A JVLA 10 degree^2 deep L-band survey[1]

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Abstract

One of the fundamental challenges for astrophysics in the 21st century is finding a way to untangle the physical processes that govern galaxy formation and evolution. Given the importance and scope of this problem, the multi-wavelength astronomical community has used the past decade to build up a wealth of information over specific extragalactic deep fields to specifically address key questions in galaxy formation and evolution. These fields generally cover at least 10 square degrees to facilitate the investigation of the rarest, typically most massive, galaxies and AGN. Furthermore, such areal coverage allows the environments to be fully accounted for, thereby linking the single halo to the two-halo terms in the halo occupation distribution. Surveys at radio wavelengths have begun to lag behind those at other wavelengths, especially in this medium-deep survey tier. However, the survey speed offered by the JVLA means that we can reached a point where we can finally begin to obtain commensurate data at radio wavelengths to those which already exists from the X-ray through to the far-infrared over ~ 10 square degrees.

We therefore propose a 10 square degree survey to 1.5μJy at L-band in B Array, requiring ~ 3700 hours to provide census of star-formation and AGN-accretion activity in the Universe. For example, the observations will allow galaxies forming stars at $10\,\mathrm{M_\odot\,yr^{-1}}$ to be detected out to $z \sim 1$ and luminous infrared galaxies ($1000\,\mathrm{M_\odot\,yr^{-1}}$) to be found out to $z \sim 6$. Furthermore, the survey area ensures that we will have enough cosmic volume to find these rare sources at all epochs. The bandwidth will allow us to determine the polarisation properties galaxies in the high-redshift Universe as a function of stellar mass, morphology and redshift. Conducting the a survey at L-band ensures the highest sensitivity for detecting extragalactic radio sources, even with the reduced effective bandwidth of 40 per cent due to RFI, compared to S-band, over such an area. However, an additional crucial aspect of carrying out this survey at L-band is that it could be carried out jointly with a deep and wide HI-survey over fields which have similar amounts of spectroscopic and imaging data as currently available to CHILES. Given the number of repeat observations, the survey will also be ideal for extending the search for faint radio transients.

Given the existing and planned multi-wavelength efforts by the astronomical community, the survey fields most appropriate for such a VLA effort are the XMMLSS field and the Extended Chandra Deep-Field South, which when combined with the CHILES survey will provide around 10 square degrees of radio continuum, polarisation and spectral-line data over the best studied regions of the extragalactic sky.

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1 Science Justification

During the first billion years of cosmic time, primordial galaxies emerged from a near-featureless early universe and began assembling into the chemically complex and morphological diverse population of galaxies that populate the present-day cosmos. The nature of this process how stars and galaxies have emerged and evolved from the Big Bang to today is one of the most compelling questions in all of science, resulting in a community-wide, multi-wavelength effort to obtain a wealth of information over carefully selected extragalactic deep fields to specifically address key questions in galaxy formation and evolution. The one wavelength that is currently lagging is the radio, however, with the dramatically increased capabilities with the JVLA, we can finally begin to obtain radio data at commensurate depths with other multi-wavelength efforts, spanning from the X-ray through the far-infrared over ~ 10 square degrees. To this end, we suggest that the VLASS has a deep continuum survey component that will provide the necessary depth to investigate the evolution of the radio source population from the Epoch of Reionization to the present day. The depth of our radio observations is designed to fully sample the luminosity function of both AGN-powered radio sources and the star-forming galaxy population, from redshifts $z = 0 \rightarrow 6$. Such a survey will also be sufficiently wide in area that it will enable us to overcome cosmic variance issues and be able to assess the evolutionary status of galaxies as a function of their environment. We outline the key science cases for the continuum survey below, critically select the best survey fields for the VLASS in Section 2, and provide detailed description of the survey strategy in Section 3.

1.1 Cosmic star-formation history and galaxy evolution

With a deep continuum survey with the JVLA, we aim to understand the basic features of galaxy formation and evolution, the volume-averaged star formation rate as a function of epoch, its distribution function within the galaxy population, and its variation with environment. Surveys of the star-formation rate (SFR) as a function of epoch suggest that the star-formation rate density rises as $\sim (1 + z)^4$ out to at least $z \sim 1$ (e.g. Lilly et al. 1996; Hopkins & Beacom 2006; Behroozi et al. 2013) and then flattens, with the bulk of stars seen in galaxies today having been formed between $z \sim 1 - 3$. Determining the precise redshift where the star-formation rate peaked is more difficult, with different star-formation indicators giving widely different measures of the integrated star-formation rate density (see Hopkins & Beacom 2006). These problems are exacerbated by the effects of cosmic variance in the current samples (multi-wavelength surveys such as COSMOS and GOODS typically cover only modest-sized areas, $\lesssim 1$ degree^2, corresponding to just ~ 30 Mpc at $z \sim 23$), as well as small sample sizes.

Below $S_{1.4\mathrm{GHz}} \sim 200\ \mu$Jy, SFGs begin to dominate the radio source population (e.g. Windhorst et al. 1985; Wilman et al. 2008; de Zotti et al. 2010). The radio continuum emission of these galaxies offers a star-formation indicator (e.g. Yun, Reddy & Condon 2001) that can be studied across the history of the Universe, and in particular right through the peak star-formation epoch at $1 \lesssim z \lesssim 3$. A JVLA continuum survey that covers a relatively large sky area but which is also sensitive enough that estimates of the integrated star-formation rate do not require large extrapolations for faint sources is required. An example of a radio continuum survey that would lead this field for years to come would be to reach star-formation rate limits of ~ 10 M$_\odot$ yr^{-1} and ~ 30 M$_\odot$ yr^{-1}, at $z \sim 1$ and $z \sim 2$ respectively, which is comparable to the star-formation rate sensitivity of deep far-infrared surveys conducted with the SPIRE instrument on *Herschel*. Crucially, radio continuum is also immune to dust extinction, and will therefore be able to identify heavily dust-obscured systems, often missed in optically-selected samples. This will be particularly valuable in combination with *Herschel*, where the high-spatial-resolution radio data will be used to de-confuse the low-spatial-resolution images and investigate the evolution of the far-infrared–radio relation (e.g. Appleton et al. 2004; Murphy 2009; Sargent et al. 2010; Ivison et al. 2010; Jarvis et al. 2010), and thus how radio emission relates to star-formation rate in galaxies at the highest redshifts. It is not only the global average star formation rate that is important for our understanding of galaxy formation and evolution, but more crucially the nature and distribution of the star-forming galaxies at high redshifts:

How does star-formation proceed as a function of galaxy mass?: it is well established that in the local Universe the stellar populations of the most massive galaxies formed earlier than those of less massive galaxies ('down-sizing'; e.g. Cowie et al. 1996) and so massive galaxies must form stars rapidly at an early epoch, and then have their star formation truncated, but how and exactly when did this occur?

What is the role of galaxy environment?: in the local Universe, star formation is suppressed in dense environments (e.g.

Lewis et al. 2002), an effect which diminishes with increasing redshift, with hints that it disappears altogether at $z \sim 2$ (e.g. Koyama et al. 2013; Ziparo et al. 2014). But where precisely, in terms of epoch and environment, does this environmental influence begin to become important? To what extent is the build-up of galaxies into groups and clusters responsible for the sharp decline in the global average star formation rate below $z = 1$. Is this indeed an environmental effect or host galaxy mass dependent effect (e.g. Peng et al. 2010; 2012)?

How does star formation relate to the growth of supermassive black holes, and AGN feedback?: it is widely believed that AGN activity (particularly radio-loud AGN) may be responsible for switching off star-formation in massive galaxies, but a direct observational link between AGN activity and star-formation at high redshifts remains elusive. Indeed, recent studies from both a theoretical (Silk 2013) and observational (Kalfountzou et al. 2012) perspective have shown that powerful radio-loud AGN may actually provide a positive form of feedback. On the other hand, there is little evidence for any type of feedback from radio-quiet objects based on the latest studies using *Herschel* (e.g. Bonfield et al. 2011; Rosario et al. 2013) Given that different forms of AGN feedback are invoked in semi-analytic models (e.g. Croton et al. 2006; Bower et al. 2006; Hopkins 2012) of galaxy formation we are required to understand such processes if we are ever to understand the evolution of galaxies.

A deep JVLA continuum survey is required to provide definitive answers to all of these questions, free from cosmic variance (e.g. Heywood, Jarvis & Condon 2013) or dust extinction biases. A survey that will detect upward of 10,000 star-forming galaxies (to a 5σ limit) in each of the redshift ranges $1 < z < 1.5$, $1.5 < z < 2$, $2 < z < 3$ and around 5000 sources at $z > 3$ would allow for detailed analyses of different sub-populations (e.g. dividing into $10 - 100$ bins in planes such as SFR vs stellar mass will allow $\gtrsim 100$ galaxies per bin). The exquisite-quality multi-wavelength datasets available in key extragalactic fields will provide spectroscopic redshifts where dedicated surveys have been or are being undertaken and excellent photometric redshifts from the deep optical and infrared photometry. Such data will also provide source properties such as masses and environments, and classifications as AGN or mergers. In Figure 1 we show the expected constraints on the radio-luminosity function for star-forming galaxies at six different epochs for a range of survey areas. One can immediately see the requirement to move to both a deep and reasonably wide survey in order to address the key science of the evolution of star-formation activity in the Universe.

1.2 The evolution of accretion activity and the exploration of the epoch of reionization

Active Galactic Nuclei (AGNs) play a major role in the framework of galaxy formation. The enormous amount of energy they release in the form of ionising radiation or relativistic jets during their short lifetime can have a significant effect on their surroundings. The energetic feedback from AGN appears to be a vital ingredient for reproducing some observed features, such as the stellar galaxy mass function (Croton et al. 2005; Bower et al. 2006), and the black-hole mass versus bulge mass (or velocity dispersion) correlation (Magorrian et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000; Haring & Rix 2004). This suggests that AGN and star formation activity may have been concurrent, even though the origins of the above correlations are not entirely clear and the subject of active debate. Indeed, the peak of QSO activity appears to take place at $z \sim 2$ (e.g. Croom et al. 2009; Hasinger et al. 2005), i.e. at epochs when star formation was also at its peak, and observational evidence has been found of the presence of an embedded AGN in 20-30% of $z \sim 2$ massive star forming galaxies in the GOODS fields (Daddi et al. 2007). Traditionally the provinces of separate research fields, it is now becoming clear that AGN and star-formation activity are intimately related, and the cosmic star formation rate appears to mirror closely the cosmic accretion rate onto AGN. However, a complete census of both star formation and AGN activity, especially at high redshifts, is complicated due to dust extinction and gas obscuration by circumnuclear material. The optimal combination of sensitivity and spatial resolution of JVLA would allow the study of the entire AGN population from classical radio-loud sources down to the realm of radio-quiet AGNs ($P \sim 10^{22-23}$ W Hz^{-1}, Jarvis & Rawlings 2004; Wilman et al. 2008; Kimball et al. 2011; Condon et al. 2013), from $z = 0 \rightarrow 6$. This would provide, for the first time, a complete view of nuclear activity in galaxies and of its evolution, unbiased by gas/dust selection effects.

Indeed, there is now strong evidence that the standard AGN unification paradigm (e.g. Antonucci 1993; Urry & Padovani 1995) for radio-loud AGN does not give a complete picture. For example, observational evidence (e.g. Hardcastle et al. 2007; Herbert et al. 2010; Best & Heckman 2012) suggests that many or most low-power ($P < 10^{25}$ W Hz^1) radio galaxies in the local universe (the numerically dominant population) correspond to a distinct type of AGN. These sources accrete through a radiatively inefficient mode (the so-called 'radio mode'), rather than the radiatively efficient accretion mode
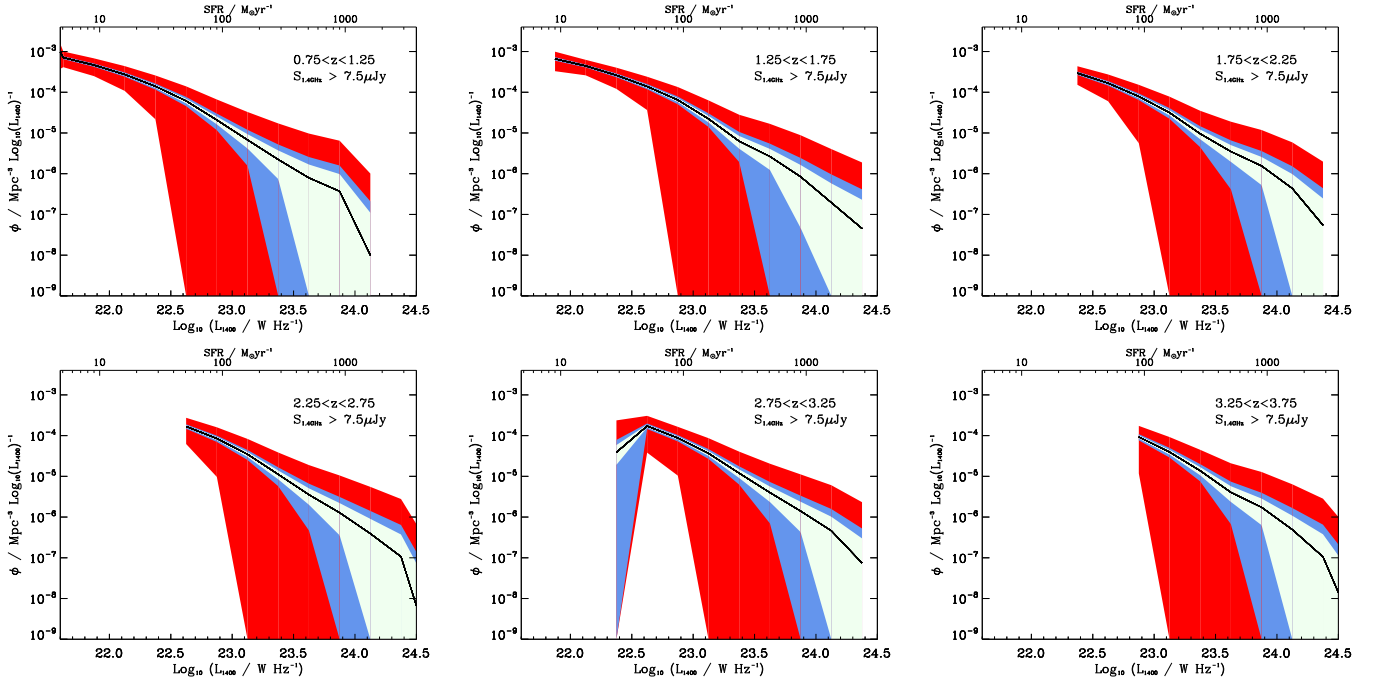
Figure 1: Predicted luminosity functions in six redshift bins for star-forming galaxies in the deep continuum survey (based on the simulations by Wilman et al. (2008; 2010)). The red regions shows the Poisson uncertainty for a 1 degree^2 survey, the blue region is for a 5 degree^2 survey and the cream regions is for the proposed 10 degree^2 survey. The equivalent star-formation rate is given on the upper x-axis.

typical of radio-quiet optically or X-ray selected AGN ('quasar mode'). The role of these two accretion modes appears to be strongly influenced by the environment (e.g. Tasse et al. 2008) while the presence or absence of a radio-loud AGN appears to be a strong function of the stellar mass of the host galaxy (e.g. Best et al. 2005; Janssen et al. 2012). Deep radio surveys covering areas of sky with the best multi-wavelength data (Section 2) will allow us to probe the evolution of these relationships and the accretion mode dichotomy over cosmic time; this is key information for any attempt to incorporate mechanical feedback from radio-loud AGN in models of galaxy, group and cluster formation and evolution.

Furthermore, the details of the mechanism(s) of interaction between radio-loud AGN and their environments, on all scales, remain unclear; such basic questions as whether the most powerful sources are expanding supersonically throughout their lifetimes (e.g. Begelman & Cioffi 1989; Hardcastle & Worrall 2000) or what provides the pressure supporting the lobes of low-power objects (e.g. Bîrzan et al. 2008; Croston et al. 2008) remain unanswered. These questions can only be addressed by the accumulation of large, statistically complete samples of radio sources with good imaging and excellent, homogeneous multi-wavelength data. Information on both large and small-scale radio structure is required. The JVLA deep continuum survey data would not only enable such an investigation for the first time, but also ensures that the radio luminosity function of all types of AGN is fully sampled at all redshifts (Fig. 2), and covers enough area that the necessary statistical analysis for such work is not severely hampered by small volumes. Furthermore, the vast array of multi-wavelength data will play a crucial role in determining the level of AGN activity in the galaxies, in addition to providing both spectroscopic and photometric redshift information and the immediate environmental density. Such studies are crucial in addressing how galaxies and their supermassive black holes build up together over cosmic time.

The key astrophysical problems related to AGN that the proposed survey will address thus include:

1) the relationship between AGN and star-formation activity (e.g. Bonfield et al. 2011; Rosario et al. 2013);

2) the evolution of low power AGN (including radio-quiet AGN), exploring the so-called "AGN cosmic downsizing" scenario, found for X-ray and optically selected AGNs (Hasinger et al. 2005; Babić et al. 2006; Smolčić et al. 2009; McAlpine, Jarvis & Bonfield 2013);
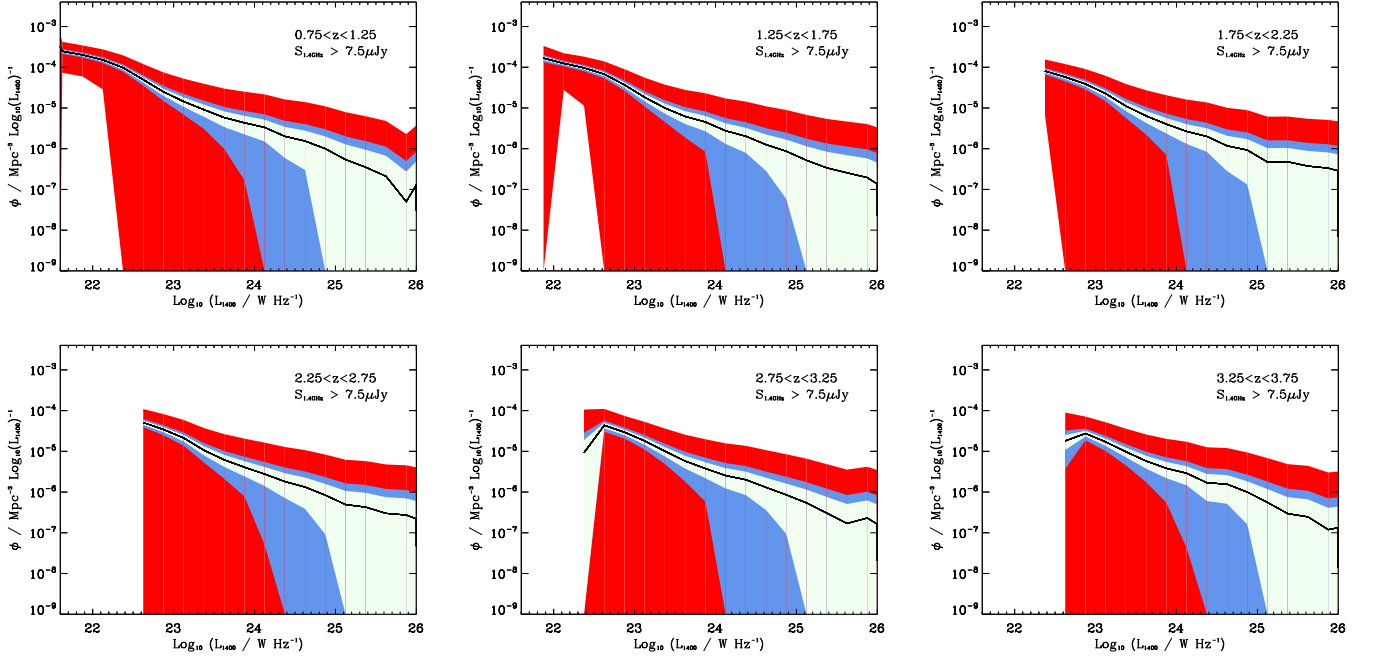
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Figure 2: Predicted luminosity functions in six redshift bins for AGN in the deep continuum survey (based on the simulations by Wilman et al. (2008; 2010)). The red regions shows the Poisson uncertainty for a 1 degree^2 survey, the blue region is for a 5 degree^2 survey and the cream regions is for the proposed 10 degree^2 survey. One can see the huge gain in accuracy by mocing to 10 degree^2 over existing ~ 1 degree^2 surveys.

3) the relative contribution of different accretion regimes (radio vs. quasar modes), its evolution with redshift, and the role played by the environment (e.g. Best & Heckman 2012);

4) the relative contribution of radiative versus jet-driven (kinetic) feedback to the global AGN feedback in models of galaxy formation;

5) the mechanisms of that feedback and the evolution in the physical properties of radio-loud AGN with redshift (e.g. Mocz, Fabian & Blundell 2013).

1.3   Galaxy Clusters

The evolution of AGN and star-formation activity can only be understood if the full range in environmental density is probed at all cosmic epochs (e.g. Tasse et al. 2008; Gendre et al. 2013; Karouzos, Jarvis & Bonfield 2013). Clusters of galaxies represent some of the most extreme environments experienced by galaxies and are therefore ideal laboratories for differentiating the physical processes which can affect and transform the morphologies and star-formation properties of galaxies and their level of AGN activity. Although most work has focused on the suppression of star-formation activity in galaxies as they become part of the cluster population, recent evidence from a small number of radio and mid-infrared studies has demonstrated that there must also be a period of star-formation enhancement to explain the growth of the galactic bulges. However, the limited size of these studies means that they urgently require confirmation. For example, work combining X-ray, optical, near-infrared, and deep radio observations over the UKIDSS-UDS (van Breukelen et al. 2009; Martini 2013) have shown that increased star-formation and/or AGN activity in clusters may be linked to their state of evolution, with more virialized clusters seeming to contain a more quiescent galaxy population than their younger, yet to virialize counterparts (van Breukelen et al. 2009). However, such studies are currently very limited in size, e.g. the study of van Breukelen et al. contains just four clusters (or overdensities) at $z \sim 1$ in ~ 0.5 degree^2. The depth and breadth offered by a 10 square degree deep continuum survey with the JVLA would provide the data to investigate the evolution of the cluster population from $z = 0.5$ to the highest redshifts, when the first clusters are believed to start virializing ($z \sim 2$).

To detect typical star forming galaxies at redshifts where there is strongest evidence for environmentally-driven evolution, at $z \sim 0.5 - 1$, requires $< 10 \mu$Jy sensitivity to reach star-formation rates of ~ 10 M$_\odot$ yr^{-1}. A VLASS JVLA deep continuum survey provides a unique opportunity to study these processes since (a) it is sensitive to the radio continuum emission produced by star-formation and AGN activity; (b) around 10 square degrees are required to serendipitously detect ~ 100 of clusters either through radio observations alone or more easily by combining with the deep optical, infrared, SZ and X-ray data over the key extragalactic fields in the $z > 0.5$ Universe; and (c) it has the angular resolution required to identify radio emission from individual galaxies within the clusters.

1.4 Cosmology and Large Scale Structure

Over the past few years there has been an increasing focus on using radio continuum surveys to address the fundamental issues related to the cosmological model, including determining the equation of state of dark energy and whether we can find evidence for departures from General Relativity on the largest scales (e.g. Raccanelli et al. 2012; Camera et al. 2012).
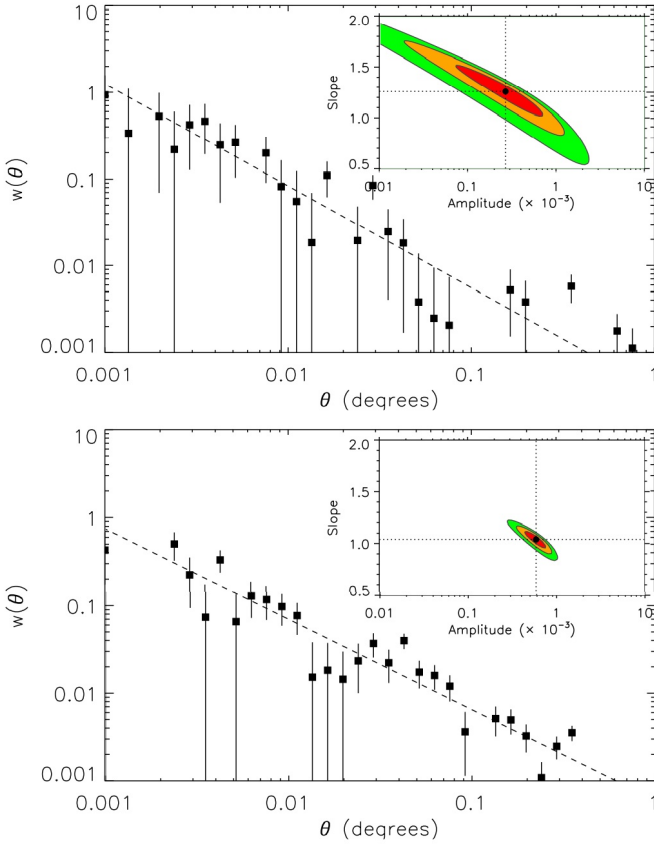

Three key tests where one can use radio continuum sources as cosmological probes are: the Integrated Sachs-Wolfe effect (e.g. Raccanelli et al. 2008); the power spectrum of the radio source populations (e.g. Blake, Ferreira & Borrill 2004); and the cosmic magnification bias (e.g. Scranton et al. 2005). However, one of the key unknowns in our understanding of how well radio sources can help determine the underlying cosmological model is their bias, i.e. how they trace the underlying dark matter density field.

It is actually very difficult to determine this quantity directly from radio continuum surveys alone, although some progress has been made by measuring the angular two-point correlation function of radio sources cross-correlated with optical imaging and spectroscopic surveys (e.g. Passmoor et al. 2013; Lindsay et al. submitted) and by assuming a redshift distribution (e.g. from the SKADS simulation of Wilman et al 2008; 2010). However, such studies are hampered by only the low-redshift sources having reliable optical counterparts, thus limiting the redshift range over which the bias can be measured to $z < 0.5$. Given that the unique niche occupied by radio continuum surveys for determining the cosmological model lie in the fact that their redshift distribution peaks at $1 < z < 2$ (depending on the precise flux-density limit), our lack of knowledge of the bias at $z > 1$ severely hampers our ability to use these sources as tracers of the Universe on large scales.

Figure 3: The angular two point correlation function for a $S > 50 \mu$Jy radio source (top) 1.5 sq.deg, and (bottom) 4.5 sq.deg. The inset shows the uncertainty contours on the slope and normalization of the power-law fit (Lindsay & Jarvis in prep.)

This problem can be tackled in two ways with a deep JVLA continuum survey. The first is to measure the two-point correlation function of the sources in the survey directly. This is analogous to what has been done at low redshifts, where the optical counterparts can be used in these deep fields to determine redshifts, using either photometric or spectroscopic redshifts. Such an experiment requires the necessary volume to determine the clustering of dark matter haloes, and with a single field of around 1 degree^2 such a measurement is extremely difficult. However, by moving to 4-5 degree^2 patches of sky then the two-halo term in halo-occupation distribution models begins to be measured at > 1 Mpc scales. Fig. 3 shows the constraints that can be achieved by moving from a 1.5 degree^2 survey to a 4.5 degree^2 survey based on the clustering model prescribed in the SKADS simulation (Wilman et al. 2008). Additional information can also be used, such as the full galaxy catalogue from optical

and near-infrared data. By measuring the cross-correlation of the much more abundant optical/near-infrared sources with the radio sources one can obtain much tighter measurements of the clustering of radio sources over all luminosity régimes, i.e. even for the rarer AGN (e.g. Donoso et al. 2010; Lindsay, Jarvis & McAlpine in prep.).

A second method to directly trace the density field at these redshifts is attainable using the CMB lensing maps recently determined using data from SZ-telescopes [e.g. the Atacama Cosmology Telescope (Das et al. 2011)]. Both the number density of radio sources and the strength of CMB lensing in a certain direction depend on the projected dark matter density in this direction, and conveniently radio sources are most common at the redshifts that produce the largest lensing deflections. This implies that the CMB lensing and radio source fields should be strongly correlated (Peiris & Spergel 2000). Measuring the cross-power spectrum and comparing it to theoretical calculations, would provide the proportionality factor which relates a fluctuation in matter density to a fluctuation in radio source number density, i.e. the bias.

The redshift range over which the CMB lensing signal is most prominent lies at $1 < z < 4$, ideal for cross-correlating with radio sources whose redshift distribution closely follows this lensing kernel. Indeed, a similar study has recently been carried out by the ACT team, where the CMB weak lensing map was cross-correlated with quasars (Sherwin et al. 2012), whose redshift distribution also peaks around $1 < z < 2$. They detect CMB lensing quasar cross-power spectrum for the first time at a significance of 3.8σ, with a bias of $b = 2.5 \pm 0.6$ (assuming a template for its redshift dependence).

Furthermore, the optical and near-infrared counterparts to the radio sources can be used to determine photometric redshifts for the radio sources that enable the redshift distribution of the radio sources to be modified such that the source concentration is shifted in redshift space. This would allow the bias to be determined for the high-redshift ($z > 1$) radio source population, which is expected to be dominated by more highly biased AGN, separately from the low-redshift ($z < 0.5$) source where the source counts become increasingly made-up of less-biased star-forming galaxies. Such an investigation has already been undertaken, based on simulations, by Camera et al. (2012) which suggests such a separation provides a unique insight in the very large-scale at high redshift.

1.5   The Polarized Sky - Cosmic Magnetic Fields

Current studies of the deep polarized sky show that it presents questions which cannot be answered by the strong source population alone (Taylor et al. 2009). Indeed Mesa et al. (2002) found that the mean fractional polarization of radio sources is anti-correlated with flux density. This result was confirmed by Tucci et al. (2004), and again by Taylor et al. (2007) who found that in a sample of 83 sources with a limiting flux density of 500 μJy the faint source population has a mean fractional polarization almost an order of magnitude larger than for sources > 100 mJy. The faint end of this flux density range contains relatively more objects below the FRI/FRII luminosity boundary than the bright end. This raises a number of questions about the nature and evolution of the faint polarized sources. How is the higher degree of polarization of faint sources related to source structure, radio luminosity, redshift, or environment? Does the trend of increasing polarization continue to lower flux densities? When does it stop? Does the polarization of all AGN increase with flux density, or can we identify a sub-class of AGN that is responsible for this trend?

The fractional polarization and intrinsic polarization angle of a source measure the order and direction of its magnetic field. It is expected that these quantities will be different for distinct classes of object due to the changed origin of the emission. In AGN they will mainly be related to the ordered magnetic field in the jets and lobes; for star-forming galaxies, which are mostly spirals, they are likely to reflect the degree of ordering in the intrinsic disk field. The fractional polarization distribution of nearby disk galaxies at 4.8 GHz was measured by Stil et. al. (2009) and Mitchell (2010), who carried out a survey of nearby (within 100 Mpc) but unresolved galaxies using the Effelsberg Telescope. These data show that at at least 60% of unresolved normal spiral galaxies are polarized higher than 1%, and in some cases higher than 10%. Moreover, there is a strong correlation between polarization position angle and the optical minor axes of the galaxy disk. A deep continuum survey over $'sim10$ square degree with the JVLA would provide direct detection of the presence and properties of ordered magnetic fields in galaxy disks to intermediate redshifts.

The combined areal coverage and depth of the survey, will also allow the polarized source population to be measured to flux-density limits an order of magnitude deeper than existing surveys. Moreover, polarized source counts can me measured to nanoJy levels by stacking the polarized emission at positions corresponding to total intensity detections. In combination with the large optical/IR datasets from VISTA, VST and *Herschel* we will be able to cleanly separate star-forming galaxies

from AGN in the same way as has been made possible with SDSS in the Northern hemisphere, but with much deeper data at all wavelengths. This multi-wavelength information can then be used to correlate the radio polarization properties with optical emission line diagnostics, galaxy type and star-formation rates. This is important as there is already evidence that magnetic fields may be important in controlling the global star formation properties of spiral galaxies.
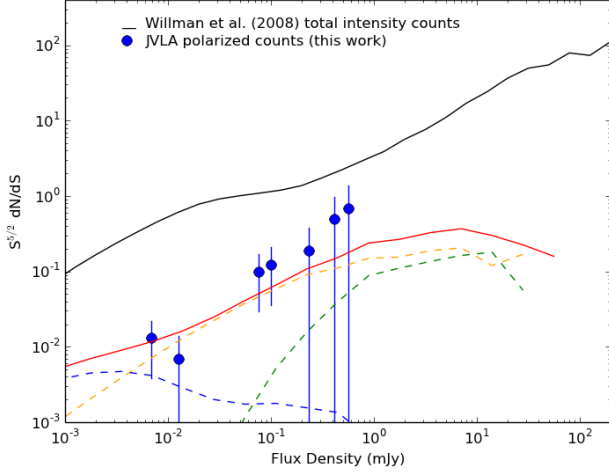

Figure 4: Polarized intensity source counts over a 0.1 sq deg field at 5 GHz (Taylor et al. in prep.) The solid black line is the Wilman et. al. (2008) SKADS simulation of total intensity counts. The red curve is the predicted total polarized flux density counts. The dashed curves are predicted counts for FR II and FRI radio galaxies (green and orange respectively), and for polarized emission from normal galaxies (blue). The proposed survey at 1.5 GHz will directly detect thousand of polarized sources spanning the transition where SF and normal galaxies become a major component of the polarized population.

Such a large population of polarized sources will allow polarization properties of galaxies to be used for cosmological applications. One of the long term aims of polarization surveys is to investigate the alignment between large-scale structure and the polarization position angle of the polarized source population. Preliminary investigation using the NVSS survey, which is dominated by jet-powered AGN, finds that there are significant correlations between the position angle of the total intensity isophotes and the polarization position angle. The proposed survey will allow us to probe substantially lower flux densities at higher resolution. Importantly, this will allow us to remove the effects of internal Faraday rotation, which strongly suppresses the intrinsic polarization and makes the correlation detectable only by stacking a substantial number of galaxies.

In addition it should also be possible to use the data to put stringent limits on the rotation of the plane of polarization due to the coupling of the electromagnetic sector to pseudo-Nambu Goldstone bosons, so called cosmic birefringence (Carroll 1998). By performing rotation measure (RM) synthesis, or otherwise extracting rotation measures for the sources, it will also be possible to statistically examine the distribution of RMs to search for the imprint of intergalactic fields on galaxies on cosmological scales. We will be sensitive to the internal Faraday rotation of the sources. The amount of depolarization by Faraday dispersion sets apart star-forming galaxies from most AGN powered radio sources potentially allowing us to separate them using the polarization observations; something which can be cross-checked using the multi-wavelength information.

The bandwidth of the survey will allow Faraday Rotation Measures to be measured with an accuracy better than 2 rad-m^{-2} down to polarized flux densities of 20 μJy. From recent JVLA imaging to 1 μJy rms of a 0.1 sq deg field at 5 GHz (Figure 4), we expect to detect several 100 sources per square degree down to 10 μJy at 1.5 GHz. The 2-point correlation function of RM will be measured on scales of arc minutes and precision of a few rad-m^{-2} , precisely the regime where fluctuations from primordial magnetic fields are expected to create detectable signal (Kolatt 1998; Akahoru & Rhy 2010). This regime of sky density and RM accuracy has not been accessible to date.

1.6 HI Deep Field

By conducting the survey at L-band rather than at S-band, we not only obtain a higher source density (approximately a factor of 2.5 higher at L-band than for S-band given the same observing time), crucial to the key science aims set out above, but also enable a complementary HI survey at the same time. Although we do not present the case for the HI survey here we emphasise that the science enabled by conducting such a survey over the best studied deep fields holds for HI as it also does for continuum. Any HI deep field survey would therefore likely choose the same fields as we do here.

It would also be possible to undertake a deep search for HI absorption against moderately bright radio sources within our fields, along with a coarse velocity resolution search for other lines, such as OH megamasers. A search for HI absorption

Table 1: Multi-wavelength data available over the key extragalactic fields accessible to the deep VLASS continuum survey. All of the optical and near-infrared data in these fields are deep enough to estimate photometric redshifts for upward of 70 per cent of the radio sources at a flux-density threshold of 7.5μJy (5σ (see e.g. McAlpine et al. 2012). All fields are also covered by the *Herschel* with the HerMES survey.

Field	Coordinates	Area	Optical Imaging	Near-IR	Mid-IR	Spectroscopy
COSMOS	10 00 29 +02 12 21	1.5	Subaru, CFHT, DES	UltraVISTA	SCOSMOS	zCOSMOS
XMMLSS	02 22 00 -04 48 00	4.5	Subaru, CFHT, DES	VIDEO, UKIDSS-UDS	SWIRE, SERVS	VVDS, OzDES
ECDFS	03 30 08 -28 38 00	4.5	DES, VST	VIDEO	SWIRE, SERVS	OzDES

could be carried out for sources at $z < 0.5$. These H I absorption studies are not limited by the brightness sensitivity to H I emission (typical $T_{spin} \approx 100$ K) but rather the spectral line sensitivity to detect absorption signals against high T_{spin} continuum sources. Thus it is possible to detect H I via absorption at much higher redshifts and with higher angular resolutions than is possible for typical H I emission experiments.

1.7 Transients

The continuum survey would be structured in such a way that it will be possible to find very slow and rapid transient phenomena. The many repeat observations will allow AGN to be found via variability to study the time domain astrophysics of extragalactic sources. Such a science case would fit naturally within a VLASS deep continuum survey.

2 Field Selection: Multi-wavelength Synergies and Long-term Legacy Value

The survey fields have been carefully chosen to ensure maximum overlap over fields which have unrivalled multi-wavelength data sets and that are extremely important in fulfilling the continuum survey science aims. The crucial data set for the continuum survey is information on the redshift of the extragalactic radio sources. Redshifts can be obtained either by spectroscopy or using photometric redshifts based on multi-band optical and/or near-infrared data.

We suggest observing three fields which will continue to be the most widely observed fields in extragalactic astronomy. The COSMOS, XMMLSS, ECDF-S have all been observed by *Spitzer* as part of the SWIRE survey (Lonsdale et al. 2003), with the data fully reduced and available. They have also being observed as part of the HerMES Guaranteed Time Programme on *Herschel* (Oliver et al. 2012) which supplies deep imaging data from 100–500μm. The deep radio data from the VLASS will be crucial for fully interpreting the *Herschel* data set due to the much higher resolution which will allow us to associate the *Herschel* sources with the correct optical and near-infrared identifications. These fields will also be covered at near-infrared wavelengths by the Ultra-VISTA Survey (McCracken et al. 2012 over the COSMOS field; Scoville et al. 2007) and the VIDEO Survey (Jarvis et al. 2013). These fields have also been surveyed by the *Spitzer* Representative Volume Survey (SERVs; Mauduit et al 2012) and at visible wavelengths they are part of the Dark Energy Survey (DES) Supernova Survey (Bernstein et al. 2012), and a VST Deep Survey as part of Guaranteed time. They will also form part of the LSST Deep Drilling Fields. As such these fields will have exquisite optical data tand near-infrared data, providing at least 20-band photometry for measuring photometric redshifts out to $z \sim 5$ for typical elliptical galaxies and beyond $z \sim 6$ for the most massive galaxies which host radio-loud AGN. In terms of more specific science aims all of these fields also have X-ray data from both *XMM-Newton* and *Chandra* allowing AGN to be found by virtue of their X-ray emission, *GALEX* data which provides UV-photometry.
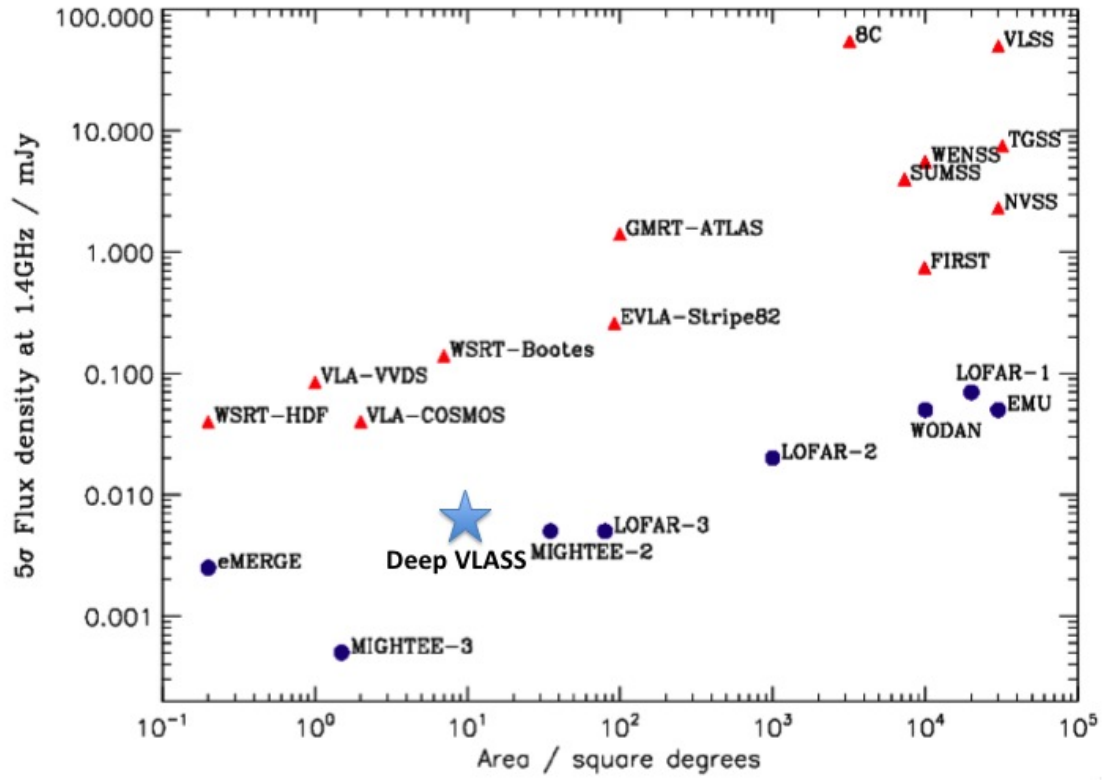
Figure 5: Current and proposed radio surveys on existing facilities and those proposed for the SKA Precursor telescopes. The JVLA Deep Survey that is detailed here is denoted by the star.

3 Observational Strategy

The VLASS continuum survey is most efficiently conducted at L-band, even with the effective bandwidth of 600 MHz compared to the 1.75 GHz of bandwidth available in S-band. This is due to a combination of enhanced field of view at L-band combined with the typical spectral index for extragalactic radio sources of $\alpha = -0.7$ (where $S_\nu \propto \nu^\alpha$). For example, for an rms flux-density limit of 1.5μJy at L-band, we would need to reach $\sim 0.9\mu$Jy at S-band to sample a similar source population density. Although this depth can be reached in roughly half the time than for a survey to 1.5μJy at L-band, the primary-beam area is reduced by a factor of four. Thus the survey speed is essentially a factor of two higher at L-band compared to S-band for a survey covering > 1 primary beam element.

As stated in Section 1.6 this also means that both H I emission and absorption surveys can be conducted at the same time, thus enhancing the scientific value of the survey, without effecting the key continuum and polarization science emphasized here.

To cover 10 degree^2 requires the equivalent of 70 pointings. To reach the 1.5μJy rms sensitivity with 600 MHz of effective bandwidth requires 57 hours per pointing. Thus the total survey would require $71 \times 57 = 4047$ hours. However, we note that the COSMOS field is part of the CHILES survey, and also other fields already have deep JVLA data to around 5-10μJy. Thus the total time request will be of the order 4000 hours (including overheads).

In Fig. 5 we show how the suggested survey fits in with current and planned radio continuum surveys in terms of the depth versus area. In terms of current or planned deep continuum survey, one can immediately see that the VLASS deep continuum survey is very competitive with the planned deep continuum survey (MIGHTEE; Jarvis 2012) for the MeerKAT telescope. Indeed, it will reach a greater depth than Tier-2 of the MIGHTEE survey, albeit with a factor of ~ 3 less area. Given the current baseline distribution for the MeerKAT telescope, Tier-3 of MIGHTEE will not be feasible as it will become confusion limited before it reaches the final depth. The ASKAP-EMU survey (Norris et al. 2011) is concerned with a different part of parameter space and is focussed on wide-field (many 1000 square degree) science. Thus, the VLASS deep continuum survey would fill a unique part of parameter space well before MeerKAT is in operation and well before such a survey could be taken to a new level by the SKA itself.

3.1 Dynamic Range

Achieving a noise-limited, full-Stokes mosaic image in the presence of the numerous sources that will be a good fraction of a Jy expected in the survey area, will require application of frequency and direction dependent calibration over the primary beam of the JVLA, including the accurate treatment of sources in the sidelobes. Future radio surveys will routinely reach depths where deficiencies in the traditional approach to calibration are the limiting factor, and overcoming this is an active and productive area of research (for several co-authors of this white paper).

The need for direction dependent calibration methods (Noordam & Smirnov 2010; Smirnov, 2011) for pathological scenarios where traditional direction-independent calibration methods are inadequate has already been demonstrated. One such example is that of extreme dynamic range imaging (Perley & Smirnov, 2013, see also Figure 6), another involves the modelling and subtraction of a phase calibrator in the first null of the primary beam, and in the presence of pointing errors (Heywood et al., 2013). We are currently developing pipelines to automatically apply these methods to moderately deep (XMM-LSS, 10 μJy, 4.5 deg^2) and wide (Stripe 82, 50 μJy, 100 deg^2) VLA surveys in order to mitigate the effects of strong sources in the field (Heywood, Jarvis, Smirnov, et al., in prep).

The derived gain solutions make physical sense, showing conclusively that time and frequency dependent beam gain variations are the dominant direction dependent effect even at L-band. Noise-limited Stokes-I images produced using these techniques can offer increased scientific return, however deficiencies remain for Q, U and V imaging. Efforts to address this are focused on deriving initial (and refined) sky models in full polarization using A-projection imaging within the calibration cycle. A-projection applies prior models of the beam patterns during gridding and has been shown to vastly improve polarization performance, correcting for frequency dependent off-axis complex gain and polarization leakage as a function of parallactic angle (Bhatnagar et al., 2008).

This work will require the survey team working with the advanced algorithm research and development (ARD) group on the implementation and commissioning of broad-band A-projection corrections within CASA. These algorithms will
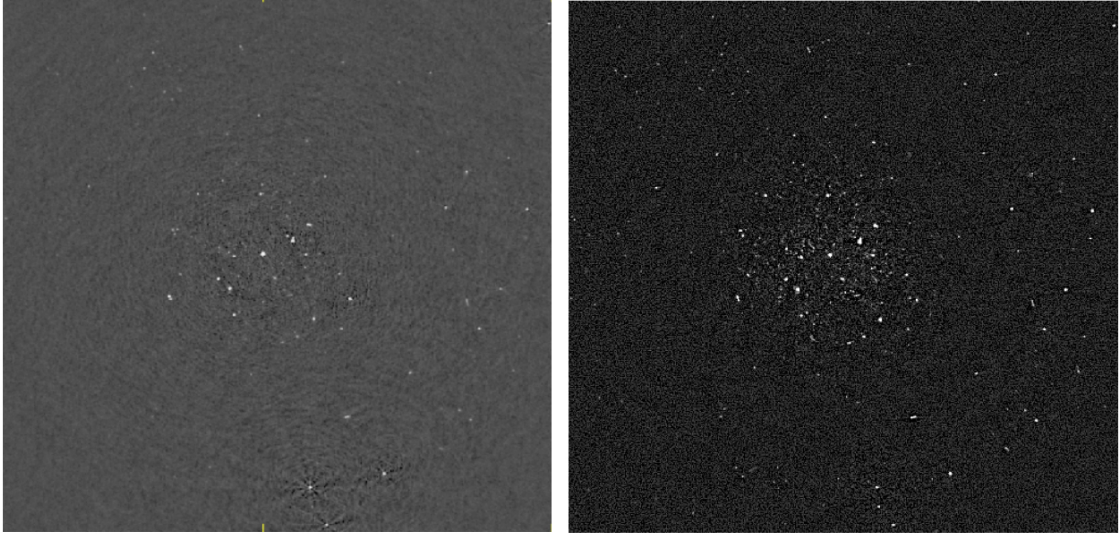
Figure 6: The 3C147 field imaged using VLA C+D array data using traditional self calibration methods (left) and direction dependent calibration using the MeqTrees software system (right). Note that part of the increased depth in the latter image comes from using three sub-bands instead of one, but the salient point here is that the PSF-like artefacts associated with off-axis sources (particularly in the first sideline) are completely eliminated. The map is thermal noise limited throughout, with a dynamic range of 3,200,000:1 (Perley & Smirnov, 2013).

correct for frequency dependent off-axis complex gain and polarization leakage as a function of parallactic angle. They can then be incorporated into a CASA-based processing pipeline for broad-band, full Stokes mosaic imaging developed as part of an EVLA Resident Shared Risk observing program.

Combined A-projection, with frequency dependent corrections over broad bands and joint deconvolution of multiple mosaic pointing is a computationally intensive problem. Therefore part of the work with the ARD group could include implementation of the CASA pipeline into HPC and/or massively parallel computing architectures.

4 Outreach and Citizen Science

There has recently been a large amount of effort devoted to constructing "Radio Galaxy Zoo", to be launched over the 2013-2014 holiday period. The aim of this Citizen Science project is to determine the morphology and cross-identification of radio sources from a range of radio surveys. These data are currently coming from wide-area surveys and being overlaid on optical imaging from the SDSS for example. With the VLASS deep continuum surveys, such a project could be taken to the high-redshift Universe. The 10 square degree scale surveys along with the VLASS continuum survey could be incorporated into Radio Galaxy Zoo and allow the public to contribute to high-redshift science in enabling cross-matching and characterisation of many 10s of thousands of radio sources at $z > 1$.

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