863</td>
<td>0.6</td>
<td>34.0432</td>
<td>0.6</td>
<td>3.6±0.9</td>
<td>2.7±0.6</td>
<td>8.2±2.0</td>
<td>4.7±0.7</td>
<td>137±18</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>J143813+335310</td>
<td>219.5529</td>
<td>0.7</td>
<td>33.8861</td>
<td>0.4</td>
<td>6.6±1.0</td>
<td>3.4±0.6</td>
<td>9.1±1.6</td>
<td>6.1±0.8</td>
<td>108±21</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>J143622+335939</td>
<td>219.0909</td>
<td>0.1</td>
<td>33.9942</td>
<td>0.1</td>
<td>223.5±11.0</td>
<td>70.5±3.5</td>
<td>14.2±0.1</td>
<td>7.1±0.1</td>
<td>9±1</td>
<td>0.4</td>
<td>3</td>
</tr>
<tr>
<td>J143622+335939a</td>
<td>219.0911</td>
<td>0.1</td>
<td>33.9955</td>
<td>0.1</td>
<td>107.0±5.3</td>
<td>32.7±1.7</td>
<td>11.5±0.1</td>
<td>8.1±0.1</td>
<td>16±2</td>
<td>0.4</td>
<td>–</td>
</tr>
<tr>
<td>J143622+335939b</td>
<td>219.0906</td>
<td>0.1</td>
<td>33.9926</td>
<td>0.1</td>
<td>79.9±4.0</td>
<td>63.0±3.1</td>
<td>6.7±0.1</td>
<td>5.4±0.1</td>
<td>117±2</td>
<td>0.4</td>
<td>–</td>
</tr>
<tr>
<td>J143622+335939c</td>
<td>219.0908</td>
<td>0.1</td>
<td>33.9014</td>
<td>0.1</td>
<td>36.6±1.9</td>
<td>22.4±1.2</td>
<td>7.8±0.1</td>
<td>6.0±0.1</td>
<td>127±4</td>
<td>0.4</td>
<td>–</td>
</tr>
<tr>
<td>J142208+342122</td>
<td>215.5341</td>
<td>0.7</td>
<td>34.3561</td>
<td>0.4</td>
<td>10.7±4.3</td>
<td>6.3±2.6</td>
<td>7.9±1.7</td>
<td>6.0±1.0</td>
<td>87±31</td>
<td>1.1</td>
<td>1</td>
</tr>
<tr>
<td>J143948+330413</td>
<td>219.9511</td>
<td>0.8</td>
<td>33.0702</td>
<td>0.4</td>
<td>26.1±9.2</td>
<td>5.8±2.2</td>
<td>8.1±1.9</td>
<td>5.5±1.0</td>
<td>172±26</td>
<td>1.0</td>
<td>2</td>
</tr>
<tr>
<td>J143948+330413a</td>
<td>219.9516</td>
<td>0.7</td>
<td>33.0690</td>
<td>0.5</td>
<td>8.0±3.2</td>
<td>5.0±2.0</td>
<td>7.7±1.8</td>
<td>5.9±1.1</td>
<td>69±38</td>
<td>1.0</td>
<td>–</td>
</tr>
<tr>
<td>J143948+330413b</td>
<td>219.9509</td>
<td>0.8</td>
<td>33.0709</td>
<td>1.0</td>
<td>18.1±6.4</td>
<td>5.3±2.1</td>
<td>12.8±2.7</td>
<td>7.6±1.3</td>
<td>38±22</td>
<td>1.0</td>
<td>–</td>
</tr>
</tbody>
</table>
2.4 Results and Discussion

2.4.1 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 2.3.2) 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 Smolčić 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 $-0.685\pm0.007$ and $-0.505\pm0.033$ respectively, is is clear that the spectral index flattens toward 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.

2.4.2 MPS Sources

To select the MPS sources, a colour-colour diagram (Fig. 2.4) 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 quadrant 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. 2.4). 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 2.4.1) from the selection. In total, 33 MPS sources were selected and presented in Table 2.4. We note that when fitting Gaussians to the sources, PYBDSM fit a single Gaussian to each of the 33
2.4 Results and Discussion

Figure 2.4: 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.
MPS sources. In the table, the columns correspond in name to the columns in Table 2.3 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 2.4, 18 have spectra that flatten ($\alpha_{low} \leq 0$) 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.
Table 2.4: List of MPS sources.

<table>
<thead>
<tr>
<th>Source ID</th>
<th>RA</th>
<th>$\sigma_{RA}$</th>
<th>DEC</th>
<th>$\sigma_{DEC}$</th>
<th>$S_i$</th>
<th>rms</th>
<th>$\alpha_{low}$</th>
<th>$\alpha_{high}$</th>
<th>$z_{EAZY}$</th>
<th>$z_{LRT}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[deg]</td>
<td>[&quot;']</td>
<td>[deg]</td>
<td>[&quot;]</td>
<td>[mJy]</td>
<td>[mJy beam$^{-1}$]</td>
<td>±</td>
<td>±</td>
<td></td>
<td></td>
</tr>
<tr>
<td>J143902+351652</td>
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<td>0.5</td>
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<td>0.6</td>
<td>0.2 ± 0.84</td>
<td>-1.16 ± 0.19</td>
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<td>-0.42 ± 0.63</td>
<td>-1.19 ± 0.12*</td>
<td>1.793$^{+0.264}_{-0.269}$</td>
<td>2.06</td>
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<td>0.5</td>
<td>36.0289</td>
<td>0.6</td>
<td>9.6 ± 3.8</td>
<td>0.9</td>
<td>-0.40 ± 0.67</td>
<td>-1.12 ± 0.27</td>
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<td>0.4</td>
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<td>4.7 ± 0.5</td>
<td>0.3</td>
<td>-0.07 ± 0.55</td>
<td>-0.74 ± 0.08*</td>
<td>0.853$^{+0.095}_{-0.094}$</td>
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<td>0.7</td>
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<td>-0.55 ± 0.21</td>
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<td>16.2 ± 1.3</td>
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<td>0.29 ± 0.42</td>
<td>-0.71 ± 0.07</td>
<td>0.899$^{+0.051}_{-0.051}$</td>
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<td>0.4</td>
<td>-0.41 ± 0.62</td>
<td>-1.15 ± 0.14*</td>
<td>2.363$^{+0.165}_{-0.165}$</td>
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<td>5.6 ± 0.4</td>
<td>0.2</td>
<td>0.44 ± 0.67</td>
<td>-0.85 ± 0.06</td>
<td>2.850$^{+0.078}<em>{-0.085}$ or 5.30 or 2.856$^{+0.108}</em>{-0.106}$</td>
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<td>6.9 ± 1.2</td>
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<td>-0.03 ± 0.62</td>
<td>-0.99 ± 0.12</td>
<td>3.162$^{+0.191}_{-0.156}$</td>
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<td>J143505+334721</td>
<td>218.7707</td>
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<td>33.7893</td>
<td>0.0</td>
<td>17.1 ± 0.9</td>
<td>0.2</td>
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<td>-0.72 ± 0.05</td>
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<td>4.2 ± 0.4</td>
<td>0.2</td>
<td>-0.23 ± 0.54</td>
<td>-0.89 ± 0.07*</td>
<td>3.615$^{+0.092}<em>{-0.092}$ or 0.62 or 1.381$^{+0.174}</em>{-0.218}$</td>
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<tr>
<td>J143339+354013</td>
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<td>10.5 ± 1.5</td>
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<td>0.07 ± 0.44</td>
<td>-0.84 ± 0.11</td>
<td>0.631$^{+0.069}_{-0.071}$</td>
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<td>0.2</td>
<td>14.6 ± 2.9</td>
<td>0.5</td>
<td>0.16 ± 0.48</td>
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<td>0.3</td>
<td>-0.14 ± 0.43</td>
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<td>35.5375</td>
<td>0.3</td>
<td>5.5 ± 0.7</td>
<td>0.3</td>
<td>-0.11 ± 0.69</td>
<td>-0.96 ± 0.10</td>
<td>0.887$^{+0.091}_{-0.069}$</td>
<td>0.69</td>
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<td>51.5 ± 3.1</td>
<td>0.2</td>
<td>-0.13 ± 0.29</td>
<td>-0.81 ± 0.05</td>
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<td>0.0</td>
<td>34.3472</td>
<td>0.0</td>
<td>29.0 ± 1.3</td>
<td>0.2</td>
<td>0.49 ± 0.34</td>
<td>-0.61 ± 0.05</td>
<td>2.364$^{+0.535}_{-0.536}$</td>
<td>2.98</td>
</tr>
</tbody>
</table>

Notes: ° RA and DEC errors smaller than 0.04 arcsec are rounded to 0.0. ° $\alpha_{low}$ was calculated between 153 MHz and 325 MHz. ° $\alpha_{high}$ was calculated between 325 MHz and 1380 MHz, the value is marked with a °°, otherwise $\alpha_{high}$ was calculated between 342.5 MHz and 1400 MHz. °° The entries containing 25 two values are because the radio source was matched to two optical sources. In the table, the redshift of both optical matches are given.
<table>
<thead>
<tr>
<th>Source ID</th>
<th>RA</th>
<th>$\sigma_{RA}$</th>
<th>DEC</th>
<th>$\sigma_{DEC}$</th>
<th>$S_i$</th>
<th>rms</th>
<th>$\alpha_{low}$</th>
<th>$\alpha_{high}$</th>
<th>$z_{EAZY}$</th>
<th>$z_{LHT}$</th>
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<td>34.1295</td>
<td>0.1</td>
<td>7.4</td>
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<td>0.52 ± 0.80</td>
<td>-0.78 ± 0.05</td>
<td>0.165</td>
<td>0.19</td>
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<td>34.6507</td>
<td>0.0</td>
<td>14.5</td>
<td>0.2</td>
<td>-0.36 ± 0.36</td>
<td>-1.10 ± 0.05</td>
<td>0.139</td>
<td>0.15</td>
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<td>8.6</td>
<td>0.3</td>
<td>0.27 ± 0.59</td>
<td>-0.76 ± 0.09</td>
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<td>17.3</td>
<td>0.3</td>
<td>0.60 ± 0.37</td>
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<td>-0.59 ± 0.14</td>
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<td>7.9</td>
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<td>-0.77 ± 0.06</td>
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<td>-0.81 ± 0.10</td>
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<td>-0.61 ± 0.57</td>
<td>-1.72 ± 0.17*</td>
<td>1.690</td>
<td>1.56</td>
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<td>0.35 ± 0.70</td>
<td>-0.67 ± 0.11</td>
<td>0.820</td>
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<td>5.2</td>
<td>0.3</td>
<td>0.04 ± 0.82</td>
<td>-0.76 ± 0.10</td>
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<td>5.5</td>
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<td>-0.11 ± 0.69</td>
<td>-0.67 ± 0.09</td>
<td>1.329</td>
<td>1.13</td>
</tr>
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<td>0.5</td>
<td>35.7775</td>
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<td>11.1</td>
<td>0.8</td>
<td>0.13 ± 0.72</td>
<td>-0.51 ± 0.25</td>
<td>0.859</td>
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<td>33.5092</td>
<td>0.2</td>
<td>18.5</td>
<td>0.9</td>
<td>-0.04 ± 0.60</td>
<td>-0.71 ± 0.26</td>
<td>–</td>
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</tr>
</tbody>
</table>

Table 2.4 continued...
2.4 Results and Discussion

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, V, 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 image; Jannuzi et al., 2010]. 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 2.4) 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 $\sim 325\,\text{MHz}$ to be selected, and these sources are expected to have a linear and angular size of $\sim 2.3\,\text{kpc}$ and $\sim 1.3\,\text{arcsec}$ 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, 1990]. 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.
Chapter 2: Megahertz peaked-spectrum sources in the Boötes field

2.4.3 USS Sources

USS source have been selected using different spectral cuts and frequency ranges eg., $\alpha_{608\, \text{MHz}}^{4.85\, \text{GHz}} < -1.1$ [Wieringa & Katgert, 1992], $\alpha_{151\, \text{MHz}}^{4.85\, \text{GHz}} < -0.981$ [Blundell et al., 1998], $\alpha_{843\, \text{MHz}}^{1.4\, \text{GHz}} < -1.3$ [De Breuck et al., 2004], $\alpha_{151\, \text{MHz}}^{1.4\, \text{GHz}} < -1.0$ [Cruz et al., 2006], $\alpha_{408\, \text{MHz}}^{843\, \text{MHz}} < -1.0$ [Broderick et al., 2007] and $\alpha_{325\, \text{MHz}}^{1.4\, \text{GHz}} \leq -1.0$ [Singh et al., 2014]. Defining USS sources as those with a spectral index steeper than -1.3, we find that only 4.2% of the sources for which $\alpha_{\text{high}}$ could be calculated can be classified as USS sources. Similarly, 4.9% of the sources for which $\alpha_{\text{low}}$ could be calculated can be classified as USS sources. This is once again consistent with both Smolčić 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 $\alpha_{\text{low}}$. 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 $25^{+1}_{-8}$ percent 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 $19^{+22}_{-6}$ percent. To check if these low values are because $\alpha_{\text{low}}$ is on average 0.2 units higher than $\alpha_{\text{high}}$ (see Section 2.4.1), 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.

2.5 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. [2002a] 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 2.1 we described an untested method of finding young and high-redshift AGN by selecting sources with a peaked spectra 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 2.4.2, 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 2.4.3 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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what are the megahertz peaked-spectrum sources?

Rocco Coppejans, Dávid Cseh, Sjoert van Velzen, Heino Falcke, Huib T. Intema, Zsolt Paragi, Cornelia Müller, Wendy L. Williams, Sándor Frey, Leonid I. Gurvits and Elmar G. Körding

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Abstract

Megahertz peaked-spectrum (MPS) sources have spectra that peak at frequencies below 1 GHz in the observer’s frame and are believed to be radio-loud active galactic nuclei (AGN). We recently presented a new method to search for high-redshift AGN by identifying unusually compact MPS sources. In this paper, we present European VLBI Network (EVN) observations of 11 MPS sources which we use to determine their sizes and investigate the nature of the sources with ~ 10 mas resolution. Of the 11 sources, we detect nine with the EVN. Combining the EVN observations with spectral and redshift information, we show that the detected sources are all AGN with linear sizes smaller than 1.1 kpc and are likely young. This shows that low-frequency colour-colour diagrams are an easy and efficient way of selecting small AGN and explains our high detection fraction (82 per cent) in comparison to comparable surveys. Finally we argue that the detected sources are all likely compact symmetric objects and that none of the sources are blazars.
Chapter 3: What are the MPS sources?

3.1 Introduction

AGN jets are powered by the accretion of material from their host galaxy onto a supermassive black hole [e.g. Blandford & Königl, 1979; Falcke & Biermann, 1995] and can grow to extend well beyond their host galaxy. The young jets can be distorted and even stopped by the ambient medium, while larger jets heat both the interstellar and intergalactic medium, quench star formation and expel material from the galaxy [e.g. Morganti et al., 2013]. Hence to understand AGN, we need to understand galaxies and vice versa [e.g. Fabian, 2012].

Young or restarted AGN can be used to study how AGN are launched and evolve from parsec-scale objects to sources of hundreds of kiloparsec such as Cygnus A and 3C175 [e.g. Snellen et al., 2000] and study how the Universe evolved from a time when it was less than 6 percent of its current age. Specifically, the fraction of jets that are frustrated by their host galaxy appears to increase with redshift [Van Velzen et al., 2015]. By comparing the number of young and small AGN at high redshifts to those in the modern Universe, we can therefore trace the evolution of the ambient medium which both feeds AGN and hampers or even confines their jets [e.g. Falcke et al., 2004]. Hence, searching for both young AGN and AGN at high redshifts is critically important to understand what triggers the nuclear activity, how AGN evolve in size, how the population evolves with redshift and, ultimately, the origin of their redshift evolution.

Compact steep-spectrum (CSS), gigahertz peaked-spectrum (GPS) and high-frequency peaked (HFP) sources are all radio-loud AGN that are identified based on their spectral energy distribution in the radio. CSS, GPS and HFP sources are characterised by steep optically thin spectra that turn over and have inverted spectra (the spectral index, $\alpha$, is defined as $S \propto \nu^\alpha$, where $S$ is the flux density and $\nu$ is the frequency) above the turnover frequency. The CSS sources have typical rest-frame turnover frequencies ($\nu_{r}$) smaller than 500 MHz and largest linear sizes (LLS) of $1 - 20 \text{kpc}$ [O’Dea, 1998]. For the GPS sources, $1 < \nu_{r} < 5 \text{GHz}$, while $\nu_{r} > 5 \text{GHz}$ for the HFP sources [Dallacasa et al., 2000]. Both the GPS and HFP sources have LLS $< 1 \text{kpc}$ [O’Dea, 1998].

Morphologically GPS and HFP sources are typically classified as compact symmetric objects (CSOs) while the CSS sources are medium-size symmetric objects (MSOs) [e.g. Snellen et al., 2000; Conway, 2002]. CSOs and MSOs are characterised by unbeamed emission from their steep-spectrum radio lobes on either side of a central position and have sizes smaller than their host galaxy [Fanti et al., 1995b; Fanti, 2009]. To strictly classify a source as a CSO or MSO, its flat-spectrum core has to be detected [Orienti & Dallacasa, 2014], which is often not the case. In addition, unlike their names suggest, CSOs and MSOs are often not symmetric around their cores. This is likely the result of the interaction of the jet with an inhomogeneous ambient medium [e.g. O’Dea, 1998; Orienti & Dallacasa, 2014].

Based on spectral and kinematic age estimates (determined by fitting models to the source spectra and measuring lobe expansion speeds), most of the HFP, GPS and CSS sources are believed to be young ($\lesssim 10^5 \text{years}$) and small ($\lesssim 20 \text{kpc}$) AGN rather than being sources that are confined by the ambient medium of their host galaxy [O’Dea, 1998; Murgia et al., 2002; Conway, 2002; Murgia, 2003; Fanti, 2009]. In addition, an empirical relation was found between $\nu_{r}$ and LLS that spans three orders of magnitude [see Section 3.5.1, O’Dea, 1998; Snellen et al., 2000; Orienti & Dallacasa, 2014]. This shows that the smallest sources have the highest turnover frequencies.
Based on this evidence, it is believed that the HFP sources evolve into GPS sources which in turn evolve into CSS sources [O’Dea, 1998; Snellen et al., 2000; Tschager et al., 2003]. There is also strong evidence from their expected luminosity evolution and the similarities between their host galaxies [Begelman, 1996; Snellen et al., 2000; De Vries et al., 2002b] that the CSS sources will evolve into the FR I and FR II radio galaxies [Faranoff & Riley, 1974].

In the past, searches for high-redshift AGN in the radio have focused on ultra-steep-spectrum (USS) sources [e.g. Jarvis et al., 2001; Cruz et al., 2006; De Breuck et al., 2006]. However, the reason why USS sources should be at higher redshifts than non-USS sources remains unclear [Miley & De Breuck, 2008]. Moreover, several recent studies have found that USS sources are not at higher redshifts than non-USS sources [Ker et al., 2012; Singh et al., 2014; Smolčić et al., 2014].

In our previous paper [Coppejans et al., 2015], we described a new method of searching for high-redshift radio-loud AGN by selecting compact megahertz peaked-spectrum (MPS; turnover frequency below 1 GHz) sources. The MPS sources are believed to be a mixture of nearby CSS sources, and smaller GPS and HFP sources whose spectral turnovers have been redshifted to lower frequencies. Hence, the most compact MPS sources should be at the highest redshifts. In Coppejans et al. [2015], we took the first steps in testing the method by making a low-frequency radio colour-colour diagram and selecting a sample of 33 MPS sources from it. Using their photometric redshifts, we concluded that there is encouraging evidence that the MPS method can be used to search for high-redshift AGN. This was the first time that a colour-colour diagram was used to select MPS sources. However, it will soon be possible to repeat the analysis over the full sky using instruments such as the Low-Frequency Array [LOFAR; Van Haarlem et al., 2013]. We therefore wish to confirm that this novel selection method yields a separate class of small and likely young AGN, where the most compact sources are at high redshifts.

Here we present very long baseline interferometry (VLBI) observations of 11 MPS sources conducted with the European VLBI Network (EVN). Combining the EVN’s sub-arcsecond resolution with the spectra of the sources, we investigate the nature of the MPS sources and test the hypothesis that these are AGN with small jets. In Section 3.2, we describe how we selected the sources and reduced the EVN data. Section 3.3 describes how the source spectra were generated, presents the source properties derived from the images and spectra, and discusses whether the radio emission is from star formation in the host galaxy or AGN activity. The individual sources are discussed in detail in Section 3.4. In Section 3.5, we discuss what the MPS sources are and present a summary in Section 3.6. Throughout this paper, we use the following cosmological parameters: \( \Omega_m = 0.3, \Omega_\Lambda = 0.7, H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

### 3.2 Target Selection, Observations and Data Reduction

#### 3.2.1 Target Selection

In Coppejans et al. [2015], we matched the sources in our 324.5 MHz Very Large Array (VLA) P-band image (hereafter referred to as the VLA-P image) of the National Optical Astronomy Observatory (NOAO) deep wide-field survey Boötes field to the VLA Faint Images of the Radio Sky at Twenty-Centimeters (FIRST) survey [White et al., 1997] and a 153 MHz Giant Metrewave
Radio Telescope (GMRT) catalogue of the field [Williams et al., 2013, hereafter referred to as the WIR catalogue]. From this we generated a colour-colour diagram of the field and selected 33 MPS sources that either show a turnover in their spectra or a significant low-frequency flattening, which could indicate a turnover below 153 MHz. Sources were excluded if they were extended in the FIRST or VLA-P catalogues or had a flux density difference of more than 20 percent between any two of the following three 1.4 GHz catalogues: FIRST, National Radio Astronomy Observatory (NRAO) VLA Sky Survey [NVSS; Condon et al., 1998] and De Vries et al. [2002a, hereafter referred to as the dVMR catalogue]. Since the resolution of the FIRST, dVMR and NVSS catalogues are 5.4, 20 and 45 arcsec, respectively (see Table 3.3), this not only removed variable sources, but also sources with extended structures that are resolved out in one of the higher resolution catalogues.

The MPS sources presented in this paper are given in Table 3.1 and were observed with the EVN during two projects, EV020 and EC053. In the table, the columns are: (1) source name, (2) the EVN project code under which the source was observed, (3) low-frequency spectral index calculated between 153 and 325 MHz, (4) high-frequency spectral index calculated between 325 and 1400 MHz, (5, 6) photometric redshifts calculated using the eazy code from Brammer et al. [2008] and lrt code from Assef et al. [2008] as described in Coppejans et al. [2015], and (7) the total time spent observing the source with the EVN. A description of how $\alpha_{\text{low}}$ and $\alpha_{\text{high}}$ were calculated are given in Section 3.3.1. Note that for the redshift values, the lrt code does not provide errors and includes an empirical AGN spectral energy distribution (SED) template in the fitting, and should therefore fit AGN spectra better. In the table, there are three sources (J142850+345420, J143718+364549 and J144230+355735) for which we do not have photometric redshifts. J142850+345420’s optical counterpart is too faint for us to find a photometric redshift for it, while J143718+364549 and J144230+355735 lie outside the multiwavelength coverage of the Boötes field.

The sources that were observed with the EVN were selected to be unresolved in FIRST, non-variable, have the highest possible flux density in FIRST and have not been previously observed with VLBII. Of the 11 MPS sources observed with the EVN, four are also in the selection of sources in Coppejans et al. [2015]. Two of the new sources (J143718+364549 and J144230+355735) lie outside the region that was imaged with the VLA-P data and were selected based on their Westerbork Northern Sky Survey [WENSS; Rengelink et al., 1997] flux densities (see Section 3.3.1). The remaining five new sources (J142850+345420, J143024+352438, J143042+351240, J143055+350852 and J143213+350940) were originally excluded in Coppejans et al. [2015] because they have a flux density difference of more than 20 percent between either FIRST and dVMR or NVSS and dVMR. In Section 3.3.4, we argue that the flux density difference with dVMR catalogue does not necessarily indicate that these sources are variable. We therefore believe that all five sources are genuine MPS sources.

### 3.2.2 Observing Setup and Data Reduction

EV020 and EC053 were observed on 15 April 2014 and 14 January 2015, respectively. Since $\alpha_{\text{high}} < -0.5$ for the MPS sources, we elected to do the observations at 1.664 GHz to maximize the flux density of the sources and reduce the required observing time. During both projects we
requested the targets to be observed with the radio telescopes at Effelsberg (Germany), Jodrell Bank (Mk2; UK), Medicina (Italy), Noto (Italy), Onsala (Sweden), Toruń (Poland), Sheshan (China) and the Westerbork Synthesis Radio Telescope (WSRT, the Netherlands). A list of the telescopes and whether or not they successfully participated in each project is given in Table 3.2. Since the baselines to Sheshan (which did not take part in EC053) form the longest baselines, the typical restoring beam size of EC053 is 32 × 10 mas compared to the 3 × 10 mas of EV020. Both projects obtained data with 2 s integrations at 1024 Mbit s⁻¹ in left and right circular polarizations with eight subbands per polarization and 16 MHz of bandwidth per subband. The technique of electronic VLBI (e-VLBI) was used, where the data are not recorded at the telescopes but streamed to the central correlator using optical fiber networks in real time. The observations of the targets were interleaved with observations of two phase calibrators, J1413+3649 and J1422+3223. The phase solutions from J1422+3223 were used to correct J142917+332626, which is 1.8° away from J1422+3223. The solutions of J1430+3649 were used to correct the remaining sources which are separated from it by between 0.5° and 2.5°.

The data were reduced using the AIPS [Greisen, 1990] software package by calibrating the visibility amplitudes using antenna gains and system temperatures measured at the telescopes. Next fringe-fitting was performed on the two phase calibrators. The phase calibrators were then imaged in the Caltech DIFMAP package [Shepherd et al., 1994] by doing several iterations of CLEAN and phase self-calibration. A final round of amplitude self-calibration was done on the phase calibrators in DIFMAP to determine the global antenna gain correction factors. The gain correction factors varied between one and five per cent and were applied to the visibility amplitudes of all the sources in AIPS. Using the clean component models derived for the phase calibrators in DIFMAP, improved phase solutions were calculated for the phase calibrators in AIPS. These

### Table 3.1: Basic parameters of the target sources.

<table>
<thead>
<tr>
<th>Source ID</th>
<th>Project code</th>
<th>α_{low} a</th>
<th>α_{high} b</th>
<th>z_{EASY}</th>
<th>z_{LRT}</th>
<th>Time on source [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>J142850+345420</td>
<td>EV020</td>
<td>0.6 ± 0.4</td>
<td>−0.5 ± 0.1</td>
<td>—</td>
<td>—</td>
<td>45</td>
</tr>
<tr>
<td>J142904+354425</td>
<td>EC053</td>
<td>0.0 ± 0.5</td>
<td>−0.6 ± 0.1</td>
<td>0.809±0.084</td>
<td>−0.81</td>
<td>0.84</td>
</tr>
<tr>
<td>J142917+332626</td>
<td>EC053</td>
<td>0.6 ± 0.4</td>
<td>−0.6 ± 0.1</td>
<td>1.583±0.290</td>
<td>2.49</td>
<td>70</td>
</tr>
<tr>
<td>J143024+352438</td>
<td>EV020</td>
<td>0.2 ± 0.6</td>
<td>−0.7 ± 0.1</td>
<td>1.196±0.116</td>
<td>−0.118</td>
<td>1.33</td>
</tr>
<tr>
<td>J143042+351240</td>
<td>EC053</td>
<td>0.0 ± 0.4</td>
<td>−0.7 ± 0.1</td>
<td>1.281±0.202</td>
<td>−0.217</td>
<td>1.13</td>
</tr>
<tr>
<td>J143050+342614</td>
<td>EV020</td>
<td>0.5 ± 0.3</td>
<td>−0.6 ± 0.0</td>
<td>2.364±0.535</td>
<td>−0.536</td>
<td>2.98</td>
</tr>
<tr>
<td>J143055+350852</td>
<td>EC053</td>
<td>−0.1 ± 0.3</td>
<td>−0.8 ± 0.1</td>
<td>2.195±0.379</td>
<td>−0.397</td>
<td>0.38</td>
</tr>
<tr>
<td>J143213+350940</td>
<td>EV020</td>
<td>−0.1 ± 0.3</td>
<td>−0.3 ± 0.1</td>
<td>0.978±0.100</td>
<td>−0.095</td>
<td>0.96</td>
</tr>
<tr>
<td>J143329+355042</td>
<td>EC053</td>
<td>0.2 ± 0.5</td>
<td>−0.5 ± 0.1</td>
<td>2.821±0.032</td>
<td>1.536</td>
<td>1.37</td>
</tr>
<tr>
<td>J143718+364549</td>
<td>EV020</td>
<td>0.2 ± 0.5</td>
<td>−0.7 ± 0.1</td>
<td>—</td>
<td>—</td>
<td>45</td>
</tr>
<tr>
<td>J144230+355735</td>
<td>EV020</td>
<td>0.1 ± 0.7</td>
<td>−1.0 ± 0.2</td>
<td>—</td>
<td>—</td>
<td>125</td>
</tr>
</tbody>
</table>

Notes:  

a α_{low} was calculated between 153 and 325 MHz.  
b α_{high} was calculated between 325 and 1400 MHz.  
c The spectral indices of the sources were calculated using their WENSS flux densities since they lie outside the area imaged with the VLA-P data (see Section 3.3.1).
Table 3.2: Telescope participation in each project.

<table>
<thead>
<tr>
<th>Radio dish</th>
<th>EC053\textsuperscript{a}</th>
<th>EV020\textsuperscript{a}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effelsberg</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Jodrell Bank</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Medicina</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Noto</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Onsala</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Toruń</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Sheshan</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>WSRT</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Notes: \textsuperscript{a} “Yes” indicates that the telescope provided useful data while “No” indicates that it did not.

solutions were applied to the target sources before they were exported from AIPS for flagging and imaging in DIFMAP. To check that we did not miss any source components, or that any of the sources were significantly offset from the phase center, we started off by making images that were at least $5 \times 5$ arcsec in size. We then cleaned the identified components in smaller images using uniform weighting to get the best possible position accuracy for the components before switching to natural weighting. Since the target sources have flux densities of only a few mJy, we did not self-calibrate them. We finally imaged all of the sources using a uv-taper with a Gaussian value of 0.1 and a Gaussian radius of 15 million wavelengths ($\mathrm{M\lambda}$). The uv-taper downweights the visibilities on baselines to Sheshan, where the uv-plane is sampled the least. This decreases both the resolution and noise of the image, allowing for the detection of diffuse emission around the source.

3.3 Results and General Discussion

In this section we will first discuss the catalogues to which the sources were matched, before presenting the results derived from the EVN observations and the spectra of the sources. This will be followed by a discussion of the 1.4 GHz variability of the sources and the cause of the radio emission.

3.3.1 Matched Catalogues

Table 3.3 contains a list of all the radio catalogues and images to which the sources were matched to constrain their radio spectra. The source matching was done using the method described in Section 3.2 of Coppejans et al. [2015]. In the final column of Table 3.3, a list of the sources with which a positive match were found is given for each of the catalogues.
Table 3.3: Catalogues that were matched to the target sources.

<table>
<thead>
<tr>
<th>Catalogue name</th>
<th>Frequency [MHz]</th>
<th>Resolution [&quot;]</th>
<th>Image noise (^a) [mJy beam(^{-1})]</th>
<th>Positive matches</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIRST</td>
<td>1400</td>
<td>5.4 × 5.4</td>
<td>0.15</td>
<td>All</td>
</tr>
<tr>
<td>NVSS</td>
<td>1400</td>
<td>45 × 45</td>
<td>0.45</td>
<td>All except J142917+332626</td>
</tr>
<tr>
<td>dVMR</td>
<td>1380</td>
<td>13 × 27</td>
<td>0.03</td>
<td>J142850+345420, J143024+352438, J143042+351240, J143050+342614, J143055+350852 and J143213+350940</td>
</tr>
<tr>
<td>GMRT-608</td>
<td>608</td>
<td>5.0 × 5.0</td>
<td>0.04</td>
<td>J142850+345420, J142904+354425, J143024+352438, J143042+351240, J143050+342614 and J143055+350852</td>
</tr>
<tr>
<td>VLA-P</td>
<td>325</td>
<td>5.1 × 5.6</td>
<td>0.2*</td>
<td>All except J143718+364549 and J144230+355735</td>
</tr>
<tr>
<td>WENSS</td>
<td>325</td>
<td>54 × 54</td>
<td>3.6</td>
<td>J143050+342614, J143055+350852, J143213+350940, J143718+364549 and J144230+355735</td>
</tr>
<tr>
<td>WIR</td>
<td>153</td>
<td>25 × 25</td>
<td>2.0*</td>
<td>All</td>
</tr>
<tr>
<td>LOFAR-150</td>
<td>150</td>
<td>5.6 × 7.4</td>
<td>0.11*</td>
<td>All except J143718+364549 and J144230+355735</td>
</tr>
<tr>
<td>LOFAR-62</td>
<td>62</td>
<td>19 × 31</td>
<td>4.8</td>
<td>None</td>
</tr>
</tbody>
</table>

Notes: * Typical catalogue noise values are quoted except for those marked with *, where the noise is measured at the center of the image.
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The GMRT-608 image referenced in Table 3.3 is a mosaic of a part of the Boötes field (at 608 MHz). A mosaic of the entire field will be published once the observations have been completed. The image was made from GMRT observations of a part of the Boötes field (project code 28_064). Four pointings covering 1.95 deg$^2$ were observed on 24 and 26 July 2015. Raw visibilities were recorded every eight seconds in two polarizations (RR and LL), using 512 frequency channels to cover 32.0 MHz of bandwidth centred on 608 MHz. The on-target time for each pointing was between 100 and 110 minutes. Primary flux density calibration was done with 3C286 using the wide-band low-frequency flux density standard of Scaife & Heald [2012]. The data reduction follows that of De Gasperin et al. [2014] and Bonafede et al. [2014] and was done in three stages: (i) initial gain and bandpass calibration, (ii) self-calibration, and (iii) direction-dependent ionospheric phase calibration using the software package SPAM [Intema et al., 2009]. The combined final mosaic reaches a root mean square (rms) noise level of $\approx 40 - 70 \mu$Jy beam$^{-1}$ with a resolution of $5 \times 5$ arcsec. We have checked the consistency of the flux density scale by interpolating between the WIR and dVMR catalogues.

The 150 MHz LOFAR-150 catalogue was made from a new LOFAR survey of the Boötes field (Williams et al., submitted). The image has a resolution of $\sim 6$ arcsec with half of the 19 deg$^2$ image having a local rms noise below 0.18 mJy beam$^{-1}$, both of which are better than the WIR image. The catalogue itself contains 5652 sources detected above a threshold of 5$\sigma$ (Williams et al., submitted). After matching our sources to the catalogue we found that all but one of the LOFAR-150 flux densities were higher than the corresponding WIR flux densities, despite the LOFAR-150 catalogue having a higher resolution. Specifically, the integrated LOFAR-150 flux densities for our sources have a median difference of 27 percent compared to those of the WIR catalogue. Since the LOFAR-150 flux density scale was checked and corrected using the flux densities of the sources in the WIR catalogue (Williams et al., submitted), we elected to use the WIR flux densities when fitting the source spectra (Section 3.3.2). We do however discuss (Section 3.4) and show (Fig. 3.2) the LOFAR-150 flux densities for each of the sources in their spectral plots. We finally note that J143718+364549 and J144230+355735 fall outside the area imaged by the LOFAR-150 catalogue.

Finally, the LOFAR-62 catalogue [Van Weeren et al., 2014] is a catalogue constructed from LOFAR Low Band Antenna (LBA) commissioning observations at 62 MHz of the Boötes field. While all our sources lie in the image, none of them are detected at the catalogue’s 5$\sigma$ detection threshold. To determine the detection threshold for each source (given in Table 3.4), we measured the the local rms noise in a $320 \times 320$ arcsec box, as was done by Van Weeren et al. [2014], centred on each of the sources’ positions and multiplied it by five. We used the local noise, rather than the typical noise of the catalogue (given in Table 3.3), since the noise at the position of each of our sources will likely differ from the typical noise. This helped us to constrain the spectra of some of the sources (see Fig. 3.2 and Section 3.4).

In Fig. 3.1, the colour-colour diagram for the sources is shown. For all the sources, except J143718+364549, J144230+355735 and J143213+350940 WENSS, $\alpha_{\text{low}}$ was calculated between the flux densities of the WIR and VLA-P catalogues. $\alpha_{\text{high}}$ was calculated between those of the VLA-P and FIRST catalogues. Since J143718+364549 and J144230+355735 are not in the VLA-P image, $\alpha_{\text{low}}$ and $\alpha_{\text{high}}$ were calculated from their WENSS flux densities. Since the VLA-P and
3.3 Results and General Discussion

<table>
<thead>
<tr>
<th>Source ID</th>
<th>Detection threshold [mJy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>J142850+345420</td>
<td>28.7</td>
</tr>
<tr>
<td>J142904+354425</td>
<td>43.8</td>
</tr>
<tr>
<td>J142917+332626</td>
<td>75.3</td>
</tr>
<tr>
<td>J143024+352438</td>
<td>46.8</td>
</tr>
<tr>
<td>J143042+351240</td>
<td>47.2</td>
</tr>
<tr>
<td>J143050+342614</td>
<td>36.2</td>
</tr>
<tr>
<td>J143055+350852</td>
<td>30.4</td>
</tr>
<tr>
<td>J143213+350940</td>
<td>32.2</td>
</tr>
<tr>
<td>J143329+355042</td>
<td>36.1</td>
</tr>
<tr>
<td>J143718+364549</td>
<td>50.9</td>
</tr>
<tr>
<td>J144230+355735</td>
<td>68.1</td>
</tr>
</tbody>
</table>

WENSS flux densities differ significantly for J143213+350940, we also plotted J143213+350940’s position in Fig. 3.1 if α_{low} and α_{high} are calculated using its WENSS flux density rather than the VLA-P flux density. This will be discussed in detail in Section 3.4.3.3. The MPS sources in Coppejans et al. [2015] were selected from the area below and to the right of the dotted lines in Fig. 3.1, which are defined by α_{high} < -0.5 and α_{high} < 1.5α_{low} - 0.5. The first constraint ensures that the sources have a steep spectrum above 1GHz. The second allows us to not only select the sources with a clear spectral peak, but also sources whose spectra flatten towards lower frequencies, which could indicate a spectral turnover below 153MHz. We note that in Fig. 3.1, J143213+350940 does not satisfy the selection criteria, while J143213+350940 WENSS does (Section 3.4.3.3).

3.3.2 Source properties

In Table 3.5, the parameters derived for the sources are presented with the sources components named as the source name followed by a letter. These components are shown in the EVN images presented in Figures 3.4 through 3.8.
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Figure 3.1: A colour-colour diagram of the sources. In the plot, $\alpha_{\text{low}}$ and $\alpha_{\text{high}}$ were calculated as explained in Section 3.3.1. The dotted vertical line indicates a spectral index of zero while the MPS sources were selected from the region below and to the right of the dashed line.
Table 3.5: Derived parameters of the sources.

<table>
<thead>
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<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
<td>(7)</td>
</tr>
<tr>
<td>J142850+345420</td>
<td>250</td>
<td>—</td>
<td>—</td>
<td>8.16 ± 0.77</td>
<td>—</td>
<td>47.6 ± 0.7 $^c$</td>
</tr>
<tr>
<td>J142850+345420a</td>
<td>250</td>
<td>14:28:50.4688(0.00007)</td>
<td>34:54:20.8346(0.0011)</td>
<td>6.25 ± 0.61</td>
<td>29.9 ± 1.7</td>
<td>29.9 ± 1.7</td>
</tr>
<tr>
<td>J142850+345420b</td>
<td>250</td>
<td>14:28:50.4689(0.00015)</td>
<td>34:54:20.8206(0.0022)</td>
<td>1.91 ± 0.47</td>
<td>21.9 ± 1.2</td>
<td>21.9 ± 1.2</td>
</tr>
<tr>
<td>J142904+354425</td>
<td>23</td>
<td>14:29:04.6*</td>
<td>35:44:25.1*</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>J142917+332626</td>
<td>170</td>
<td>14:29:17.4220(0.00003)</td>
<td>33:26:26.6001(0.0004)</td>
<td>3.47 ± 0.32</td>
<td>13.0 ± 0.5</td>
<td>13.0 ± 0.5</td>
</tr>
<tr>
<td>J143024+352438</td>
<td>11</td>
<td>14:30:24.3*</td>
<td>35:24:38.1*</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<tr>
<td>J143042+351240</td>
<td>18</td>
<td>14:30:42.57796(0.00004)</td>
<td>35:12:40.6253(0.0006)</td>
<td>0.20 ± 0.03</td>
<td>12.1 ± 1.5</td>
<td>12.1 ± 1.5</td>
</tr>
<tr>
<td>J143050+342614</td>
<td>198</td>
<td>14:30:50.90925(0.00003)</td>
<td>34:26:14.1890(0.0004)</td>
<td>3.53 ± 0.50</td>
<td>3.0 ± 0.4</td>
<td>15.4 ± 1.8</td>
</tr>
<tr>
<td>J143055+350852</td>
<td>88</td>
<td>—</td>
<td>—</td>
<td>5.81 ± 0.37</td>
<td>—</td>
<td>137.9 ± 4.4 $^c$</td>
</tr>
<tr>
<td>J143055+350852a</td>
<td>88</td>
<td>14:30:55.0759(0.00001)</td>
<td>35:08:52.8445(0.0002)</td>
<td>3.78 ± 0.23</td>
<td>13.1 ± 0.4</td>
<td>13.1 ± 0.4</td>
</tr>
<tr>
<td>J143055+350852b</td>
<td>88</td>
<td>14:30:55.0795(0.00020)</td>
<td>35:08:52.9619(0.0030)</td>
<td>2.03 ± 0.29</td>
<td>47.0 ± 5.9</td>
<td>47.0 ± 5.9</td>
</tr>
<tr>
<td>J143213+350940**</td>
<td>400</td>
<td>—</td>
<td>—</td>
<td>14.41 ± 1.64</td>
<td>30.1 ± 2.2</td>
<td>69.6 ± 5.2</td>
</tr>
<tr>
<td>J143213+350940a**</td>
<td>201</td>
<td>14:32:13.54889(0.00016)</td>
<td>35:09:40.8707(0.0023)</td>
<td>5.35 ± 0.86</td>
<td>31.5 ± 4.7</td>
<td>31.5 ± 4.7</td>
</tr>
<tr>
<td>J143213+350940b**</td>
<td>201</td>
<td>14:32:13.55036(0.00001)</td>
<td>35:09:40.8569(0.0002)</td>
<td>2.81 ± 0.32</td>
<td>4.1 ± 0.3</td>
<td>4.1 ± 0.3</td>
</tr>
<tr>
<td>J143329+355042</td>
<td>95</td>
<td>14:33:29.85779(0.00001)</td>
<td>35:50:22.2509(0.0001)</td>
<td>5.85 ± 0.33</td>
<td>4.0 ± 0.1</td>
<td>19.3 ± 0.4</td>
</tr>
<tr>
<td>J143718+364549</td>
<td>175</td>
<td>14:37:18.09615(0.00009)</td>
<td>36:45:49.8219(0.0013)</td>
<td>6.07 ± 0.53</td>
<td>40.2 ± 2.7</td>
<td>40.2 ± 2.7</td>
</tr>
<tr>
<td>J144230+355735**</td>
<td>30</td>
<td>—</td>
<td>—</td>
<td>2.32 ± 0.17</td>
<td>—</td>
<td>134.4 ± 0.7 $^c$</td>
</tr>
<tr>
<td>J144230+355735a**</td>
<td>36</td>
<td>14:42:30.69966(0.00036)</td>
<td>35:57:35.0993(0.0054)</td>
<td>0.56 ± 0.21</td>
<td>29.4 ± 10.8</td>
<td>29.4 ± 10.8</td>
</tr>
<tr>
<td>J144230+355735b**</td>
<td>36</td>
<td>14:42:30.69602(0.00019)</td>
<td>35:57:35.0979(0.0028)</td>
<td>0.63 ± 0.19</td>
<td>11.4 ± 3.3</td>
<td>33.3 ± 9.6</td>
</tr>
<tr>
<td>J144230+355735c**</td>
<td>36</td>
<td>14:42:30.69416(0.00053)</td>
<td>35:57:35.0776(0.0080)</td>
<td>0.31 ± 0.19</td>
<td>26.3 ± 15.8</td>
<td>26.3 ± 15.8</td>
</tr>
</tbody>
</table>

Notes: $^a$ The uncertainty, in arcseconds, is given in brackets after the value. $^b$ For all the multi-component sources except J143213+350940 and J144230+355735 (see note **), the value is the sum of the integrated flux densities of their components. $^c$ The value is the source size (distance between the centroids of the two furthest components). $^d$ For sources with two values, the first was calculated using $z_{\text{ext}}$ and the second using $z_{\text{int}}$. $^e$ For sources without redshifts, the values were calculated using a redshift of zero. $^f$ For sources with upper limits, the limit was calculated using $z = 1$. $^g$ The uncertainty, in seconds, is given in brackets after the value. $^h$ Since the source was not detected with the EVN, the RA and DEC values are taken from FIRST. ** The values of the source were derived from the uv-tapered image while the values of the components were derived from the non-uv-tapered image (see Sections 3.4.3.3 and 3.4.3.5).
### Table 3.5 continued...

<table>
<thead>
<tr>
<th>Source ID</th>
<th>% flux density (1)</th>
<th>$T_b^{d,e}$ [×10^6 K] (9)</th>
<th>$\nu_o$ [GHz] (10)</th>
<th>$\nu_r^d$ [GHz] (11)</th>
<th>LLS $^{d,f}$ [pc] (12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J142917+332626</td>
<td>57 ± 6</td>
<td>23.4 ± 3.9 &amp; 31.6 ± 3.4</td>
<td>0.39 ± 0.06</td>
<td>1.00 ± 0.20 &amp; 1.35 ± 0.21</td>
<td>107 ± 8 &amp; 102 ± 7</td>
</tr>
<tr>
<td>J143024+352438</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>J143042+351240</td>
<td>4 ± 1</td>
<td>1.4 ± 0.4 &amp; 1.3 ± 0.3</td>
<td>0.23 ± 0.11</td>
<td>0.51 ± 0.25 &amp; 0.49 ± 0.23</td>
<td>97 ± 14 &amp; 96 ± 12</td>
</tr>
<tr>
<td>J143050+342614</td>
<td>33 ± 5</td>
<td>113.0 ± 30.7 &amp; 133.7 ± 29.4</td>
<td>0.34 ± 0.08</td>
<td>1.13 ± 0.31 &amp; 1.33 ± 0.30</td>
<td>122 ± 20 &amp; 115 ± 15</td>
</tr>
<tr>
<td>J143055+350852</td>
<td>71 ± 6</td>
<td>—</td>
<td>0.18 ± 0.09</td>
<td>0.56 ± 0.30 &amp; 0.24 ± 0.13</td>
<td>1105 ± 99 &amp; 698 ± 56</td>
</tr>
<tr>
<td>J143055+350852a</td>
<td>—</td>
<td>31.5 ± 4.6 &amp; 13.6 ± 1.0</td>
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<td>—</td>
<td>—</td>
</tr>
<tr>
<td>J143055+350852b</td>
<td>—</td>
<td>1.3 ± 0.3 &amp; 0.6 ± 0.1</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>J143213+350940**</td>
<td>94 ± 12</td>
<td>6.1 ± 1.0 &amp; 6.0 ± 0.9</td>
<td>0.27 ± 0.13</td>
<td>0.54 ± 0.26 &amp; 0.53 ± 0.25</td>
<td>539 ± 66 &amp; 537 ± 53</td>
</tr>
<tr>
<td>J143213+350940a</td>
<td>—</td>
<td>4.7 ± 1.3 &amp; 4.7 ± 1.2</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>J143213+350940b</td>
<td>—</td>
<td>145.7 ± 24.0 &amp; 144.3 ± 22.6</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>J143329+355042</td>
<td>92 ± 9</td>
<td>128.1 ± 68.6 &amp; 79.5 ± 5.0</td>
<td>0.35 ± 0.10</td>
<td>1.33 ± 0.80 &amp; 0.83 ± 0.23</td>
<td>139 ± 26 &amp; 158 ± 8</td>
</tr>
<tr>
<td>J143718+364549</td>
<td>68 ± 9</td>
<td>&gt; 1.7 ± 0.2</td>
<td>0.34 ± 0.10</td>
<td>—</td>
<td>&lt; 313 ± 29</td>
</tr>
<tr>
<td>J144230+355735**</td>
<td>69 ± 14</td>
<td>—</td>
<td>0.30 ± 0.10</td>
<td>—</td>
<td>&lt; 1046 ± 28</td>
</tr>
<tr>
<td>J144230+355735a</td>
<td>—</td>
<td>&gt; 0.3 ± 0.2</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>J144230+355735b</td>
<td>—</td>
<td>&gt; 0.7 ± 0.4</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>J144230+355735c</td>
<td>—</td>
<td>&gt; 0.2 ± 0.2</td>
<td>—</td>
<td>—</td>
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</tr>
</tbody>
</table>
3.3 Results and General Discussion

Columns (2), (3) and (4) in Table 3.5 are the rms noise, the right ascension (RA) and declination (DEC), respectively, of each of the components of the source in the EVN image. The uncertainty of the RA and DEC are given in brackets after the value. The uncertainties were calculated using the equation given in Fomalont [1999], to this we added the uncertainty of the position of the phase calibrator from the VLBA calibrator list\(^1\) (0.14 mas and 0.11 mas for J1422+3223 and J1430+3649, respectively), in quadrature.

Column (5) gives the EVN integrated flux density at 1.7 GHz. The values were determined by fitting circular Gaussian brightness distribution models in difmap to all of the sources and source components except J143050+342614, J143213+350940, J143329+355042 and J144230+355735b. These sources were fitted with elliptical Gaussians since the fit did not converge when fitting circular Gaussians or the circular fit clearly does not describe the flux density distribution of the source. Since difmap does not report an error on the integrated flux density, the errors were calculated using the equations in Fomalont [1999] and adding an additional five percent to account for the VLBI amplitude calibration uncertainty, as done by e.g. Frey et al. [2015] and An et al. [2012]. The integrated flux densities for all the multi-component sources except J143213+350940 and J144230+355735 are the sum of the individual components where the flux density errors were calculated by adding the errors of the individual components in quadrature. See Sections 3.4.3.3 and 3.4.3.5 on how the values for J143213+350940 and J144230+355735 were calculated.

Columns (6) and (7) contain the minor- and major-axis full width at half-maximum (FWHM) of the Gaussians fitted to the sources. The errors were calculated using the equations in Fomalont [1999]. For the sources which were fitted with a circular Gaussian, the values in columns (6) and (7) are the same. For all of the sources, the values in column (7) were used as the source size. If the source was resolved into multiple components, the size was determined by calculating the distance between the centers of the two components that are the furthest apart, taking into account the uncertainties of the central positions. Note, however, that while J143213+350940 is composed of multiple components, we fitted both components simultaneously with a single elliptical Gaussian (see Section 3.4.3.3). Hence the values reported for J143213+350940 are the minor- and major-axis of the fitted Gaussian.

Column (8) gives the percentage of the predicted flux density that was recovered from the image. The value was calculated using \(100S_i/S_{\text{predicted}}\), where \(S_i\) is the integrated EVN flux density of the sources given in column (5) and \(S_{\text{predicted}}\) is the sources’ predicted flux density at 1.7 GHz. \(S_{\text{predicted}}\) was calculated using \(\alpha_{\text{high}}\) from Table 3.1 in combination with the equation \(S_{\text{predicted}} = k\nu^\alpha\). The constant \(k\) was calculated for each source using its integrated FIRST flux density. The errors of the values in Column (8) were calculated by propagating the errors of \(S_i\) and \(S_{\text{predicted}}\).

The redshift-corrected brightness temperatures of the sources in column (9) were calculated using

\[
T_b = 1.22 \times 10^{12}(1 + z)\frac{S_i}{\theta_1\theta_2\nu^2}
\]

[Condon et al., 1982]. Here, \(z\) is the redshift, \(S_i\) is the integrated flux density in Jy, \(\theta_1\) and \(\theta_2\) are the major- and minor-axis of the Gaussian fitted to the source in mas, and \(\nu\) is the observing frequency in GHz. If the source component was fitted with a circular Gaussian, \(\theta_1 = \theta_2\). Since we

\(^1\)http://www.vlba.nrao.edu/astro/calib/
have two photometric redshifts for each source, we opted to calculate two values for each source for the relevant parameters in Table 3.5. Since the upper and lower uncertainties of $z_{\text{Eazy}}$ are not symmetrical, we used the larger of the two as the uncertainty to calculate the errors reported for the relevant parameters. For the LRT code, which does not report an uncertainty on the redshift, we used an uncertainty of zero. Finally, to get robust lower limits for $T_b$ for the sources without redshifts, we used a redshift of zero for these sources.

Column (10) contains the fitted observed turnover frequency ($\nu_o$) for each source. Following Orienti et al. [2007], Scaife & Heald [2012] and Orienti & Dallacasa [2014], we calculate $\nu_o$ by fitting a second order polynomial of the form $\log_{10}(S_i) = a(\log_{10}(\nu) - \log_{10}(\nu_o))^2 + b$ to the spectral plot of each of the sources where $a$ and $b$ are constants. The spectral points to which that function was fitted are composed of the flux densities from the FIRST, GMRT-608, VLA-P and WIR catalogues and are shown in Fig. 3.2. For J143718+364549 and J144230+355735, which do not have VLA-P flux densities, we used the WENSS flux density. Since this involves fitting a function with three unknown parameters to three data points for the sources without GMRT-608 flux densities, the error values reported by the fitting algorithm can not be trusted for these sources. To improve the error estimates, we used a Monte Carlo method to estimate $\nu_o$ and its error for all the sources. To do this, we used a random number generator to find new flux density values at each frequency for the source and calculated a new value of $\nu_o$. The flux densities returned by the random number generator are Gaussian distributed values centred on the original flux density with a standard deviation equal to the error on the flux density. Repeating the procedure 100,000 times, we generated a histogram of all the solutions and fitted a Gaussian to it. The final value reported for $\nu_o$ is the median of the fitted Gaussian and the error is its standard deviation. We note that the addition of the GMRT-608 flux densities significantly decreased the uncertainty on the position of the peak frequency for the relevant sources.

Column (11) gives the rest-frame turnover frequency of the sources with known redshifts. The values were calculated using $\nu_r = \nu_o (1 + z)$ where the errors of the $z_{\text{Eazy}}$ values were dealt with as was described for columns (7) and (8).

Column (12) contains the largest linear sizes (LLS) of the sources calculated using their angular sizes and redshifts. For the sources which have EVN sizes but not redshifts, we calculated upper limits using $z = 1$. This can be done because, given a source with fixed linear size, its angular size will decrease as a function of redshift from $z = 0$ to $z \sim 1$. However, at $z > 1$, increasing the redshift of the source results in a slight, but systematic, increase in its angular size (see for example fig. 10 in Falcke et al. [2004]). Because of this, for a fixed angular size, a plot of the linear size to which it corresponds as a function of redshift peaks at $z = 1$.

### 3.3.3 Are they resolved?

To test if the source components are resolved in the EVN images, we calculated the minimum resolvable size of each of the Gaussian components fitted to the sources using Equation 2 in Kovalev et al. [2005]. Since all the fitted source sizes are larger than the minimum resolvable size, we conclude that all the sources and their components are resolved in the EVN images.
Figure 3.2: The spectral plots of the sources where the solid line is added to guide the eye. For J143050+342614, the VLA-P and WENSS flux densities are indistinguishable, with the larger of the two error bars being associated with the WENSS flux density. The LOFAR-62 detection limits, given in Table 3.4, are shown as a empty downward triangle for the sources where they help to constrain the spectrum.
Chapter 3: What are the MPS sources?

Figure 3.3: Figure 3.2 continued.
### 3.3 Results and General Discussion

#### 3.3.4 1.4 GHz Variability

In Section 3.2.1, we pointed out that J142850+345420, J143024+352438, J143042+351240, J143055+350852 and J143213+350940 have flux density differences of more than 20 percent between either FIRST and dVMR or NVSS and dVMR. This could potentially indicate that these sources are variable. However, it is surprising that all five sources have flux density differences of more than 20 percent with the dVMR catalogue, while they all have a flux density difference of less than 12 percent between FIRST and NVSS. We therefore checked the flux density offset between the dVMR catalogue and FIRST and dVMR and NVSS for the 190 VLA-P sources that we matched to all three catalogues in Coppejans et al. [2015], excluding only the sources that were flagged as extended. Doing this, we found that the median values of \( \frac{S_{dVMR}}{S_{FIRST}} \), \( \frac{S_{dVMR}}{S_{NVSS}} \) and \( \frac{S_{NVSS}}{S_{FIRST}} \) are 1.16, 1.07 and 1.07, respectively. Since the dVMR flux densities were calibrated against NVSS [De Vries et al., 2002a], it is not surprising that their flux densities agree well with each other. What is interesting is that the flux densities of FIRST and NVSS, the highest and lowest resolution catalogues, agree well with each other but that the values for dVMR and FIRST do not agree as well. If anything we would expect that the dVMR values should be higher than those of FIRST since its resolution is three and a half times lower than that of FIRST. Of the 190 sources, the dVMR flux density of 124 are higher than both those of FIRST and NVSS. This seems to indicate that the dVMR flux densities are slightly higher than those of FIRST for our sub-selection of sources. Hence, the five sources that have a flux density difference of more than 20 percent between FIRST or NVSS and dVMR are not necessarily variable.

One possible reason why the sources could be variable is that they are blazars, which are radio-loud AGN whose jet is pointed within a small angle of our line of sight [e.g. Urry, 1999; Krawczynski & Treister, 2013]. It is however very unlikely that any of the sources (including J142904+354425 and J143024+352438 which we did not detect) are blazars since blazars have brightness temperatures above \( \sim 10^{10} \)K [Readhead, 1994; Homan et al., 2006], which is significantly higher than the values derived for our targets. In addition, blazars have flat spectra in the MHz regime [Massaro et al., 2013a] which is not the case for any of our sources. Hence we do not believe that any of the sources are blazars and are therefore highly unlikely to be variable. It is also worth pointing out that the GPS and CSS sources are the least variable class of radio AGN [O’Dea, 1998].

#### 3.3.5 The origin of the radio emission

To test if the observed radio emission could be the result of star formation in the host galaxies, we used the same method as Magliocchetti et al. [2014] to differentiate between star forming galaxies and AGN using only radio luminosity. The method presented by Magliocchetti et al. [2014] is based on the results of McAlpine et al. [2013] who used the optical and near-infrared spectral energy distributions of 942 1.4 GHz radio sources to calculate luminosity functions and redshifts for star forming and AGN dominated radio galaxies. Using these results, Magliocchetti et al. [2014] calculated that the radio power beyond which AGN-powered sources are dominant over star forming sources scale with redshift as

\[
\log_{10} P_{\text{cross}}(z) = \log_{10} P_{0,\text{cross}} + z
\]
up to \( z \sim 1.8 \). Where \( P_{0,\text{cross}} = 10^{21.7} \text{W Hz}^{-1} \text{sr}^{-1} \) is the value at \( z = 0 \).\(^2\) Magliocchetti et al. [2014] notes that for a given redshift, the amount of star forming galaxies with radio powers larger than this value drops steeply and that at all redshifts, the radio luminosity function of star-forming galaxies drops off much steeper than that of AGN. Hence, the authors expect there to be very little contamination between the selections of star-forming and AGN galaxies [Magliocchetti et al., 2014].

To calculate the radio power of our sources, we used the same relation as Magliocchetti et al. [2014]:

\[
P_{1.4\text{GHz}} = S_{1.4\text{GHz}}D^2(1+z)^{3-\alpha}.
\]

Here \( P_{1.4\text{GHz}} \) is in units of \([\text{W Hz}^{-1} \text{sr}^{-1}]\), \( S_{1.4\text{GHz}} \) is the FIRST flux density in Jy converted to units of \([\text{W m}^{-2} \text{Hz}^{-1} \text{sr}^{-1}]\), \( D \) is the angular diameter distance in meters and \( \alpha \) is the high-frequency spectral index of the source reported in Table 3.1. Note that we use an exponent of \( 3 - \alpha \) as opposed to \( 3 + \alpha \) in Equation 3.3 since Magliocchetti et al. [2014] define the spectral index as \( S \propto \nu^{-\alpha} \).

Following Magliocchetti et al. [2014], sources at \( z \leq 1.8 \) are classified as AGN powered if \( P_{1.4\text{GHz}} > P_{\text{cross}}(z) \), and as star formation powered if \( P_{1.4\text{GHz}} < P_{\text{cross}}(z) \). For sources at \( z > 1.8 \), the classification is done in the same way except that \( P_{\text{cross}}(z) \) is always equal to \( 10^{23.5} \text{W Hz}^{-1} \text{sr}^{-1} \). Using both the minimum EAZY redshift allowed inside the errors and the LRT redshift, we found that in all the sources for which we have redshifts, the radio emission is from an AGN not star formation. While we do not have redshifts for J142850+345420, J143718+364549 and J144230+355735, the minimum redshift at which the emission would be the result of star formation is 0.06 for both J142850+345420 and J143718+364549 and 0.1 for J144230+355735.

Brightness temperatures can also be used to differentiate between star formation and AGN activity. Thermal radio emission caused by star formation typically has \( T_b < 10^5 \text{K} \) [Sramek & Weedman, 1986; Condon et al., 1991; Kewley et al., 2000] while \( T_b \geq 10^6 \text{K} \) can be used as an indicator of non-thermal emission from AGN [e.g. Kewley et al., 2000; Middelberg et al., 2011]. Since all the sources have \( T_b \geq 10^6 \text{K} \) inside their errors, this confirms that the radio emission is from AGN activity. This is further supported by the morphologies of the sources that are resolved into multiple components (Section 3.4). We note that non-thermal emission could also originate from a supernova remnant or a nuclear supernova remnant complex [e.g. Alexandroff et al., 2012]. However, this possibility is excluded by the power cut described above.

### 3.4 Comments on Individual Sources

#### 3.4.1 Non-detections

The following two sources were not detected in the EVN images. Tapering the data also did not result in a detection, and from Section 3.3.5 we do not expect that the radio emission is caused by star formation. Below we conclude that the non-detections are because the sources have extended lobes which were resolved out by the high-resolution EVN observations while the

\(^2\)We note that in Magliocchetti et al. [2014] the units for \( P_{0,\text{cross}} \) are incorrectly shown as \([\text{W Hz sr}^{-1}]\).
faint core remains undetected. We note that this conclusion could be tested by observing the sources with an instrument that probes angular sizes between 0.15 and 5 arcsec.

3.4.1.1 J142904+354425

J142904+354425 is not detected in the naturally weighted, 5×5 arcsec EVN image with 23μJy beam⁻¹ noise and a 30 × 34 mas restoring beam. J142904+354425 was included in our MPS selection in Coppejans et al. [2015] and was not flagged as being variable based on its FIRST and NVSS flux densities. No match could be found for it in the dVMR catalogue because it lies outside the area that was imaged. J142904+354425 was detected by Garrett et al. [2005] using the WSRT at 1.4 GHz and found to be smaller than 5 arcsec, having an integrated flux density of 3.026 ± 0.026 mJy³ which is only 45 percent of the FIRST value. Hence we cannot rule out the possibility that J142904+354425 is variable, but based on the arguments at the end of Section 3.3.4, we consider this to be very unlikely.

To constrain J142904+354425 size we note that it has a deconvolved major and minor axis FWHM of 2.8 ± 0.5 and 1.7 ± 0.5 arcsec, respectively, in FIRST at a position angle of 41.6° east of north. We can estimate its minimum size by assuming it consists of a single component that has a surface brightness below the EVN’s detection threshold. Taking the detection threshold to be five times the rms noise of the image (0.115 mJy beam⁻¹), the flux density has to be spread out over at least 3.026/0.115 = 26.3 beams which translates to a minimum angular size of approximately 0.9 arcsec.

Considering that J142904+354425’s predicted flux density at 1.7 GHz is 4.9 ± 0.4 mJy, that it is an AGN (Section 3.3.5) and non-variable, we conclude that the non-detection is because J142904+354425 was resolved out by the EVN observations. Finally, as is evident from the Fig. 3.2, we cannot say for certain that J142904+354425’s spectrum turns over.

3.4.1.2 J143024+352438

J143024+352438 is not detected in the naturally weighted, 5×5 arcsec EVN image with 11μJy beam⁻¹ noise and a restoring beam of 6 × 18 mas. Considering that J143024+352438 has a predicted 1.7 GHz flux density of 2.7 ± 0.2 mJy, we should have easily detected it if it is a compact source. From Fig. 3.2 it is clear that the flux density difference between the WIR and LOFAR-150 catalogues (7.0 ± 3.0 and 14.6 ± 1.5 mJy, respectively) can have a significant impact on the shape of J143024+352438’s spectrum. It is worth pointing out that J143024+352438 has a signal-to-noise ratio (SNR; defined as the peak brightness divided by the local rms noise) of 49 and 5 in the LOFAR-150 and WIR images, respectively. It is therefore possible that the spectrum can be described by a single power law between 150 and 1400 MHz.

Since we do not expect that the radio emission is caused by star formation⁴, we conclude

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³We note that Garrett et al. [2005] did not include the absolute calibration error (which the authors estimate to be less than 2 percent) in their flux density error.

⁴We note that matching J143024+352438 to the SDSS Data Release 10 catalogue [https://www.sdss3.org/dr10/; Ahn et al., 2014], we found a source (SDSS J143025.19+352441.3) 3.3 arcsec away from J143024+352438 with a photometric redshift of 0.342±0.1167. This could influence whether J143024+352438 is classified as being dominated by star formation or an AGN. However, using the analysis in Section 3.3.5, J143024+352438 would only be classified as being dominated by star formation if it is at a redshift below 0.11.
that J143042+351240 has lobes which were resolved out by the EVN observations while the faint core remains undetected. J143024+352438’s maximum size is set by its deconvolved major axis FWHM of $4.2 \pm 0.8$ arcsec in FIRST, which is at a position angle of $164.7^\circ$. J142904+354425’s minor axis is unresolved in FIRST. Using the same argument presented for J142904+354425, we calculated a minimum angular size of approximately 1 arcsec for J143024+352438.

### 3.4.2 Marginally resolved sources

The following four sources appear as single components in the EVN images that do not have a discernible structure. Note that from Section 3.3.3, all of the sources are resolved. Below we discuss each of the sources individually, focusing on, among other things, the percentage of the predicted flux density that was recovered from the image and the source variability. If the percentage of the predicted flux density recovered from the image is low, it could indicate that the measured source size is not a good estimate of the true source size. If, however, the sources are variable, it would mean that the predicted flux density is unreliable. Hence the source could be more extended or has an additional component that could have been missed in the EVN image. While we argue that none of the sources are variable, based on the percentage of the predicted flux densities recovered from the images, we conclude that J143042+351240 and J143050+342614 likely have undetected structure, and are therefore larger than indicated in Table 3.5.

#### 3.4.2.1 J142917+332626

J142917+332626 is present in both the NVSS and dVMR image cutouts, but not in the catalogues because there is another source $\sim 35$ arcsec away which blends with it. To determine its flux density in NVSS we simultaneously fit it and the nearby source using the PYBDSM source detection package\(^5\). From this we found that it has an integrated flux density of $6.96 \pm 1.01$ mJy, which differs by 2.5 percent from the FIRST value. J142917+332626 was also observed by Ciliegi et al. [1999a] at 1.4 GHz with the VLA in C configuration. The authors found a flux density of $6.27 \pm 0.04$ mJy for J142917+332626 which differs by 11 percent from the FIRST value. Considering that we recovered between 51 and 63 percent of the predicted flux density, we expect that the reported size for J142917+332626 is a good estimate of the true size.

Matching the VLA-P sources to the Chandra XBoötes X-ray survey of the Boötes field [Murray et al., 2005] with a search radius of 10 arcsec, J142917+332626 was the only source from our 11 sources for which we found a counterpart. The centroid of the matched source, CXOXB J142917+332626.4, is 0.32 arcsec away from the VLA-P source and was detected in all three of Chandra’s bands with seven, one and six counts in the 0.5–7, 0.5–2 and 2–7 keV bands, respectively.

We note that, since J142917+332626 can unambiguously be classified as an MPS source (Fig. 3.1), it is one of the few turnover sources with a X-ray counterpart.

Matching the FIRST sources to those in XBoötes, El Bouchefry [2009] associated CXOXB J142917+332626.4 with the same FIRST source to which we matched the VLA-P source. In addition, CXOXB J142917+332626.4 was matched to an optical source in the NOAO Deep Wide-Field Survey (NDWFS) survey of the field by Brand et al. [2006]. Using the publicly available

3.4 Comments on Individual Sources

EL Bouchefry [2009] determined a photometric redshift of $0.960^{+1.227}_{-0.806}$ for J142917+332626. This value is consistent with the EAZY redshift of J142917+332626 and is lower than the LRT value.

Based on its high X-ray to optical flux ratio, $\log_{10}(f_{\text{(2-7)keV}}/f_{\text{opt}}) = 1.37$, J142917+332626 is expected to either be a high-redshift source and/or dust obscured [El Bouchefry, 2009, and references therein]. The author classifies it as an obscured AGN (AGN-2) using its hardness ratio and X-ray luminosity.

3.4.2.2 J143042+351240

J143042+351240’s EVN flux density of 0.2 mJy is only $4 \pm 1$ percent of the predicted value. Tapering the data did not increase J143024+352438’s flux density significantly. Since the emission is related to AGN activity and J143042+351240 is not variable (Sections 3.3.5 and 3.3.4), this leads us to conclude that the true size of J143042+351240 is larger than indicated in columns (7) and (12) in Table 3.5. If this is the case, the remaining flux density could be in low surface brightness emission surrounding the source. In this case the true source size will be larger than the measured value, but likely not significantly. If however the missing flux density is in a second component, the size could be a significant underestimate of the true source size.

We were able to match J143042+351240 to a source in the AGN and Galaxy Evolution Survey [AGES; Kochanek et al., 2012] catalogue which measured redshifts for 23,745 galaxies and AGN in the Boötes field. The photometric redshift of the AGES source (0.96) agrees very well with the values reported in Table 3.1. The flux density difference between the WIR and LOFAR-150 catalogues ($14.0 \pm 4.0$ and $23.8 \pm 2.4$ mJy, respectively) can have a significant impact on the shape of J143042+351240’s spectrum (Fig. 3.2). The two catalogues have SNRs of 9 and 98, respectively. It is therefore possible that the spectrum (Fig. 3.2) can be described by a single power law between 150 and 1400 MHz.

3.4.2.3 J143050+342614

We only recovered 33 percent of the predicted flux density for J143050+342614. This percentage did not increase when we applied an uv-taper to the image. The emission is related to AGN activity and the source is not variable (Sections 3.3.5 and 3.3.4). As is the case with J143042+351240, this leads us to conclude that J143050+342614 is larger than indicated in columns (7) and (12) in Table 3.5. We note that J143050+342614 can unambiguously be classified as an MPS source when including the errors on its spectral indices. It is also matched to a WENSS source with the WENSS and VLA-P flux densities differing by less than one per cent. This results in the two points being indistinguishable in J143050+342614’s spectral plot (Fig. 3.2) with the larger of the two error bars being associated with the WENSS flux density.

3.4.2.4 J143329+355042

J143329+355042 is composed of a single component in the EVN image and lies outside the survey area covered by the dVMR catalogue. We recovered $92 \pm 9$ percent of J143329+355042’s

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*http://webast.ast.obs-mip.fr/hyperz/*
Chapter 3: What are the MPS sources?

predicted flux density. This indicates that its measured size is a good estimate of its true size. J143329+355042's spectrum (shown in Fig. 3.2) flattens toward lower frequencies and could turn over (Table 3.1).

3.4.3 Resolved sources

The following five sources are resolved in the EVN images and have a discernible structure. Below we discuss each of the sources individually and argue that the observed structures are lobes and/or hotspots in their jets.

3.4.3.1 J142850+345420

J142850+345420, shown in Fig. 3.4, has a double structure in the EVN image with J142850+345420a and J142850+345420b being detected at a $14\sigma$ and $5\sigma$ level, respectively. Fig. 3.4 was made using natural weighting and applying an uv-taper. The full-resolution, uniformly weighted image has a typical resolution of $3 \times 10$ mas, but we could not confirm the detection of J142850+345420b. Applying the uv-taper increased the beam size to $24.1 \times 26.8$ mas and resulted in the flux density of both components increasing. Specifically, the flux density of J142850+345420a increased by a factor of 1.7 and the percentage of recovered flux density of the source as a whole increases from 44 to 99 percent. This is a clear indication that both components were resolved in the full resolution image.

For J142850+345420, we recovered 99 percent of the predicted flux density, this indicates that its measured size is a good estimate of its true size. J142850+345420 was however flagged as being variable because of a 26 percent flux density difference between the FIRST and dVMR catalogues. Considering that the NVSS and FIRST flux densities only differ by 7 percent, and that, as discussed in Section 3.2.1, the dVMR flux densities seem to be systematically higher than the FIRST and NVSS values for our sample of sources, it is unlikely that J142850+345420 is variable.

J142850+345420 lies inside the multiwavelength optical coverage of the Boötes field, but no match could be found for the source. Consequently, we could not determine a photometric redshift for it. This likely indicates that J142850+345420 is at $z > 2$. If this is the case, J142850+345420 is AGN dominated since we calculated in Section 3.3.5 that the radio emission would be the result of AGN activity if the source is at $z > 0.06$. Since we do not have a redshift for J142850+345420, we calculated the brightness temperatures for J142850+345420a,b using a redshift of zero. The values are therefore lower limits and allow us to conclude that J142850+345420 is consistent with being an AGN with a core-jet structure.

Since we do not have a redshift for J142850+345420, we calculated the brightness temperatures for J142850+345420a,b using a redshift of zero. The values are therefore lower limits and allow us to conclude that J142850+345420 is consistent with being an AGN with a core-jet structure. We also note that, J142850+345420 lies inside the multiwavelength optical coverage of the Boötes field, but no match could be found for the source. Consequently, we could not determine a photometric redshift for it. This likely indicates that J142850+345420 is at $z > 2$. It also indicates that J142850+345420 is AGN dominated since we calculated in Section 3.3.5 that the radio emission would be the result of AGN activity if the source is at $z > 0.06$. 52
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Figure 3.4: Naturally weighted EVN image of J142850+345420 that was made using an uv-taper. The restoring beam is shown in the bottom left corner and has a size of $24.1 \times 26.8$ mas at a major axis position angle of $29.4^\circ$. The contours are drawn at $-3$ and $3$ times the image noise, increasing in factors of $\sqrt{2}$ thereafter.
Figure 3.5: Uniformly weighted EVN image of J143055+350852. The restoring beam is shown in the bottom left corner and has a size of $26.4 \times 32.1$ mas at a major axis position angle of $-24.5^\circ$. The contours are drawn at $-3$ and $3$ times the image noise, increasing in factors of $\sqrt{2}$ thereafter.

3.4.3.2 J143055+350852

J143055+350852, shown in Fig. 3.5, is composed of two components. The EAZY and LRT redshift values for J143055+350852 differ significantly. Despite this, the brightness temperature of J143055+350852a is consistent with it being an AGN. Considering that J143055+350852b is extended in the direction parallel to the line between the components and that it is fainter than J143055+350852a, we suggest that J143055+350852 has a core–jet structure. Since we recovered most of the predicted flux density ($71 \pm 6$ per cent), and the remaining flux density is likely located either between the two components or very near them, we do not expect that J143055+350852 is significantly more extended than indicated in Table 3.5. From Fig. 3.2, it is clear that the upper limit on the LOFAR-62 flux density indicates that the spectrum is turning over.
3.4 Comments on Individual Sources

3.4.3.3 J143213+350940

The uniformly weighted EVN image of J143213+350940 (Fig. 3.6) has a likely symmetric double structure. Both components have brightness temperatures consistent with emission from AGN activity. After imaging J143213+350940 with uniform weighting, we also imaged it using natural weighting with an uv-taper. Note that the information given for J143213+350940 in Table 3.5 was derived from the naturally weighted, uv-tapered image, while the information for J143213+350940a,b was derived using the uniformly weighted image. Because the beam size of the uv-tapered image is $24 \times 29$ mas and J143213+350940a,b are only separated by $\sim 31$ mas, their flux densities merge in the uv-tapered image. Fitting the resulting single source with a single elliptical Gaussian, we found it to have a FWHM of nearly 70 mas and flux density of 14.41 mJy. This is $\sim 6$ mJy more than the sum of the flux densities of the individual components. Hence, while the source is resolved, it is clear that there is a significant amount of extended emission between and surrounding the components. From the uv-tapered image, we recover $94 \pm 12$ percent of the predicted flux density. Hence, the size measured from the uv-tapered image is a good estimate of J143213+350940’s true size.

From Fig. 3.2 it is clear that the VLA-P and WENSS flux densities differ (26.9 $\pm$ 1.4 and 34.0 $\pm$ 5.0, respectively), but are nearly consistent within their 1$\sigma$ errors. If we take the VLA-P flux density to be the correct value at 325 MHz, J143213+350940 is not an MPS source (Fig. 3.1) whose spectrum either flattens towards lower frequencies or can be described by a single power law between 153 and 1400 MHz (Table 3.1). This means that the turnover frequencies and linear sizes reported in Table 3.5 will not be good estimates of the true values. However, if we take the WENSS flux density to be the correct value, $\alpha_{\text{low}}$ and $\alpha_{\text{high}}$ changes to 0.2 $\pm$ 0.3 and $-0.5 \pm 0.1$, respectively. This means that J143213+350940 is an MPS source as is shown by the point labeled “J143213+350940 WENSS” in Fig. 3.1. The percentage of the predicted flux density that was recovered from the image changes to $97 \pm 13$ percent while $\nu_o = 337 \pm 75$ MHz and $\nu_r = 666 \pm 152$ & 660 $\pm$ 146 MHz in Table 3.5.

To try to find a reason for the flux density difference between the VLA-P and WENSS catalogues, we double checked both catalogues and images of the source. Since the nearest neighboring source is more than 3 arcmin away, J143213+350940 is unresolved in the WENSS, VLA-P, FIRST and NVSS images, and there is nothing in the images that can explain the difference. One possibility is that J143213+350940 is intrinsically variable. However, as discussed in Section 3.3.4, we consider this to be very unlikely. Another possibility is that the difference could be caused by (as a whole or in part) interplanetary or interstellar scintillation. Typically, interstellar scintillation results in flux density variations of a few per cent [e.g. Stinebring et al., 2000; Gelfand et al., 2005], which is much less than the 21 percent difference observed here. In addition, the VLA-P observations were carried out over four days during a period of more than a month [Coppejans et al., 2015], while each field in WENSS was observed in 18 snapshots spread over a 12-h period [Rengelink et al., 1997]. This averaged out the variations, which have maximum typical time scales of about an hour [Cordes & Rickett, 1998; Gelfand et al., 2005].

The WIR and LOFAR-150 flux densities for J143213+350940 are 29.0 $\pm$ 6.0 and 46.3 $\pm$ 4.6 mJy, respectively. If the LOFAR-150 flux density is correct, it would indicate that the spectrum is steep between 150 and 1400 MHz, irrespective of whether the VLA-P or WENSS flux densities are
Figure 3.6: Uniformly weighted EVN image of J143213+350940 without uv-tapering showing a likely CSO structure. The restoring beam is shown in the bottom left corner and has a size of $7.8 \times 18.9$ mas at a major axis position angle of $19.4^\circ$. The contours are drawn at $-3$ and $3$ times the image noise, increasing in factors of $\sqrt{2}$ thereafter.
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correct. However, it is clear from Fig. 3.2 that the LOFAR-62 flux density upper limit shows that J143213+350940’s spectrum either flattens towards lower frequencies or turns over irrespective of which of the four catalogues are correct at 153 and 325 MHz.

Finally, we note that matching J143213+350940 to the AGES catalogue, we found a counterpart within 1.1 arcsec from our central position that has a photometric redshift of 1.02. The value agrees very well with those in Table 3.1.

3.4.3.4 J143718+364549

We selected J143718+364549 for observation based on its WENSS flux density. Unfortunately, because it is 2.7° from the phase center of the VLA-P image, we do not have a VLA-P flux density for it. The naturally weighted EVN image of J143718+364549 (Fig. 3.7) shows that the source is composed of a single resolved component that is significantly extended towards the North. To check if any flux density is resolved out in the naturally weighted image, we made an image in which we applied an uv-taper. The values derived from this image is reported in Table 3.5. Tapering increased the recovered flux density from 2.9 mJy to 6.1 mJy, resulting in 68 ± 9 per cent of the predicted flux density being recovered.

From J143718+364549’s spectrum (Fig. 3.2), it is clear that it either turns over or flattens towards lower frequencies. Finally, we point out that because we do not have a redshift for J143718+364549, the brightness temperature lower limit in Table 3.5 was derived using a redshift of zero.

3.4.3.5 J144230+355735

Like J143718+364549, J144230+355735 lies outside the area imaged in the VLA-P image and was selected for observations with the EVN based on its WENSS flux density. From its spectrum (Fig. 3.2), the source can either be turning over or flattening towards lower frequencies.

The EVN image of J144230+355735 (Fig. 3.8) is composed of three resolved components and has a CSO structure. J144230+355735’s overall structure is that of a core with two lobes. From J144230+355735b a jet-like structure extends towards J144230+355735c.

To check if any of the flux density is resolved out in the naturally weighted image, we made an image in which we applied an uv-taper. The values derived from the uv-tapered image are reported for J144230+355735 in Table 3.5 while the values for J144230+355735a,b,c are derived from the non-uv-tapered image. Since the flux densities of J144230+355735b and J144230+355735c merge in the uv-tapered image, the component was fitted using a single elliptical Gaussian. In this image, J144230+355735a has a flux density of 1.07 ± 0.13 mJy and a size of 46.7 ± 3.4 mas. The combined component from J144230+355735b and J144230+355735c has a minor and major axis of 21.9 ± 1.3 and 64.0 ± 3.7 mas, respectively, and a flux density of 1.26 ± 0.11 mJy. Hence, after tapering, the total flux density of J144230+355735 increased by 0.6 mJy resulting in 69 ± 14 per cent of the predicted flux density being recovered. The missing flux density likely originates from low surface brightness emission along the jet axis between the central and outer components. It is however possible that at least some of the missing flux density is located beyond the outer components and that the jet is larger than what we measured. We note that while J144230+355735a is only
Figure 3.7: Naturally weighted EVN image of J143718+364549 without uv-tapering. J143718+364549 is significantly extended towards the North. The restoring beam is shown in the bottom left corner and has a size of $7.7 \times 18.4$ mas at a major axis position angle of $19.3^\circ$. The contours are drawn at $-3$ and $3$ times the image noise, increasing in factors of $\sqrt{2}$ thereafter.
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Figure 3.8: Naturally weighted EVN image of J144230+355735 without uv-tapering showing a CSO structure. The restoring beam is shown in the bottom left corner and has a size of $6.3 \times 16.7$ mas at a major axis position angle of 16.6°. The contours are drawn at $-3$ and 3 times the image noise, increasing in factors of $\sqrt{2}$ thereafter.
detected at a 4.2σ level in Fig. 3.8, it is detected above 6σ in the uv-tapered image. Similarly the central position of J144230+355735c is encircled by a 6σ contour in the uv-tapered image.

The brightness temperature of the central component is consistent with the emission being non-thermal within its uncertainty. Furthermore, the brightness temperatures of all three components are lower limits as they were calculated using a redshift of zero since we could not determine a redshift for the source. Hence, if J144230+355735 is at a redshift above 0.45, the central component would clearly indicate AGN activity. Combining this with the structure of the source and the results in Section 3.3.5, we conclude that J144230+355735 is an AGN with a central core-jet structure and two lobes and/or hotspots.

### 3.5 Discussion

#### 3.5.1 What are the MPS sources?

From Sections 3.3.5 and 3.4, we know that all the sources detected with the EVN are AGN. For the sources with redshifts, columns (11) and (12) in Table 3.5 show that they are GPS and CSS sources whose spectral turnovers have been redshifted to lower frequencies. Column (12) shows that J142850+345420 and J143718+364549, for which we do not have redshifts, are both smaller than \( \sim 1 \) kpc and are therefore either GPS or HFP sources. Hence, since all the sources that were detected with the EVN are either CSS, GPS or HFP sources, they are likely all young AGN [O'Dea, 1998; Murgia et al., 2002; Conway, 2002; Murgia, 2003; Fanti, 2009].

In Fig. 3.9, we used the information in table 5 of Orienti & Dallacasa [2014] to generate the plot that the authors used to derive the turnover frequency–linear size relation. To determine the empirical relation, the authors compiled a list of CSOs for which the core components have been detected. The authors argue that this allows them to select genuine young radio galaxies and exclude other populations of sources such as blazars that could contaminate the sample. The resulting list of sources span redshifts between 0.08 and 2.93, linear sizes between 10 pc and 56 kpc and rest-frame turnover frequencies from 10.9 GHz to below 45 MHz. By minimizing the chi-squared error statistics, Orienti & Dallacasa [2014] found the relation

\[
\log_{10}(\nu_r) = (-0.21 \pm 0.04) - (0.59 \pm 0.05) \log_{10}(\text{LLS}),
\]

where \( \nu_r \) is in GHz and the LLS is in kpc. This relation agrees well with those found by both O'Dea [1998] and Falcke et al. [2004]. Fig. 3.9 shows the data used to derive the relation, with Fig. 3.10 zooming into the region around our sources.

To check if our sources lie within the scatter of points around the relation, we calculated the vertical distance between the relation and the sources used to derive it. From this we found that the median distance between the points and the line is 0.06 and has a 1σ deviation of 0.29. J143042+351240 EAZY and J143042+351240 LRT are 2.5σ and 2.7σ from the relation, with the remaining sources being within 2σ and J143050+342614 LRT, J143055+350852 EAZY, J143213+350940 EAZY, J143213+350940 LRT, J143213+350940 WENSS and J143329+355042 EAZY being within 1σ. The maximum distance between the relation and the points used to derive it is 5.8 GHz, which is more than the maximum distance between the relation and our sources. We note that since Equation 3.4 has a constant slope, the vertical, horizontal and diagonal distances
3.5 Discussion

Figure 3.9: The figure used by Orienti & Dallacasa [2014] to derive the turnover frequency–linear size relation (shown as the solid line) with our sources included. The points and downward triangles show the sources from which Orienti & Dallacasa [2014] derived the relation. The downward triangles show sources for which the authors could only determine an upper limit for the turnover frequency. For each of our sources, the position is plotted using the redshifts from both the EAZY and LRT codes. For J142850+345420, J143718+364549 and J144230+355735, for which we cannot calculate $\nu_r$, we plotted $\nu_o$ which is a lower limit for $\nu_r$. Lower and upper limits on the LLS are indicated by arrows. A zoom-in of the region around our sources is shown in Fig. 3.10.
Figure 3.10: A zoomed-in image of the region around our sources in Fig. 3.9 in which the sources from which Orienti & Dallacasa [2014] derived the relation was omitted for clarity. The figure legend is the same as that of Fig. 3.9 and is not shown here for clarity. For J142850+345420, J143718+364549 and J144230+355735, for which we cannot calculate \( \nu_r \), we plotted \( \nu_0 \) which is a lower limit for \( \nu_r \). Lower and upper limits are indicated by arrows.
between each point and the relation are related to each other by constant factors. Hence, the number of $\sigma$ that each point is from the relation is independent of whether the vertical, horizontal or diagonal distance is used.

As discussed in Section 3.4.3.3, the VLA-P and WENSS flux densities for J143213+350940 differ, resulting in a large uncertainty on the shape of its spectrum. Consequently, we plotted its position in Fig. 3.9 and 3.10 for both the cases where $\nu_t$ was derived using the VLA-P and WENSS flux densities. Since the EAZY and LRT redshifts are so close to each other (Table 3.1), the points are indistinguishable in the plots and we only plot the position of the EAZY redshift point for the case where $\nu_t$ was derived from the WENSS flux density.

Since the redshift derived for J142917+332626 by El Bouchefry [2009] differs from that of the EAZY and LRT values, we added an additional point (labeled as ‘J142917+332626 z=0.96’) showing its position using the their redshift. J142917+332626 and J143055+350852 (for which the EAZY and LRT redshift values differ significantly) illustrate the effect of redshift uncertainty on the position of the sources. Typically, an uncertainty in the redshift will have a larger effect on the rest-frame turnover frequency than on the linear size of the source, resulting in the sources primarily being displaced vertically. The reason for this is, for a source with a fixed linear size, its angular size does not simply decrease as a function of redshift (see the discussion on Column (12) of Table 3.5 in Section 3.3), as is the case for its observed turnover frequency. Hence for sources around $z = 1$ and above, an uncertainty in the redshift primarily has an affect on the rest-frame turnover frequency. However, for sources at $z < 1$, a redshift uncertainty can have a significant effect on both $\nu_t$ and the linear size.

Since we do not have redshifts for J142850+345420, J143718+364549 and J144230+355735, we used their observed turnover frequencies and size upper limits to plot their positions in Fig. 3.9 and 3.10. Since $\nu_t = \nu_o(1 + z)$, $\nu_o$ is a lower limit for $\nu_t$. From the arguments in the previous paragraph, we expect that the true positions of the sources will primarily be vertical displaced compared to their current positions. As plotted, the sources are between 1.2 and 2.1$\sigma$ from the relation.

Looking at Fig. 3.9, it is striking that all but two of our sources unambiguously lie below the correlation. There are several possible reasons for this, the first of which being that the sources were resolved out by the EVN, or that we missed components because they are too faint to be detected in the EVN images. In this case, the LLS will be underestimated and the sources should be towards the right of where they are plotted, closer to the relation. This is specifically the case for J143042+351240 and J143050+342614, for which, based on the percentage of the predicted flux density that was recovered from the EVN image, we concluded in Sections 3.4.2.2 and 3.4.2.3 that they are larger than their measured sizes. We also cannot rule out this possibility for the remainder of the detected sources (for which we recovered a larger percentage of the predicted flux density). For J143042+351240 and J143050+342614, the limits are indicated by arrows in Fig. 3.9 and 3.10. The second possibility why the sources lie below the correlation is selection effects. The first selection effect is that we can only select sources that have $\nu_o \lesssim 500$ MHz. Assuming that all of the sources that we can detect are at $z < 10$, this excludes sources with $\nu_t \gtrsim 5.5$ GHz. The second selection effect is that the EVN’s lack of short spacings prevents us from detecting extended emission on scales larger than $\sim 35$ mas. Hence, we cannot detect a source if it has
a single, or multiple, components larger than $\sim 35$ mas, in which the flux density is uniformly distributed over the component or components. This is also the most likely explanation for why we did not detect J142904+354425 and J143024+352438. Since we cannot place an upper limit on the distance between two $\gtrsim 35$ mas components, it is impossible to determine the true limitations imposed by this selection effect. Another selection effect is that the MPS sources were selected to be compact in FIRST (see Section 3.2 in Coppejans et al. [2015]). However since this only sets the constraint that $\text{LLS} \lesssim 54.5 \text{kpc}$, this effect is irrelevant. In conclusion, we cannot therefore say whether the sources lying below the correlation is because of selection effects or not.

From the above it appears that the sources plotted in Fig. 3.9 and 3.10 lie within the scatter of the points around the relation. We do note that the uncertainties on LLS and the peak frequency could influence this result. Since all the sources are AGN (Sections 3.3.5 and 3.4), we therefore expect that at least some, if not all, of the sources will reveal themselves as CSOs if observed at high enough resolution. This can be said with certainty for, and is confirmed by, J143213+350940 and J144230+355735 which have CSO structures. We also point out again that, as discussed in Section 3.3.4, it is very unlikely that any of the sources are blazars.

As a final point, we note that the redshift range of the sources is similar to those of the sources from which Orienti & Dallacasa [2014] constructed the relation. Hence, if we assume that the sources are below the correlation purely because of their LLS’s, and that they were not resolved out by the EVN, it is possible that they are less powerful than the sources in the relation and, therefore, get frustrated at smaller distances. Since AGN activity can be discontinuous [e.g. Schoenmakers et al., 2000; Jamrozy et al., 2007], it is also possible that their central engines have (temporarily) switched off. This would result in the core being undetected while the low surface density radio lobes continue to expand and fade. There are, however, two arguments against this. First, switched off AGN typically have spectra with $\alpha < -1.5$ [Komissarov & Gubanov, 1994; Shulevski et al., 2015], which is steeper than the spectra of our sources. Secondly, the core accounts for a relatively small fraction of the total flux density [e.g. Orienti & Dallacasa, 2014], and therefore often remains undetected.

### 3.5.2 Detection Fraction

In this section we compare our detection fraction of 0.818 to that of the mJy Imaging VLBA Exploration at 20 cm [mJIVE-20; Deller & Middelberg, 2014] survey. mJIVE-20 is a VLBA survey to study the VLBI structure of FIRST sources. The survey has an angular resolution of 5 mas, median noise of 0.178 mJy beam$^{-1}$ and targets sources with FIRST peak intensities ($I_{\text{FIRST}}$) between 1 and 200 mJy beam$^{-1}$. To date, nearly 20 000 sources have been observed of which 4336 were detected at or above a detection threshold of 6.75 $\sigma$, giving the survey an overall detection fraction of 0.217. Since our sources have $2.5 < I_{\text{FIRST}} < 15.7$ mJy beam$^{-1}$, we used the information in table 2 of Deller & Middelberg [2014] to calculate that mJIVE-20 has a detection fraction of $0.151 \pm 0.007$ for sources with $2 < I_{\text{FIRST}} < 16$ mJy beam$^{-1}$. The fact that we have a higher detection fraction is in part be due to our lower detection threshold (6$\sigma$) and median noise (0.095 mJy beam$^{-1}$). To correct for this, we calculated that with mJIVE-20’s median noise and detection threshold, our survey would detect 7 of our 11 sources. This means a detection fraction of 0.636, which is 3 times that of the mJIVE-20 survey as a whole and 4 times that achieved for
the sources in our peak intensity range.

As discussed in Section 3.5.1, MPS sources are some of the smallest AGN, which explains our high detection fraction in comparison to mJIVE-20. mJIVE-20 targets all sources with FIRST peak intensities above 1 mJy beam\(^{-1}\), while all our sources should be intrinsically small and thus good targets for VLBI.

### 3.6 Summary and final points

In this paper, we presented high-resolution 1.7 GHz EVN observations of 11 MPS sources. Of the 11 sources we detected nine with the EVN, recovering more than 50 percent of the predicted flux density for seven. Based on their radio luminosities, brightness temperatures and morphologies, we conclude that the radio emission of the sources detected with the EVN is from AGN activity (Sections 3.3.5 and 3.4). In Section 3.5.1, we used their peak frequencies and linear sizes to show that the MPS sources are a mixture of CSS, GPS and HFP sources whose spectral turnovers have been redshifted to lower frequencies. Hence, the MPS sources are likely all young AGN. We also argue that the detected sources are all likely CSOs. We do, however, emphasize that the uncertainties on the rest-frame turnover frequencies and the largest linear sizes could influence this conclusion. From their steep high-frequency spectra and brightness temperatures, we argue that none of the sources are blazars. We conclude that the radio emission from the two sources that were not detected with the EVN are likely from AGN activity, and that the reason for the non-detections is that they were resolved out by the EVN. Finally we conclude that our high detection fraction of 82 percent is due to the MPS sources being intrinsically small AGN, which makes them good targets for VLBI observations.

Because of small number statistics, we cannot say whether the sources at the highest redshifts are more compact than those at lower redshifts. However, all the detected sources, with the possible exceptions of J143042+351240 and J143050+342614, have linear and angular sizes smaller than 1.1 kpc and 0.15 arcsec, respectively. This shows that low-frequency colour-colour diagrams are an easy and efficient way of selecting small and likely young AGN. This also seems to indicate that when selecting a group of MPS sources that are compact on a scale of 5 arcsec, most of the sources are compact on a scale below 0.5 arcsec. Hence it is possible that to fulfill the criteria of selecting compact sources for the MPS method of searching for high-redshift AGN, all that is required is to select sources that are unresolved at 5 arcsec.

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On the nature of bright compact radio sources at z > 4.5

Rocco Coppejans, Sándor Frey, Dávid Cseh, Cornelia Müller, Zsolt Paragi, Heino Falcke, Krisztina É. Gabányi, Leonid I. Gurvits, Tao An and Oleg Titov


Abstract

High-redshift radio-loud quasars are used to, among other things, test the predictions of cosmological models, set constraints on black hole growth in the early universe and understand galaxy evolution. Prior to this paper, 20 extragalactic radio sources at redshifts above 4.5 have been imaged with very long baseline interferometry (VLBI). Here we report on observations of an additional ten z > 4.5 sources at 1.7 and 5 GHz with the European VLBI Network (EVN), thereby increasing the number of imaged sources by 50 percent. Combining our newly observed sources with those from the literature, we create a substantial sample of 30 z > 4.5 VLBI sources, allowing us to study the nature of these objects. Using spectral indices, variability and brightness temperatures, we conclude that of the 27 sources with sufficient information to classify, the radio emission from one source is from star formation, 13 are flat-spectrum radio quasars and 13 are steep-spectrum sources. We also argue that the steep-spectrum sources are off-axis (unbeamed) radio sources with rest-frame self-absorption peaks at or below GHz frequencies and that these sources can be classified as gigahertz peaked-spectrum (GPS) and megahertz peaked-spectrum (MPS) sources.
4.1 Introduction

High-redshift quasars are among the most intriguing objects because they are thought to be associated with the youngest supermassive ($10^6$ to $10^9 M_\odot$) black holes in the Universe. These accreting black holes play a key role in the evolution of their host galaxies via feedback [e.g. Best et al., 2005; Fabian, 2012; Morganti et al., 2013]. The observed properties of the highest-redshift black holes set constraints on their accretion process and thus on the black hole growth [e.g. Wyithe & Loeb, 2012; Page et al., 2014]. They are also indispensable for 21-cm absorption studies as they serve as illuminating background objects [e.g. Pritchard & Loeb, 2012]. However, their evolution and radio loudness are not well understood. Whether these properties are related to the accretion process or to the density of the cosmic microwave background (CMB) photons at these redshifts is still an open question [Fabian et al., 2014].

The compact core–jet structures in high-redshift radio-loud quasars are valuable additions to the samples used for classical cosmological tests like the apparent angular size–redshift [e.g. Gurvits et al., 1999] and the apparent proper motion–redshift relations [e.g. Kellermann et al., 1999]. The redshift $z = 4.5$ corresponds to less than 10 percent of the present age of the Universe. Here the predictions of cosmological models can be radically different, yet useful test objects are sparse. These tests require high-resolution radio interferometric data on the compact radio structures and their variation with time.

High-redshift radio-loud quasars provide critical input into source counts and quasar luminosity function studies [e.g. Haiman et al., 2004]. From geometrical considerations of the jet inclination angles with respect to the line of sight, we expect that for each active galactic nucleus (AGN) whose jet is pointed within a small angle of our line of sight [blazars; e.g. Urry, 1999; Krawczynski & Treister, 2013], there should be hundreds of sources with jets pointing elsewhere [Volonteri et al., 2011]. In Volonteri et al. [2011], the authors compare the number of high-redshift radio-loud sources in the Sloan Digital Sky Survey (SDSS) and Very Large Array (VLA) Faint Images of the Radio Sky at Twenty-centimeter (FIRST) survey [White et al., 1997] with the number of blazars between $z = 1$ and $z = 6$ and find that they are consistent at $z < 3$ but disagree at $z > 3$. Beyond $z = 3$, the number of high-redshift radio-loud sources is significantly lower than what is expected from the number of blazars at these redshifts. The authors propose three possible explanations for the discrepancy: 1) the average bulk Lorentz factor decreases as a function of redshift; 2) there is a bias in SDSS and FIRST against detecting high-redshift radio-loud sources; 3) there is a bias in SDSS against detecting high-redshift radio-loud and radio-quiet sources. The apparent lack of AGN with misaligned jets at very high redshifts led Ghisellini & Sbarrato [2016] to propose a model in which a dusty “bubble” surrounding the central regions obscures the nucleus. The AGN is visible in the optical only if it is observed along the jet which cleared up the obscuring material in that direction.

The reason for the missing misaligned high-redshift sources can be investigated using very long baseline interferometry (VLBI) observations of the known high-redshift sources. By determining the variability properties, spectral indices, Doppler boosting and morphologies of the sources from VLBI observations, the sources can be classified as blazars or misaligned sources. In the case of

1Ghisellini & Sbarrato [2016] showed that for every blazar that we observe with a viewing angle $\theta < 1/\Gamma$ (where $\Gamma$ is the Lorentz factor), there exists $2\Gamma^2$ sources with $\theta > 1/\Gamma$. 

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resolved sources, the VLBI observations can be used as a first epoch to measure the jet proper motion from which the Lorentz factor can be calculated [e.g. Frey et al., 2015].

In this paper, we present 1.7 and 5 GHz VLBI observations of ten $z > 4.5$ sources conducted with the European VLBI Network (EVN). These observations increase the number of $z > 4.5$ sources that have been imaged with VLBI from 20 to 30. Combining our new observations with those from the literature, we investigate the nature of the $z > 4.5$ VLBI sources. In Section 4.2, we describe how we selected the sources and reduced the EVN data. The source properties derived from the images are presented in Section 4.3. Section 4.4 contains a summary of the properties of the $z > 4.5$ sources that have previously been imaged with VLBI. In Section 4.5 we discuss the origin of the radio emission, variability properties, spectral indices and Doppler boosting of the sources, which we then use to classify them in Section 4.6. Finally, a summary and conclusion are presented in Section 4.7. The following cosmological model parameters are assumed throughout this paper: $\Omega_m = 0.3$, $\Omega_o = 0.7$, $H_0 = 72 \text{km s}^{-1}\text{Mpc}^{-1}$.

4.2 Target selection, Observations, data reduction and VLBI images

4.2.1 Target selection

The radio-emitting sources with spectroscopic redshifts greater than 4.5 in the SDSS Data Release 10 (DR10) quasar catalogue [Pâris et al., 2014] and the Million quasars catalogue [Flesch, 2015] were considered for observation. From this list we selected all of the sources that are unresolved (< 5 arcsec) in the FIRST survey and have integrated 1.4 GHz flux densities exceeding 5 mJy. In addition to the catalogue samples above, the spectroscopic redshifts of J1013+2811, J1454+1109 and J1628+1154 have recently been measured by Titov et al. [2013]. The final list of $z > 4.5$ sources we observed with the EVN is given in Table 4.3.

4.2.2 Observing setup

The sources were observed with the EVN at central frequencies of 1.658 and 4.990 GHz during six project segments: EC052A, EC052B, EC052C, EC052D, EC052E and EC052F. In Table 4.1, the observing frequency, the date of the observations and the radio telescopes that successfully participated in each project segment are shown. The following radio observatories participated in the experiments: Effelsberg (Ef; Germany), Hartebeesthoek (Hh; South Africa), Jodrell Bank Mk2 (Jb; United Kingdom), Onsala (On; Sweden), Toruń (Tr; Poland), Noto (Nt; Italy), Medicina (Mc; Italy), Sheshan (Sh; China), the Westerbork Synthesis Radio Telescope (Wb; the Netherlands) and Yebes (Ys; Spain).

The observations at both frequencies were done using 2s integrations at a data rate of 1024 Mbit s$^{-1}$ in left and right circular polarizations with eight subbands per polarization and 16 MHz of bandwidth per subband. The technique of electronic VLBI was used, where the data are streamed to the central correlator using optical fiber networks in real time. The observations

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\[2\text{http://quasars.org/milliquas.htm} \]

\[3\text{See http://www.jive.eu/e-vlbi and www.evlbi.org/evlbi} \]
of each target source were interleaved with observations of a phase calibrator. The same phase calibrator (listed in Table 4.2) was used for each target source at both observing frequencies. The distances between the target sources and their phase calibrators are given in Table 4.2. Additionally, VLBI images and flux densities at two or more frequencies between 2.3 and 8.3GHz of all of the phase calibrators are available in the Astrogeo data base. In Table 4.3, the project segments during which each source were observed at each frequency are given.

Three radio telescopes experienced problems during EC052A resulting in only the six stations shown in Table 4.1 successfully producing data. The sources that were initially observed at 1.7GHz during EC052A were therefore re-observed during EC052C, EC052E and EC052F. This resulted in some of the sources being observed two or three times at 1.7GHz.

### 4.2.3 Data reduction and VLBI images

The EVN data were reduced using the NRAO Astronomical Image Processing System [AIPS, Greisen, 2003] software package. The visibility amplitudes were first calibrated using antenna

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4http://astrogeo.org/, maintained by L. Petrov.
### Table 4.3: Image parameters

<table>
<thead>
<tr>
<th>ID</th>
<th>FIRST flux density [mJy]</th>
<th>$\nu$ [GHz]</th>
<th>Project segment</th>
<th>Restoring beam [mas×mas]</th>
<th>PA [$^\circ$]</th>
<th>1σ image noise [mJy beam$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0011+1446</td>
<td>24.3 ± 1.2</td>
<td>1.7</td>
<td>EC052A, C</td>
<td>3.0 × 6.6</td>
<td>82.3</td>
<td>0.11</td>
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<tr>
<td></td>
<td></td>
<td>5.0</td>
<td>EC052B</td>
<td>1.4 × 1.8</td>
<td>64.4</td>
<td>0.14</td>
</tr>
<tr>
<td>J0210−0018</td>
<td>8.5 ± 0.4</td>
<td>1.7</td>
<td>EC052A, C</td>
<td>3.1 × 6.6</td>
<td>80.2</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.0</td>
<td>EC052B</td>
<td>1.5 × 1.8</td>
<td>59.6</td>
<td>0.06</td>
</tr>
<tr>
<td>J0940+0526</td>
<td>58.5 ± 2.9</td>
<td>1.7</td>
<td>EC052A, E, F</td>
<td>3.2 × 6.1</td>
<td>80.8</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>EC052B</td>
<td>1.4 × 1.5</td>
<td>30.9</td>
<td>0.12</td>
</tr>
<tr>
<td>J1013+2811</td>
<td>14.4 ± 0.7</td>
<td>1.7</td>
<td>EC052A, C, F</td>
<td>3.3 × 7.0</td>
<td>82.9</td>
<td>0.06</td>
</tr>
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<td>EC052B</td>
<td>1.5 × 1.6</td>
<td>47.9</td>
<td>0.10</td>
</tr>
<tr>
<td>J1311+2227</td>
<td>6.5 ± 0.3</td>
<td>1.7</td>
<td>EC052A, C</td>
<td>3.1 × 6.0</td>
<td>79.8</td>
<td>0.05</td>
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<td></td>
<td></td>
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<td>EC052B</td>
<td>1.4 × 1.6</td>
<td>35.7</td>
<td>0.03</td>
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<tr>
<td>J1400+3149</td>
<td>20.5 ± 1.0</td>
<td>1.7</td>
<td>EC052E</td>
<td>4.1 × 5.9</td>
<td>80.8</td>
<td>0.06</td>
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<td></td>
<td></td>
<td>5.0</td>
<td>EC052D</td>
<td>1.3 × 1.6</td>
<td>28.0</td>
<td>0.15</td>
</tr>
<tr>
<td>J1454+1109</td>
<td>15.1 ± 0.8</td>
<td>1.7</td>
<td>EC052E</td>
<td>3.5 × 5.5</td>
<td>86.4</td>
<td>0.08</td>
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<td>1.4 × 1.5</td>
<td>45.2</td>
<td>0.10</td>
</tr>
<tr>
<td>J1548+3335</td>
<td>37.8 ± 1.9</td>
<td>1.7</td>
<td>EC052A, F</td>
<td>3.4 × 9.4</td>
<td>83.9</td>
<td>0.06 &amp; 0.09$^a$</td>
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<td>EC052B</td>
<td>1.6 × 1.8</td>
<td>52.9</td>
<td>0.06</td>
</tr>
<tr>
<td>J1628+1154</td>
<td>41.0 ± 2.0</td>
<td>1.7</td>
<td>EC052A, E</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.0</td>
<td>EC052B</td>
<td>1.5 × 1.7</td>
<td>63.0</td>
<td>0.06</td>
</tr>
<tr>
<td>J1720+3104</td>
<td>10.6 ± 0.5</td>
<td>1.7</td>
<td>EC052A, E</td>
<td>3.6 × 5.7</td>
<td>80.5</td>
<td>0.10</td>
</tr>
<tr>
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<td></td>
<td>5.0</td>
<td>EC052B</td>
<td>1.5 × 1.8</td>
<td>36.8</td>
<td>0.15</td>
</tr>
</tbody>
</table>

**Columns:** Col. 1 – source name (J2000); Col. 2 – the source flux density in the FIRST survey; Col. 3 – observing frequency; Col. 4 – project segment(s) during which the source was observed; Col. 5 – Gaussian restoring beam size (FWHM) in Fig. 4.1; Col. 6 – Gaussian restoring beam major axis position angle (measured from north through east) in Fig. 4.1; Col. 7 – image noise in Fig. 4.1.

**Note:** * The first noise value is for J1548+3335a and the second is for J1548+3335b.
gains and system temperatures measured at the radio telescopes. Next the phase calibrators were fringe-fitted before exporting their visibilities from aips for imaging in the Caltech DIFMAP package [Shepherd et al., 1994]. The imaging was done using several iterations of CLEAN and phase self-calibration before doing a single round of amplitude self-calibration across the entire observing time as the solution interval using the DIFMAP task GSCALE. This gave an antenna gain correction from each phase calibrator for each radio telescope. For each project segment, we calculated the median gain correction factors for each of the radio telescopes, which were applied to the visibility amplitudes of the phase calibrators and target sources in AIPS.

The DIFMAP CLEAN component models of the phase calibrators were then used to improve the phase solutions of the phase calibrators in AIPS during fringe-fitting. The improved solutions of each phase calibrator were then applied to its target source before exporting the visibility data from AIPS for imaging in DIFMAP. The naturally weighted images shown in Fig. 4.1 were made using several rounds of CLEAN. The image parameters are presented in Table 4.3. Phase-only self-calibration was only applied to the sources in which the sum of the CLEAN component flux densities exceeded $\sim 10 \text{ mJy}$.

For the sources that were observed more than once at 1.7 GHz during different project segments, the visibility data from all of the project segments were combined into a single data set. This is discussed in detail in Section 4.3. In Fig. 4.1, the images made from the combined visibility data sets are shown for these sources. The source J1548+3335 has two widely-separated components at 1.7 GHz. For clarity, apart from the full view, zoomed-in images of both components are also shown in Fig. 4.1.

Finally, using the visibility data we estimated the flux densities of the phase calibrators on the longest baselines for each project segment (Table 4.2). We note that from the Astrogeo data base, the phase calibrators show significant flux density variability. For the phase calibrators that were observed more than once at 1.7 GHz, the value in Table 4.2 is the minimum flux density.

### 4.3 Results

The flux densities and sizes of the sources were calculated by fitting circular Gaussian brightness distribution models to the source visibility data in DIFMAP. The parameters derived for each of the sources are presented in Table 4.4. The uncertainties were calculated using the equations in Fomalont [1999]. An additional five percent uncertainty of the flux densities were also assumed to account for the EVN amplitude calibration uncertainty [e.g. An et al., 2012; Frey et al., 2015]. The spectral index, $\alpha$, in Col. 9 is defined as $S \propto \nu^\alpha$, where $S$ is the flux density and $\nu$ is the frequency. The right ascension (RA) and declination (DEC) of the sources were calculated from the 5 GHz images using the AIPS task MAXFIT. For J1548+3335b, which was not detected at 5 GHz, the coordinates were derived from the 1.7 GHz image. The uncertainties of RA and DEC were derived by adding the contributions from (1) the statistical uncertainty of the position of the source (which is a function of the angular resolution of the EVN in the given direction and the signal-to-noise ratio), (2) the uncertainty of the position of the phase-reference calibrator, and (3) the uncertainty introduced by the angular separation between the calibrator and the target source.
Figure 4.1: Naturally weighted 1.7 and 5 GHz EVN images. The restoring beam (FWHM) is shown in the bottom left corner. The lowest contours are drawn at $-3$ and $3$ times the image noise, the positive contours increase in factors of $\sqrt{2}$ thereafter. For the source J1548+3335, separate images of its two 1.7 GHz components are shown, as well as a zoomed-out version displaying both components in the same image.
Chapter 4: VLBI sources at $z>4.5$

**Figure 4.2:** Continued from Figure 4.1...
4.3 Results

Figure 4.3: Continued from Figure 4.1...
Chapter 4: VLBI sources at $z > 4.5$

Figure 4.4: Continued from Figure 4.1...
4.3 Results

All of the sources have fitted sizes that are smaller than the Gaussian restoring beam (Table 4.3) except J1400+3149 at 5 GHz and J1548+3335b at 1.7 GHz. To check whether the remaining sources are resolved, we calculated the minimum resolvable size of each of the sources using Eq. 2 in Kovalev et al. [2005]. All of the sources and source components are resolved at both frequencies, except J0210–0018. This object remains unresolved with the array at 1.7 GHz but it is resolved at 5 GHz in our observations.

The redshift-corrected 5 GHz brightness temperatures of the sources were calculated using

\[ T_b = 1.22 \times 10^{12} (1 + z) \frac{S}{\theta^2 \nu^2} \text{ K} \]  

[Condon et al., 1982]. Here, \( z \) is the redshift, \( S \) is the integrated flux density in Jy, \( \theta \) is the fitted circular Gaussian full width at half-maximum (FWHM) diameter in mas, and \( \nu \) is the observing frequency in GHz.
### Table 4.4: Source parameters

<table>
<thead>
<tr>
<th>ID</th>
<th>z</th>
<th>1.7 GHz flux density [mJy]</th>
<th>5 GHz flux density [mJy]</th>
<th>α</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>EC052A</td>
<td>EC052C</td>
<td>EC052E</td>
</tr>
<tr>
<td>J0011+1446</td>
<td>4.96</td>
<td>19.3 ± 1.0</td>
<td>17.9 ± 1.1</td>
<td>—</td>
</tr>
<tr>
<td>J0210−0018</td>
<td>4.65</td>
<td>2.0 ± 0.2 c</td>
<td>1.2 ± 0.2 c</td>
<td>—</td>
</tr>
<tr>
<td>J0940+0526</td>
<td>4.50</td>
<td>12.8 ± 0.8</td>
<td>—</td>
<td>19.0 ± 2.7</td>
</tr>
<tr>
<td>J1013+2811</td>
<td>4.75</td>
<td>9.4 ± 0.5</td>
<td>11.6 ± 0.7</td>
<td>—</td>
</tr>
<tr>
<td>J1311+2227</td>
<td>4.61</td>
<td>4.1 ± 0.2 c</td>
<td>3.4 ± 0.2 c</td>
<td>—</td>
</tr>
<tr>
<td>J1400+3149</td>
<td>4.64</td>
<td>—</td>
<td>—</td>
<td>10.7 ± 0.5</td>
</tr>
<tr>
<td>J1454+1109</td>
<td>4.93</td>
<td>—</td>
<td>—</td>
<td>19.7 ± 1.0</td>
</tr>
<tr>
<td>J1548+3335a</td>
<td>4.68</td>
<td>7.1 ± 0.4</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>J1548+3335b</td>
<td>4.68</td>
<td>0.6 ± 0.1</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>J1628+1154</td>
<td>4.47</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>J1720+3104</td>
<td>4.62</td>
<td>14.3 ± 0.8</td>
<td>—</td>
<td>10.1 ± 0.5</td>
</tr>
</tbody>
</table>

**Columns:** Col. 1 – source name (J2000); Col. 2 – redshift; Cols. 3 to 7 – fitted 1.7 GHz flux densities and uncertainties; Col. 8 – fitted 5 GHz flux density and uncertainty; Col. 9 – 1.7 to 5 GHz spectral index; Col. 10 – right ascension and uncertainty in mas (in brackets); Col. 11 – declination and uncertainty in mas (in brackets); Cols. 12 and 13 – fitted 1.7 and 5 GHz circular Gaussian diameter (FWHM); Col. 14 and 15 – 1.7 and 5 GHz brightness temperature; Col. 16 – monochromatic rest-frame 5 GHz luminosity.

**Notes:** a J1628+1154 was not detected at 1.7 GHz, the quoted limit corresponds to the 6σ detection threshold. b For the sources that were observed more than once at 1.7 GHz, the value was calculated using the combined 1.7 GHz flux density. c Phase self-calibration was not performed. See Section 4.3.1 for a discussion. d The value is a lower limit since the source is unresolved. e Since the source is unresolved, the value is the minimum resolvable size calculated using Eq. 2 in Kovalev et al. [2005].
<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>J0011+1446</td>
<td>00:11:15.23392 (0.07)</td>
<td>14:46:01.8116 (1.0)</td>
<td>2.73 ± 0.02</td>
<td>0.82 ± 0.01</td>
<td>6.64 ± 0.35</td>
</tr>
<tr>
<td>J0210−0018</td>
<td>02:10:43.16430 (0.07)</td>
<td>−00:18:18.4449 (1.6)</td>
<td>&lt; 1.09</td>
<td>0.46 ± 0.01</td>
<td>&gt; 3.54 ± 0.36</td>
</tr>
<tr>
<td>J0940+0526</td>
<td>09:40:04.80070 (0.08)</td>
<td>05:26:30.9478 (1.9)</td>
<td>1.91 ± 0.02</td>
<td>0.63 ± 0.01</td>
<td>12.29 ± 0.67</td>
</tr>
<tr>
<td>J1013+2811</td>
<td>10:13:35.44036 (0.07)</td>
<td>28:11:19.2424 (1.0)</td>
<td>1.31 ± 0.01</td>
<td>0.59 ± 0.01</td>
<td>15.52 ± 0.80</td>
</tr>
<tr>
<td>J1311+2227</td>
<td>13:11:21.32190 (0.07)</td>
<td>22:27:38.6313 (1.0)</td>
<td>2.38 ± 0.04</td>
<td>1.08 ± 0.03</td>
<td>1.57 ± 0.10</td>
</tr>
<tr>
<td>J1400+3149</td>
<td>14:00:25.41675 (0.07)</td>
<td>31:49:10.6764 (1.0)</td>
<td>3.01 ± 0.02</td>
<td>2.69 ± 0.28</td>
<td>2.97 ± 0.16</td>
</tr>
<tr>
<td>J1454+1109</td>
<td>14:54:59.30513 (0.08)</td>
<td>11:09:27.8855 (1.4)</td>
<td>0.94 ± 0.01</td>
<td>0.46 ± 0.01</td>
<td>59.30 ± 3.00</td>
</tr>
<tr>
<td>J1548+3335a</td>
<td>15:48:24.01400 (0.08)</td>
<td>33:35:00.0862 (1.4)</td>
<td>1.76 ± 0.02</td>
<td>0.77 ± 0.01</td>
<td>6.28 ± 0.33</td>
</tr>
<tr>
<td>J1548+3335b</td>
<td>15:48:23.95861 (0.14)</td>
<td>33:34:59.6640 (2.1)</td>
<td>20.58 ± 14.03</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>J1628+1154</td>
<td>16:28:30.46537 (0.07)</td>
<td>11:54:03.4658 (1.1)</td>
<td>—</td>
<td>1.40 ± 0.24</td>
<td>—</td>
</tr>
<tr>
<td>J1720+3104</td>
<td>17:20:26.68897 (0.07)</td>
<td>31:04:31.6451 (1.2)</td>
<td>1.18 ± 0.01</td>
<td>0.51 ± 0.01</td>
<td>19.57 ± 1.05</td>
</tr>
</tbody>
</table>

Continued from Table 4.4...
4.3.1 Phase self-calibration

In Section 4.2 we noted that phase-only self-calibration was only applied to the sources in which the sum of the clean component flux densities exceeded $\sim 10$ mJy. The sources for which phase-only self-calibration was not applied are marked in Table 4.4. The flux densities of these sources may be underestimated by about 10 percent [e.g. Martí-Vidal et al., 2010; Frey et al., 2010a]. Consequently, the brightness temperatures and luminosities of these sources could also be about 10 percent higher than indicated in Table 4.4.

4.3.2 1.7GHz flux densities

In this section we check the consistency of the flux densities of the sources that were observed in more than one different project segments at 1.7GHz. Among these sources, all the flux densities of J0011+1446 and J1548+3335a are consistent with each other within their formal errors (Table 4.4). This is not the case for J0210−0018, J0940+0526, J1013+2811, J1311+2227, J1548+3335b, and J1720+3104. Therefore we cannot exclude that these sources are variable. Another possibility is that the sources are not variable but the errors of the fitted flux densities are somewhat underestimated. The flux density errors are dominated by the assumed 5 percent calibration uncertainty. Since it is not possible to do absolute flux density calibration during VLBI experiments using standard calibrator sources, it may be that the systematic uncertainty in the flux densities is occasionally larger than five percent. Increasing the assumed systematic uncertainty to 10 percent, all of the 1.7GHz flux densities of J1013+2811 and J1311+2227 also become consistent with each other within their errors. In addition, the quoted errors are $1\sigma$ uncertainties. This means that there is a 32 percent chance that the flux density lies outside of the indicated error bar. Taking all of the above into account, we consider it unlikely that J0210−0018 is variable since the flux densities between the observations differ by at most 0.8 mJy. For J1548+3335b, the EC052F and the combined flux densities are consistent within their uncertainties and inconsistent with the EC052A flux density. Considering how faint and extended the component is, it is unlikely that it is variable. The flux density of J0940+0526 measured in the project segment EC052A is lower than the values from EC052E, EC052F and the combined data set. For J1720+3104, the EC052A flux density is higher than the EC052F and the combined values. It is therefore possible that J0940+0526 and J1720+3104 are indeed variable.

Since the combined data sets that include data from all project segments have better ($u,v$) coverage and sensitivity than the individual data sets, these were used for imaging (Fig. 4.1), and the flux densities from the combined data sets were used to calculate the relevant parameters in Table 4.4. Unless specified otherwise, the discussions in this paper will be based on the results from the combined 1.7GHz datasets.

4.3.3 Comments on peculiar sources

J1548+3335. The 1.7GHz VLBI image of the source shows two components separated by $812 \pm 3$ mas, corresponding to a projected linear separation of $5267 \pm 17$ pc (Fig. 4.1). This source structure is reminiscent of that of the medium-size symmetric objects (MSOs) [e.g. Fanti et al., 1995b]. The fainter component, J1548+3335b, is not detected in the naturally weighted 5 GHz
image with a local 6σ noise of 0.18 mJy beam\(^{-1}\). Considering how faint J1548+3335b is and that it has a size of 20.58 ± 14.03 mas, we conclude that it was resolved out by the higher resolution 5 GHz observations. It is also likely that its spectrum is steep therefore its flux density is lower at 5 GHz than at 1.7 GHz. J1548+3335a is an AGN (see Section 4.5.1). Because of the large uncertainty on the size of J1548+3335b, the emission from this component could either be from an AGN or star formation (Section 4.5.1). The SDSS source is ~ 60 mas away from J1548+3335a, indicating that this radio component positionally coincides with the optical AGN, since SDSS sources have a positional uncertainty of ~ 60 mas [e.g. Orosz & Frey, 2013].

There are in principle four possibilities for what J1548+3335b could be: (1) it is an unrelated foreground or background AGN or star-forming source; (2) J1548+3335b is a lobe or hotspot in the kpc-scale extended radio structure of J1548+3335a; (3) J1548+3335 is a kpc-scale separation dual AGN system; (4) J1548+3335a and J1548+3335b are gravitationally lensed images of the same source. If J1548+3335a and J1548+3335b are produced by gravitational lensing they should have the same spectral index, in which case J1548+3335b is predicted to have a 5 GHz flux density of 1.1 ± 0.8 mJy. Consequently, if J1548+3335b is compact, it should have been detected in our experiment at 5 GHz. However, because of the large uncertainty on its size, it is still possible that it was resolved out by the higher resolution 5 GHz observations. Therefore we cannot rule out the possibility of gravitational lensing, although the positional coincidence of the corresponding SDSS quasar with J1548+3335a is at odds with the scenario where the optical object should be the blend of the two putative lensed images. A straightforward way to test if J1548+3335a and J1548+3335b are related would be to do lower resolution, higher sensitivity radio interferometric observations of the system. Such observations could detect the emission from a jet or a flat spectrum core between the components. The former confirming that J1548+3335b is a lobe or hotspot of J1548+3335a and the latter that J1548+3335 is a MSO, ruling out the other possibilities. If no emission is detected between the components, this could also allow a spectral index to be calculated for J1548+3335b, thereby refuting or strengthening the possibility that J1548+3335a and J1548+3335b are gravitationally lensed images of the same source.

Calculating the spectral index of J1548+3335 using the sum of the flux densities of the 1.7 GHz components (rather than calculating the spectral indices separately for each component, as was done in Table 4.4) gives \( \alpha_{\text{source}} = -1.07 ± 0.07 \). By extrapolating the power-law spectrum using \( \alpha_{\text{source}} \) we calculated a predicted 1.4 GHz flux density (\( S_{\text{pred}} \)) from our high-resolution VLBI data. From that, we calculated a 1.4 GHz flux density ratio with FIRST, \( S_{\text{pred}} / S_{\text{FIRST}} = 0.38 ± 0.06 \). Assuming that J1548+3335 is not variable, this indicates that most of its radio emission is resolved out by the EVN and strengthens the possibility that some of the missing flux density is located in a jet between the two components or in other extended structures such as radio lobes.

As a result of the large uncertainty of the size of J1548+3335b and the brightness temperature being inversely proportional to the size of the source squared, the formal uncertainty of the J1548+3335b brightness temperature becomes twice as large as the value itself. Hence, no value is shown in Table 4.4.

J1628+1154. This source is not detected in the naturally weighted 1.7 GHz image with 0.6 mJy beam\(^{-1}\) (6σ) noise. J1628+1154 is detected in the higher resolution 5 GHz image with a flux density slightly above the detection threshold of the 1.7 GHz image. This suggests a positive
spectral index or perhaps flux density variability over the time scale of several months.

### 4.4 VLBI images of z$>4.5$ sources from the literature

To the best of our knowledge, twenty $z > 4.5$ sources have been imaged with VLBI prior to this paper. These were collected from the literature and the Optical Characteristics of Astrometric Radio Sources (OCARS) catalogue\(^5\) ([Malkin & Titov, 2008; Titov & Malkin, 2009]). Table 4.5 contains a summary of these sources. If a source is composed of two or more components, the integrated flux density in Col. 4 is the sum of the flux densities of the components. The spectral indices in Col. 5 were calculated using the flux densities in Col. 4, and are therefore the spectral indices of the sources as a whole rather than individual component spectral indices (as is the case in Table 4.4). Column 6 contains a visual classification of each of the sources. A source is marked with S if its VLBI image shows a single component that is symmetric with no appreciable extension. Extended (E) sources have single components that are asymmetric with respect to one of their axes, and are therefore resolved. Multi-component (MC) sources have two or more distinct components. The brightness temperatures (Col. 7) and monochromatic rest-frame luminosities (Col. 8) are either from the VLBI reference given in Col. 9 or are calculated in the same way as described in Section 4.3. In case of multi-component sources, both the brightness temperatures and luminosities are of the main (brightest) source component. For these sources, the luminosity is calculated using the spectral index of the main source component, where the spectral index is derived between the same frequencies as the source spectral index reported in Col. 5. Brightness temperatures of unresolved sources and source components are indicated as lower limits.

---

\(^5\)http://www.gao.spb.ru/english/as/ac_vlbi/ocars.txt
<table>
<thead>
<tr>
<th>ID</th>
<th>$z$</th>
<th>$\nu$</th>
<th>Flux density$^d$</th>
<th>$\alpha_{\text{source}}$$^b$</th>
<th>Classification$^d$</th>
<th>$T_b$</th>
<th>$L$</th>
<th>VLBI ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
<td>(7)</td>
<td>(8)</td>
<td>(9)</td>
</tr>
<tr>
<td>J0131−0321</td>
<td>5.18</td>
<td>1.7</td>
<td>64.4 ± 0.3</td>
<td>—</td>
<td>S</td>
<td>&gt; 2.8 × 10$^{11}$</td>
<td>&gt; 30.00</td>
<td>11</td>
</tr>
<tr>
<td>J0311+0507</td>
<td>4.51</td>
<td>1.7</td>
<td>417.7</td>
<td>−1.48$^{1.7,5}$</td>
<td>MC</td>
<td>&gt; 2.0 × 10$^{7}$</td>
<td>&gt; 11.88</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>82.0</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>J0324−2918</td>
<td>4.63</td>
<td>2.3</td>
<td>214.0 ± 10.9</td>
<td>−0.48 ± 0.06$^{2,3,8,7}$</td>
<td>S</td>
<td>(1.13 ± 0.06) × 10$^{11}$</td>
<td>188.70 ± 21.68</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>8.6</td>
<td>113.8</td>
<td>± 6.9</td>
<td></td>
<td>S</td>
<td>(6.8 ± 0.5) × 10$^{10}$</td>
<td>100.34 ± 11.98</td>
<td>22</td>
</tr>
<tr>
<td>J0813+3508</td>
<td>4.92</td>
<td>1.6</td>
<td>17.1 ± 0.9</td>
<td>−0.77 ± 0.07$^{1.6,5}$</td>
<td>MC</td>
<td>—</td>
<td>15.04 ± 1.71</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>7.3</td>
<td>± 0.4</td>
<td></td>
<td>E</td>
<td>(1.5 ± 0.1) × 10$^{9}$</td>
<td>8.40 ± 0.40</td>
<td>10</td>
</tr>
<tr>
<td>J0836+0054</td>
<td>5.77</td>
<td>1.6</td>
<td>1.1</td>
<td>−1.03$^{1.6,5}$</td>
<td>S</td>
<td>&gt; 3.2 × 10$^{7}$</td>
<td>&gt; 4.25</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>0.34</td>
<td>0.34</td>
<td></td>
<td></td>
<td>S</td>
<td>&gt; 3.4 × 10$^{6}$</td>
<td>&gt; 1.40</td>
<td>7</td>
</tr>
<tr>
<td>J0906+6930</td>
<td>5.47</td>
<td>16</td>
<td>121.3 ± 0.5</td>
<td>−0.94 ± 0.05$^{15,43}$</td>
<td>MC</td>
<td>&gt; 5.3 × 10$^{9}$</td>
<td>&gt; 351.77 ± 28.79</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>43</td>
<td>46.1</td>
<td>± 2.2</td>
<td></td>
<td>MC</td>
<td>&gt; 1.1 × 10$^{9}$</td>
<td>&gt; 128.47 ± 12.01</td>
<td>5</td>
</tr>
<tr>
<td>J0913+5919</td>
<td>5.11</td>
<td>1.4</td>
<td>19.4 ± 0.1</td>
<td>—</td>
<td>S</td>
<td>&gt; 4.2 × 10$^{10}$</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td>J1026+2542</td>
<td>5.27</td>
<td>1.7</td>
<td>180.4 ± 5.0</td>
<td>−0.75 ± 0.04$^{1.7,5}$</td>
<td>E</td>
<td>(2.3 ± 0.1) × 10$^{12}$</td>
<td>56.01 ± 7.26</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>4.9</td>
<td>69.6</td>
<td>± 2.5</td>
<td></td>
<td>MC</td>
<td>(1.7 ± 0.1) × 10$^{10}$</td>
<td>—</td>
<td>12 &amp; 13</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>79.2</td>
<td>± 2.9</td>
<td></td>
<td>MC</td>
<td>(5.7 ± 0.3) × 10$^{11}$</td>
<td>&gt; 28.65 ± 3.70</td>
<td>18</td>
</tr>
</tbody>
</table>

**Columns:** Col. 1 – source name (J2000); Col. 2 – redshift; Col. 3 – VLBI observing frequency; Col. 4 – integrated VLBI flux density; Col. 5 – source spectral index; Col. 6 – visual classification of the compact radio structure; Col. 7 – brightness temperature of the main (brightest) source component; Col. 8 – monochromatic rest-frame luminosity at the VLBI observing frequency of the main (brightest) source component; Col. 9 – VLBI literature reference.

**Notes:**
- $^a$ The value is the peak brightness in mJy beam$^{-1}$.
- $^b$ The frequencies (in GHz) between which the spectral indices were calculated are given as superscripts to the values.
- $^c$ Veres et al. [2010a] imaged the source twice to search for variability. The first value corresponds to the first image and the second value to the second image.
- $^d$ S: single-component; E: extended; MC: multi-component.
- $^e$ The value is a lower limit since the source or component (in the case of a multi-component source) is unresolved.
- $^f$ For sources composed of multiple components, the quoted value is the sum of the flux densities of the components.
- $^g$ Parijskij et al. [2014] found that J0311+0507 is composed of eight components. The flux density of the third component was used to calculate the value as the authors conclude that it is the core.
- $^h$ The value was calculated using the spectral index between 2.3 and 8.3 GHz.
- $^i$ The value was calculated using the spectral index between 2.3 and 8.6 GHz.
- $^j$ The value was calculated using the Beasley et al. [2002] 2.3 GHz flux density.
- $^k$ The value was calculated using the Petrov et al. [2008] 2.3 GHz flux density.

**References:**
<table>
<thead>
<tr>
<th>ID</th>
<th>z</th>
<th>$\nu$ [GHz]</th>
<th>Flux density [mJy]</th>
<th>$\alpha_{\text{source}}$</th>
<th>Classification</th>
<th>$T_b$ [K]</th>
<th>$L$ [$10^{26}$ W Hz$^{-1}$]</th>
<th>VLBI ref.</th>
</tr>
</thead>
<tbody>
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<td>5.01</td>
<td>1.6</td>
<td>15.5 ± 0.8</td>
<td>−0.53 ± 0.06$^{(1,6,5)}$</td>
<td>S</td>
<td>—</td>
<td>18.28 ± 2.29</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>8.6 ± 0.4</td>
<td>—</td>
<td>E</td>
<td>(4.5 ± 0.3) $\times$ 10$^9$</td>
<td>10.70 ± 0.50</td>
<td>10</td>
</tr>
<tr>
<td>J1205−0742</td>
<td>4.69</td>
<td>1.4</td>
<td>0.57 ± 0.05</td>
<td>—</td>
<td>MC</td>
<td>(2.2 ± 0.3) $\times$ 10$^4$</td>
<td>—</td>
<td>2</td>
</tr>
<tr>
<td>J1235−0003</td>
<td>4.69</td>
<td>1.4</td>
<td>17.2 ± 0.1</td>
<td>—</td>
<td>S</td>
<td>$&gt;5.4\times10^9$</td>
<td>—</td>
<td>1</td>
</tr>
<tr>
<td>J1242+5422</td>
<td>4.73</td>
<td>1.6</td>
<td>17.7 ± 0.9</td>
<td>−0.55 ± 0.07$^{(1,6,5)}$</td>
<td>E</td>
<td>—</td>
<td>17.59 ± 2.28</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>9.7 ± 0.5</td>
<td>—</td>
<td>S</td>
<td>(5.9 ± 0.5) $\times$ 10$^9$</td>
<td>9.00 ± 0.50</td>
<td>10</td>
</tr>
<tr>
<td>J1427+3312</td>
<td>6.12</td>
<td>1.4</td>
<td>1.8 ± 0.1</td>
<td>−1.06$^{(1,6,5)}$</td>
<td>MC</td>
<td>3.9 $\times$ 10$^8$</td>
<td>—</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.6</td>
<td>1.5</td>
<td>—</td>
<td>MC</td>
<td>9.4 $\times$ 10$^7$</td>
<td>1.78</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>0.46</td>
<td>—</td>
<td>E</td>
<td>1.5 $\times$ 10$^7$</td>
<td>0.89</td>
<td>9</td>
</tr>
<tr>
<td>J1429+5447</td>
<td>6.21</td>
<td>1.6</td>
<td>3.3 ± 0.1</td>
<td>−1.09 ± 0.06$^{(1,7,5)}$</td>
<td>S</td>
<td>(1.40 ± 0.06) $\times$ 10$^9$</td>
<td>13.48 ± 1.53</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>0.99 ± 0.06</td>
<td>—</td>
<td>E</td>
<td>(7.7 ± 0.7) $\times$ 10$^8$</td>
<td>4.50</td>
<td>16</td>
</tr>
<tr>
<td>J1430+4204</td>
<td>4.72</td>
<td>2.3</td>
<td>232.0$^a$</td>
<td>0.17 &amp; 0.04$^{(5,15,c)}$</td>
<td>E</td>
<td>—</td>
<td>—</td>
<td>14 &amp; 15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>173.0</td>
<td>—</td>
<td>S</td>
<td>2.7 $\times$ 10$^{11}$</td>
<td>50.92 &amp; 73.40$^c$</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.6</td>
<td>111.0$^a$</td>
<td>—</td>
<td>E</td>
<td>—</td>
<td>—</td>
<td>14 &amp; 15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>209.0 &amp; 166.0$^c$</td>
<td>—</td>
<td>E</td>
<td>4.3 &amp; 6.0 $\times$ 10$^{11}$</td>
<td>61.52 &amp; 70.43$^c$</td>
<td>4</td>
</tr>
<tr>
<td>J1606+3124</td>
<td>4.56</td>
<td>2.3</td>
<td>952.1 ± 48.2</td>
<td>−0.38 ± 0.09$^{(2,4,4,8)}$</td>
<td>S</td>
<td>(3.8 ± 0.2) $\times$ 10$^{11}$</td>
<td>908.45 ± 154.23</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.8</td>
<td>712.0 ± 32.8</td>
<td>—</td>
<td>MC</td>
<td>(2.2 ± 0.1) $\times$ 10$^{11}$</td>
<td>602.30 ± 102.27</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.3</td>
<td>471.7 ± 23.4</td>
<td>—</td>
<td>MC</td>
<td>(5.8 ± 0.3) $\times$ 10$^{10}$</td>
<td>—</td>
<td>20</td>
</tr>
<tr>
<td>J1611+0844</td>
<td>4.54</td>
<td>1.6</td>
<td>13.0 ± 0.8</td>
<td>−0.01 ± 0.07$^{(1,6,5)}$</td>
<td>S</td>
<td>—</td>
<td>5.24 ± 0.71</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>12.9 ± 0.6</td>
<td>—</td>
<td>E</td>
<td>(4.7 ± 0.3) $\times$ 10$^9$</td>
<td>4.60 ± 0.20</td>
<td>10</td>
</tr>
<tr>
<td>J1659+2101</td>
<td>4.78</td>
<td>1.6</td>
<td>29.3 ± 1.5</td>
<td>−0.92 ± 0.08$^{(1,6,5)}$</td>
<td>E</td>
<td>—</td>
<td>21.41 ± 3.04</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>10.6 ± 0.7</td>
<td>—</td>
<td>E</td>
<td>(3.0 ± 0.4) $\times$ 10$^8$</td>
<td>12.30 ± 0.80</td>
<td>10</td>
</tr>
<tr>
<td>J2102+6015</td>
<td>4.58</td>
<td>2.3</td>
<td>298.6 ± 14.9</td>
<td>−0.99 ± 0.07$^{(2,3,8,3)}$</td>
<td>S</td>
<td>(4.1 ± 0.2) $\times$ 10$^{10}$</td>
<td>618.26 ± 77.67$^h$</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.3</td>
<td>296.4 ± 14.9</td>
<td>−0.57 ± 0.05$^{(2,3,8,6)}$</td>
<td>S</td>
<td>(2.7 ± 0.1) $\times$ 10$^{10}$</td>
<td>296.42 ± 31.45$^i$</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.3</td>
<td>82.4 ± 5.9</td>
<td>—</td>
<td>S</td>
<td>$&gt;1.14\times10^{11}$</td>
<td>170.66 ± 23.18$^h$</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.6</td>
<td>140.6 ± 7.2</td>
<td>—</td>
<td>S</td>
<td>(1.49 ± 0.08) $\times$ 10$^{10}$</td>
<td>140.57 ± 15.00$^i$</td>
<td>21</td>
</tr>
<tr>
<td>J2228+0110</td>
<td>5.95</td>
<td>1.7</td>
<td>0.30 ± 0.12</td>
<td>—</td>
<td>S</td>
<td>$&gt;3.1\times10^8$</td>
<td>—</td>
<td>17</td>
</tr>
</tbody>
</table>

Continued from Table 4.5...
4.5 Discussion

4.4.1 Comments on peculiar literature sources

**J0311+0507.** The VLBI image of the source [shown in Parijskij et al., 2014] has a complex structure with eight components. J0311+0507 has an angular size of 2.8 arcsec which translates to a linear size of 18.7 kpc.

**J0324−2918, J1606+3124 and J2102+6015.** The sources are bright VLBI calibrators [Beasley et al., 2002; Petrov et al., 2006, 2008]. Since we could not find published brightness temperature or luminosity values, we downloaded the calibrated Very Long Baseline Array (VLBA) visibility data from the Astrogeo data base. The data were imaged and model-fitted in *difmap*, and the values in Table 4.5 were calculated in the same way as described in Sections 4.2 and 4.3.

**J1205−0742.** Based on its brightness temperature, the spectral index between 1.4 and 350 GHz, linear size and morphology, Momjian et al. [2005] concluded that J1205−0742 is a nuclear starburst without a radio-loud AGN.

**J1430+4204.** Veres et al. [2010a] reported on VLBA observations of J1430+4204 made at two different epochs at 15 GHz and found the source to be variable (Table 4.5), which is consistent with the results of the 15 GHz total flux density monitoring [Fabian et al., 1999].

### 4.5 Discussion

In this section, we discuss the origin of the radio emission, variability properties, spectral indices and Doppler boosting of the $z > 4.5$ VLBI sources. The sample consists of the objects for which VLBI images are reported in this paper for the first time, and those found in the literature. A summary of the properties of each source is given in Table 4.7.

#### 4.5.1 The origin of the radio emission

Thermal emission from star formation typically has $T_b < 10^5$ K [Sramek & Weedman, 1986; Condon et al., 1991; Kewley et al., 2000] while $T_b \geq 10^6$ K indicates non-thermal emission from AGN [e.g. Kewley et al., 2000; Middelberg et al., 2011]. Since all of the sources have $T_b > 10^6$ K, the expectation is that they are all AGN except J1205−0742 in which the radio emission is from a nuclear starburst (Section 4.4.1). Non-thermal emission could, however, also originate from a supernova remnant or a nuclear supernova remnant complex [e.g. Alexandroff et al., 2012]. Hence, brightness temperature on its own is not sufficient to prove that the emission is from an AGN.

Using optical and near-infrared spectral energy distributions of 942 1.4 GHz radio sources, McAlpine et al. [2013] calculated luminosity functions and redshifts for star forming and AGN dominated radio galaxies. From this, Magliocchetti et al. [2014] showed that at $z > 1.8$ sources with 1.4 GHz radio luminosities smaller than $4 \times 10^{24}$ W Hz$^{-1}$ are powered by star formation while sources with radio luminosities larger than $4 \times 10^{24}$ W Hz$^{-1}$ are AGN powered. While it is possible that a source powered by star formation could be classified as AGN powered or vice versa, Magliocchetti et al. [2014] noted that the probability of this happening is very small.

Using the spectral indices of the main source components we calculated predicted 1.4 GHz flux densities for the main components of the $z > 4.5$ sources and from that derived the 1.4 GHz monochromatic rest-frame luminosities of the components. Using the smallest values of the luminosities allowed inside their uncertainties, the sources indicated in Table 4.7 are all powered...
by AGN. 1.4 GHz luminosities could not be calculated for the remaining five sources because, for these sources, the flux densities of the main components are not available at both frequencies over which the spectral indices are calculated. It is therefore possible that the radio emission in these sources are form star formation. We do, however, consider it unlikely because of their large brightness temperatures, all of which are lower limits except in the case of J1628+1154. This conclusion is supported by the result that the majority of extragalactic sources with 1.4 GHz flux densities greater than $\sim 10$ mJy are AGN while star forming sources start to dominate at flux densities below $\sim 1$ mJy [e.g. Thuan & Condon, 1987; de Zotti et al., 2010; Condon et al., 2012, and references therein].

4.5.2 Variability

Based on the available radio flux density data, we make an attempt to assess the variability of the sources. To check source variability in a uniform way, we matched all of the $z > 4.5$ sources to the FIRST and the National Radio Astronomy Observatory (NRAO) VLA Sky Survey [NVSS; Condon et al., 1998] catalogues, and calculated the integrated flux density ratio ($S_{\text{FIRST}}/S_{\text{NVSS}}$) between the catalogue values (Table 4.6). Both surveys were performed at the same observing frequency of 1.4 GHz, using different configurations of the VLA. The resulting angular resolutions are $\sim 5$ arcsec (B configuration) and $\sim 45$ arcsec (D configuration) in FIRST and NVSS, respectively.

Using a search radius of 2.5 and 23 arcsec for FIRST and NVSS, respectively, we found unique matches for all of the sources except J0324−2918, J0906+6930, J1205−0742, J1427+3312, J2102+6015 and J2228+0110. For J1205−0742, J1427+3312 and J2228+0110, the FIRST flux densities are all smaller than 1.32 mJy. These sources are below the NVSS detection threshold of 2.5 mJy beam$^{-1}$ [Condon et al., 1998]. No match could be found for J0324−2918, J0906+6930 and J2102+6015 in FIRST because they lie outside the survey coverage.

In Table 4.6, the ratio of the sources’ ‘predicted’ 1.4 GHz VLBI flux density and the FIRST flux density ($S_{\text{pred}}/S_{\text{FIRST}}$) is also given. As described in Section 4.3.3, $S_{\text{pred}}$ is calculated for each source by extrapolating its measured VLBI flux density to 1.4 GHz using its spectral index ($\alpha_{\text{source}}$) and assuming a power-law radio spectrum. We consider $S_{\text{pred}}$ as characteristic to the compact VLBI structure at 1.4 GHz, which can be directly compared with the FIRST and NVSS values measured at this frequency.

For assessing the variability, we first consider the $S_{\text{FIRST}}/S_{\text{NVSS}}$ values, defining a source to be variable if its FIRST and NVSS flux densities differ by more than 10 per cent. If the flux density difference could be less than 10 per cent inside the uncertainties we do not classify the source as being variable. As discussed later in this section, we note that this does not mean that the source is not variable. We also note that because of the difference in resolution between FIRST and NVSS, we only classify a source as being variable if the FIRST (the higher resolution catalogue) flux density is higher than the NVSS flux density. If the NVSS flux density is higher than the FIRST flux density, the difference could be because the source is resolved in FIRST, or it could be caused by variability. Based on their $S_{\text{FIRST}}/S_{\text{NVSS}}$ values, the only sources that could be variable are J0011+1446, J0836+0054, J1429+5447 and J1454+1109.

J0011+1446 has a FIRST and NVSS flux density of 24.3±1.2 and 35.8±1.5 mJy, respectively. Looking at the higher-resolution FIRST image, there is a second and third source that are 16.4 and
Table 4.6: Flux density ratios of the $z > 4.5$ sources

<table>
<thead>
<tr>
<th>ID</th>
<th>$S_{\text{FIRST}}/S_{\text{NVSS}}$</th>
<th>$S_{\text{pred}}/S_{\text{FIRST}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0011+1446</td>
<td>0.68 ± 0.04</td>
<td>0.84 ± 0.07</td>
</tr>
<tr>
<td>J0131−0321</td>
<td>1.07 ± 0.06</td>
<td>—</td>
</tr>
<tr>
<td>J0210−0018</td>
<td>0.85 ± 0.06</td>
<td>0.18 ± 0.02</td>
</tr>
<tr>
<td>J0311+0507</td>
<td>1.02 ± 0.06</td>
<td>1.05</td>
</tr>
<tr>
<td>J0324−2918</td>
<td>—</td>
<td>1.15 ± 0.09^c</td>
</tr>
<tr>
<td>J0813+3508</td>
<td>1.05 ± 0.06</td>
<td>0.52 ± 0.04</td>
</tr>
<tr>
<td>J0836+0054</td>
<td>0.44 ± 0.09</td>
<td>1.14</td>
</tr>
<tr>
<td>J0906+6930</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>J0913+5919</td>
<td>0.99 ± 0.06</td>
<td>1.11 ± 0.06^b</td>
</tr>
<tr>
<td>J0940+0526</td>
<td>0.95 ± 0.06</td>
<td>0.33 ± 0.03</td>
</tr>
<tr>
<td>J1013+2811</td>
<td>0.91 ± 0.06</td>
<td>0.78 ± 0.06</td>
</tr>
<tr>
<td>J1026+2542</td>
<td>0.93 ± 0.05</td>
<td>0.85 ± 0.05</td>
</tr>
<tr>
<td>J1146+4037</td>
<td>1.00 ± 0.06</td>
<td>1.35 ± 0.11</td>
</tr>
<tr>
<td>J1205−0742</td>
<td>—</td>
<td>1.05 ± 0.32^a</td>
</tr>
<tr>
<td>J1235−0003</td>
<td>1.01 ± 0.06</td>
<td>0.93 ± 0.05^b</td>
</tr>
<tr>
<td>J1242+5422</td>
<td>1.03 ± 0.06</td>
<td>0.96 ± 0.08</td>
</tr>
<tr>
<td>J1311+2227</td>
<td>0.87 ± 0.07</td>
<td>0.61 ± 0.05</td>
</tr>
<tr>
<td>J1400+3149</td>
<td>0.94 ± 0.06</td>
<td>0.58 ± 0.06</td>
</tr>
<tr>
<td>J1427+3312</td>
<td>—</td>
<td>1.72</td>
</tr>
<tr>
<td>J1429+5447</td>
<td>0.78 ± 0.11</td>
<td>1.35 ± 0.09</td>
</tr>
<tr>
<td>J1430+4204</td>
<td>1.02 ± 0.06</td>
<td>—</td>
</tr>
<tr>
<td>J1454+1109</td>
<td>1.54 ± 0.11</td>
<td>1.24 ± 0.10</td>
</tr>
<tr>
<td>J1548+3335</td>
<td>0.99 ± 0.06</td>
<td>0.38 ± 0.06</td>
</tr>
<tr>
<td>J1606+3124</td>
<td>1.03 ± 0.06</td>
<td>1.67 ± 0.18</td>
</tr>
<tr>
<td>J1611+0844</td>
<td>1.01 ± 0.08</td>
<td>1.48 ± 0.13</td>
</tr>
<tr>
<td>J1628+1154</td>
<td>0.97 ± 0.06</td>
<td>—</td>
</tr>
<tr>
<td>J1659+2101</td>
<td>0.98 ± 0.06</td>
<td>1.19 ± 0.10</td>
</tr>
<tr>
<td>J1720+3104</td>
<td>0.93 ± 0.06</td>
<td>0.97 ± 0.08</td>
</tr>
<tr>
<td>J2102+6015</td>
<td>—</td>
<td>1.51 ± 0.13 &amp; 1.24 ± 0.09^c,d</td>
</tr>
<tr>
<td>J2228+0110</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

**Columns:** Col. 1 – source name (J2000); Col. 2 – ratio of integrated FIRST to NVSS flux densities; Col. 3 – ratio of ‘predicted’ 1.4 GHz VLBI flux density to FIRST flux density.

**Notes:** ^a The value was calculated using the flux densities of the 1.4 GHz VLBI and VLA A configuration observations of the source reported in Momjian et al. [2005]. ^b The value was calculated using the Momjian et al. [2004] 1.4 GHz VLBI flux density. ^c The value was calculated using the NVSS flux density. ^d The two values were calculated using the 2.3 to 8.3 GHz and 2.3 to 8.6 GHz spectral indices reported in Table 4.5, respectively.
29.3 arcsec away from J0011+1446 with flux densities of 3.0 ± 0.2 and 2.8 ± 0.2 mJy, respectively. Since the NVSS beam size is 45 arcsec [Condon et al., 1998], both of the nearby sources will blend with J0011+1446 in NVSS. However, the sum of the flux densities of these two sources is still less than the difference between the FIRST and NVSS flux densities. The remaining flux density difference could be explained by variability of J0011+1446 or of the two nearby sources. Given that we did not find evidence for variability in the multi-epoch EVN observations of J0011+1446, it is likely that J0011+1446 is non-variable. Another possible explanation is that J0011+1446 or the nearby sources are extended beyond 5 arcsec and this structure may be resolved out in FIRST. From Table 4.6, $S_{\text{pred}}/S_{\text{FIRST}}$ nearly equals 1 for J0011+1446. Considering that the source is not variable, this indicates that J0011+1446 is compact on angular scales between 5 arcsec and ~ 5 mas. Hence, it is unlikely that J0011+1446 is extended beyond 5 arcsec.

The FIRST and NVSS flux densities of J0836+0054 are 1.11 ± 0.06 mJy and 2.5 ± 0.5 mJy, respectively. This could indicate that J0836+0054 is extended at angular scales beyond 5 arcsec. However, Petric et al. [2003] observed J0836+0054 with the VLA in A configuration at 1.4 GHz with a resolution of 1.5 arcsec and found a flux density of 1.75 ± 0.04 mJy. Considering that the Petric et al. [2003] observations have higher resolution than FIRST and show ~ 60 per cent higher flux density, we conclude that J0836+0054 is variable. It appears that this conclusion is supported by $S_{\text{pred}}$ being higher than that of FIRST (Table 4.6). However, as no error is available for the predicted flux density, this cannot be said for certain.

The NVSS flux density of J1429+5447 (3.8 ± 0.5 mJy) is higher than that of FIRST (3.0 ± 0.2 mJy) and $S_{\text{pred}} = 4.0 ± 0.2$ mJy, which is equal to or slightly higher than the NVSS flux density. We therefore conclude that J1429+5447 is variable.

From Table 4.6, the EVN flux density of J1454+1109 is higher than its FIRST flux density, which is higher than its NVSS flux density. We therefore conclude that J1454+1109 is variable.

We now turn to $S_{\text{pred}}/S_{\text{FIRST}}$. J1146+4037, J1427+3312, J1429+5447, J1454+1109, J1606+3124, J1611+0844 and J2102+6015 all have $S_{\text{pred}}/S_{\text{FIRST}} > 1.1$. In the discussion above, we already concluded that J1429+5447 and J1454+1109 are variable. For J1146+4037, J1427+3312, J1606+3124, J1611+0844 and J2102+6015, $S_{\text{pred}}/S_{\text{FIRST}} > 1.1$ could indicate that they are also variable. However, care should be taken. When calculating $S_{\text{pred}}$ it is assumed that the spectral index of the source is constant between the two frequencies over which it is calculated. This assumption is not necessarily true since it is likely that at least some of the sources are gigahertz peaked-spectrum (GPS) and megahertz peaked-spectrum (MPS) sources [Coppejans et al., 2015, 2016a]. GPS and MPS sources are radio-loud AGN that are identified based on their peaked spectra with steep optically thin spectra above the spectral turnover. The only difference between the GPS and MPS sources are that they have spectral turnovers above and below 1 GHz, respectively. If a source has a spectral turnover between 1.7 and 5 GHz, $S_{\text{pred}}$ will be overestimated resulting in $S_{\text{pred}}/S_{\text{FIRST}} > 1$, without the source being variable. In Section 4.6, we argue that a significant fraction of the sources are GPS and MPS sources. Consequently, while it is possible that J1146+4037, J1427+3312, J1606+3124, J1611+0844 and J2102+6015 are variable based on their $S_{\text{pred}}/S_{\text{FIRST}}$ values, no definite statement can be made. No $S_{\text{pred}}/S_{\text{FIRST}}$ values are given for J0906+6930 and J1430+4204, since the lowest of the frequencies used for

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4.5 Discussion

determining their spectral index is above 5 GHz. Consequently, there is a very large uncertainty of their predicted 1.4 GHz flux density. Additionally, it is very likely that their spectra cannot be described by a simple power-law with a constant spectral index between 1.4 and 15 GHz, and 1.4 and 43 GHz, respectively.

The most likely explanation for the sources with $S_{\text{pred}}/S_{\text{FIRST}} < 1$ is that some of their radio emission is diffuse and extended beyond the angular scales probed by VLBI. Therefore they are partly resolved out. It is, however, also possible that they are variable. Carilli et al. [2001] observed J1235–0003 at 1.4 GHz with the VLA in A configuration and a resolution of $\sim 1.5$ arcsec, and found a flux density of $18.8 \pm 0.4$ mJy. Considering that the NVSS and FIRST flux densities of J1235–0003 are $18.4 \pm 0.9$ mJy and $18.1 \pm 0.7$ mJy, respectively, and that its 1.4 GHz VLBI flux density is within 7 percent of the FIRST flux density (Tables 4.5 and 4.6), we conclude that J1235–0003 is likely not variable. In the case of J0913+5919, comparing its 1.4 GHz VLA flux densities with FIRST, Momjian et al. [2004] concluded that J0913+5919 is not variable. The flux density values of J0131−0321 in NVSS, FIRST, and the 1.7 GHz VLBI flux density [Gabányi et al., 2015] are $31.4 \pm 1.0$ mJy, $33.7 \pm 1.7$ mJy and $64.4 \pm 0.3$ mJy, respectively. J0131−0321 was only observed at 1.7 GHz with VLBI and we therefore do not have a spectral index for it. To reconcile the VLBI and FIRST flux densities, J0131−0321 would be required to have a spectral index of $\sim 3.3$, which is unphysical. We therefore conclude that J0131−0321 is variable. J2228+0110 was also only observed at 1.7 GHz with VLBI [Cao et al., 2014a]. Considering that its VLBI flux density in Table 4.5 is significantly lower than its FIRST flux density of $1.32 \pm 0.07$ mJy, it is likely resolved out.

J0311+0507, J0913+5919, J1235–0003, J1242+5422, J1659+2101 and J1720+3104 all have $0.9 < S_{\text{FIRST}}/S_{\text{NVSS}} < 1.1$ and $0.9 < S_{\text{pred}}/S_{\text{FIRST}} < 1.1$ within their uncertainties. This indicates that these sources are likely not variable, as was already concluded for J0913+5919 and J1235–0003 in the previous paragraph. In Section 4.3.2 we concluded from our multi-epoch EVN observations that J1720+3104 could be variable, apparently contradicting this result. Consequently, it is possible that J1720+3104 is variable. As mentioned in Section 4.3.2, from the multi-epoch EVN observations of J0940+0526, it is possible that it is variable.

It should be made clear that, just because its NVSS and FIRST flux densities are similar, an individual source cannot be claimed as non-variable. It is possible that an otherwise variable source was observed by NVSS and FIRST when it showed the same flux density by chance. In other words, regular flux density monitoring observations would be essential to reach a firm conclusion on the invariability of any individual radio source. This is clearly illustrated by J1430+4204 whose FIRST and NVSS flux densities are nearly identical (Table 4.6) but for which Fabian et al. [1999] and Veres et al. [2010a] found strong 15 GHz variability (Section 4.4.1). Similarly the two 2.3 GHz VLBI observations of J2102+6015 (Table 4.5) indicate that it is not variable. However, to reconcile the 8.3 and 8.6 GHz VLBI flux densities requires an unphysical spectral index of $\sim 15$, indicating that J2102+6015 is variable. We note that in both cases, the lack of low frequency variability could be the result of the lower frequencies probing regions farther away from the black hole. In these regions, the variability amplitude will be lower, and the time scale will be longer than in the regions closer to the black hole, that are probed by the higher frequency observations.

In summary, it is striking that in only four of the 24 sources for which we have NVSS and
Chapter 4 : VLBI sources at z > 4.5

FIRST flux densities, the values indicate variability, and even in one of those cases (J0011+1446) the difference is likely because of other factors. If the majority of the sources would be strongly variable, a few of them could have, by chance, been observed by FIRST and NVSS at the same flux density. However, the majority of the sample should still show variability. It therefore appears that most of the known $z > 4.5$ VLBI radio sources are not significantly variable. This tendency is qualitatively consistent with the finding by Lovell et al. [2008]; Koay et al. [2011, 2012] that sources at $z \lesssim 2$ are more variable than sources at $2 \lesssim z \lesssim 4$. We do, however, point out that the authors in these studies searched for variability on timescales of a few days and only studied flat-spectrum sources. Consequently, care should be taken when comparing the results. A dedicated follow-up study on the combined sample would allow conclusive statements to be made.

4.5.3 Spectral index

From the summary of the properties of the $z > 4.5$ radio sources found in the literature (Table 4.5), the spectral indices of the sources with multiple components were calculated by summing the flux densities of all components at each frequency. J1548+3335 is the only source in our new EVN sample that is resolved into more than one component (Table 4.4). As noted in Section 4.3.3, its source spectral index equals $-1.07 \pm 0.07$.

If we conventionally define a flat spectral index as $|\alpha_{\text{source}}| < 0.5$, there are nine sources that have flat spectra. Taking the uncertainties of the spectral index into consideration, there are three sources that have flat spectra, but could have positive or negative spectral indices within their uncertainties. Similarly, there are four sources that have negative spectral indices, but they could have flat spectra within the uncertainties.

The spectral index of all of the sources except J0906+6930 and J1430+4204 were calculated between observing frequencies of $\sim 1.7$ and $\sim 8$ GHz. At $z = 5$ this corresponds to the rest-frame frequencies of $\sim 10$ and $\sim 50$ GHz, respectively. The spectral index for J1430+4204 was calculated between the rest-frame frequencies of 29 and 86 GHz, while for J0906+6930 between 97 and 278 GHz, assuming a power-law dependence of the flux density from the frequency. Excluding J1628+1154 (for which we only have a lower limit on its spectral index), J0906+6930 and J1430+4204, there are $8^{+4}_{-3}$ sources with flat spectra, out of the 22 objects which have reliable spectral indices. In other words, $36^{+18}_{-14}$ per cent of the sources have flat VLBI source spectra between $\sim 10$ and $\sim 50$ GHz in their rest frames.

4.5.4 Doppler boosting

For the intrinsic brightness temperature of the sources we assume the equipartition brightness temperature of a relativistic compact jet. It is estimated as $T_{b,\text{eq}} \simeq 5 \times 10^{10}$ K [Readhead, 1994]. Since the Doppler factor is $\delta = T_b/T_{b,\text{eq}}$ [e.g. Veres et al., 2010a, and references therein], the jet emission in sources with $T_b > T_{b,\text{eq}}$ is Doppler-boosted. We therefore conclude that 12 sources are Doppler-boosted.

Excluding the five sources for which we only have lower limits on $T_b$ and that have $T_b < T_{b,\text{eq}}$, there are 13 sources out of the remaining 25 with $T_b < T_{b,\text{eq}}$. There are two possible physical reasons for why a source could have $T_b < T_{b,\text{eq}}$: (1) the jet viewing angle is moderate, resulting in the emission being Doppler-deboosted; (2) the flux density of the source is measured far away
from the spectral peak frequency caused by synchrotron self-absorption. It is therefore possible that the sources with $T_b < T_{b,\text{eq}}$ could still be Doppler-boosted. Finally, brightness temperature is inversely proportional to the size of the source squared (Eq. 4.1). A source could therefore have $T_b < T_{b,\text{eq}}$ because its size is overestimated or the error on its size is underestimated. In cases where the sources are too faint for phase self-calibration, or where the source components are not clearly resolved, the brightness temperatures should consequently be taken as lower limits.

### 4.6 What are the z>4.5 VLBI sources?

Based on their spectra, variability and whether or not they are Doppler-boosted, we now classify the $z > 4.5$ radio sources studied with VLBI to date into three basic classes. A summary of the parameters used for the classification, and the classification of each source are given in Table 4.7.

The first one, which only contains a single object, J1205–0742, is the class of star-forming sources. The second class is the flat-spectrum radio quasars (FSRQs). J1454+1109 is the archetypal example of a FSRQ, having a flat spectrum over a wide spectral range, showing variability and being Doppler-boosted. J1430+4204 similarly satisfies all three criteria, albeit the frequencies used for calculating its spectral index are higher than for the other sources. We do, however, note that calculating its spectral index based on the integrated 5GHz flux density and the 2.3GHz peak intensity gives $\alpha_{\text{source}} = -0.38$, which also indicates a flat spectrum. While there is no solid evidence that J0940+0526, J1606+3124 and J1720+3104 are variable, there are indications that they are (Section 4.5.2), and they all have flat radio spectra and Doppler-boosted jet emission. J0210−0018, J0324−2918 and J1013+2811 are FSRQs since they have flat spectra and are Doppler-boosted. J0131−0321, J0913+5919 and J1026+2542 join the FSRQs based on Doppler-boosting, and, in the case of J0131−0312, variability. For the three sources above, we do not have spectral information regarding their VLBI structure. In Section 4.5.2 we concluded that J0913+5919 is not variable. While this seems to indicate that it is not a FSRQ, non-variability based on a few sparsely obtained flux density measurements cannot be regarded as certain. Therefore we leave it in this class, based on its high measured brightness temperature as the evidence for Doppler-boosting. J1026+2542 has a steep negative spectral index, which would also contradict the FSRQ classification. However, this is likely the result of two components which are resolved in the 5GHz VLBI observations but not at 1.7GHz (Table 4.5). The steep spectrum could also (at least in part) be caused by variability. J2102+6015 is a FSRQ because it is Doppler-boosted and variable, the latter of which likely explains its steep negative spectral index. Finally J1611+0844 joins the FSRQs based on its flat spectrum and indications of variability.

The final, third class of objects is the steep-spectrum sources. All of them have negative spectral indices with $\alpha_{\text{source}} < -0.5$, are therefore not FSRQs, and have $T_b < T_{b,\text{eq}}$. Since their flux densities cannot continue to increase indefinitely toward lower frequencies, their spectra will turn over because of synchrony self absorption at some point. These sources are thus likely MPS or GPS sources, something that could be proven using low-frequency (< 1GHz) observations. We note that the two wide-separation double sources (J0311+0507 and J1548+3335) are also included in this class. For the majority of the sources in this class, there is either insufficient
### Chapter 4: VLBI sources at \( z > 4.5 \)

#### Table 4.7: Classification of the \( z > 4.5 \) sources

<table>
<thead>
<tr>
<th>ID</th>
<th>Origin of the radio emission(^{c})</th>
<th>Spectrum(^{a,c})</th>
<th>Variable(^{c})</th>
<th>Boosted(^{c})</th>
<th>Classification(^{c})</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0011+1446</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Negative (flat)</td>
<td></td>
<td></td>
<td>Steep-spectrum</td>
</tr>
<tr>
<td>J0131−0321</td>
<td>AGN: ( T_b )</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td>FSRQ</td>
</tr>
<tr>
<td>J0210−0018</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Flat (positive)</td>
<td>Yes</td>
<td></td>
<td>FSRQ</td>
</tr>
<tr>
<td>J0311+0507</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Negative</td>
<td>No</td>
<td></td>
<td>Steep-spectrum/wide double</td>
</tr>
<tr>
<td>J0324−2918</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Flat (Negative)</td>
<td>Yes</td>
<td></td>
<td>FSRQ</td>
</tr>
<tr>
<td>J0813+3508</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Negative</td>
<td></td>
<td></td>
<td>Steep-spectrum</td>
</tr>
<tr>
<td>J0836+0054</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Negative</td>
<td>Yes</td>
<td></td>
<td>Steep-spectrum</td>
</tr>
<tr>
<td>J0906+6930</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Negative(^{b})</td>
<td></td>
<td></td>
<td>Steep-spectrum</td>
</tr>
<tr>
<td>J0913+5919</td>
<td>AGN: ( T_b )</td>
<td>No</td>
<td>Yes</td>
<td></td>
<td>FSRQ</td>
</tr>
<tr>
<td>J0940+0526</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Flat</td>
<td>Possibly</td>
<td>Yes</td>
<td>FSRQ</td>
</tr>
<tr>
<td>J1013+2811</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Flat (Negative)</td>
<td>Yes</td>
<td></td>
<td>FSRQ</td>
</tr>
<tr>
<td>J1026+2542</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Negative</td>
<td>Yes</td>
<td></td>
<td>FSRQ</td>
</tr>
<tr>
<td>J1146+4037</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Negative (flat)</td>
<td>Possibly</td>
<td></td>
<td>Steep-spectrum</td>
</tr>
<tr>
<td>J1205−0742</td>
<td>Star-forming(^{d})</td>
<td>No</td>
<td></td>
<td></td>
<td>Star-forming</td>
</tr>
<tr>
<td>J1235−0003</td>
<td>AGN: ( T_b )</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1242+5422</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Negative (flat)</td>
<td>No</td>
<td></td>
<td>Steep-spectrum</td>
</tr>
<tr>
<td>J1311+2227</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Negative</td>
<td></td>
<td></td>
<td>Steep-spectrum</td>
</tr>
<tr>
<td>J1400+3149</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Negative (flat)</td>
<td></td>
<td></td>
<td>Steep spectrum</td>
</tr>
<tr>
<td>J1427+3312</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Negative</td>
<td>Possibly</td>
<td></td>
<td>Steep-spectrum</td>
</tr>
<tr>
<td>J1429+5447</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Negative</td>
<td>Yes</td>
<td></td>
<td>Steep-spectrum</td>
</tr>
<tr>
<td>J1430+4204</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Flat(^{b})</td>
<td>Yes</td>
<td>Yes</td>
<td>FSRQ</td>
</tr>
<tr>
<td>J1454+1109</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Flat</td>
<td>Yes</td>
<td>Yes</td>
<td>FSRQ</td>
</tr>
<tr>
<td>J1548+3335</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Negative</td>
<td></td>
<td></td>
<td>Steep-spectrum/wide double</td>
</tr>
<tr>
<td>J1606+3124</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Flat</td>
<td>Possibly</td>
<td>Yes</td>
<td>FSRQ</td>
</tr>
<tr>
<td>J1611+0844</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Flat</td>
<td>Possibly</td>
<td>Yes</td>
<td>FSRQ</td>
</tr>
<tr>
<td>J1628+1154</td>
<td>AGN: ( T_b )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>J1659+2101</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Negative</td>
<td>No</td>
<td></td>
<td>Steep-spectrum</td>
</tr>
<tr>
<td>J1720+3104</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Flat</td>
<td>Possibly</td>
<td>Yes</td>
<td>FSRQ</td>
</tr>
<tr>
<td>J2102+6015</td>
<td>AGN: ( T_b ) &amp; ( L )</td>
<td>Negative</td>
<td>Yes</td>
<td>Yes</td>
<td>FSRQ</td>
</tr>
<tr>
<td>J2228+0110</td>
<td>AGN: ( T_b )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Columns:** Col. 1 – source name (J2000); Col. 2 – the origin of the radio emission from Section 4.5.1; Col. 3 – spectral classification from Section 4.5.3; Col. 4 – source variability from Section 4.5.2; Col. 5 – Doppler boosting from Section 4.5.4; Col. 6 – source classification.

**Notes:**
- \(^{a}\) Wording such as ‘Negative (flat)’ indicates that the source has a negative spectral index, but that it could be flat within the uncertainties.
- \(^{b}\) The spectral index is calculated between higher rest frame frequencies than for the other sources. See Section 4.5.3.
- \(^{c}\) Blank space indicates that the property could not be determined because of insufficient information. See Section 4.4.1.
- \(^{d}\) Wording such as ‘AGN: \( T_b \) & \( L \)’ indicates that the source is AGN powered based on both its brightness temperature and 1.4 GHz luminosity.
4.7 Summary and conclusions

information about variability, or we concluded that they are not variable in Section 4.5.2. The exceptions to this are J0836+0054, J1146+4037, J1427+3312 and J1429+5447 for which we found indication of variability or concluded that they are variable in Section 4.5.2. While the GPS (and therefore the MPS) sources are the least variable class of radio sources [O’Dea, 1998], there are GPS sources which show significant variability [e.g. Wehrle et al., 1992; O’Dea, 1998]. Hence, variability does not necessarily mean that the source is not a GPS or MPS source. We also note that some of the flat-spectrum sources could be GPS sources with a spectral turnover near the center of the frequency range over which the spectral index is measured. Finally, for J1235−0003, J1628+1154 and J2228+0110, the information available at present is not sufficient to assign them with any of the three classes above.

4.6.1 Correlations between variability, brightness temperature and spectral index

To check for potential correlations between variability and brightness temperature/spectral index, we derived a characteristic brightness temperature and spectral index for each of the sources using the values in Tables 4.4 and 4.5. For both spectral index and brightness temperature, the characteristic value is the average of all of the values for the source that are not upper or lower limits. The median spectral index and brightness temperature of the sources that are indicated as being variable, or possibly variable, in Table 4.7 are $-0.38$ and $1.5 \times 10^{10}$ K, respectively. Repeating this for the remaining sources, gives median values of $-0.65$ and $3.9 \times 10^{9}$ K for the spectral index and brightness temperature, respectively.

We note that caution should be taken when interpreting these values since there is insufficient information to say whether 13 of the sources are variable or not and, as mentioned previously, regular flux density monitoring observations are essential to reach a firm conclusion on the invariability of any individual radio source. Despite this, it would appear that the sources in our sample that are variable, or for which there are indications that they are variable, have flatter spectra and higher brightness temperatures than the other sources. This result fits the picture that the variable sources are FSRQs, which have flat spectra and in which the emission is Doppler boosted, which causes their brightness temperatures to be higher than for the other classes.

We finally also checked for a correlation between brightness temperature and spectral index, but could not find one.

4.7 Summary and conclusions

In this paper, we presented 1.7 and 5 GHz EVN observations of ten $z > 4.5$ sources. These observations increased the number of $z > 4.5$ sources that have been imaged with VLBI by 50 per cent from 20 to 30. Combining our new sources with those from the literature, we investigated the origin of the radio emission, variability properties, spectral indices and Doppler boosting of the $z > 4.5$ VLBI sources (Section 4.5). Based on these properties we classified the sources as star-forming, flat-spectrum radio quasars (FSRQ) and steep-spectrum sources (Section 4.6).

Of the 27 sources that can be classified, 13 (48 per cent) are FSRQs. One of the sources is star-forming, illustrating that even at $z > 4.5$ not all VLBI-detected sources are necessarily AGN.
The remaining 13 objects are steep-spectrum sources that are likely GPS or MPS sources. The idea that a large fraction of the high-redshift sources are GPS and MPS sources was first proposed by Peterson et al. [1982] and O’Dea et al. [1991]. Our conclusion that \( \sim 50 \) per cent of the sources are GPS and MPS sources is supported by the finding in Section 4.5.2 that the majority of the sources are not significantly variable, since the GPS and MPS sources are the least variable class of radio sources [O’Dea, 1998]. It is likely that our classification is uncertain for a few sources, i.e. some of the steep-spectrum sources are in fact FSRQs and vice versa. Despite this, it is clear that roughly half of the sources are FSRQs. This result seems to support the finding by Volonteri et al. [2011] that beyond \( z = 3 \), the number of high-redshift radio-loud sources is significantly lower than what is expected from the number of blazars at these redshifts (Section 4.1). However, it is difficult to accurately assess the selection effects that are at play here. The presently known sample of \( z > 4.5 \) radio sources imaged with VLBI is incomplete and rather inhomogeneous, but can be regarded as optically selected because of their measured spectroscopic redshifts. Moreover, like in the case of the new 10-element sample reported in this paper, the selection for follow-up high-resolution VLBI observations generally involves a flux density lower limit and arcsec-scale structural compactness based on e.g. FIRST data. Both the optical and radio selection criteria may result in a sample biased towards sources with high luminosities, high radio-loudness and Doppler-boosted radio emission. In this respect, not the significant fraction of FSRQs in Table 4.7 is surprising, but the relatively large number of steep-spectrum sources with unboosted radio jet emission.

While the new observations presented in this paper significantly increased the number of \( z > 4.5 \) sources imaged with VLBI, the overall number of sources that have been observed is still very small. Continuing observing efforts are therefore needed to classify new sources as star-forming, FSRQ or steep-spectrum, address open questions such as whether the average bulk Lorentz factor evolves with redshift and to test cosmological models. Complementary to this, non-VLBI observations at frequencies between 100 MHz and \( \sim 20 \) GHz will allow the sources to be classified based on their broad-band spectra and variability. Specifically, observations below 1.4 GHz will allow the GPS and MPS nature of the steep-spectrum sources to be confirmed or refuted.

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Chapter 5

Radio spectra of bright compact sources at z>4.5

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Submitted to MNRAS

Abstract

High-redshift quasars are important to study galaxy and active galactic nuclei (AGN) evolution, test cosmological models, and study supermassive black hole growth. Optical searches for high-redshift sources have been very successful, but radio searches are not hampered by dust obscuration and should be more effective at finding sources at even higher redshifts. Identifying high-redshift sources based on radio data is, however, not trivial. In this article, we report on new multi-frequency Giant Metrewave Radio Telescope (GMRT) observations of eight $z > 4.5$ sources previously studied at high angular resolution with very long baseline interferometry (VLBI). Combining these observations with those from the literature, we construct broad-band radio spectra of all 30 $z > 4.5$ sources that have been observed with VLBI. In the sample we found flat, steep and peaked spectra in approximately equal proportions. Despite several selection effects, we conclude that the $z > 4.5$ VLBI (and likely also non-VLBI) sources have diverse spectra and that only about a quarter of the sources in the sample have flat spectra. Previously, the majority of high-redshift radio sources were identified based on their ultra-steep spectra (USS). Recently a new method has been proposed to identify these objects based on their megahertz-peaked spectra (MPS). Neither method would have identified more than 14 percent of the high-redshift sources in this sample. More effective methods are necessary to reliably identify complete samples of high-redshift sources based on radio data.
Chapter 5 : Radio spectra of z\textgreater{}4.5 sources

5.1 Introduction

To understand the present, we have to understand the past. It is believed that there is a supermassive black hole at the center of nearly every galaxy. These objects power active galactic nuclei (AGN) and were formed in the early Universe. They continue to influence, shape, and grow with their host galaxy via feedback [e.g. Best et al., 2005; Fabian, 2012; Morganti et al., 2013]. To understand present-day galaxies, we consequently need to understand AGN evolution [e.g. Fabian, 2012]. A critical aspect of this is identifying AGN at high redshifts.

In the optical, AGN have been found at distances of up to redshift 7.1 [Mortlock et al., 2011]. However, due to Ly-alpha absorption, detecting sources beyond \( z = 6.5 \) is very difficult in the optical [Mortlock et al., 2011; Becker et al., 2001]. In addition optical searches are hampered by dust obscuration, which does not affect radio observations [e.g. Osmer, 2004]. With radio observations, we should therefore be able to detect sources at all redshifts more effectively, and detect sources out to higher redshifts. It is worth noting that optical spectroscopy is still essential to determine redshifts of the candidate high-redshift sources detected in the radio.

One of the main techniques that is used to identify high-redshift sources in radio images, is the ultra-steep-spectrum (USS) method. This method is based on an observed correlation between the spectral index (\( \alpha \); defined as \( S \propto \nu^\alpha \) where \( S \) is the flux density at frequency \( \nu \)) and redshift [e.g. Whitfield, 1957; Laing & Peacock, 1980; De Breuck et al., 2000]. According to this correlation, sources that have steeper spectra are at higher redshifts. The USS method has proven successful: most of the high-redshift sources identified through radio observations were selected using this method [De Breuck et al., 2000; Verkhodanov & Khabibullina, 2010; Singh et al., 2014], and it has also succeeded in finding sources out to \( z > 4 \) [e.g. van Breugel et al., 1999; Jarvis et al., 2001; Kopylov et al., 2006].

Despite this success, there is no physical explanation for why USS sources should be at higher redshifts than non-USS sources [e.g. Miley & De Breuck, 2008; Verkhodanov & Khabibullina, 2010; Singh et al., 2014], and several recent studies have failed to find a correlation between the spectral index and redshift [Ker et al., 2012; Singh et al., 2014; Smolčić et al., 2014]. The exact definition of a USS source (based on spectral index) differs between authors, e.g., \( \alpha_{608\text{MHz}}^{1415\text{MHz}} < -1.1 \) [Wieringa & Katgert, 1992], \( \alpha_{151\text{MHz}}^{4.5\text{GHz}} < -0.981 \) [Blundell et al., 1998], \( \alpha_{843\text{MHz}}^{1.4\text{GHz}} < -1.3 \) [De Breuck et al., 2004], \( \alpha_{151\text{MHz}}^{1.4\text{GHz}} < -1.0 \) [Cruz et al., 2006], \( \alpha_{843\text{MHz}}^{408\text{MHz}} < -1.0 \) [Broderick et al., 2007] and \( \alpha_{325\text{MHz}}^{1.4\text{GHz}} < -1.0 \) [Singh et al., 2014]. However, Coppejans et al. [2015] pointed out that in their sample of sources, in which all of the sources are detected at 153, 325 and 1400 MHz, when first selecting USS sources between 153 and 325 MHz and then selecting USS sources between 325 and 1400 MHz, less than 26 percent of the sources appear in both selections. Pedani [2003] have also pointed out that the USS sources may not be representative of the entire high-redshift source population, since USS sources are typically smaller and more powerful than non-USS sources [Blundell et al., 1999]. This argument is supported by the discovery of two non-USS sources at \( z = 4.4 \) and 4.9 with \( \alpha_{1.4\text{GHz}}^{8.5\text{GHz}} = 0.94 \pm 0.06 \) and \( \alpha_{325\text{MHz}}^{1.4\text{GHz}} = 0.75 \pm 0.05 \), respectively, [Waddington et al., 1999; Jarvis et al., 2009]. Pedani [2003] have shown that up to 40 percent of the high-redshift sources in a survey can be lost by applying a spectral index cut.

Falcke et al. [2004] and Coppejans et al. [2015] proposed a new method for searching for high-redshift AGN, namely the megahertz peaked-spectrum (MPS) method. Compact steep-spectrum
5.1 Introduction

(CSS), MPS, gigahertz peaked-spectrum (GPS) and high-frequency peaked (HFP) sources are all AGN that show spectral turnovers in their synchrotron spectra, that are believed to be produced by synchrotron self-absorption. GPS, MPS and CSS sources make up between 15 and 30 percent of the sources in flux density limited catalogues [O’Dea, 1998; Orienti, 2016]. The observed turnover frequencies (ν₀) of the CSS, MPS, GPS and HFP sources are ν₀ < 0.5 GHz, ν₀ < 1 GHz, 1 < ν₀ < 5 GHz and ν₀ > 5 GHz [O’Dea, 1998; Dallacasa et al., 2000; Coppejans et al., 2015], respectively. These sources are believed to be young (rather than confined) AGN, some of which will likely evolve into FRI and FRII radio galaxies [Begelman, 1996; O’Dea, 1998; Snellen et al., 2000; Conway, 2002; De Vries et al., 2002b; Murgia et al., 2002; Murgia, 2003; Fantin, 2009; An & Baan, 2012; Orienti, 2016]. For the nearby (z ∼ 1) CSS, MPS, GPS and HFP sources, an empirical relation exists between the rest-frame turnover frequencies (νᵣ, where νᵣ = ν₀(1 + z)) and the linear sizes of the sources [O’Dea, 1998; Snellen et al., 2000; Orienti & Dallacasa, 2014]. From this relation, sources with lower values of νᵣ have larger linear sizes.

The premise of the MPS method is that there are two classes of sources that have peak frequencies below 1 GHz. The first class, which includes the CSS sources, are nearby sources for which ν₀ ∼ νᵣ. The second class of sources have νᵣ > 1 GHz, but ν₀ < 1 GHz due to their higher redshifts. There are two differences between these two classes. First, we expect the high-redshift sources to have smaller angular sizes than the CSS sources, as they are at larger redshifts. Second, the high-redshift sources have higher rest-frame turnover frequencies than the nearby sources. From the turnover frequency–linear size relation, we therefore expect the high-redshift sources to have smaller physical sizes than the CSS sources. It should therefore be possible to distinguish between the CSS and the high-redshift sources based on the high-redshift sources having smaller angular sizes than the CSS sources.

To date no new high-redshift sources have been found using the MPS method. However, Coppejans et al. [2015] identified 33 MPS sources in the NOAO Boötes field and were able to determine redshifts for 24. Given that the average redshift of the sources is 1.3, that there are five sources at z > 2 and that four of the sources for which they could not find redshifts are likely also at z > 2, the authors concluded that there is encouraging evidence in support of the method. Like the USS method, the MPS method likely only selects a subset of the high-redshift sources. However, the MPS method selects a different class of high-redshift sources than the USS method as it is believed that the MPS sources are young AGN [O’Dea, 1998; Murgia et al., 2002; Conway, 2002]. For this reason, the MPS method is important for understanding AGN evolution. The two methods are therefore complementary and will allow for a better understanding of the high-redshift population as a whole.

In Coppejans et al. [2016b, hereafter CFC2016], we presented very long baseline interferometry (VLBI) observations of ten new z > 4.5 sources at 1.7 and 5 GHz with the European VLBI Network (EVN). This increased the number of z > 4.5 sources that have been observed with VLBI by 50 percent, from 20 to 30 sources. Using the VLBI spectra, brightness temperatures, luminosities, morphologies, and 1.4 GHz variability of all 30 z > 4.5 VLBI sources, we concluded that in all of the sources except one, the radio emission is from AGN activity. In one of the sources the emission is from star formation, which illustrates that even at z > 4.5, not all sources detected with VLBI are AGN. We also concluded that the z > 4.5 VLBI sources are a mixture
Chapter 5: Radio spectra of \( z > 4.5 \) sources

of steep-spectrum sources and flat-spectrum radio quasars (FSRQs), or blazars, i.e. sources in which the jet is aligned within a small angle of our line of sight [e.g. Urry, 1999; Krawczynski & Treister, 2013]. We finally argued that the steep-spectrum sources are in fact GPS and MPS sources.

In this paper, we continue our study of all \( 30 \, z > 4.5 \) VLBI sources by investigating their broadband radio spectra. We restricted ourselves to only studying sources that have been observed with VLBI in this paper: (1) it is a continuation of the work in CFC2016 and (2) VLBI observations are necessary to get accurate brightness temperatures for the sources. As discussed in CFC2016, this allows us to distinguish between emission from AGN and star formation and is critical to explain the spectra of J1429+5447 and J1205−0742 in Sections 5.4.2.6 and 5.4.4.2.

For a source at \( z = 4.5 \), its entire rest-frame spectrum below 5.5GHz will be redshifted into observed frequencies below 1GHz. Consequently, to accurately characterize the spectrum, multi-frequency observations of the source below 1GHz are required. In Section 5.2, we present multi-frequency Giant Metrewave Radio Telescope (GMRT) observations below 1GHz of eight \( z > 4.5 \) sources that have been observed at two frequencies with the EVN. Section 5.3 contains a description of how we matched all \( 30 \, z > 4.5 \) VLBI sources to previous radio observations. The spectra and classifications are presented for each source individually in Section 5.4. In Section 5.5 we discuss the spectral classification of the \( z > 4.5 \) VLBI sources, before presenting a summary and conclusion in Section 5.6. Throughout this paper we assume the following cosmological model parameters: \( \Omega_m = 0.3 \), \( \Omega_{\lambda} = 0.7 \), \( H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

5.2 Observations with the GMRT

The sources presented in Table 5.1 were observed with the GMRT during two projects: 21_013 and 29_007. During project 21_013 the following three sources were observed: J1146+4037, J1242+5422 and J1659+2101. The remaining five sources were observed during project 29_007. The sources for project 21_013 were selected from Frey et al. [2010b], while the sources for project 29_007 were selected from CFC2016. In these two publications, 15 \( z > 4.5 \) sources were observed with the EVN at 1.6 and 5GHz, or 1.7GHz and 5GHz. In project 21_013, sources were only considered for observation if they have steep \( (\alpha < -0.5) \) VLBI spectra. To ensure that the sources were sufficiently bright to be detected with the GMRT, in project 29_007, we selected sources based on their 1.4GHz flux densities in the Very Large Array (VLA) Faint Images of the Radio Sky at Twenty-centimeter (FIRST) survey [White et al., 1997], and based on whether they were detected at 325 or 148 MHz with the Westerbork Northern Sky Survey [WENSS; Rengelink et al., 1997] and the Tata Institute of Fundamental Research GMRT Sky Survey [TGSS; Intema et al., 2016], respectively.

During project 21_013, the observations of J1146+4037, J1242+5422 and J1659+2101 were carried out using 32MHz of bandwidth in the 325MHz band and 16MHz of bandwidth in the 610, 235 and 150MHz bands. The central frequencies in each of these bands were 612, 322, 235 and 148 MHz. In project 29_007, J0210−0018, J0940+0526, J1400+3149, J1548+3335 and J1628+1154 were observed using 32MHz of bandwidth in the 610, 325 and 150MHz bands, which had central frequencies of 608, 323 and 148 MHz. In both projects the observations of the target
sources were flanked (where possible), or preceded or followed (where not possible), by 5–10 minute observations of one or two of the following calibrator sources: 3C48, 3C147, 3C286, J1146+399, J1219+484, J1427+3312, J1506+375 and J1719+177. In total, 24.5 hours of observations were taken for project 21_013 and 13.5 hours for project 29_007.

The data were reduced using the SPAM pipeline as described by Intema et al. [2016]. The flux density scale was set by the calibrator(s) for each source and was tied to the Scaife & Heald [2012] standard with an accuracy of $\sim 10$ per cent [e.g. Chandra et al., 2004]. The source parameters in Table 5.1 were extracted from the images using the pybdsm source detection package [Mohan & Rafferty, 2015]. As the VLBI positions of all of the sources are known [Coppejans et al., 2016b, and references therein], we set the source detection threshold, defined as the source’s peak brightness divided by the local root mean square (rms) noise ($\sigma_{\text{local}}$), to $3\sigma_{\text{local}}$. All of the sources, except J0210−0018, were detected in all the observations as single components. J0210−0018 had two components in the GMRT610 image and one component in the GMRT325 and GMRT150 images. This is discussed in detail in Section 5.4.1.3. Following Intema et al. [2016], the uncertainties on the flux densities in Table 5.1 were increased by 10 per cent to account for systematic uncertainties.
## Table 5.1: GMRT image parameters

<table>
<thead>
<tr>
<th>ID</th>
<th>Observation name</th>
<th>Flux density [mJy]</th>
<th>Local noise [mJy beam(^{-1})]</th>
<th>Source size [arcsec]</th>
<th>PA [°]</th>
<th>Restoring beam [arcsec]</th>
<th>PA [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0210--0018</td>
<td>GMRT610</td>
<td>10.5 ± 1.1 &amp; 4.4 ± 0.5</td>
<td>0.04</td>
<td>7.1 × 4.2 &amp; 7.2 × 4.2</td>
<td>100 &amp; 97</td>
<td>7.1 × 4.0</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>GMRT325</td>
<td>19.0 ± 2.1</td>
<td>0.32</td>
<td>10.7 × 6.9</td>
<td>40</td>
<td>9.3 × 6.7</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>GMRT150</td>
<td>23.0 ± 8.0</td>
<td>4.50</td>
<td>33.0 × 17.4</td>
<td>69</td>
<td>32.2 × 16.7</td>
<td>64</td>
</tr>
<tr>
<td>J0940+0526</td>
<td>GMRT610</td>
<td>102.8 ± 10.3</td>
<td>0.09</td>
<td>5.0 × 4.1</td>
<td>89</td>
<td>4.8 × 4.0</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>GMRT325</td>
<td>135.1 ± 13.6</td>
<td>0.62</td>
<td>10.3 × 9.1</td>
<td>0</td>
<td>10.1 × 8.9</td>
<td>0</td>
</tr>
<tr>
<td>J1146+4037</td>
<td>GMRT610</td>
<td>6.8 ± 0.7</td>
<td>0.08</td>
<td>5.8 × 4.1</td>
<td>110</td>
<td>5.8 × 4.1</td>
<td>112</td>
</tr>
<tr>
<td></td>
<td>GMRT325</td>
<td>4.6 ± 0.5</td>
<td>0.05</td>
<td>9.9 × 7.6</td>
<td>59</td>
<td>9.7 × 7.4</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>GMRT235</td>
<td>4.9 ± 1.1</td>
<td>0.61</td>
<td>15.6 × 10.5</td>
<td>112</td>
<td>14.7 × 10.8</td>
<td>113</td>
</tr>
<tr>
<td></td>
<td>GMRT150</td>
<td>4.6 ± 1.4</td>
<td>0.73</td>
<td>30.4 × 15.4</td>
<td>13</td>
<td>25.0 × 16.8</td>
<td>13</td>
</tr>
<tr>
<td>J1242+5422</td>
<td>GMRT610</td>
<td>29.7 ± 3.0</td>
<td>0.10</td>
<td>6.0 × 4.1</td>
<td>136</td>
<td>5.8 × 4.1</td>
<td>138</td>
</tr>
<tr>
<td></td>
<td>GMRT325</td>
<td>30.0 ± 3.0</td>
<td>0.10</td>
<td>10.8 × 7.6</td>
<td>46</td>
<td>10.8 × 7.6</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>GMRT235</td>
<td>27.6 ± 2.9</td>
<td>0.56</td>
<td>14.7 × 10.9</td>
<td>147</td>
<td>14.8 × 10.7</td>
<td>146</td>
</tr>
<tr>
<td></td>
<td>GMRT150</td>
<td>26.1 ± 2.9</td>
<td>0.69</td>
<td>26.2 × 17.4</td>
<td>1</td>
<td>27.2 × 17.3</td>
<td>1</td>
</tr>
<tr>
<td>J1400+3149</td>
<td>GMRT610</td>
<td>24.6 ± 2.5</td>
<td>0.08</td>
<td>4.7 × 3.7</td>
<td>50</td>
<td>4.6 × 3.6</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>GMRT150</td>
<td>56.2 ± 6.5</td>
<td>2.11</td>
<td>33.4 × 17.7</td>
<td>67</td>
<td>24.9 × 15.6</td>
<td>70</td>
</tr>
<tr>
<td>J1548+3335</td>
<td>GMRT610</td>
<td>77.6 ± 7.8</td>
<td>0.19</td>
<td>9.5 × 4.2</td>
<td>82</td>
<td>9.4 × 4.0</td>
<td>83</td>
</tr>
<tr>
<td>J1628+1154</td>
<td>GMRT610</td>
<td>107.7 ± 10.8</td>
<td>0.13</td>
<td>6.2 × 3.8</td>
<td>78</td>
<td>6.0 × 3.5</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>GMRT325</td>
<td>152.4 ± 15.3</td>
<td>0.63</td>
<td>11.6 × 7.3</td>
<td>83</td>
<td>11.6 × 7.1</td>
<td>83</td>
</tr>
<tr>
<td>J1659+2101</td>
<td>GMRT610</td>
<td>48.1 ± 4.8</td>
<td>0.13</td>
<td>4.7 × 3.7</td>
<td>28</td>
<td>4.6 × 3.6</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>GMRT325</td>
<td>53.0 ± 5.3</td>
<td>0.13</td>
<td>10.6 × 6.9</td>
<td>63</td>
<td>10.2 × 6.7</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>GMRT235</td>
<td>54.7 ± 5.7</td>
<td>0.84</td>
<td>11.9 × 9.5</td>
<td>22</td>
<td>12.0 × 9.5</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>GMRT150</td>
<td>48.2 ± 5.4</td>
<td>1.45</td>
<td>22.9 × 15.7</td>
<td>23</td>
<td>21.6 × 15.1</td>
<td>17</td>
</tr>
</tbody>
</table>

**Columns:** Col. 1 – source name (J2000); Col. 2 – observation name; Col. 3 – integrated flux densities and uncertainties; Col. 4 – rms noise at the source position; Col. 5 – fitted source size (FWHM); Col. 6 – fitted major axis position angle (measured from north through east); Col. 7 – Gaussian restoring beam size (FWHM); Col. 8 – Gaussian restoring beam major axis position angle (measured from north through east).
5.3 Flux densities from the literature

In this section we describe the procedure we followed to obtain previously recorded radio observations $(10 \text{ MHz} < \nu < 250 \text{ GHz})$ for all $30 \, z > 4.5$ VLBI sources from the literature. These literature values are included with our observations (Section 5.2) to produce the final spectra in Section 5.4.

For each source, we obtained the detected radio flux densities from the NASA/IPAC Extragalactic Database (NED). Additionally, we recorded all unique matches to the source in the catalogues in the VizieR database [Ochsenbein et al., 2000] and in articles in the SAO/NASA Astrophysics Data System (ADS). In each case, a matching radius of 20 arcsec from the VLBI position was used.

A number of our targets were observed, but not detected, in the following large surveys: The VLA Low-Frequency Sky Survey Redux [VLSSr, 74 MHz; Lane et al., 2014], TGSS, WENSS, the Green Bank 4.85 GHz survey [GB6, 4850 MHz; Gregory et al., 1996] and the 62 MHz Low-Frequency Array (LOFAR) image of the Boötes field made by Van Weeren et al. [2014]. To determine consistent upper limits for these non-detections, we downloaded the survey images and measured $\sigma_{\text{local}}$ within the $10 \times 10$ arcmin area surrounding the VLBI position. The flux density upper limit was then recorded as $3\sigma_{\text{local}}$. As there were no images available for the GB6 survey, we used the detection threshold of 18 mJy [Gregory et al., 1996] as an upper limit.

As we have known VLBI coordinates for our targets, we used a lower detection threshold ($3\sigma_{\text{local}}$) than the VLSSr, WENSS ($5\sigma_{\text{local}}$) and TGSS surveys ($7\sigma_{\text{local}}$). To include the $3\sigma_{\text{local}}$ detections from these surveys, we ran source extraction on the survey images using PYBDSM as described in Section 5.2. The flux densities of sources that were detected at a significance (defined as the sources peak brightness divided by $\sigma_{\text{local}}$) greater than $3\sigma_{\text{local}}$, and for which the source position differed by less than half the FWHM of the restoring beam of the image were recorded as detections. These detections are listed in Table 5.2. For these sources, the uncertainties on the TGSS and VLSSr flux densities were increased by 10 and 12 per cent, respectively, to account for systematic uncertainties, as was done in Intema et al. [2016] and Lane et al. [2014].

The observations and surveys have different angular resolutions, so we checked for possible blended sources. Using the FIRST survey, we recorded the separation between each of our targets.

Table 5.2: Flux densities of sources that are not in the survey catalogues but that were detected

<table>
<thead>
<tr>
<th>ID</th>
<th>Observation name</th>
<th>$\nu$ [MHz]</th>
<th>Flux density [mJy]</th>
<th>Detection significance $[\sigma_{\text{local}}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0131−0321</td>
<td>TGSS</td>
<td>148</td>
<td>24.6 ± 4.5</td>
<td>~ 7.5</td>
</tr>
<tr>
<td>J0210−0018</td>
<td>TGSS</td>
<td>148</td>
<td>30.3 ± 6.0</td>
<td>~ 6.6</td>
</tr>
<tr>
<td>J1026+2542</td>
<td>VLSSr</td>
<td>74</td>
<td>631 ± 237</td>
<td>~ 4.1</td>
</tr>
<tr>
<td>J1628+1154</td>
<td>VLSSr</td>
<td>74</td>
<td>611 ± 239</td>
<td>~ 4.3</td>
</tr>
</tbody>
</table>

Notes: *The detection significance was calculated by dividing the source peak brightness by the local rms noise.
Table 5.3: Flux density upper limits

<table>
<thead>
<tr>
<th>ID</th>
<th>Observation name</th>
<th>$\nu$ [MHz]</th>
<th>Upper limit [mJy]</th>
<th>ID</th>
<th>Observation name</th>
<th>$\nu$ [MHz]</th>
<th>Upper limit [mJy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0324−2918</td>
<td>VLSSr</td>
<td>74</td>
<td>282.5</td>
<td>J1427+3312</td>
<td>WWT2014</td>
<td>62</td>
<td>19.1</td>
</tr>
<tr>
<td>J0813+3508</td>
<td>GB6</td>
<td>4850</td>
<td>18.0</td>
<td>J1430+4204</td>
<td>VLSSr</td>
<td>74</td>
<td>372.4</td>
</tr>
<tr>
<td>J0836+0054</td>
<td>TGSS</td>
<td>148</td>
<td>6.1</td>
<td>J1454+1109</td>
<td>TGSS</td>
<td>148</td>
<td>12.0</td>
</tr>
<tr>
<td>J0906+6930</td>
<td>TGSS</td>
<td>148</td>
<td>4.8</td>
<td>GB6</td>
<td>4850</td>
<td>18.0</td>
<td></td>
</tr>
<tr>
<td>J0913+5919</td>
<td>TGSS</td>
<td>148</td>
<td>6.9</td>
<td>J1548+3335</td>
<td>VLSSr</td>
<td>74</td>
<td>205.6</td>
</tr>
<tr>
<td></td>
<td>WENSS</td>
<td>325</td>
<td>10.6</td>
<td>GB6</td>
<td>4850</td>
<td>18.0</td>
<td></td>
</tr>
<tr>
<td>J0940+0526</td>
<td>VLSSr</td>
<td>74</td>
<td>583.4</td>
<td>J1606+3124</td>
<td>TGSS</td>
<td>148</td>
<td>10.5</td>
</tr>
<tr>
<td></td>
<td>GB6</td>
<td>4850</td>
<td>18.0</td>
<td>J1611+0844</td>
<td>TGSS</td>
<td>148</td>
<td>10.0</td>
</tr>
<tr>
<td>J1013+2811</td>
<td>TGSS</td>
<td>148</td>
<td>14.6</td>
<td>GB6</td>
<td>4850</td>
<td>18.0</td>
<td></td>
</tr>
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<td>GB6</td>
<td>4850</td>
<td>18.0</td>
<td>J1628+1154</td>
<td>GB6</td>
<td>4850</td>
<td>18.0</td>
</tr>
<tr>
<td>J1146+4037</td>
<td>GB6</td>
<td>4850</td>
<td>18.0</td>
<td>J1659+2101</td>
<td>GB6</td>
<td>4850</td>
<td>18.0</td>
</tr>
<tr>
<td>J1235−0003</td>
<td>TGSS</td>
<td>148</td>
<td>8.9</td>
<td>J1720+3104</td>
<td>TGSS</td>
<td>148</td>
<td>7.2</td>
</tr>
<tr>
<td>J1242+5422</td>
<td>GB6</td>
<td>4850</td>
<td>18.0</td>
<td>WENSS</td>
<td>325</td>
<td>10.4</td>
<td></td>
</tr>
<tr>
<td>J1311+2227</td>
<td>TGSS</td>
<td>148</td>
<td>9.7</td>
<td>GB6</td>
<td>4850</td>
<td>18.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GB6</td>
<td>4850</td>
<td>18.0</td>
<td>J2228+0110</td>
<td>TGSS</td>
<td>148</td>
<td>7.0</td>
</tr>
<tr>
<td>J1400+3149</td>
<td>GB6</td>
<td>4850</td>
<td>18.0</td>
<td>GB6</td>
<td>4850</td>
<td>18.0</td>
<td></td>
</tr>
</tbody>
</table>

and their nearest neighbouring source. If the target was not in the FIRST survey, we used TGSS or the 1.4 GHz Sloan Digital Sky Survey (SDSS) southern Equatorial Stripe [STRIPE82; Hodge et al., 2011] catalogue (which have resolutions of 25 and 1.8 arcsec, respectively) instead. For each of the detections we then checked whether the nearest neighbour could be distinguished from the target. All blended sources were discarded. These cases are discussed individually for each source in Section 5.4.

As a final step, we plotted each of the spectra (Section 5.4) and discarded the upper limits that were too high to valuably constrain the spectra. A final list of all of the upper limits that were used are given in Table 5.3.

5.4 Radio spectra

In this section we will discuss each of the sources individually, and classify their spectra into one of the following classes: flat-spectrum sources, sources with steep spectra, sources with peaked spectra, and sources with unusual spectra (or spectra that could be classified into more than one class). A summary of the classification of each source, as well as their redshifts, is given in Table 5.4.

Each flux density point in the spectra is labelled with the name of the survey, or else according to the following convention: the first characters are the initial letters of the surnames for the lead authors of the article in which the flux density was published. These characters are followed by the year of publication. If the flux density is from a VLBI observation, the year is followed by ‘(V)’. In the spectra (Figures 5.1, 5.2 and 5.5 – 5.32 ) VLBI flux densities are also shown as filled grey
### Table 5.4: Summary of the spectral classification of each source

<table>
<thead>
<tr>
<th>ID</th>
<th>$z$</th>
<th>Classification$^a$</th>
<th>ID</th>
<th>$z$</th>
<th>Classification$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0011+1446</td>
<td>4.96</td>
<td>Flat</td>
<td>J1242+5422</td>
<td>4.73</td>
<td>Peaked</td>
</tr>
<tr>
<td>J0131−0321</td>
<td>5.18</td>
<td>Flat</td>
<td>J1311+2227</td>
<td>4.61</td>
<td>Inverted or flat or peaked</td>
</tr>
<tr>
<td>J0210−0018</td>
<td>4.65</td>
<td>Flat (steep)</td>
<td>J1400+3149</td>
<td>4.64</td>
<td>Flat</td>
</tr>
<tr>
<td>J0311+0507</td>
<td>4.51</td>
<td>USS</td>
<td>J1427+3312</td>
<td>6.12</td>
<td>Steep (flat)</td>
</tr>
<tr>
<td>J0324−2918</td>
<td>4.63</td>
<td>Peaked</td>
<td>J1429+5447</td>
<td>6.21</td>
<td>Steep</td>
</tr>
<tr>
<td>J0813+3508</td>
<td>4.92</td>
<td>Steep</td>
<td>J1430+4204</td>
<td>4.72</td>
<td>Flat</td>
</tr>
<tr>
<td>J0836+0054</td>
<td>5.77</td>
<td>Steep (USS)</td>
<td>J1454+1109</td>
<td>4.93</td>
<td>Unknown</td>
</tr>
<tr>
<td>J0906+6930</td>
<td>5.47</td>
<td>Peaked</td>
<td>J1548+3335</td>
<td>4.68</td>
<td>Steep</td>
</tr>
<tr>
<td>J0913+5919</td>
<td>5.11</td>
<td>Peaked</td>
<td>J1606+3124</td>
<td>4.56</td>
<td>Peaked</td>
</tr>
<tr>
<td>J0940+0526</td>
<td>4.50</td>
<td>Steep</td>
<td>J1611+0844</td>
<td>4.54</td>
<td>Inverted or flat or peaked</td>
</tr>
<tr>
<td>J1013+2811</td>
<td>4.75</td>
<td>Flat or peaked</td>
<td>J1628+1154</td>
<td>4.47</td>
<td>Steep</td>
</tr>
<tr>
<td>J1026+2542</td>
<td>5.27</td>
<td>Flat</td>
<td>J1659+2101</td>
<td>4.78</td>
<td>Peaked</td>
</tr>
<tr>
<td>J1146+4037</td>
<td>5.01</td>
<td>Peaked (inverted)</td>
<td>J1720+3104</td>
<td>4.62</td>
<td>Flat or peaked</td>
</tr>
<tr>
<td>J1205−0742</td>
<td>4.69</td>
<td>Concave</td>
<td>J2102+6015</td>
<td>4.58</td>
<td>Peaked</td>
</tr>
<tr>
<td>J1235−0003</td>
<td>4.69</td>
<td>Peaked</td>
<td>J2228+0110</td>
<td>5.95</td>
<td>Not USS$^b$</td>
</tr>
</tbody>
</table>

**Notes:**

$^a$ Wording such as ‘Flat (steep)’ indicates that the source has a flat spectral index, but that it could be steep within the uncertainties. Wording such as ‘Flat or peaked’ is used when there is insufficient information to classify the spectrum of the source, but (often using upper limits) it is possible to exclude certain spectral types. $^b$ In other words, J2228+0110 can have an inverted, flat, steep, peaked or concave spectrum.
symbols to distinguish them from non-VLBI flux densities. We note that for some publications
and catalogues, no flux density errors are available. This is the case for the PBW1992, B2.2
and B3 catalogues, however, following Vollmer et al. [2005], we assumed errors of 10 per cent for
PBW1992 and 20 per cent for B2.2 and B3. A table containing all of the flux density labels, the
observing frequency at which the measurement was taken, and the literature reference is given in
Appendix 5.7.

Throughout this section, when fitting the spectra we used a linear least-squares fitting routine.
Because of their much higher angular resolution, VLBI measurements are insensitive to the large-
scale radio emission. VLBI flux densities are therefore usually underestimates of the total flux
densities, unless the source is very compact. Consequently, unless specifically noted, the spectral
fits do not include VLBI flux densities, flux densities without uncertainties and flux density upper
limits. Note that the values in the spectra are integrated flux densities unless only the peak
brightness was available. We finally point out that in most cases the flux density measurements
used here are taken at different epochs. In the case of source variability, this may affect the
estimated spectral index.

All of the sources have single components in their non-VLBI images unless noted otherwise
in the discussion of the source. The VLBI morphological classifications of all of the sources are
given in CFC2016.

5.4.1 Flat-spectrum sources

The following six sources all have flat spectra (they can be fitted by a single power law with
\(-0.5 < \alpha < 0.5\)).

5.4.1.1 J0011+1446

J0011+1446 was matched to sources in the TGSS, National Radio Astronomy Observatory (NRAO)
VLA Sky Survey [NVSS; Condon et al., 1998] and GB6 catalogues. However, in the FIRST cat-
ologue there are two sources that are 16.4 and 29.3 arcsec away from the J0011+1446 VLBI
position. Since the flux density of these sources will blend with that of J0011+1446 in the lower
resolution TGSS, NVSS and GB6 catalogues, we discarded these matches. The spectrum is shown
in Fig. 5.1. Fitting a power law between the FIRST and CLASS flux densities gives a spectral
index of \(\alpha = -0.25 \pm 0.11\). J0011+1446 is therefore a flat-spectrum source. From the spectrum it
is clear that some of the source’s flux density was resolved out in the VLBI observations, or the
source is variable.

5.4.1.2 J0131−0321

The power-law fit for the spectrum of J0131−0321 (Fig. 5.2) gives \(\alpha = 0.12 \pm 0.10\). GCF2015(V)
observed this source with the EVN at 1.7 GHz and found it to be unresolved, with a flux density
of 64.4 \(\pm 0.3\) mJy. Comparing this to the FIRST and NVSS flux densities of 33.7 \(\pm 1.7\) and
31.4 \(\pm 1.0\) mJy, respectively, GCF2015(V) concluded that J0131−0321 is likely variable. However,
if J0131−0321 is variable it would require that the FIRST and NVSS observations were done
at two epochs when J0131−0321 serendipitously had the same flux density. The argument that
5.4 Radio spectra

Figure 5.1: The radio spectrum of J0011+1446.

Table 5.5: J0210−0018 component flux densities

<table>
<thead>
<tr>
<th>Image</th>
<th>Component</th>
<th>Flux density [mJy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMRT610</td>
<td>north</td>
<td>4.36 ± 0.45</td>
</tr>
<tr>
<td></td>
<td>south</td>
<td>10.46 ± 1.05</td>
</tr>
<tr>
<td>STRIPE82</td>
<td>north</td>
<td>2.22 ± 0.33</td>
</tr>
<tr>
<td></td>
<td>south</td>
<td>7.72 ± 0.34</td>
</tr>
</tbody>
</table>

J0131−0321 is variable is, however, supported by our finding that J0131−0321 has a flat spectrum, and GCF2015(V)’s conclusion that the VLBI emission is Doppler-boosted.

5.4.1.3 J0210−0018

Fig. 5.3 and 5.4 show the GMRT610 and 1.4 GHz VLA STRIPE82 images of J0210−0018. In both of these images the source has two components. Table 5.5 gives the flux densities of the individual components. Using the GMRT610 and STRIPE82 flux densities we calculate spectral indices of $-0.79 \pm 0.21$ and $-0.36 \pm 0.13$ for the northern and southern components, respectively.

In all the other observations (except for FIRST), J0210−0018 only has a single component due to a lack of resolution. Although FIRST has sufficient resolution to resolve J0210−0018, the source is fit by a single component with major and minor axes of 4.3 and 1.3 arcsec, respectively. The FIRST image does show an indication of a second component at the position of the northern component. It is not detected however, because the separation between the two components
is small, and the northern component is significantly fainter than the southern component. At 1.4 GHz the two components are therefore only detected in the STRIPE82 catalogue, which has both higher resolution and sensitivity than FIRST. Using the STRIPE82 positions of the two components, the angular separation between the components is 7.0 arcsec, which translates to a linear separation of \( \sim 45.6 \) kpc.

The southern component coincides positionally with the optical AGN. In principle there are four possibilities for what J0210−0018 could be: (1) the two components are unrelated sources at different redshifts; (2) the northern and southern components are gravitationally lensed images of the same source; (3) the northern component is a hotspot, or a lobe, in the brighter southern component’s jet; (4) the two components are separate, unrelated AGN at the same redshift.

If the two components of J0210−0018 are formed by gravitational lensing, they will have the same spectral index. As this is not the case, this possibility is ruled out. One way to confirm that the two components are related is to search for a jet between them. Using our previous 1.7 and 5 GHz EVN observations of J0210−0018 [Coppejans et al., 2016b], in which the southern component was detected at both frequencies, we searched for a jet and did not find anything. We do, however, note that the 1.7 GHz EVN flux density is only 22 per cent of the 1.4 GHz STRIPE82 flux density of the southern component. This indicates that the VLBI observations resolved out a significant fraction of the source’s flux density. Consequently it is possible that this flux density is contained in a jet between the components that was resolved out. This possibility is further supported by the fact that the southern and northern components have flat and steep spectra,
respectively. This likely indicates that the southern component is the AGN core (which will have a flat spectrum), and the northern component is a lobe or a hotspot (which typically have steep spectra) in the southern component’s jet.

In Fig. 5.5 we show the spectrum of J0210−0018. In the spectrum, the GMRT610 and STRIPES82 flux densities are the sums of the flux densities of the two components. Fig. 5.5 is therefore the sum of the spectra of both components. A power law fit to the spectrum gives $\alpha = -0.49 \pm 0.07$. We therefore classify J0210−0018 as having an overall flat spectrum. We do, however, note that J0210−0018 can be a steep spectrum source (defined in Section 5.4.2) within its uncertainties.

5.4.1.4 J1026+2542

The spectrum of J1026+2542 (Fig. 5.6) is fit with a single power law (the solid line in Fig. 5.6) with a spectral index of $\alpha = -0.41 \pm 0.02$. This is consistent with the value of $\alpha = -0.4$ found by FFP2013(V), and the fact that the source is Doppler-boosted [Coppejans et al., 2016b].

5.4.1.5 J1400+3149

We fitted the spectrum of J1400+3149 (shown in Fig. 5.7) with a power law with a spectral index of $-0.36 \pm 0.07$. 

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Figure 5.3: 608 MHz GMRT610 image of J0210−0018. The lowest contours are drawn at $-0.18$ and $0.18\,\text{mJy beam}^{-1}$, the positive contours increase in factors of $\sqrt{2}$ thereafter.
5.4.1.6 J1430+4204

Fig. 5.8 shows the spectrum of J1430+4204. WFP2006 observed J1430+4204 at 15.2 GHz over a period of \( \sim 7.5 \) years, during which time they found the flux density to vary between \( \sim 70 \) and \( \sim 430 \) mJy. Based on these findings and Fig. 5.8, we conclude that J1430+4204 is extremely variable. Fig. 5.8 gives the average 15.2 GHz WFP2006 flux density. Fitting a power law to the spectrum, we find a spectral index of \( 0.10 \pm 0.03 \). While this spectral index is likely not a good indication of the spectral index of the source at any given time, it can be considered as an average spectral index. Combining this with the finding that J1430+4204 is Doppler-boosted [Coppejans et al., 2016b], we conclude that J1430+4204 is a flat-spectrum radio quasar.

5.4.2 Steep-spectrum sources

The eight sources discussed in this section are all fitted with a single power-law spectrum with \( \alpha < -0.5 \). Included in this class of sources are the USS sources, which we will define as objects with \( \alpha < -1.0 \) across their entire spectral range.

5.4.2.1 J0311+0507

Matching the VLBI position for J0311+0507 to FIRST, we find that there are 15 sources within two arcminutes of the source and that the nearest neighbour is 5.2 arcsec away. Looking at the image of J0311+0507 in FIRST, the VLA beam pattern is clearly visible around the source,
Figure 5.5: The radio spectrum of J0210−0018. The power law fit to the spectrum (shown as the solid line) has $\alpha = -0.49 \pm 0.07$. 
Figure 5.6: The radio spectrum of J1026+2542. The fit to the spectrum (shown as the solid line) gives $\alpha = -0.41 \pm 0.02$. 
5.4 Radio spectra

![Graph of radio spectrum](http://third.ucllnl.org/cgi-bin/firstcutout)

**Figure 5.7:** The radio spectrum of J1400+3149. The fit to the spectrum is shown as a solid line.

with the neighbouring sources all lying on the beam pattern\(^3\). Comparing the FIRST and NVSS images, we conclude that the nearest real source to J0311+0507 is 330 arcsec away, and that the 15 neighbouring sources in FIRST are all artefacts.

We fitted the spectrum (shown in Fig. 5.9) with a single power law with a spectral index of \(\alpha = -1.09 \pm 0.06\), and therefore classify J0311+0507 as a USS source. We do note that our spectral index is higher than the spectral index of \(-1.31\) between 365 and 4850 MHz found by Goss et al. [1992] and Parijskij et al. [2014, and references therein]. As a final point, we note that the PTK2014(V) VLBI observations of J0311+0507 showed that it has a FR II structure, and an angular and linear size of 2.8 arcsec and 18.7 kpc, respectively.

### 5.4.2.2 J0813+3508

In FIRST there is a second source that is 6.9 arcsec distant from the J0813+3508 VLBI position, which translates to a linear size of \(\sim 43.7\) kpc. FPG2010(V) observed both sources with the EVN at 1.7 and 5 GHz. While the second source was not detected, the authors did find a jet pointing from J0813+3508 towards the second source in the 1.7 GHz image. From this, FPG2010(V) concluded that the second source is a lobe of J0813+3508 that is resolved out by the VLBI observations. The only non-VLBI observation that has high enough resolution to resolve the two components is FIRST, in which the main and second components have flux densities of 37.5 ± 1.9 and 11.5 ± 0.6 mJy, respectively. In the source spectrum (shown in Fig. 5.10), the FIRST flux

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\(^3\)http://third.ucllnl.org/cgi-bin/firstcutout
Chapter 5: Radio spectra of z>4.5 sources

Figure 5.8: The radio spectrum of J1430+4204.
Figure 5.9: The radio spectrum of J0311+0507. The power law fit to the spectrum (solid line) gives $\alpha = -1.09 \pm 0.06$. 
The radio spectrum of J0813+3508. The power law fit to the spectrum (solid line) gives $\alpha = -0.80 \pm 0.12$.

The spectrum of J0836+0054 is shown in Fig. 5.11. Fitting the spectrum with a power law gives a spectral index of $\alpha = -0.89 \pm 0.29$. This indicates that the source can be a USS source within the uncertainties. J0836+0054 has FIRST and NVSS flux densities of $1.11 \pm 0.06$ mJy and $2.5 \pm 0.5$ mJy, respectively. In addition, PCB2003 found a 1.4GHz flux density of $1.75 \pm 0.04$ mJy during their observations with the VLA at a resolution of 1.5 arcsec. Since these observations have a higher resolution than FIRST, and a $\sim 60\%$ higher flux density, we concluded in CFC2016 that J0836+0054 is variable. Consequently, the fitted spectral index may not be a good estimate of the instantaneous spectral index, but is rather a time-averaged spectral index. We also note that the fitted spectrum predicts a 148MHz flux density of $\sim 12.0$ mJy, while the TGSS upper-limit indicates that the flux density is below 6.1 mJy. This could either be due to the variability, or a potential spectral turnover.

We fitted the spectrum for J0940+0526 (shown in Fig. 5.12) with a single power law with a spectral index of $\alpha = -0.77 \pm 0.10$. 

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Figure 5.11: The radio spectrum of J0836+0054.

Figure 5.12: The radio spectrum of J0940+0526. The fitted power law (solid line) has a spectral index of $\alpha = -0.77 \pm 0.10$. 

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5.4.2.5 J1427+3312

The spectrum of J1427+3312 is shown in Fig. 5.13, and was fitted by a power law with $\alpha = -0.62 \pm 0.17$. Although we classify the source as having a steep spectrum, it is also possible that it has a flat spectrum within the errors. Take note that the reason why the fitted line does not fit the MCM2008 point very well is because the smaller errors on the WWR2016 and CMM1999 flux densities give these points larger weights during the fitting. Finally, we also note that the FIRST and CMM1999 flux densities differ ($1.03 \pm 0.05$ and $1.82 \pm 0.02$ mJy, respectively), and the FGP2008(V) and MCM2008(V) flux densities are higher than the FIRST flux density. The difference between the FIRST and CMM1999 flux densities could be caused by the CMM1999 observations having a resolution of $\sim 15$ arcsec, which is about three times lower than that of FIRST. The difference, specifically between FIRST and the VLBI flux densities, could also indicate that J1427+3312 is variable.

5.4.2.6 J1429+5447

The spectrum of J1429+5447 is shown in Fig. 5.14. OWB2013 and CFC2016 concluded that the emission below 100 GHz is from AGN activity. OWB2013 also observed J1429+5447 at 250 GHz and concluded that the majority of the 250 GHz emission is thermal emission from hot dust. The authors do however note that it is possible that a significant fraction of the 250 GHz emission could be from AGN driven synchrotron emission. Excluding the OWB2013 value and fitting the spectrum with a power law gives $\alpha = -0.79 \pm 0.04$. We therefore classify J1429+5447 as a
steep-spectrum source.

5.4.2.7 J1548+3335

We fitted a power law to the spectrum of J1548+3335 (shown in Fig. 5.15) with a spectral index of $\alpha = -0.64 \pm 0.05$. We note that in the 1.7 GHz EVN observations, it was found to have two components that are separated by $812 \pm 3$ mas, which translates to a projected linear size of $5267 \pm 17$ pc [Coppejans et al., 2016b]. The primary component coincides with the SDSS position and no jet was detected between the two components. It is, therefore, possible that the second component is a lobe or hotspot of the first component, an unrelated AGN at the same redshift, a foreground or background source that is unrelated to J1548+3335, or that the two components are gravitationally lensed images of the same source [Coppejans et al., 2016b].

5.4.2.8 J1628+1154

We fitted the spectrum of J1628+1154 (shown in Fig. 5.16) with a power law with $\alpha = -0.94 \pm 0.04$.

5.4.3 Peaked-spectrum sources

The following nine sources all have peaked spectra. Where appropriate, and following Orienti et al. [2007], Scaife & Heald [2012] and Orienti & Dallacasa [2014], we fitted the spectra with log parabolas of the form $\log_{10}(S) = a[\log_{10}(\nu) - \log_{10}(\nu_o)]^2 + b$, where $a$ and $b$ are constants and $S$ is flux density.
5.4.3.1 J0324−2918

The spectrum of J0324−2918 is shown in Fig. 5.17. There is a discrepancy between the AT20G flux densities, and the CRATES and PMN flux densities. Regardless of which set of points are considered, it is clear from the TGSS flux density that J0324−2918 is a peaked-spectrum source. The spectral turnover would be at \( \sim 1.4 \) GHz or 7 GHz (depending on which observations are considered).

There are two possible explanations for the discrepancy in flux densities between these observations. First, the AT20G values are peak brightnesses, rather than integrated flux densities. Second, the AT20G observations have a resolution between \( \sim 30 \) and \( \sim 2 \) arcsec [Murphy et al., 2010], the PMN observations have a resolution of 4.2 arcmin and we could not determine the resolution of the CRATES observations. Resolution effects could consequently have produced the difference in flux densities. It is also possible that the difference is due to variability. J0324−2918 is a VLBI calibrator [Petrov et al., 2006] and in CFC2016 we concluded that its VLBI emission is Doppler-boosted, which strengthens the argument that it is variable.

5.4.3.2 J0906+6930

The spectrum of J0906+6930 (Fig. 5.18) shows a clear spectral turnover. RMP2011 observed J0906+6930 55 times at 15 GHz between 2009 March 19 and 2009 December 29. During this time they observed the flux density to vary between 97 and 180 mJy. As the source is variable, the

![Figure 5.15: The radio spectrum of J1548+3335. The fitted power law (solid line) has \( \alpha = -0.64 \pm 0.05 \).](image-url)
5.4 Radio spectra

Figure 5.16: The radio spectrum of J1628+1154. The fitted power law (solid line) has $\alpha = -0.94 \pm 0.04$.

Figure 5.17: The radio spectrum of J0324−2918.
Figure 5.18: The radio spectrum of J0906+6930. The solid line shows the fitted log parabola.

value in Fig. 5.18 is the intrinsic mean 15 GHz flux density \((136 \pm 2\) mJy) calculated by RMP2011. Fitting the spectrum, we find a turnover frequency of \(6.4 \pm 0.8\) GHz. Since J0906+6930 is at \(z = 5.47\), this translates to a rest-frame turnover frequency of \(41.4 \pm 5.2\) GHz. Considering that J0906+6930 is variable and that the fitted function does not fit the TGSS upper limit and the flux densities above 20 GHz very well, the uncertainty on the turnover frequency is likely underestimated.

5.4.3.3 J0913+5919

The spectrum for J0913+5919 is shown in Fig. 5.19. CWH2007 found a 233 MHz flux density of \(30 \pm 3\) mJy for J0913+5919 which is incompatible with the 148 and 325 MHz upper limits of 6.9 and 10.6 mJy from TGSS and WENSS, respectively. To check this apparent discrepancy, we re-processed the same data used by CWH2007. The raw visibility data, available from the GMRT archive under project code 04CCA01, consist of three observing sessions (2003 September 15 to 17) with a total of 11.4 hours on source. It was recorded over 4 MHz of bandwidth centered on 232.5 MHz and used the calibrator 3C48. We extracted the flux densities in the same way as described in Section 5.2. This yielded an image with a local rms noise level of 0.36 mJy beam\(^{-1}\) at a resolution of \(16.4 \times 10.5\) arcsec, with a source position angle of \(3^\circ\).

The integrated flux density of J0913+5919 in the reprocessed image is \(10.7 \pm 1.2\) mJy, which is a factor \(~3\) lower than what was found by CWH2007. The new value is compatible with the upper limits from WENSS and TGSS. In the initial (preliminary) image created by our pipeline, there were strong image-plane ripples in the central region near the source. This was a rather
common feature in older (hardware-correlator-based) GMRT data, and is likely the result of baseline-based errors. It is not straightforward to suppress, and might have affected the flux density measurement in CWH2007. The SPAM pipeline has dedicated image-based flagging routines to excise the visibility data causing these artefacts, yielding ripple-free images. We will therefore continue using the new flux density which is labeled as CWH2007(re) in Fig. 5.19.

Fitting a log parabola to the spectrum gives $\nu_o = 928 \pm 89$ MHz, which translates to a rest-frame turnover frequency of $5670 \pm 544$ MHz. We note that due to the lack of spectral coverage, the uncertainty on the turnover frequency is likely underestimated.

5.4.3.4 J1146+4037

If we were to fit a power law to the spectrum of J1146+4037 (excluding the upper limits and VLBI observations), it would give a spectral index of $\alpha = 0.64 \pm 0.05$ (see Fig. 5.20). However, the predicted flux density at 4850 MHz would then be $\sim 27$ mJy, which is well above the GB6 upper limit of 18 mJy. It is therefore most likely that the spectrum flattens towards higher frequencies, and considering that the spectral index of the FPG2010(V) VLBI points is $-0.53 \pm 0.06$ [Coppejans et al., 2016b], it appears to turn over. While care should be taken when comparing non-VLBI and VLBI spectral indices, we believe it is justified in this case, as the FIRST and 1.6 GHz FPG2010(V) flux densities are comparable ($12.4 \pm 0.6$ and $15.5 \pm 0.8$ mJy, respectively). Crucially, the GB6 upper limit also indicates a turnover. We therefore conclude that J1146+4037 likely has a spectral turnover around 1.4 GHz and we classify it as a peaked spectrum source.
Figure 5.20: The radio spectrum of J1146+4037. The fitted power law (solid line) has $\alpha = 0.64 \pm 0.05$. 
5.4 Radio spectra

5.4.3.5 J1235−0003

The spectrum of J1235−0003 is shown in Fig. 5.21. It is clear that J1235−0003 has a peaked spectrum. However, due to a lack of spectral coverage, we can not constrain the location of the spectral peak.

5.4.3.6 J1242+5422

The spectrum for J1242+5422 is shown in Fig. 5.22. Fitting a power law (the solid line in Fig. 5.22) between the FIRST, NVSS and GMRT610 flux densities gives $\alpha = -0.49 \pm 0.05$. Fitting a power law (the dashed line in Fig. 5.22) between all of the flux densities excluding FIRST and NVSS, gives $\alpha = 0.12 \pm 0.06$. It is therefore clear that the spectrum either turns over, or flattens. This conclusion is supported by the GB6 upper limit.

5.4.3.7 J1606+3124

Matching the VLBI position of J1606+3124 to FIRST, we find that there are five sources within three arcminutes, with the nearest neighbour at a distance of 70 arcsec. However, the VLA beam pattern is clearly visible in the image, and all five neighbouring sources lie on this beam pattern\(^4\). As the NVSS and WENSS images show that the nearest neighbour is at a distance of 232 arcsec

\(^4\)http://third.ucllnl.org/cgi-bin/firstcutout
Figure 5.22: The radio spectrum of J1242+5422. The solid line is fitted between the GMRT610, FIRST and NVSS flux densities, while the dashed line is fitted between all of the flux densities excluding FIRST and NVSS.
from J1606+3124, we conclude that the five neighbouring sources in the FIRST image are all image artefacts.

The spectrum of J1606+3124 is shown in Fig. 5.23. RMP2011 observed J1606+3124 98 times at 15 GHz between 2008 January 1 and 2009 December 28 with the 40 m telescope at the Owens Valley Radio Observatory. From this they concluded that J1606+3124 is not variable. MST2012 observed J1606+3124 six times with the RATAN-600 telescope between 2006 July and 2010 May at 21.7, 11.2, 7.7, 4.8 and 2.3 GHz, and five times at 1 GHz over the same period. These observations also indicate that J1606+3124 is not variable at these frequencies. The average flux densities of RMP2011 and MST2012 at each frequency are plotted in Fig. 5.23. It is therefore strange that the 87GB and GB6 observations are so much fainter than the LHC1990 and MST2012 observations. One possible reason for this is that both the 87GB and the GB6 observations are given as peak brightness values, rather than integrated flux densities.

It has been known for some time that J1606+3124 has a peaked spectrum [e.g. Spoelstra et al., 1985], with de Vries et al. [1997] and Mingaliev et al. [2013] reporting peak frequencies of 1.5 and 3.5 GHz, respectively. Fitting a log parabola to the spectrum, we found \( \nu_o = 3394 \pm 280 \) MHz, which is consistent with the value found by Mingaliev et al. [2013]. Taking into account the redshift of J1606+3124, our observed turnover frequency translates to a rest-frame turnover frequency of 18.9 \pm 1.6 GHz. We finally note that in the HTT2007(V) and BGP2002(V) VLBI observations, J1606+3124 has a Compact Symmetric Object (CSO) structure. CSOs are characterised by unbeamed emission from their steep-spectrum radio lobes on either side of a central position, and have sizes smaller than their host galaxy [Fanti et al., 1995b; Fanti, 2009].

### 5.4.3.8 J1659+2101

The spectrum of J1659+2101 is shown in Fig. 5.24. The TGSS and GMRT150 flux densities are not consistent within their 1\( \sigma \) uncertainties, but are within their 2\( \sigma \) uncertainties. The TGSS and GMRT150 flux densities are 27.6 \pm 5.7 and 48.2 \pm 5.4 mJy, respectively, which translates to a 75 per cent difference in flux density. Visual inspection of the images did not reveal an explanation for the offset. To try find an explanation, we matched the sources in the GMRT150 image to those in TGSS using a 10 arcsec search radius. We found 22 matches within a 1 \times 1 arcmin box centred on J1659+2101. For each of these sources, we calculated the ratio between the GMRT150 and the TGSS flux densities: The median of all of the ratios was 0.95, and the average was 1.02. The discrepancy can consequently not be attributed to a systematic flux density offset between the catalogues. Another possible explanation for the difference could be that J1659+2101 is variable. This is contradicted, but not ruled out, by the FIRST and NVSS flux densities that are within 2 per cent of each other. Resolution effects also cannot explain the difference, as the resolutions of the surveys are similar (25 \times 25 arcsec and 23 \times 16 arcsec, respectively). We can therefore not explain the difference between the TGSS and GMRT150 flux densities.

Fitting a power law to the spectrum, and excluding the TGSS and GMRT150 flux densities, gives \( \alpha = -0.40 \pm 0.05 \). Repeating the fit using only the GMRT150 and GMRT235 values give \( \alpha = 0.27 \pm 0.33 \), while fitting only the TGSS and GMRT235 values gives \( \alpha = 1.47 \pm 0.49 \). It is therefore clear that irrespective of whether the TGSS or the GMRT150 flux densities are correct, at the very least the spectrum flattens, and it likely turns over around 235 MHz. We therefore
Figure 5.23: The radio spectrum of J1606+3124. The solid line shows the fitted log parabola.
classify J1659+2101 as having a peaked spectrum.

5.4.3.9 J2102+6015

The J2102+6015 spectrum (Fig. 5.25) shows a clear turnover. Fitting the spectrum with a log parabola (the solid line in Fig. 5.25) gives $\nu_0 = 1031 \pm 51 \text{ MHz}$. This corresponds to a rest-frame turnover frequency of $5753 \pm 283 \text{ MHz}$.

5.4.4 Unusual and unclassified spectra

The last class contains the seven sources that cannot be classified into one of the three previous classes, and those that (due to a lack of spectral coverage) could have spectra that fall into more than one of the classes.

5.4.4.1 J1013+2811

Assuming that the spectrum of J1013+2811 (Fig. 5.26) can be fitted with a single power law, and using only the FIRST flux density and the GB6 upper limit, produces a spectral index $\alpha < 0.18$. Similarly, a fit using only the FIRST flux density and the TGSS upper limit, produces a spectral index greater than zero. Based on these limits, J1013+2811 can either have a flat or a peaked spectrum.
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Figure 5.25: The radio spectrum of J2102+6015. The solid line shows the fitted log parabola.

Figure 5.26: The radio spectrum of J1013+2811.
5.4 Radio spectra

5.4.4.2 J1205$-$0742

J1205$-$0742 has a concave spectrum (Fig. 5.27), with evidence of variability at 1.4 GHz. Using its spectral index between 1.4 and 350 GHz, morphology, brightness temperature and linear size, MCP2005(V) showed that the radio emission from J1205$-$0742 is from a nuclear starburst, and that the source does not have a radio-loud AGN. This explains why J1205$-$0742 has a concave spectrum. At $\nu_o < 100$ GHz, the negative spectral index is caused by starburst-driven radio synchrotron emission, while at $\nu_o \gtrsim 100$ GHz $\approx \nu_r \gtrsim 570$ GHz, the increase in flux density is the result of thermal dust emission [e.g. Yun et al., 2000; Momjian et al., 2005; Planck Collaboration et al., 2011].

5.4.4.3 J1311+2227

Assuming that the spectrum of J1311+2227 (Fig. 5.28) can be fitted with a single power law, and using the FIRST flux density and the TGSS and GB6 upper limits, the spectral index is $-0.19 < \alpha < 0.84$. J1311+2227 can therefore either have a flat, inverted or peaked spectrum.

5.4.4.4 J1454+1109

The J1454+1109 spectrum is shown in Fig. 5.29. Based on the VLBI flux densities being higher than the non-VLBI flux densities and the GB6 upper limit, we conclude that J1454+1109 is variable. In addition, due to a lack of spectral coverage, we cannot constrain the spectrum. However,
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5.4.4.5 J1311+2227

Based on its variability, and the fact that the VLBI emission is Doppler-boosted [Coppejans et al., 2016b], J1454+1109 is likely a blazar with a flat time-averaged spectrum.

5.4.4.6 J1611+0844

The spectrum of J1611+0844 is shown in Fig. 5.30. Assuming that the spectrum can be fitted with a single power law, and using the FIRST flux density and the TGSS and GB6 upper limits, \(-0.06 < \alpha < 0.57\). The time-averaged spectrum can therefore be either inverted, flat or peaked. Since the VLBI flux densities are higher than the non-VLBI flux densities, it is likely that J1611+0844 is variable. This does, however, require that the FIRST and NVSS observations were done when J1611+0844 was serendipitously at the same flux density.

5.4.4.6 J1720+3104

The spectrum of J1720+3104 is shown in Fig. 5.31. Assuming that the spectrum can be fitted with a single power law, and using the FIRST flux density, and the TGSS (which is more constraining than WENSS) and GB6 upper limits, \(0.17 < \alpha < 0.43\). This is consistent with the spectral index of \(\alpha = 0.36 \pm 0.07\) measured between the 1.7 and 5 GHz CFC2016(V) VLBI flux densities. J1720+3104 can therefore have either a flat or a peaked spectrum.
5.4 Radio spectra

Figure 5.29: The radio spectrum of J1454+1109.

Figure 5.30: The radio spectrum of J1611+0844.
5.4.4.7 J2228+0110

The spectrum of J2228+0110 is shown in Fig. 5.32. Assuming that the spectrum can be fitted by a single power law and using the STRIPE82 flux density and the TGSS and GB6 upper limits, \(-0.74 < \alpha < 2.13\). Consequently, we can only conclude that J2228+0110 is not a USS source.

5.5 Discussion

In Table 5.6, the number and the percentage of sources in each spectral class are given (see the table caption for a description of the nomenclature used). This table was compiled from the classifications in Table 5.4 in the following way: (1) if a source is classified as e.g. ‘Flat’ in Table 5.4, then the number of flat sources is increased by one; (2) if a source is classified as ‘flat (steep)’, then the number of flat sources is increased by one, the lower uncertainty on the number of flat sources is decreased by one, and the upper uncertainty on the number of steep sources is increased by one; (3) if a source is classified as ‘flat or peaked’, the upper uncertainty on the number of flat and peaked sources are both increased by one. Finally, the percentage of sources in each class was calculated using a total number of 29 sources, since the spectrum of J1454+1109 is completely unconstrained (Section 5.4.4.4). We also point out again, that all of the sources except J1205−0742 (which has a concave spectrum), are AGN.

The primary selection effects in our sample of sources are that all of the sources have spectroscopic redshifts and were selected for follow-up high-resolution VLBI observations. In general the
5.5 Discussion

Figure 5.32: The radio spectrum of J2228+0110.

Table 5.6: Spectral classification summary of the entire sample

<table>
<thead>
<tr>
<th>Spectral classification</th>
<th>Number of sources $^a$</th>
<th>% of sources $^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverted</td>
<td>$0^{+4}_{-0}$</td>
<td>$0^{+14}_{-0}$</td>
</tr>
<tr>
<td>Flat</td>
<td>$6^{+6}_{-1}$</td>
<td>$21^{+21}_{-3}$</td>
</tr>
<tr>
<td>Steep</td>
<td>$7^{+2}_{-2}$</td>
<td>$24^{+7}_{-7}$</td>
</tr>
<tr>
<td>USS</td>
<td>$1^{+1}_{-0}$</td>
<td>$3^{+3}_{-0}$</td>
</tr>
<tr>
<td>Peaked</td>
<td>$9^{+5}_{-1}$</td>
<td>$31^{+17}_{-3}$</td>
</tr>
<tr>
<td>Concave</td>
<td>$1^{+1}_{-0}$</td>
<td>$3^{+3}_{-0}$</td>
</tr>
</tbody>
</table>

Notes: $^a$ The format $b^{+c}_{-d}$ should be interpreted as follows: There are $b$ sources in the given spectral class, and an additional $c$ sources that are not in the class but could be. Of the $b$ sources, $d$ are in the class but could have a different spectral classification within the errors on their spectral indices.
Chapter 5: Radio spectra of \( z > 4.5 \) sources

Table 5.7: Spectral classification summary of the unbiased sub-sample

<table>
<thead>
<tr>
<th>Spectral classification</th>
<th>Number of sources (^a)</th>
<th>% of sources (^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverted</td>
<td>( 0_{-0}^{+4} )</td>
<td>( 0_{-0}^{+18} )</td>
</tr>
<tr>
<td>Flat</td>
<td>( 5_{-1}^{+6} )</td>
<td>( 23_{-5}^{+27} )</td>
</tr>
<tr>
<td>Steep</td>
<td>( 7_{-2}^{+2} )</td>
<td>( 32_{-9}^{+9} )</td>
</tr>
<tr>
<td>USS</td>
<td>( 0_{-0}^{+1} )</td>
<td>( 0_{-0}^{+5} )</td>
</tr>
<tr>
<td>Peaked</td>
<td>( 5_{-1}^{+5} )</td>
<td>( 23_{-5}^{+23} )</td>
</tr>
<tr>
<td>Concave</td>
<td>( 0_{-0}^{+1} )</td>
<td>( 0_{-0}^{+5} )</td>
</tr>
</tbody>
</table>

Notes: The values in the table were calculated in the same way as for Table 5.6.

latter involves a flux density lower limit and the sources being compact on arcsec scales in previous (e.g. FIRST) observations. In addition, some authors selected sources for VLBI observations because of their spectral type. Since this can bias the values in Table 5.6, we created a unbiased sub-sample of sources that were not selected for VLBI observation with a spectral bias. To do this we checked how each of the sources was selected for VLBI observation the first time that they were observed. If a source was selected for VLBI observations with a spectral bias it was not included in the unbiased sub-sample. This resulted in the following seven sources not being in the unbiased sub-sample: J0311+0507, J0324−2918, J0906+6930, J1026+2542, J1205−0742, J1606+3124 and J2102+6015. In Table 5.7 we re-calculated the values in Table 5.6 for our unbiased sub-sample. The percentage of sources in each class was calculated using a total number of 22 sources, since the spectrum of J1454+1109 is completely unconstrained (Section 5.4.4.4).

In Tables 5.6 and 5.7, the low number of USS sources is striking considering that the USS technique is specifically used to search for high-redshift sources. All of the VLBI observations of the sources were carried out above 1.4 GHz (Table 5.8), where the flux densities of the USS sources are rapidly decreasing (Section 5.4.2). The lack of USS sources could therefore be the result of sources typically only being considered for VLBI observation if, in previous non-VLBI observations, they have flux densities above a certain minimum.

To attempt to test if this is the case, we downloaded the 12th data release of the Sloan Digital Sky Survey quasar catalog [Pâris et al., 2016] and removed all sources with SDSS pipeline redshifts smaller than 4.5. Of the remaining 1054 sources, 16 are VLBI sources discussed in this paper. Using a search radius of 5 arcsec, we matched all the sources in FIRST to the list of \( z > 4.5 \) SDSS sources and the TGSS catalogue. From this we found 22 sources which have both FIRST and TGSS flux densities, and of these, six are in this paper. Removing these six sources and calculating two-point spectral indices between FIRST and TGSS for the remaining sources, we found one USS source and one source that could be a USS source within its uncertainties. We do, however, note that since the FIRST and TGSS typical detection thresholds are 1 and 35 mJy, respectively, only USS sources with FIRST flux densities above 4 mJy will be detected in TGSS. Only \( 6_{-0}^{+6} \) per cent of the FIRST–TGSS sources are USS sources. This is in agreement with the percentages of USS sources in Tables 5.6 and 5.7. As the fraction of USS sources in these three samples are consistent, it is likely that the requirements for VLBI follow-up observations do not produce a bias against USS sources.

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The largest group of sources in Table 5.6, and the second largest group of sources in Table 5.7, are the peaked sources. These sources are believed to be young AGN [e.g. O’Dea, 1998; Conway, 2002; Murgia et al., 2002; Murgia, 2003; Orienti, 2016] and make up nearly a quarter of the sources in our unbiased sub-sample. Of the nine peaked sources in the sample, sufficient spectral coverage is available to determine the turnover frequency of six of them to within $\sim 1$ GHz (Section 5.4). For two of these sources (J0913+5919 and J1659+2102), the observed spectral turnover lies below 1 GHz, and for two more sources (J1242+5422 and J2102+6015) the turnover could lie below 1 GHz (but definitely lies below 1.4 GHz). The final two sources (J0906+6930 and J1606+3124) both have observed spectral turnovers above $\sim 3$ GHz. Consequently, the peaked sources show a wide range of observed turnover frequencies, and an even wider range of rest-frame turnover frequencies. Based on their turnover frequencies, the peaked sources are MPS, GPS and HFP sources. This also shows that there are between two and three MPS sources in the unbiased sub-sample. Consequently, although there are more MPS sources than USS sources, neither of these methods would have selected more than $\sim 14$ per cent of the sources in the unbiased sub-sample. Interestingly, four of the sources (J0324+2918, J0906+6930, J1606+3124 and J2102+6015) that were excluded form the unbiased sub-sample were excluded because they were selected for VLBI observation based on having flat two-point spectral indices [Beasley et al., 2002; Romani et al., 2004; Petrov et al., 2006]. However, all four sources actually have peaked spectra and only appeared to have flat spectra because their spectral indices were determined close to the spectral peak.

It is worth noting that the spectra of the steep, and USS, sources have to turn over at some point due to synchrotron self-absorption. In addition, assuming $z = 5$, any source with a rest-frame spectral turnover below $\sim 3$ GHz will appear as a steep-spectrum source in our sample since the observed frame turnover frequency will be below $\sim 300$ MHz. For six of the steep and USS sources in the sample, the turnover has to be below an observed frequency 1 GHz, while for two of the sources it has to be below 1.4 GHz (Section 5.4). In total there are $12^{+6}_{-2}$ sources that are steep, USS or peaked in the unbiased sub-sample, which translates to $55^{+27}_{-6}$ per cent of the sources in the unbiased sub-sample. It is therefore safe to say that, if the steep-spectrum sources are observed at lower frequencies ($\nu_o < 100$ MHz), more of the sources in both the sample and unbiased sub-sample would be classified as peaked sources, and there would likely be significantly more MPS sources.

In CFC2016 we pointed out that the selection effects discussed previously likely bias the sample towards flat-spectrum sources in which the radio emission is Doppler-boosted (which increases the sources’ flux density). It was therefore surprising that we found that less than half of the sources could be classified as flat-spectrum radio quasars [Coppejans et al., 2016b]. This conclusion is supported by our new finding that $23^{+27}_{-8}$ per cent of the sources in the unbiased sub-sample have flat spectra.

5.6 Summary and conclusions

In this paper, we presented new multi-frequency GMRT observations at $\nu < 1$ GHz of eight $z > 4.5$ VLBI sources (Section 5.2). Matching these eight, and the remaining 22 $z > 4.5$ VLBI sources,
to the literature (Section 5.3), we constructed broad-band radio spectra of all 30 $z > 4.5$ VLBI sources. In Section 5.4 we discussed and classified the spectra of each of the sources as flat, steep, peaked, unusual and unclassified. In Section 5.5 we looked at the properties of the sample – particularly the fraction of sources in each spectral class. We point out that there is only one USS source in the sample and argued that the requirements for VLBI follow-up observations likely do not produce a bias against USS sources. We also show that the USS and MPS methods would each have selected less than $\sim 5$ and $\sim 14$ per cent of the sources in the sample, respectively. This supports the argument by Pedani [2003] that the USS sources are not representative of the entire high-redshift source population. We do note that because of the small number of MPS and USS sources in the sample, larger samples are required to draw a definitive conclusion.

In Section 5.5 we also noted that the spectra of the steep-spectrum sources have to turn over at some point. If these sources are observed at lower frequencies ($\nu_0 < 100$ MHz), the percentage of peaked and MPS sources in the sample would likely increase significantly. This would result in even more MPS than USS sources. We also note that due to a lack of spectral coverage, the classification of some of the sources is uncertain. This problem can be resolved with multi-frequency observations below 2 GHz, since, for a source at $z = 5$, its entire rest-frame spectrum below 12 GHz will be shifted into observed frequencies below 2 GHz.

The most striking feature of Table 5.7 is that there is no single spectral class that has the majority of sources. The sources are spread roughly evenly between the flat, steep and peaked classes. In addition, in one of the sources the radio emission is related to star-forming activity (Section 5.4.4.2). Despite several selection effects, we have to conclude that the $z > 4.5$ VLBI sources (and likely also the $z > 4.5$ non-VLBI sources) have diverse radio spectra. Considering that we expect the Square Kilometre Array (SKA) to be able to detect sources out to beyond redshift 10 [e.g. Falcke et al., 2004], and knowing the general importance of these sources, it is critical that methods are found with which to reliably identify complete samples of high-redshift sources based on radio data.

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5.7 Appendix A: Flux density references
### Chapter 5: Radio spectra of $z > 4.5$ sources

#### Table 5.8: Flux density references

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<tr>
<th>Observation name</th>
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<td>4850</td>
<td>Gregory &amp; Condon [1991]</td>
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<td>AT20G</td>
<td>4800 &amp; 8640 &amp; 19904</td>
<td>Murphy et al. [2010]</td>
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<td>1400</td>
<td>Croft et al. [2010]</td>
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<tr>
<td>B2.2</td>
<td>408</td>
<td>Colla et al. [1972]</td>
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<td>B3</td>
<td>408</td>
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<td>Beasley et al. [2002]</td>
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5.7 Appendix A: Flux density references

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Table 5.8 continued...
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Summary and conclusion

High-redshift sources are important for, among other things, studying AGN and galaxy evolution, understanding the growth of supermassive black holes and testing cosmological models. New, upgraded and planned radio telescopes such as LOFAR, MeerKat, the VLA, the GMRT and the SKA are detecting (or will be able to detect) more sources at all redshifts and sources at even higher redshifts. However, as of writing there is no method with which to identify complete samples of high-redshift sources in radio data. It is therefore critically important that work be done to find a method to accomplish this. In this thesis I investigated both the ultra-steep-spectrum (USS) and megahertz peaked-spectrum (MPS) methods. Using very long baseline interferometry (VLBI) I also increased the number of \( z > 4.5 \) sources that have been observed with VLBI by 50% and compiled broad band spectra for these sources. This allowed me to study the nature of the \( z > 4.5 \) sources and look at the completeness of the current methods of selecting high-redshift sources.

The MPS sources

In Falcke et al. [2004] the authors proposed a new, and previously untested, method of identifying high-redshift AGN using MPS sources. In Chapter 2 I reviewed this method and, using new 325 MHz observations of the NOAO Boötes field in combination with existing 150 MHz and 1.4 GHz observations, selected 33 MPS sources. Of the 33 sources, 24 have known redshifts that range between 0.1 and 3.2. Five of the sources are at \( z > 2 \) and the expectation is that an additional four sources are at \( z > 3 \). Based on this I concluded that there is encouraging evidence that the MPS method can be used to select high-redshift sources. In this chapter I also pointed out a problem with the USS method of selecting high-redshift sources. For the identified USS sources, I showed that when a selection of USS sources is made between 150 and 325 MHz and another selection of USS sources is made between 325 MHz and 1.4 GHz, less than 26% of the sources that are selected appear in both selections.

In Chapter 3 I continued my study of the MPS sources in the Boötes field with 1.7 GHz European VLBI Network (EVN) observations of 11 sources. Of the 11 sources I detected nine with the EVN and showed that all of the sources, including the two that were not detected,
Summary and conclusion

are likely AGN. Using the spectra and brightness temperatures of the nine detected sources, I argued that these sources are not blazars. From their low-frequency spectra I also showed that the MPS sources are a mixture of compact steep-spectrum (CSS), gigahertz peaked-spectrum (GPS) and high-frequency peaked (HFP) sources whose spectral peaks have been redshifted to lower frequencies. Finally, the EVN observations showed that the detected sources have linear sizes smaller than 1.1 kpc, which, combined with their spectra indicate that they are likely young AGN.

The $z > 4.5$ VLBI sources

There are two ways of solving the problem of how to select high-redshift sources. In Chapters 2 and 3 I approached the problem by investigating the redshifts of MPS sources. The largest obstacle to this approach is that there are simply not redshifts for a large percentage of the sources. In Chapters 4 and 5 I approach the problem from the other side. Instead of selecting sources and then checking if their redshifts are known, I studied the spectra of a sample of sources which all have spectroscopic redshifts greater than 4.5, and are, therefore, bone-fide high-redshift sources.

In Chapter 4 I present observations of ten $z > 4.5$ sources with the EVN at 1.7 and 5 GHz. This increased the number of $z > 4.5$ sources that have been observed with VLBI from 20 to 30. Combining these new observations with those from the literature I compiled a sample of high-redshift sources with which to study the nature of these sources. Using the VLBI observations I showed that for 29 of the 30 $z > 4.5$ VLBI sources, the radio emission is from an AGN and for one source the radio emission is from star formation. Using 1.4 GHz variability and the VLBI spectra of the sources I also showed that roughly half of the sources are flat-spectrum radio quasars and that the remaining sources likely have peaked spectra.

In Chapter 5 I presented new multi-frequency GMRT observations of eight of the $z > 4.5$ sources, which I combined with observations from the literature to construct broad-band radio spectra of all of the $z > 4.5$ VLBI sources. From this I showed that there is roughly an equal number of sources that have peaked, steep and flat spectra. Despite several selection effects and the classification of some of the sources being uncertain, I conclude that the $z > 4.5$ VLBI (and likely also non-VLBI) sources have diverse spectra and that no single spectral class contains the majority of the sources. I also showed that the USS and MPS methods would have selected less than $\sim 5$ and $\sim 14\%$ of the sources in the sample, respectively. I do, however, note that if the sources were observed at frequencies below 100 MHz the fraction of peaked and MPS sources would likely increase significantly. In addition, due to the small number of USS and MPS sources detected, larger samples are required to draw a definitive conclusion. Finally, I conclude that effective methods need to be found which can reliably identify complete samples of high-redshift sources in radio data.
Conclusion and looking forward

In Chapter 1 I discussed the general importance of high-redshift sources and that radio surveys should be able to detect more sources and sources at higher-redshifts than what is possible in the optical. In Chapter 5 I showed that neither of the current methods used to select high-redshift sources in the radio would have selected more than 15% of the \( z > 4.5 \) VLBI (and likely also non-VLBI) sources. Considering the general importance of the high-redshift sources and that telescopes such as the SKA are expected to detect them out to \( z = 10 \), it is critical to find methods to reliably identify high-redshift sources based on radio data. Preferably the sources that are selected with these methods should also be complete in the sense that the identified sources are representative of all of the different types of sources found at high-redshifts.

In Chapter 5 I argued that neither the USS nor MPS methods are able to select complete samples of sources. However, they are useful to increase the number of high-redshift sources and, since they select different groups of sources, are complimentary. The results in Chapter 5 indicate that the MPS method is likely better than the USS method at selecting high-redshift sources. However, in Chapter 5 I also found that a large fraction of the peaked sources are not MPS sources. The question should therefore be asked, whether the MPS method should be modified to not only include sources that peak below 1 GHz but rather include all peaked sources.

The best way to answer this question is using a large flux density limited sample of sources with known redshifts and densely sampled spectra. When searching for peaked sources authors often only have flux densities at three or four different frequencies. The problem with this is that it often severely limits the range of peak frequencies that the search is sensitive too. What is therefore required is that the spectra of the sources are densely sampled between \( \sim 100 \) MHz and \( \sim 10 \) GHz. This will allow the spectra of the sources to be accurately characterized. By combining the spectra and redshifts of the sources it will then be possible to determine if the peaked sources are on average at higher redshifts than the steep, inverted, flat and USS sources. Such a study will also allow the efficiency at which the MPS and USS methods select high-redshift sources to be calculated and compared, something that is not currently possible due to a lack of complete flux density limited samples of sources with known redshifts. In addition, such a study could lead to better methods of identifying high-redshift sources. Finally it would also allow for a comparison between the percentages of sources in each spectral class at different redshifts, thereby constraining and shedding light on AGN evolution. Another related study that would be useful to constrain AGN evolution and that could lead to better methods of identifying high-redshift sources would be to check if the turnover frequency–linear size relation changes as a function of redshift. This could, for example, be caused by the ambient mediums of higher-redshift sources being denser than their low redshift counterparts, which could cause the high-redshift sources to have smaller linear sizes.

One way to do such a study would be to use data from large scale surveys such as FIRST, TGSS, MSSS and VLASS. This can be combined with targeted surveys of fields with large numbers of sources with known redshifts and observations of individual local and high-redshift sources. While this is a daunting task, the scientific rewards are potentially very large. In addition, as more and more telescopes upgrade to wide band receivers, which allow in-band spectral indices to be calculated, it is also becoming easier.
Radiobronnen in ons heelal met grote roodverschuiving (m.a.w., op grote afstand van ons) spelen een belangrijke rol in onderzoek naar actieve kernen van sterrenstelsels (afgekort met AGN), de lange-termijn ontwikkeling van sterrenstelsels, de groei van supermassieve zwarte gaten en in het testen van kosmologische modellen. Onlangs gebouwde, uitgebreide en geplande radiotelescopen zoals LOFAR, MeerKat, de VLA, de GMRT en de SKA breiden het bestand aan gedetecteerde bronnen met hoge roodverschuivingen sterk uit, en zijn bovendien in staat om bronnen met steeds grotere roodverschuiving te detecteren. Op het moment van dit schrijven is er echter nog geen methode voorhanden die ons in staat stelt om de populatie van deze klasse van bronnen compleet te karakteriseren in radiodata. Het ontwikkelen van een dergelijk methode is dus een belangrijke stap in het wetenschappelijk onderzoek naar deze bronnen. In dit proefschrift heb ik twee classificatiemethoden onderzocht, die bronnen respectievelijk kunnen classificeren als ultra-steep-spectrum (USS) en als megahertz-peaked spectrum (MPS). Door gebruikmaking van de techniek van Very Long Baseline Interferometry (VLBI) heb ik tevens het aantal radiobronnen op $z > 4.5$ dat is waargenomen met VLBI uitgebreid met 50%, en daarbij ook de spectra van deze bronnen opgesteld over een breed golflengtebereik. Hierdoor heb ik de aard van deze bronnen kunnen onderzoeken, en tevens de volledigheid van bestaande classificatiemethoden voor bronnen op grote roodverschuiving kunnen beoordelen.

De MPS-bronnen

In Falcke et al. [2004] is een (voorheen nog ongeteste) methode voorgesteld om AGN op grote roodverschuivingen te identificeren door het classificeren van MPS-bronnen. Ik heb deze methode beschreven in Hoofdstuk 2 en daarmee 33 MPS-bronnen geëxtraheerd uit recente waarnemingen op 325 MHz van het NOAO Boötes-veld, gecombineerd met bestaande waarnemingen op 150 MHz en 1.4 GHz. Van deze 33 bronnen hebben er 24 roodverschuivingen tussen $z = 0.1$ en $z = 3.2$. Vijf van de bronnen hebben roodverschuivingen van $z > 2$, en de verwachting is dat vier verdere bronnen nog op $z > 3$ liggen. Gebaseerd op deze bevindingen concludeer ik dat er motiverend bewijs bestaat dat de MPS-methode op een succesvolle wijze bronnen op grote roodverschuiving kan identificeren. In dit hoofdstuk vestig ik ook de aandacht op een probleem binnen de USS-
selectiemethode: wanneer USS-bronnen worden geselecteerd over het spectrale bereik van 150 tot 325 MHz en er een tweede selectie wordt gemaakt tussen 325 MHz en 1.4 GHz, komt minder dan 26% van het totale aantal geselecteerde bronnen voor in beide selecties.

Mijn onderzoek naar de MPS-bronnen in het Boötes-veld wordt voortgezet in Hoofdstuk 3, waarin ik een analyse doe van waarnemingen van 11 bronnen in dit veld, genomen op 1.7 GHz met het Europese VLBI Netwerk (EVN). Van deze 11 bronnen heb ik er 9 weten te detecteren in deze waarnemingen en kan ik van alle 11 bronnen, dus inclusief de 2 ongedetecteerde bronnen, aantonen dat het hoogstwaarschijnlijk AGN zijn. Van de 9 gedetecteerde bronnen poneer ik middels hun spectra en afgeleide helderheidstemperaturen dat het geen blazars zijn. Gebruikmakend van de spectra op lagere frequenties heb ik laten zien dat de MPS-bronnen een verzameling zijn van compacte steil-spectrum (CSS) bronnen, gigahertz-piek spectrum (GPS) bronnen en hoogfrequente-piek (HFP) bronnen waarvan de spectrale pieken zijn roodverschoven naar lagere frequenties. Tenslotte hebben de EVN-waarnemingen aangetoond dat de gedetecteerde bronnen lineaire afmetingen hebben van kleiner dan 1.1 kpc, hetgeen in combinatie met hun spectra aantoont dat het waarschijnlijk jonge AGN zijn.

De \( z > 4.5 \) VLBI-bronnen

Er zijn twee manieren beschikbaar om de selectie van bronnen op hoge roodverschuiving succesvol te doen. In de Hoofdstukken 2 en 3 heb ik deze kwestie benaderd door de roodverschuivingen van de gevonden MPS-bronnen te onderzoeken in reeds beschikbare data. Het grootste probleem met deze methode is dat er botweg geen roodverschuivingen bekend zijn voor een aanzienlijke fractie van de bronnen in het onderzoek. In de Hoofdstukken 4 en 5 heb ik het probleem van de andere kant benaderd. In plaats van het opzoeken van bekende roodverschuivingen voor geselecteerde bronnen heb ik me beperkt tot het onderzoeken van de spectra voor een steekproef van bronnen die allen een bekende roodverschuiving hebben meer dan 4.5 - en die daarom bevestigde bronnen op hoge roodverschuiving zijn.

In Hoofdstuk 4 presenteer ik waarnemingen van tien bronnen met \( z > 4.5 \), genomen met de EVN op 1.7 en 5 GHz. Deze waarnemingen hebben het aantal bronnen op \( z > 4.5 \) dat is bestudeerd met VLBI vergroot van 20 naar 30. Door de gevonden objecten in deze waarnemingen te combineren met de reeds bekende objecten op hoge roodverschuiving heb ik een verzameling gevormd waarmee ik de aard van deze objecten kon onderzoeken. Met de VLBI-waarnemingen heb ik laten zien dat voor 29 van de 30 VLBI-bronnen op \( z > 4.5 \) hun radio- emissie afkomstig is van AGN, en voor de laatste bron afkomstig is van stervormingsprocessen. Via de variabiliteit op 1.4 GHz en de VLBI-spectra van de bronnen heb ik ook aangetoond dat ruwweg de helft van de onderzochte bronnen vlakke-spectrum radio quasars zijn, en dat de overige bronnen een duidelijke piek in hun spectra hebben.

In Hoofdstuk 5 heb ik nieuwe waarnemingen van acht van de \( z > 4.5 \) bronnen op meerdere frequenties gepresenteerd die genomen zijn met de GMRT. Deze waarnemingen heb ik gecomбинeerd met eerder gepubliceerde waarnemingen om breedbandige spectra op te stellen van deze \( z > 4.5 \) VLBI bronnen. Uit deze resultaten is te zien dat de aantallen bronnen met gepiekte, steile en vlakke spectra ongeveer gelijkwaardig verdeeld zijn. Ondanks het voorkomen van diverse
Samenvatting

selectie-effecten en de onzekere classificatie van enkele bronnen concludeer ik dat de VLBI (en waarschijnlijk ook de non-VLBI) bronnen op $z > 4.5$ diverse typen spectra vertonen, en dat geen enkele spectrale klasse de overgrote meerderheid van bronnen beslaat. Tevens toon ik aan dat de USS en MPS selectiemethoden minder dan respectievelijk 5% en 14% van de bronnen in de verzameling zouden hebben geïdentificeerd. Ik merk hierbij echter op dat de fracties van gepiekte en MPS-bronnen waarschijnlijk significant groter zou zijn als de bronnen op frequenties onder de 100 MHz zouden zijn waargenomen. Vanwege het kleine aantal gedetecteerde USS- en MPS-bronnen zal een grotere selectie aan bronnen nodig zijn om robuuste conclusies te trekken over hun voorkomendheid. Tot slot concludeer ik dat er een duidelijke behoefte bestaat aan een betrouwbare en effectieve methode om volledige verzamelingen bronnen met hoge roodverschuivingen te identificeren in radiowaarnemingen.

Conclusie en vooruit kijken

In Hoofdstuk 1 heb ik de algemene relevantie van bronnen op hoge roodverschuiving besproken, en gesteld dat radiowaarnemingen in staat zouden moeten zijn om meer van deze bronnen (en bronnen op hogere roodverschuivingen) te detecteren dan wat mogelijk is met optische waarnemingen. Ik heb in Hoofdstuk 5 laten zien dat geen van de huidige in gebruik zijnde methodes voor de selectie van VLBI-bronnen (en naar alle waarschijnlijkheid ook de non-VLBI) op hoge roodverschuivingen ($z > 4.5$) meer dan 15% van de bronnen sucesvol identificeert. De algemene relevantie van bronnen op hoge roodverschuiving in acht genomen, naast de verwachting dat telescopen zoals SKA deze bronnen tot op $z = 10$ zullen kunnen detecteren, is het belangrijk dat er methoden gevonden worden die deze bronnen op een betrouwbare wijze kunnen classificeren afgaande op slechts de radio-waarnemingen. Bij voorkeur vormen de bronnen die geclasseerd worden met een dergelijk algoritme ook een volledige verzameling, in die zin dat de geïdentificeerde bronnen een representatieve selectie vormen van de daadwerkelijk aanwezige bronnen op hoge roodverschuivingen.

Ik heb in Hoofdstuk 5 beargumenteerd dat zowel de USS- als de MPS-methoden niet in staat blijken te zijn om verzamelingen van bronnen volledig te categoriseren. Niettemin zijn ze nuttig voor het vergroten van de aantallen bekende bronnen op hoge roodverschuivingen en zijn ze complementair aan elkaar, omdat ze verschillende subgroepen identificeren. De resultaten in Hoofdstuk 5 wijzen erop dat de MPS-methode waarschijnlijk beter geschikt is in het selecteren van bronnen met hoge roodverschuiving dan de USS-methode. Nochthans heb ik in Hoofdstuk 5 gevonden dat een grote fractie van de gepiekte bronnen geen MPS-bronnen zijn. We zouden onszelf daarom de vraag moeten stellen of de MPS-methode aangepast zou moeten worden om niet alleen bronnen te selecteren die hun spectrale piek onder de 1 GHz hebben maar om alle gepiekte bronnen te selecteren.

De beste manier om deze vraag te beantwoorden is om een grotere verzameling bronnen te gebruiken die flux dichtheidsgeïnactiveerd is, waarvan de roodverschuiving bekend zijn en waarvan de spectra met hoge resolutie bekend zijn. Bij de zoektocht naar gepiekte bronnen hebben onderzoekers vaak slechts spectra met flux dichthen op 3 of 4 frequentiewaarden tot hun beschikking. Dit leidt tot het probleem dat het zoekalgoritme vaak slechts gevoelig is voor spectrale pieken
Samenvatting

in een zeer beperkt bereik. Wat daarom nodig is, is dat spectra gemeten worden op veel meer frequenties tussen $\sim 100$ MHz en $\sim 10$ GHz - dit biedt de mogelijkheid om de bronnen nauwkeurig te karakteriseren. Door vervolgens de spectra te combineren met de roodverschuivingen voor elke bron zal het dan mogelijk zijn om na te gaan of de gepiekte bronnen gemiddeld een grotere roodverschuiving hebben dan de stiele, geïnverteerde, vlakke en USS-bronnen. Een dergelijke studie stelt ons ook in staat om de efficiëntie waarmee de MPS- en USS-methoden bronnen op hoge roodverschuiving identificeren te berekenen en te vergelijken, iets dat op dit moment niet mogelijk is vanwege het gebrek aan een complete, dichtheidsgelimiteerde verzameling bronnen met bekende roodverschuivingen. Als bijkomend voordeel zou een dergelijk studie kunnen leiden tot betere methoden voor het succesvol identificeren van bronnen op hoge roodverschuiving. Tenslotte zou de studie een vergelijking mogelijk maken tussen de percentages van bronnen in de verschillende spectrale klassen op verschillende roodverschuivingen, en op die manier een licht werpen op de evolutie van AGN. Een andere mogelijke studie die ook deze voordelen zou bieden zou zijn om na te gaan of de relatie tussen de piekfrequentie en de lineaire grootte van bronnen verandert als functie van hun roodverschuiving. Een dergelijke afhankelijkheid zou bijvoorbeeld verklaard kunnen worden door de notie dat het omliggende medium van bronnen op hogere roodverschuivingen een hogere dichtheid heeft dan dat van bronnen op lagere roodverschuivingen. Zo’n relatie zou leiden tot een kleinere lineaire grootte van bronnen op hogere roodverschuivingen.

Een mogelijke manier waarop de genoemde studies gedaan zouden kunnen worden is door gebruik te maken van de data uit grootschalige onderzoeken zoals FIRST, TGSS, MSSS en VLASS. De data uit deze onderzoeken kan gecombineerd worden met specifieke onderzoeken van velden met daarin grote aantallen bronnen met bekende roodverschuivingen, alsmede waarnemingen van individuele bronnen op zowel kleine als grote afstand met bekende roodverschuivingen. Hoewel dit een zeer grote hoeveelheid werk zal zijn, biedt een dergelijk onderzoek mogelijk grote wetenschappelijke waarde. Bovendien zal dit werk gaandeweg eenvoudiger gemaakt kunnen worden doordat een toenemend aantal telescopen de mogelijkheid heeft om spectrale indices te meten binnen de waargenomen frequentieband, vanwege de vergroting van de bandbreedte van hun ontvangers.
Publication List


523, “High-speed photometry of faint cataclysmic variables – VIII. Targets from the Catalina Real–Time Transient Survey”


Rocco Coppejans was born in Pretoria, South Africa, and attended school at Garsfontein Primary and High Schools. In my school years I developed a keen interest in the natural sciences, favouring subjects such as biology, physiology and geography. To satisfy my curiosity, I enrolled in BSc Physics at the University of Pretoria in 2006, receiving my degree at the end of 2009. In my first year at the University of Pretoria, I took an introduction to astronomy class that developed into a passion during the subsequent years. At the end of my studies, I applied for, and was awarded, a scholarship to do my BSc Honours and MSc in the National Astrophysics and Space Science Program (NASSP) hosted at the University of Cape Town (UCT).

During my first year in NASSP I was exposed to a broad range of topics in astrophysics and space science. I also got my first taste of observing at the 1 meter telescope at the South African Astronomical Observatories (SAAO) Sutherland observatory, while doing a project with Dr. John Menzies to search for exoplanets using gravitational microlensing. At the end of 2010 I received my BSc Honours (with distinction) from UCT. At the start of 2011, I was one of two organizers of the annual NASSP summer school for new BSc Honours students. This involved organizing all aspects of the four week school for the 30 participants, including planning, logistics, speakers, events and the day to day running of the school. After six months of course work I started my MSc project, entitled “Characterizing and commissioning the Sutherland high-speed optical cameras”, at the SAAO under the supervision of Dr. Amanda Sickafoose. During this project I commissioned, tested, characterized and took the first scientific observations with two new high-speed optical cameras on the SAAO’s 1.9, 1 and 0.75 meter telescopes at the Sutherland observatory. In total I accumulated nine and a half weeks of observing experience and received my MSc in astrophysics and space science from UCT at the end of 2012.

In January of 2013 I moved to the Netherlands to start my PhD in astrophysics at Radboud University Nijmegen under the supervision of Professor Heino Falcke. During this time I used radio data to search for the youngest and most distant active galactic nuclei. The main projects and results of this research are presented in this thesis.

Over the course of my studies I have worked as a research assistant in the University of Pretoria’s solid state physics laboratory, tutored courses, written operation manuals for the Sutherland high-speed optical cameras and Radboud university’s Ulrich J. Schwarz radio interferometer and
written scientific proposals for observing time on local and international optical and radio telescopes. I have also given talks about my research at local and international conferences, given telescope tours to astronomers and the public, participated in astronomy outreach events and contributed to the Siyavula open source high-school textbooks program in South Africa.

After my PhD I will move to Chicago, Illinois, in the United States of America where I will begin a new chapter of my life outside of astrophysics.
A lot of people have helped me over the years. Without these people this thesis would not be what it is or, in the case of a few very special people, would not have existed. In this section I would like to thank these people.

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In 2010 I was awarded a scholarship to do my BSc Honours and MSc in the National Astrophysics and Space Science Program (NASSP). To everyone at NASSP, thank you for the scholarship and for giving me a broad knowledge of astronomy. In particular I would like to thank Amanda Sickafoose under whose supervision I did my MSc project at the South African Astronomical Observatories (SAAO). You taught me a lot, without which this PhD would have been much harder, and you also helped me write my first paper on my MSc work during the first year of my PhD. Thank you for everything that you did Amanda.

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