# The Jansky-Very Large Array Sky Survey (VLASS)

The VLA Survey Science Group

October 15, 2014

## Contents

1. Executive Summary/Overview 3

2. VLASS – A Launchpad for the Future 5

3. VLASS Themes and Headline Science 6
   3.1 Hidden Explosions ........................................... 6
   3.2 Faraday Tomography of The Magnetic Sky .................. 9
   3.3 Imaging Galaxies Through Time and Space .................. 11
   3.4 Peering Though Our Dusty Galaxy .......................... 14
   3.5 Radio Sources as Cosmological Probes ..................... 17
   3.6 Missing Physics ........................................... 19
   3.7 A Lasting Legacy into the SKA Era ......................... 20

4. Survey Strategy 21
   4.1 All-Sky .................................................. 22
      4.1.1 Context ............................................... 22
      4.1.2 Description .......................................... 23
      4.1.3 Survey Science ....................................... 24
   4.2 Wide ...................................................... 25
      4.2.1 Context ............................................... 25
      4.2.2 Description .......................................... 26
      4.2.3 Survey Science ....................................... 27
   4.3 Galactic .................................................. 28
      4.3.1 Context ............................................... 28
      4.3.2 Description .......................................... 29
      4.3.3 Survey Science ....................................... 29
   4.4 Deep ...................................................... 30
      4.4.1 Context ............................................... 30
      4.4.2 Description .......................................... 31
      4.4.3 Survey Science ....................................... 33
5 Data Products
  5.1 Basic Data Products ........................................ 35
  5.2 Enhanced Data Products .................................... 37
  5.3 Enhanced Data Services and the VLASS Archive .......... 37

6 Implementation Plan
  6.1 Mosaic Observing Patterns .................................. 38
  6.2 Scheduling Considerations .................................. 39
  6.3 Overall Observing Schedule ................................ 40
  6.4 Calibration ................................................ 41
  6.5 Imaging .................................................. 41
  6.6 Image Analysis and Sky Catalogs ......................... 42
  6.7 Archiving and Data Distribution ......................... 43
  6.8 Test and Development Plan ............................... 43

7 Education and Public Outreach ............................... 44
  7.1 Audiences ................................................ 44
    7.1.1 Scientists ........................................... 44
    7.1.2 Staffers, Managers ................................ 44
    7.1.3 Educators ........................................... 45
    7.1.4 General public ..................................... 45
  7.2 Social media and communication .......................... 45
  7.3 Examples of Community Educational Outreach Activities .. 46
    7.3.1 Picture of the Week ................................ 46
    7.3.2 Citizen Science ..................................... 46
    7.3.3 Science Stories .................................... 46
    7.3.4 Education Activities ............................... 47

8 Summary ...................................................... 47

A Motivation and Process ...................................... 55

B Impact of VLASS Sky Survey on Overall EVLA Science: The High Impact of Surveys ........................................ 56
  B.1 FIRST survey data usage .................................. 57
  B.2 NVSS/FIRST publications & citations .................... 57
  B.3 Will VLASS have the same impact as FIRST & NVSS? .... 58

C The “S/N model” of Positional Accuracy ..................... 59

D Additional Science Enabled by VLASS ...................... 62
  D.1 Extragalactic Science .................................... 62
  D.2 Galactic Science .......................................... 63
  D.3 Time Domain Science .................................... 64
1 Executive Summary/Overview

The Very Large Array Sky Survey (VLASS) is a community driven project initiated to develop and carry out a new generation large radio sky survey using the recently upgraded Karl G. Jansky Very Large Array (VLA). VLASS will open the radio sky to a new exploration of the time and spectral domains. VLASS was developed through unprecedented community involvement and consensus building, including a public workshop at the AAS, the submission of over 26 white papers and long competitive debate in the Survey Science Group (SSG), along with its community working groups of more than 200 multi-wavelength astronomers (see Appendix A). The resulting VLASS is a modern, multi-tiered survey designed to provide a broad, cohesive science program with forefront scientific impact, capable of generating unexpected scientific discoveries. VLASS will engage radio astronomy experts, multi-wavelength astronomers and citizen scientists alike, while leaving a lasting legacy value for decades to come. The data from VLASS will be available in the NRAO archive immediately with no proprietary period and science data products will be provided to the community in a timely manner. The design of VLASS paid extremely close attention to future Square Kilometer Array (SKA) pathfinders, leading to a survey that will both stand out, and be complimentary to those other pathfinder surveys at 1.4 GHz.

The proposed VLASS is a \( \sim 9000 \) hour comprehensive multi-tiered survey, with 20% invested in All-Sky, 40% in Wide, and 40% in Deep, as summarized in Table 1, and detailed in §4 below. This design optimizes utilization of the unique capabilities of the Jansky VLA, namely high-resolution imaging and exquisite point-source sensitivity, critical for source identification, wide bandwidth coverage enabling instantaneous spectral index determination, and full polarimetry with good performance even in lines of sight with high Faraday depth, enabling instantaneous rotation measure determination. Much of VLASS will be carried out in multiple passes, providing a synoptic view of the dynamic radio sky similar to those now available through the new generation of synoptic imagers at other wavelengths. VLASS will also provide a unique snapshot of the radio sky at a key epoch and sensitivity level between that from FIRST and NVSS and the new upcoming radio surveys. This will be a critical enabler for early identification and filtering for the most interesting transient events. Using the Jansky VLA to capture the radio spectrum from 2 – 4 GHz, VLASS will measure or constrain spectral shapes (e.g. power-law spectral indexes). Along with full polarimetry, the spectral breadth of VLASS is an important unique enabler for survey science.

<table>
<thead>
<tr>
<th>Tier</th>
<th>Area ( (\text{deg}^2) )</th>
<th>Resolution (arcsec)</th>
<th>rms ( (\mu\text{Jy/bm}) )</th>
<th>Total Time (hr)</th>
<th>Epochs</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) – “All-Sky”</td>
<td>33,885 ( (\delta &gt; -40^\circ) )</td>
<td>2' 1</td>
<td>100</td>
<td>1860</td>
<td>1</td>
</tr>
<tr>
<td>(2) – Wide</td>
<td>10,000 (SDSS-III)</td>
<td>2' 1</td>
<td>50</td>
<td>2824</td>
<td>4</td>
</tr>
<tr>
<td>(2) – Galactic</td>
<td>3160</td>
<td>0'' 76</td>
<td>50</td>
<td>840</td>
<td>4</td>
</tr>
<tr>
<td>(3) – Deep</td>
<td>10 (COSMOS, ECDFS, ELAIS-N1)</td>
<td>0'' 65</td>
<td>1.5</td>
<td>3391</td>
<td>4</td>
</tr>
</tbody>
</table>

VLASS will observe from 2 – 4 GHz and is structured to combine comprehensive all sky coverage with sequentially deeper coverage in carefully identified parts of the sky, including the Galactic plane and the SDSS-III footprint, and will be capable of informing time domain studies. Figure 1 and Table 2 provide an indication of the expected extragalactic source counts from VLASS based on the S^3 simulated radio sky (Wilman et al., 2008). Why is a 2 – 4 GHz, high-resolution, synoptic, polarimetry survey able to deliver such high value science?

- High angular resolution is required to not only identify and associate the radio emission with its optical host galaxy, but also to identify the location of the emission within the galaxy.
Figure 1: The anticipated cumulative extragalactic source count distribution by VLASS tier using the S$^3$ simulated radio sky (Wilman et al., 2008). The vertical line indicates the 5$\sigma$ surface brightness sensitivity of each tier.

Table 2: Expected VLASS Source Statistics

<table>
<thead>
<tr>
<th>Tier</th>
<th>Area (deg$^2$)</th>
<th>Density (deg$^{-2}$)</th>
<th>Total Detections</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-Sky</td>
<td>33,885</td>
<td>205</td>
<td>7,000,000</td>
</tr>
<tr>
<td>Wide</td>
<td>10,000</td>
<td>350</td>
<td>3,500,000</td>
</tr>
<tr>
<td>Deep</td>
<td>10</td>
<td>9200</td>
<td>92,000</td>
</tr>
</tbody>
</table>

Note: Sky coverage, expected extragalactic source density, and total number of extragalactic detections per VLASS tier above a 5$\sigma$ surface brightness limit.

- The 2 $-$ 4 GHz band allows polarimetry on lines of sight with high Faraday depth without depolarization.
- The 2 $-$ 4 GHz band allows for earlier identification of explosive event afterglows when they are brighter, and unlike at 1 $-$ 2 GHz, allows for multiple independent epochs occurring within the survey time span.
- Observing at 2 $-$ 4 GHz provides the highest yield of flat or inverted spectrum compact sources while still detecting a large number of sources with “normal” modestly steep spectra.
- Employing the 2 $-$ 4 GHz band at high angular resolution will result in a survey that will provide maximum complimentary utility when combined with the lower-frequency, lower-resolution surveys planned for the SKA precursors and pathfinders later this decade.
- Even in the era of the Phase 1 SKA science observing next decade, VLASS will provide a reference epoch this decade for transient object identification, as well as coverage of the Northern sky not accessible to those instruments.

This survey approach enables both focused and wide ranging scientific discovery through the coupling of deeper, narrower tiers with increasing sky coverage at shallower depths, addressing key science issues and providing a statistical interpretational framework. Such an approach provides both astronomers and the citizen scientist with information for every accessible point of the radio sky, while simultaneously addressing fundamental questions about the nature and evolution of astrophysical objects. VLASS will follow the evolution of galaxies and their central black hole engines, measure the strength and topology of cosmic magnetic fields, unveil hidden explosions throughout the Universe, and chart our galaxy for stellar remnants and ionized bubbles. Multi-wavelength communities studying rare objects, the Galaxy, radio transients, or galaxy evolution out to the peak of the cosmic star formation rate density will equally benefit from VLASS. The **VLASS Key Science Theme** can be summarized as:

- **Hidden Explosions** – Unbiased Measurements of Energetic Events.
• **Faraday Tomography of The Magnetic Sky** – Charting the Emergence of Large-Scale Magnetic Fields in Galaxies.

• **Imaging Galaxies Through Time and Space** – Following the Ecology of Galaxies, Star Formation, and their Black Hole Engines.

• **Peering Though Our Dusty Galaxy** – Finding and Studying the Tracers of Stellar and Chemical Evolution.

• **Radio Sources as Cosmological Probes** – Tracing the Underlying Dark Matter Density Field.

• **Missing Physics** – Enabling the Incorporation of Radio Astrophysics in Multi-Wavelength Astronomy.

These are described in more detail in §3 below, demonstrating that VLASS will have a strong legacy across a broad landscape of astronomical science.

## 2 VLASS – A Launchpad for the Future

VLASS builds upon the newly upgraded Jansky Very Large Array (VLA) to employ its enhanced bandwidth, time resolution, and survey speed to carry out a new generation sky survey. The Jansky VLA has been in science operation since 2010, with commissioning completed at the end of 2012. Consequently, the capabilities required for VLASS have largely been proven in past and ongoing science programs, making this the ideal time to utilize the VLA for a science survey that will both inform future VLA PI science for decades to come, while simultaneously infusing radio astronomy firmly within the multi-wavelength framework of astronomical research. For instance, VLASS will provide an important and unique reference atlas for the science that will be enabled by a new suite of multi-wavelength surveys and observatories coming online now through the end of the decade across the electromagnetic spectrum and beyond – Pan-STARRS, ALMA, DES, JWST, eROSITA, Advanced LIGO/VIRGO, LSST, to name but a few.

VLASS stands on the shoulders of the pioneering NVSS and FIRST surveys carried out with the VLA from 1993 – 2002. VLASS additionally sets the stage for future radio surveys and facilities [i.e., Meer Karoo Array Telescope (MeerKAT), the Australian Square Kilometer Array Pathfinder (ASKAP) and the Westerbork Synthesis Radio Telescope (WSRT/AperTIF)], leading to Phase 1 SKA science operations that will commence in ≳2020. Each of these facilities include dedicated 1.4 GHz surveys as a prime component of their science programs. The observing band and parameters of VLASS complement these lower frequency programs and provide a foundation for the next decade. Thus, the Jansky VLA, with its greatly enhanced and unique suite of capabilities, is well positioned to be at the forefront of this new suite of deep radio surveys. VLASS, as proposed here, provides a qualitative improvement in observations of and understanding of the radio sky, will detect the radio counterparts to the current and emerging multi-wavelength suite of surveys (from the sub-millimeter to γ-rays), and will serve as a technical proving ground for future radio telescopes and their intended surveys. VLASS has been designed with both SKA Pathfinders and the SKA itself in mind, and it showcases the unique capabilities of the VLA.

While a major survey such as VLASS must self-evidently reduce the time available for direct PI science in the short term (by roughly 25% over five years), it is important to note that the survey itself will obviate the need for some fraction of future PI proposals (by providing the data needed directly through the survey itself), that it is the lowest rated and frequently only partially completed PI proposals which will be impacted, and that VLASS will provide radio measurements for a broad component of the astronomical community. The existing VLA sky surveys, NVSS (Condon et al., 1998) and FIRST (Becker et al., 1995; White et al., 1997), provide powerful evidence that the telescope time dedicated to these surveys repays the investment many times over. In Appendix B, we provide a detailed analysis that demonstrates the scientific impact of FIRST and
NVSS as measured by publications, citations and data utilization. There are a number of key ways in which PI science itself is enhanced by the survey science, including:

- VLA sky surveys have a science impact per observing hour that is demonstrably greater than the average VLA observing program. This is at least partly because surveys expand the usage of radio data beyond the usual radio astronomy community.

- Once VLA sky survey products are available, many science projects that require pointed observations of a sample of objects (e.g., to measure spectral indices for a sample of quasars) can be carried out directly from the catalogs rather than requiring an observing proposal. That reduces the time requested for such observing proposals and so increases the time available for other projects.

- The survey products themselves become a key resource for astronomers in identifying targets and projects for followup proposals. That leads to an increase in the science done by enabling projects that are not possible without the inputs from a sky survey.

The balance to be considered between the scientific impact from VLASS for the broad astronomical community and increased competition for PI science time needs to take all these elements into consideration.

3 VLASS Themes and Headline Science

There are six themes that run throughout the VLASS design and science goals. These exploit the unique capabilities of the upgraded Jansky VLA. In each of these themes we highlight the “Headline Science” that will be done with VLASS. These are exemplary key science projects that illustrate both known and unknown science potential for VLASS, a survey we anticipate will open new frontiers for discovery. In Appendix D, we describe extensive additional science areas that VLASS is likely to impact. The lasting legacy value of VLASS in light of future radio surveys on the horizon is discussed in §3.7.

3.1 Hidden Explosions

The 2010 Astronomy and Astrophysics Decadal Survey (National Research Council, 2010) highlights time domain astronomy as an area with great potential for new discoveries. Like the sky viewed in other wave-bands, the radio sky is dynamic, exhibiting variability on timescales from milliseconds to years. Such radio transients often signal explosive events, in some cases probing the highest energy particle populations in the known universe. These diverse phenomena include astrophysical blast waves, catastrophic gravitational collapses, magnetic acceleration of relativistic charged particles, shocks in high energy particle jets and in magnetized diffuse interstellar plasma, flaring reconnection events in the atmospheres of low mass stars, and the cosmic beacons of rotating neutron stars, white dwarfs, and black hole accretion disks. While the detection of such events has previously relied on the synoptic survey capability of modern wide-field optical, X-ray and \( \gamma \)-ray observatories, VLASS now also offers the potential to systematically characterize the dynamic sky at radio frequencies, targeting both galactic and extragalactic transient populations. It so happens that the most numerous radio transients with the greatest potential impact, are actually those populations that have been hidden from view at these other wavebands, being largely detectable only at radio wavelengths.

What is the true rate of explosions in the local Universe?

Phenomena associated with the explosive death throes of massive stars have been studied for decades at all wavelengths. These myriad phenomena include the various classes of supernovae
(type Ia, type Ib, Ic and type II), the highly relativistic outflows of γ-ray bursts (GRBs) and the mergers of compact objects (e.g., see Figure 2). As well as providing a window into the life cycles massive stars, such events also probe the formation of compact objects and can provide a standard candle for precision cosmology. However, the true rate of such events is poorly constrained; specifically:

(i) A comparison of the star formation rate and supernova discovery in the local universe implies that as many as half of the supernovae remain undetected in the traditional optical searches, largely due to extinction via dust obscuration, with far reaching consequences for models of stellar and galaxy evolution.

(ii) The relativistic outflows associated with GRBs and compact object mergers are highly collimated. Thus, only those bursts that are collimated in the direction of Earth are detected. Best estimates suggest this corresponds to a small fraction of the true event rate, dependent on the typical opening angle of the collimated jet, with poor constraints on the latter.

VLASS can provide the means to establish an unbiased measure of the true rates of these phenomena. Radio observations, unlike optical, can penetrate the dusty environments of obscured supernovae. Similarly, the late-time, sub-relativistic afterglows of GRBs and compact object mergers are not highly collimated. Thus, while such events are not detectable at γ-ray or X-ray wavelengths, they can be detected at radio wavelengths by VLASS.

VLASS has sufficient sensitivity and area coverage to deliver guaranteed high impact return for these known classes of transient events — at higher frequencies the emission from these blasts arrives earlier, and has shorter rise and decay times. Therefore, the VLASS observing at 2–4 GHz over the span of 5 years is ideally suited for finding and triggering follow-up observations of these events. The Wide component of VLASS will be the workhorse for this search. Wide will be carried out in four epochs spread through the 5 years of the VLASS observations, with a roughly 16 month cadence set by the VLA configuration cycle. Each epoch will reach a image rms depth of 100 µJy/beam. At its reference frequency of 3 GHz, the light curves from explosive events have a characteristic span of around 1 year, and thus these will essentially be four independent epochs. In contrast, future surveys at 1.4 GHz will be sampling light curves that have in some cases a characteristic scale of a few years, requiring epochs spanning a decade or more to effectively identify these events.

At these depths, a transient event should be identified with an known optical/infrared host galaxy, as there should be no “hostless” events for the known classes discussed below. Furthermore, the high angular resolution of VLASS allows identification of the location within the host galaxy, a capability not possessed by the proposed surveys from upcoming lower frequency arrays. This discriminator allows us to assess the likelihood that the event is due to AGN variability or a TDE (if located at host galaxy center), or a supernova or NS-NS merger associated with a catastrophic stellar demise.

What is the rate of coalescence of neutron star binary systems?

One of the most exciting prospects of the Synoptic VLASS is the opportunity to find and strongly constrain the rate of merging binary neutron star systems. Advanced LIGO (aLIGO) and Advanced Virgo (AdV) are scheduled to commence collecting data in 2015 and are expected to eventually yield the first direct observations of gravitational waves. The network will not be at full design sensitivity in 2015, but will grow in capacity over subsequent science runs (2016-2019) as detectors improve and with the eventual installation of a LIGO detector in India ∼ 2020 (LIGO Scientific Collaboration et al., 2013).

Compact binary coalescences, particularly the inspiral of binary neutron star (BNS) systems, are expected to be the most common source for detection and also the most promising to yield a corresponding electromagnetic counterpart. BNS mergers are thought to be the likely progenitor of short γ-ray bursts (S-GRBs), but only a small fraction of such events are detected in γ-rays due
to the narrow beaming of the emission (Fong et al., 2012) The fraction of S-GRBs that are not detected due to this narrow beaming is also poorly constrained. It is likely to be large however with the number of undetected events exceeding detected events by an estimated factor of $10^2 - 10^3$, as evidenced by the lack of detection of a S-GRB within range of aLIGO and AdV during the nine year Swift mission. It is clear that an unbeamed electromagnetic signature is required, both to 1) determine the true rate of BNS merger events to allow well defined predictions for the aLIGO and AdV era and 2) to provide a reliable means to unambiguously identify and localize a counterpart to a GW event. The radio emission produced by the mildly relativistic outflows interacting with the surrounding medium in the wake of a BNS merger has recently been highlighted as one of the most promising means to detect such events (Nakar & Piran, 2011). This radio afterglow would be produced in the weeks to months following the merger, peaking at frequencies in the range 1–4 GHz.

VLASS will play a two-fold role in the search for such merger events, 1) determining or
strongly constraining the true rate of merger events through identification of an unbeamed radio afterglow population and 2) delivering reference image data on a large fraction of the sky with sufficient depth to allow constraining follow-up observations of potential GW events out to the aLIGO/AdV horizon (200 Mpc). Crucially, we note that the VLASS All-Sky tier is sufficiently deep to provide an unambiguous reference map for searches for counterparts to those first events, based on the range of predicted radio flux densities (Nakar & Piran, 2011) for compact object mergers out to the detection horizon for the early Advanced LIGO and VIRGO runs (LIGO Scientific Collaboration et al., 2013).

A Unique Snapshot in Time: VLASS is not just an engine for the discovery of radio transients, but also a resource for use by the whole astronomical community in support of worldwide transient and variable studies at all wavelengths and with all messengers. Providing a new high-resolution standard reference atlas of the 2–4 GHz radio sky, VLASS will constitute a key legacy dataset for opening the time domain astronomy discovery frontier. VLASS will also be a key resource for next generation synoptic surveys at other wavebands, such as the LSST. The depth of the latter survey (20,000 sq. deg. to a depth of V = 27.5) is such that, of the planned radio synoptic surveys of the coming decade, only VLASS has the spatial resolution necessary to offer unique identification of radio counterparts with > 95% certainty.

3.2 Faraday Tomography of The Magnetic Sky

The WIDAR correlator has opened a major new window for wideband polarization work, enabling us to characterize properties of the magneto-ionic medium in AGNs and in galaxies across a wide range of redshifts. Faraday rotation in a magneto-ionic medium produces various external or internal depolarization processes (e.g., Burn, 1966; Tribble, 1991; Sokoloff et al., 1998). These provide a unique and critical diagnostic of the magneto-ionic medium, but only when observed over a wide, continuous frequency range (e.g., O’Sullivan et al., 2012) Almost all studies to date have either relied on a selected number of narrow bands or have observed over a continuous but relatively narrow fractional bandwidth. However, both these approaches have severe shortcomings (Farnsworth et al., 2011). Degeneracies between different types of depolarization behavior, and hence the underlying physical properties of polarized sources and foreground gas, can only be broken by wideband spectro-polarimetry.

A 2–4 GHz (S-band) polarization survey will uncover previously unknown populations of sources with extremely large Faraday depths and those that are heavily depolarized. For many sources, we will be able to combine these data with 1–1.5 GHz polarization measurements from ASKAP and AperTIF, which will enable the characterization of complex and interesting cases in compact and extended AGN regions, absorption line systems and galaxies, where magnetized relativistic and thermal plasmas are mixed.

Using broadband VLA data, we can uniquely address such questions as:

1. What is the covering fraction, the degree of turbulence and the origin of absorption line systems? Mg II absorbers are associated with $\sim 10^4$ K photo-ionized circum-galactic medium in a wide range of host galaxy types and redshifts (see Churchill et al., 2005, for a review). These systems potentially trace outflows from star formation (e.g., Norman et al., 1996) and cold-mode accretion (e.g., Kacprzak et al., 2010). When seen against polarized background sources, the Faraday depth provides a direct measure of the electron density and the magnetic field strength in Mg II absorbing systems, parameters that are both currently poorly constrained. Bernet et al. (2008, 2013) and Farnes et al. (2014) have demonstrated the presence of large values of |RM| associated with Mg II absorbers, and have interpreted this as evidence for $\mu$G field at $z \sim 1$, possibly associated with outflows. We can use such data to test photo-ionization models, and to infer the evolution of large-scale magnetic fields over cosmic time. With deep observations and high angular resolution,
we can use Mg II catalogs derived from SDSS (Quider et al., 2011; Zhu & Ménard, 2013) to identify sight lines through absorbers (current total number $\sim 40,000$).

(2) What is the the magneto-ionic medium in AGNs, galaxies and their immediate environments? Feedback from AGN is important in galaxy formation: it is intimately linked to the star formation history (e.g., Hopkins & Beacom, 2006), and could suppress cooling in massive galaxies, producing the bright-end cut-off of the luminosity function (e.g., Best et al., 2006; Croton et al., 2006). The nature of this AGN feedback is very much under debate: it has been shown that energy deposited by radio jets can either trigger or quench star formation (e.g., Wagner et al., 2012). AGNs are also thought to influence their surrounding intergalactic medium by enrichment of metals (Aguirre et al., 2001) and magnetic fields (Furlanetto & Loeb, 2001). Thus, investigating how radio galaxies impart energies into the ISM/IGM is crucial.

While minimal interaction between radio lobes and the environment would lead to a thin “skin” of thermal material around the lobes (e.g., Bicknell et al., 1990), significant interaction should lead to large-scale mixing of thermal gas with the synchrotron emitting material throughout the lobe, causing internal Faraday dispersion. Recently O’Sullivan et al. (2013) fitted the depolarization trend of the lobes in one such radio galaxy, Centaurus A, and found a thermal gas of density $10^{-4}$ cm$^{-3}$ well mixed in with synchrotron emitting gas in the lobes. A sensitive wide-band polarization survey allows statistical studies of this phenomenon through estimation of the thermal gas content in a large number of radio galaxies, covering a range of luminosities, redshifts, and environments.

Additionally, while we now have new extragalactic source catalogs of rotation measure vs redshift (e.g., Hammond et al., 2012), we are severely limited by our inability to correct polarization data for cosmological expansion. A “polarization k-correction” is only possible with wide-band polarization data, with which we can then infer intrinsic rest frame properties of the magneto-ionic medium in AGNs, galaxies and their immediate environments, and can then investigate how all these properties evolve with redshift.

(4) Emergence and growth of large-scale magnetic fields in galaxies? Spatially resolved images of the polarized synchrotron emission from nearby galaxies demonstrate the existence of µG azimuthal fields (e.g., Beck et al., 1996). However, the evolution of galactic-scale magnetic fields over cosmic time is poorly constrained, because this traditional approach becomes increasingly challenging for distant galaxies. An alternative approach is to utilize the statistics of integrated synchrotron polarization of unresolved galaxies to infer their overall magnetic field properties (e.g., Stil et al., 2009). In the presence of a large, scale galactic field the position angle of the integrated polarized radiation is aligned with the minor axis of the galaxy for rest frame frequencies above a few GHz.

At lower frequencies the effects of internal Faraday rotation from the galactic ISM both depolarizes the radiation and breaks the global symmetry of the observed field, leading to reduced polarized signal and variance of the correlation between the polarization position angle and the optical axes of the galaxy. On the other hand strong turbulence in starbursts can lead to depolarization that is largely independent of wavelengths.

Observations between 2 – 4 GHz spans the low and high depolarization frequency regimes, and can thus be used to test theoretical predictions from various galactic magnetic field generation mechanisms (see for example, Zweibel & Heiles, 1997), with which we can provide the first constraints on the time scales for galactic magnetic field amplification and the strength of the initial seed fields (Arshakian et al., 2009). Average fractional polarization of unresolved Milky-Way type galaxies is a factor of 3–4 higher at 2 GHz than at 1.4 GHz (Stil et al., 2009; Braun et al., 2010; Sun & Reich, 2012), a 2–4 GHz survey with sufficient sensitivity thus opens enormous potential for characterizing the development of galactic magnetic fields.
3.3 Imaging Galaxies Through Time and Space

The star-formation history of the Universe:

In almost all existing large-scale radio surveys, the vast majority of the sources detected are the accretion-dominated AGN and quasar populations. However, thanks to the well-known correlation between far-infrared (FIR) and radio emission (e.g., Helou et al., 1985; Appleton et al., 2004; Murphy, 2009; Sargent et al., 2010; Ivison et al., 2010; Jarvis et al., 2010) the star-forming galaxy population becomes detectable at flux densities around $S_{1.4\text{GHz}} \sim 1 \text{ mJy beam}^{-1}$, growing to dominate the source counts at fainter flux densities (e.g., Windhorst et al., 1985; Wilman et al., 2008; de Zotti et al., 2010). The radio is a particularly important tracer for this population, as it is relatively immune to dust extinction, providing an unbiased view into the basic features of galaxy formation across the history of the universe, including the volume-averaged star formation rate, its distribution function within the galaxy population, and its variation with environment.

Surveys of the cosmic star-formation rate 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 $z \sim 1 - 3$ in the so-called epoch of galaxy assembly. However, the effect of dust on the traditional optical and UV measurements of the star-formation rate means that the behavior of the cosmic star-formation rate density at redshifts above $z \sim 1$ is still uncertain (e.g., Bouwens et al., 2012), as is the importance of downsizing (Cowie et al., 1996). These uncertainties 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, $\lesssim 1 \text{ deg}^2$, corresponding to just $\sim 30 \text{ Mpc at } z \sim 2$), as well as small sample sizes. Given that star-formation is environmentally dependent (e.g., Lewis et al., 2002), any investigation on the evolution of star-forming galaxies requires the ability to detect them over the full range of cosmic environments (e.g., from rich clusters to voids).

VLASS is ideal for tracing the cosmic history of star-formation, free from cosmic variance (e.g., Heywood et al., 2013) or dust extinction biases. The Deep tier will detect star forming galaxies out to $z \lesssim 4$, and the large area of the Wide tier will provide a baseline sample of relatively nearby ($z \lesssim 0.5$) objects with which to compare them to. The targeted deep fields have the best multi-wavelength data available, making the VLA’s angular resolution essential for establishing reliable counterparts in these crowded fields, as well as measuring the sizes of star-forming disks at such early epochs. In addition to the overall star-formation history of the Universe, such a large-scale survey is necessary for answering closely-related questions regarding the dependence of star-formation on host galaxy mass (e.g., Peng et al., 2010, 2012) and the emergence and growth of large-scale magnetic fields in the star-forming ISM of these galaxies – the latter which is ideally obtained using wide-band spectro-polarimetry with the VLA’s S-band (see §3.2). In Figure 3 we show the predicted constraints on the radio luminosity function for star-forming galaxies in three redshift bins of width dictated by the expected photometric redshift error of $\delta z/(1+z) \sim 0.05$. One can see that moving from 2 deg$^2$ (the area covered by the COSMOS survey) to 10 deg$^2$ greatly reduces the Poisson uncertainty on the luminosity function for star-forming galaxies. Figure 4 shows the sample variance due to large-scale structure in various survey areas for difference galaxy masses, demonstrating again that the move towards larger areas/volumes is key to developing understanding of the link between star-formation, galaxy mass and environment.

AGN and the Evolution of Accretion Activity:

It is widely thought 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. Recent studies from both a theoretical (Silk, 2013) and observational (Kalfountzou et al., 2012, 2014) 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.
Figure 3: Predicted luminosity function at 0.95 < z < 1.05 (left), and 2.90 < z < 3.10 (right) for star-forming galaxies in the deep continuum survey [based on the simulations of Wilman et al. (2008, 2010)]. The red region shows the Poisson uncertainty for a 2 deg\(^2\) survey, the green region is for a 4 deg\(^2\) survey and the blue region is for the proposed 10 deg\(^2\) survey. The equivalent star-formation rate is given on the upper x-axis.

Figure 4: Sample/cosmic variance for galaxies of mass $10^{10} M_\odot$ (left) and $10^{11} M_\odot$ (right) for different survey areas. Moving from a 1 deg\(^2\) area to 10 deg\(^2\) reduces the sample variance from $\sim 15\%$ to $\sim 5\%$ at the crucial epoch around $z \sim 2$ for $10^{10} M_\odot$, and from $\sim 30\%$ to $\sim 10\%$ for $10^{11} M_\odot$.

using Herschel (e.g., Bonfield et al., 2011; Rosario et al., 2013). Moreover, the interplay between jets (also rare AGN—requiring a large survey area) and associated satellite galaxies is even more poorly understood. As Herschel studies are limited due to resolution and confusion noise, and optical surveys miss all of the obscured galaxies, radio is again the best line of attack. However, current radio surveys are unable to probe radio emission from star formation over the epoch where AGN activity is having an impact on the environment. Given that different forms of AGN feedback are invoked in current semi-analytic models of galaxy formation (e.g., Croton et al., 2006; Bower et al., 2006; Hopkins, 2012), it is essential that we understand such processes if we are ever to understand
the evolution of galaxies.

Indeed, there is now strong evidence that the standard AGN unification paradigm (e.g., Antonucci, 1993; Urry & Padovani, 1995) 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 typical of radio-quiet optically or X-ray selected AGN [sometimes called ‘quasar mode’]; see Heckman & Best (2014) for a recent review covering these feedback processes. 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). Deeper radio surveys covering areas of sky with the best multi-wavelength data are required 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., Birzan 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 optimal combination of sensitivity and spatial resolution of VLASS allows the study of the entire AGN population from classical radio-loud sources down to the realm of radio-quiet AGNs (P~10^{22−23} W Hz^{-1}, Jarvis & Rawlings, 2004; Wilman et al., 2008; Kimball et al., 2011a; Condon et al., 2013a), from z~ 0 – 6. This will provide a complete view of nuclear activity in galaxies and its evolution, unbiased by gas/dust selection effects. The All-Sky and Wide tiers are required to obtain a good baseline of radio AGN at low redshifts, while the deep tier is needed to push out to z~1-2, where feedback needs to be most active to prevent galaxy growth. The VLA’s high-resolution is crucial for morphologically distinguishing different types of AGN (e.g. FRI and FRII) from star-forming galaxies, and to establish reliable cross-identifications in all tiers. The wide-band spectro-polarimetry provided by VLASS will enable statistical studies of depolarization trends in radio lobes, lending insight into the interaction between radio lobes and the environment (e.g., O’Sullivan et al., 2013), and the spectral index made possible by the wide bandwidth is important for inferring the physical state of the AGN and surrounding environment as well as constraining the power of jets. Some broader themes that we will explore include:

**Why are some AGN strong radio emitters and others not?**

Except for the radio, there nothing in the optical/UV properties of quasars (continuum, emission, absorption) that specifically identifies a quasar as radio-loud or not (e.g., Kratzer, 2014). An important avenue forward to is have better demographics across a broad range of luminosity and redshift (see Figure 5), seeking to confirm marginal evidence that objects are more likely to be strong radio sources at lower redshift and higher luminosity. Further insight can be gained from radio demographics across the Eigenvector 1 parameter space (Schmidt & Green, 1983) that maximizes the dispersion of quasar properties.

**What is the origin of radio emission in radio-quiet quasars?**

Even radio-quiet quasars are not radio-silent. Is the radio emission from failed jets, star formation, or shocks (e.g., Kimball et al., 2011b; Condon et al., 2013b; Zákmiska & Greene, 2014)? There is evidence that all three may contribute. Again, better demographics – both for high S/N detection
Figure 5: Fraction of quasars that are radio loud (colored blocks) as a function of luminosity and redshift. There appears to be evolution in both redshift and luminosity. Data are limited to the “uniform” SDSS sample and are robust only for $z < 2.5$ (dashed red line). Deeper data over a wide area are needed to confirm (or reject) these apparent trends.

and stacking analysis – are key to understanding this question.

In both of the above cases, radio depth over a large area at high resolution is key. Strong radio sources are rare, and those at high-redshift are even rarer, so large areas are needed. Depths comparable to FIRST over new area and deeper than FIRST over existing area are needed. High resolution is important to minimize false positives when matching to depths in the optical where we expect many optical sources within a radio beam.

Along what line of sight are we viewing individual quasars?
Quasars are not spherically symmetric; however, at least for unobscured quasars, we have very little handle on the line of sight orientation of the systems. Radio spectral indices provide a rare opportunity to further quasar investigations by grouping them by orientation (or marginalizing over orientation). Understanding the orientation has implications for our understanding of quasar continua, emission lines, absorption lines, masses, accretion rates, and bolometric luminosities (e.g., Wills & Browne, 1986; Runnoe et al., 2013).

To investigate quasars as a function of orientation, we need robust spectral indices. Ideally these would be contemporaneous and/or at the same resolution as measurements at other radio frequencies. In that sense, S-band is ideal, as it provides an internal spectral index measurement within a single VLA observation.

3.4 Peering Though Our Dusty Galaxy
The combination of its sensitivity, angular resolution, and wavelength results in VLASS being a powerful survey for identifying compact objects and discrete sources where energetic phenomena are occurring. These energetic phenomena are either of interest in and of themselves (e.g., fundamental aspects of particle acceleration) or they provide a means of studying the objects and their
effects on the surrounding media. Further, obscuration and absorption effects are not problematic at the wavelength of VLASS, and the survey can probe deep into the Galaxy. Finally, there have been a host of surveys of the Galaxy from the infrared to $\gamma$-ray (e.g., with Spitzer, Chandra, and Fermi) that the VLASS will complement, allowing for a richer characterization of sources detected. Here we highlight three classes of objects that drive the Galactic component of the VLASS.

**Searching for Exotic Radio Pulsars:**
Neutron stars are extraordinary laboratories for extreme astrophysics and General Relativity. An imaging survey can identify candidate radio pulsars as compact sources which can be then targeted for more intensive periodicity searches. The advantage of this approach is that, for a fixed amount of telescope time in which to conduct a periodicity search, more efficient searches can be conducted by focusing on the relatively few sky positions containing the most interesting candidates rather than spending an equal amount of time on all sky positions.

This approach is most likely to be effective for pulsars that suffer large amounts of pulse broadening or for pulsars in compact binary systems. Compact binary systems have already proven to be powerful laboratories for General Relativity (Kramer et al., 2006), while rare pulsars (whether isolated or not) are likely to be at large distances, and therefore deep in the Galaxy and subject to strong pulse broadening.

An early example of this approach was the initial identification of 4C 21.53 West as a compact, steep-spectrum object in an imaging survey (Erickson, 1983) followed quickly by the detection of millisecond pulsations from it (Backer et al., 1982), leading it to be classified as the PSR B1937+21, the first “millisecond pulsar.” More recently, an imaging survey serving to find candidate radio pulsars followed by a targeted periodicity search has had considerable success with unidentified Fermi sources (e.g., Ray et al., 2012).

Specific examples of radio pulsars for which an initial detection in a imaging search is more likely than by a traditional periodicity search include

**Extreme Double Neutron-Star (DNS) Binaries** The DNS with the shortest known orbital period is PSR J0737−3039A/B, for which $P_{\text{orb}} = 2.4$ hr. In principle, though, DNS binaries could exist down to periods as short as 10 minutes. The double pulsar PSR J0737−3039A/B (Lyne et al., 2004) requires post-Newtonian order 1.5 for its orbital description and has provided tests of GR to 0.05% (Kramer et al., 2006). More compact binaries will test General Relativity to higher order and, with suitable geometries, will provide strong gravity tests from lensing. DNS binaries also provide better calibration of the event rate for LIGO. Based on estimated merger rates, there should be approximately 2000 DNS binaries in the Galaxy with $P_{\text{orb}} < 10$ hr with about 20% of these (400) beamed toward us. The lifetime to GW emission implies a period distribution scaling as $P_{\text{orb}}^{8/3}$, so there should be about 10 DNS binaries with orbital periods less than 2.4 hr with favorable beaming.

**Sub-)Millisecond Pulsars (MSPs)** These short period pulsars, with especially high spin stability, are being employed in pulsar timing arrays for gravitational wave detection. Standard periodicity surveys using single-dish telescopes will miss some MSPs, including some of the most interesting ones, because binary motion will not be mitigated by acceleration searches in the more extreme cases. Further, our current understanding of the equation of state of nuclear matter allows MSP spin periods as short as 0.5 ms. However, the fastest known MSP has a period of 1.4 ms (Hessels et al., 2006). Periodicity surveys suffer from selection effects (orbital motion and plasma scattering in the interstellar medium) that are strongest for the shortest-period pulsars. A VLA finding survey may find sub-ms MSP candidates that can be identified as such in follow-up periodicity surveys. If these objects do not exist, then the combined hybrid approach will provide very important constraints on the evolution and physics of accretion-driven spin-up.
Neutron Star-Black Hole Binary Systems
No such system is known yet, but they should exist on basic binary evolutionary grounds. The detection of a single NS-BH binary will be of profound importance because timing measurements will probe space-time around a black hole to much higher precision than any other technique.

Finally, electron-density and magnetic field models for the Milky Way will be calibrated and improved by column density and scattering measurements from confirmation observations of new pulsar discoveries in the Galactic plane and bulge.

Magnetic Activity on M Dwarfs:
The radio emission from nearby active stars provides a unique probe of accelerated particles and magnetic fields that occur in them, which is useful for a broader understanding of dynamo processes in stars, as well as the particle environment around those stars. The large magnetic field strengths now known to occur around some brown dwarfs was first detected through their effect on cm-wavelength radio emission (Hallinan et al., 2006) before the signatures were seen through Zeeman splitting of absorption lines at near infrared wavelengths (Reiners & Basri, 2007). The stellar byproduct of exoplanet transit probes like Kepler and TESS will yield information on key stellar parameters like rotation, white-light flaring, and asteroseismic constraints on stellar ages. These parameters can be used together to address fundamental questions such as those identified in the New Worlds, New Horizons Decadal Survey (“How do rotation and magnetic fields affect stars?”).

Combined with the LSST and eROSITA surveys, the all-sky component of VLASS will be a foundational aspect of identifying and studying nearby active stars. Particularly powerful will be cross-correlating variable or transient sources identified in LSST surveys with VLASS. Such cross-correlations, as a way of identifying nearby active stars, will allow more robust statistics from which to compare the distribution of optical flares with the efficiency of strong particle acceleration.

Scaling from the luminosity distribution of currently known active stars, VLASS will be able to detect ultracool dwarfs to 10–20 pc, active dwarf stars to a few tens of parsecs, and active binaries to slightly less than 2 kpc.

Planetary Nebulae and Galactic Structure:
At the end of a lower mass star’s life, its planetary nebula phase represents the expansion of its stellar layers into the interstellar medium. This ionized material emits free-free radio emission along with many optical spectral lines (Acker et al., 1992). In addition to their use as a tracer of the timescales for mass loss and stellar evolutionary processes, planetary nebulae (PNe) are one
of the best tracers of Galactic stellar and chemical evolution. Due to dust obscuration, PNe can be
difficult to find optically (from optical emission lines) in the plane of our Galaxy. However, the
radio emission from PNe is well understood. The Strasbourg catalog, which seems to be the best
one out there, is not well-selected; it preferentially selects compact and nearby objects.

Population synthesis models predict a range of expected Galactic planetary nebulae (Sabin
et al., 2014) yet the total number of known nebulae is far lower than even the most conservative
expectations. Figure 6 illustrates the distribution of planetary nebulae from the Strasbourg and
follow-on optical catalogs and the need for even broader coverage in the sky.

3.5 Radio Sources as Cosmological Probes

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 et al., 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.,
Lindsay et al., 2014a) and by assuming a redshift distribution (e.g., from the S$^3$ 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 $z > 1$ hampers
our ability to use these sources as tracers of the universe on large scales.

This problem can be tackled through a deep VLA continuum survey by measuring 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 deg$^2$ such a measurement is extremely difficult. However, by moving to $\sim$4 deg$^2$
patches of sky (i.e., as is the case for two of the VLASS Deep fields), the two-halo term in halo-occupation
distribution models begins to be measured at $> 1$ Mpc scales. The left panels of Figure 7 shows the
constraints that can be achieved by moving from a 1.5 deg$^2$ survey to a 4 deg$^2$ survey based on the
clustering model prescribed in the S$^3$ 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 regimes, i.e. even for the rarer AGN (e.g., Lindsay et al., 2014b).

Probing the dark Universe with VLASS:
The nature of dark energy remains the most outstanding question in cosmology. Weak gravi-
tational lensing - the effect whereby images of faint, distant background galaxies are coherently
distorted by intervening large scale structures - is recognized as one of the key probes that will
Figure 7: Left: The angular two point correlation function for a $S_{3\,\text{GHz}} > 30\,\mu\text{Jy}$ radio source (top) 1.5 deg$^2$ and (bottom) 4.5 deg$^2$. The inset shows the uncertainty contours on the slope and normalization of the power-law fit (Lindsay et al., 2014b). Right: Forecasted constraints on the cosmic shear power spectrum from the VLASS Deep tier observations assuming a survey depth of 1.5 $\mu$Jy and assuming a total shape noise error of $\gamma_{\text{rms}} = 0.3$. Two sets of forecasted errors are plotted to represent the two scenarios in which useable shape measurements can or cannot be extracted from the CDFS observations (which will suffer from an elliptical beam due to the low declination of the CDFS field). The predicted signal-to-noise of the cosmic shear detection in each case is also indicated.

allow us to constrain dark energy in future surveys (Albrecht et al. 2006; Peacock et al. 2006). The Deep tier of VLASS offers an exciting opportunity to extend this science area to radio surveys (see right panel of Figure 7). Its combination of excellent sensitivity and high angular resolution (both of which are essential for weak lensing) will remain unsurpassed until the advent of the SKA and will make it the world's premier resource with which to spearhead the development of radio weak lensing in preparation for the SKA.

The radio band offers unique and powerful added value to the field of weak lensing. Firstly, deep radio surveys will probe the lensing power spectrum at significantly higher redshift than most of the planned optical lensing surveys. The addition of radio can therefore offer a more powerful redshift "lever arm" with which to measure the effects of dark energy on the evolution of structure. Secondly, instrumental systematic effects are a serious concern for weak lensing studies for which a very accurate representation of the beam or point spread function (PSF) of the telescope is required. The highly stable and deterministic beam response of radio interferometers could therefore prove a major advantage for weak lensing science. Radio observations offer unique advantages over traditional lensing analyses by enabling fitting of galaxy shapes directly from $uv$-visibility data (Chang & Refregier, 2002; Chang et al., 2004). Another unique aspect comes from the VLA's wide bandwidth at both L- and S-band which allows direct measurement of the frequency dependence of the beam. This is a potential major advantage over optical broad-band photometry since while galaxy optical-uv SEDs vary wildly, in the radio galaxies typically exhibit smooth power-law type spectra. Perhaps most importantly, the radio offers unique and novel opportunities to independently evaluate the effects of weak lensing such as through polarization...
measurements.

Polarization observations of weak lensing provide unique information on the intrinsic (unlensed) shapes of background galaxies. The position angle of the integrated polarized emission from a background galaxy is unaffected by gravitational lensing (Brown & Battye, 2011). If the polarized emission (which is polarized synchrotron emission sourced by the galaxy’s magnetic field) is also strongly correlated with the disk structure of the galaxy then measurements of the radio polarization position angle can be used as estimates of the galaxy’s intrinsic (unlensed) position angle. Thus, polarization observations can be used to reduce the primary astrophysical contaminant of weak lensing measurements – intrinsic galaxy alignments (see e.g., Heavens et al., 2000; Catelan et al., 2001; Brown et al., 2002; Hirata & Seljak, 2004) – which are a severe worry for ongoing and future precision cosmology weak lensing experiments. Additionally, depending on the polarization properties of distant background disk galaxies, the polarization technique has the potential to reduce the effects of noise due to the intrinsic dispersion in galaxy shapes. VLASS will allow the first demonstration of these new techniques.

3.6 Missing Physics

The radio portion of the spectrum for astrophysical objects provides diagnostics for a whole range of physical processes that are not easily ascertained in other parts of the spectrum. For instance, VLASS will be able to: peer through high columns of dust, finding classes of objects unseen or un-studiable in other parts of the spectrum; characterize the properties of deeply embedded star formation; observe polarized emission from cosmic rays spiraling in magnetic fields; measure spectral indices that elucidate the origin and geometry of emission; and observe variability that both constrains scales of compact sources and reveals wholly new classes of objects.

When multi-wavelength astronomers lack radio information, they are unable to compile a complete picture of the physics of individual objects and the statistical properties of the sky. VLASS, however, will enable the discovery and study of rare classes of objects in the radio, while also allowing the broader astronomical community to determine the radio emitting properties of rare classes of objects that are identified at other wavelengths (e.g., brown dwarfs, γ-ray bursts, or objects from future surveys such as LSST). Additionally, later this decade, the Advanced LIGO and VIRGO gravitational-wave observatories (GWO) are expected to turn on, ushering in a new astronomical land rush across the electromagnetic spectrum to make the first identifications within the large (∼ 500 deg$^2$) error regions of the first events$^1$. The existence of high quality dynamic radio images over a substantial region of the sky from the VLASS All-Sky tier will provide future GWO transient hunters a critical baseline from which to discern newly appearing objects from extant static and run-of-the-mill variable sources.

VLASS Wide will focus on portions of the sky for which major investments are already in place to gather optical/NIR spectroscopy, thus allowing meaningful astrophysical investigations of sources. Wide will focus on covering a major portion of the 14,000 deg$^2$ area being targeted by the Dark Energy Spectroscopic Instrument (DESI), which will obtain optical spectra for tens of millions of galaxies and quasars, constructing a 3-dimensional map spanning the nearby universe to 10 billion light years. As hundreds of thousands of spectra already exist in the proposed area, the radio data from Wide will immediately enable investigations of stars, stellar remnants, galaxies, clusters, and AGN.

By peering through the dusty Galaxy, the Galactic survey component will enable both individual and statistical studies including the study of the mass-energy-chemical cycle in galaxies, star formation, the influence of rotation and magnetic fields on non-degenerate stars, nailing down the progenitors of type Ia supernovae, the end lives of massive stars, and what controls the parameters of compact stellar remnants.

Unlike any other radio survey to date, VLASS Deep will achieve a depth that is sensitive to the population of star-forming galaxies at the critical epoch of star formation between $1 \lesssim z \lesssim 3$, while simultaneously covering an area that is free from the effects of cosmic variance. In doing so, Deep will provide the astronomical community with a critical new dataset to study the evolution of star-forming galaxies. Furthermore, with its sub-arcsecond resolution, VLASS Deep will remain the only radio survey that will resolve star-forming galaxy disks at $z \gtrsim 1$ over many $\text{deg}^2$ until the Phase 1 of the SKA.

Thus, in a host of ways, VLASS will bring the critical diagnostics provided by observing in the radio part of the spectrum to the broad multi-wavelength astronomical community, enhancing our ability to model and interpret the physics at play.

### 3.7 A Lasting Legacy into the SKA Era

VLASS will not only deliver unprecedented science as described above, but will also build a lasting legacy well into the SKA era by consciously being designed to highlight the capabilities of the VLA that will remain state for the art well into $>>2020$. Specifically, the survey capitalizes on the exquisite point source sensitivity and high angular resolution that will not be superseded until SKA1-MID begins operating in the Karoo. For comparison, MeerKAT/MIGHTEE (Tier2: $\sim 1\mu\text{Jy}/\text{bm}$ with $\theta_s \approx 5'5$) will be able to detect the same sources as we would with the VLA in the Deep tier, however it will be unable to characterize these sources from a radio perspective or unambiguously associate them with an optical/near-infrared counterpart. This is because the source density at these depths is $\sim 20,000 \text{ per deg}^2$ for the MIGHTEE-Tier2 survey, and the MeerKAT beam is approaching the confusion limit of $\sim 30$ beams per source. Another crucial advantage that the VLA has over MeerKAT is its ability to resolve typical star-forming galaxies (and AGN) at all redshifts – MeerKAT will never be able to do this. This is a unique science case that will not be superseded until the SKA1-MID is fully operational with $>100$ km baselines. Consequently, the first generation SKA1 reference surveys, which are now being designed and will soon be proposed for, are currently being benchmarked against the deep imaging component of VLASS (Prandoni et al. 2014, in preparation).

In addition to delivering deep, high-resolution imaging, the WIDAR correlator has opened a major new window for spectral index and wideband polarization work, enabling the characterization of the magneto-ionic medium in AGNs and in galaxies across a wide range of redshifts. The polarization for MeerKAT L-band surveys will be much more difficult than in the S-band, where depolarization will be lower. A deep S-band survey over the same fields as the MeerKAT deep survey will provide 3 GHz of frequency baseline to increase the signal-to-noise on polarization and rotation measure synthesis, opening up new and exciting science that combines the strengths of the VLA and MeerKAT, rather than setting them up to compete. For AGN science, the requirement to morphologically distinguish different types of AGN (e.g., FRI and FRII) from star-forming galaxies and the need for reliable cross-IDs is again the driver for doing this survey with the VLA rather than MeerKAT. However, the synergies between these two facilities can and should be capitalized on. For example, MIGHTEE will provide accurate total flux densities and luminosities for extended AGN, whilst also providing a longer baseline for spectral index measurement that can be used to infer the physical state of the AGN and the environment in which it resides. Thus, not only will the deep, high resolution imaging from VLASS remain state of the art well into $>>2020$, the synergy of these observations (in frequency and resolution) with those of the SKA pathfinders coming online over the next $\sim 5$ yr will ultimately enable even more new science than that which is discussed here.

From the point of view of the dynamic radio sky, VLASS will also provide a unique snapshot of the Universe some 20 years after the FIRST survey, and leading up to the advent of the SKA pathfinders and the SKA itself. Current large-area radio transient detection surveys, such as the recent Stripe82 survey of Mooley et al. (2014, in preparation), successfully utilized the “Epoch
0" provided from FIRST as well as other historical VLA-based surveys, as a starting point for identification of newly appearing objects from the first new Jansky VLA epochs. As the VLA surveys go deeper, the utility of FIRST and other earlier shallow surveys will decrease. VLASS — with its depth, area, and angular resolution — will provide a new launching point for future surveys, taking us into the SKA and LSST eras. This will be the case across the breadth of transient and variability studies touched upon in § 3.1 above, and well beyond.

Finally, it is certainly worth mentioning that experience shows that when telescopes enter unexplored areas of observational phase space, as will be the case with VLASS, they make unexpected discoveries. It has been shown that the most significant discoveries with major telescopes often end up being those that were completely unexpected. As an example, of the top ten discoveries with HST, only one was identified as one of the key goals used to justify telescope. So while specific science goals detailed below have focused the design of VLASS, it may not be surprising if they do not end up being its greatest scientific achievements. It will undoubtedly be the scientific imagination and curiosity of community that will ultimately drive the best science to come out of VLASS.

### Table 3: Summary of VLASS

<table>
<thead>
<tr>
<th>Component</th>
<th>Comb. Depth µJy/beam</th>
<th>Total Area deg²</th>
<th>Epochs (Pass/Epoch)</th>
<th>Time (Pass) hours</th>
<th>Config.</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-Sky</td>
<td>100</td>
<td>33885</td>
<td>1</td>
<td>1860</td>
<td>B/BnA</td>
<td>23885 deg² excl. Wide</td>
</tr>
<tr>
<td>Wide</td>
<td>50</td>
<td>10000</td>
<td>4 (1)</td>
<td>2824</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>Galactic</td>
<td>50</td>
<td>3160</td>
<td>4 (1)</td>
<td>840</td>
<td>A (+B)</td>
<td>incl. All-Sky</td>
</tr>
<tr>
<td>Deep/COSMOS</td>
<td>1.5</td>
<td>2</td>
<td>4 (10)</td>
<td>300</td>
<td>A</td>
<td>incl. prev. observations</td>
</tr>
<tr>
<td>Deep/ECDFS</td>
<td>1.5</td>
<td>4.5</td>
<td>4 (98)</td>
<td>1960</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Deep/ELAIS-N1</td>
<td>1.5</td>
<td>3.5</td>
<td>4 (39)</td>
<td>1131</td>
<td>A</td>
<td></td>
</tr>
</tbody>
</table>

### 4 Survey Strategy

The VLASS science goals drive a survey structured in roughly equal-time tiers that cover a range of depths and areas. We call the tiers All-Sky (100 µJy, 33885 deg²), Wide+Galactic (50 µJy, 10000+3160 deg²), and Deep (1.5 µJy, 10 deg²). A detailed discussion of the survey implementation is presented in § 6.

The overall VLASS request is for ~9000 hours of VLA time. The detailed scheduleing (below, and in § 6.3) come to a total of 8915 hours. See Table 3 for a summary of the tiers.

**Sensitivity Assumptions:** The sensitivity of the Jansky VLA for mosaicking is computed using the procedure given in the Guide to VLA Observing: Mosaicking². For continuum (Stokes I) at S-band (2–4 GHz) we assume a Survey Speed (SS) of

\[ SS = 16.55 \left( \frac{\sigma_I}{100 \, \mu Jy/beam} \right)^2 \, \text{deg}^2 \, \text{hr}^{-1} \]  

(1)

of on-sky integration time for an assumed image rms of \( \sigma_I \). This assumes 1500 MHz of useable bandwidth (after RFI excision) and an image averaged over the band using multi-frequency synthesis. The integration time needed to survey a given area to a depth is given by dividing that area by the survey speed.

²https://science.nrao.edu/facilities/vla/docs/manuals/obsguide/modes/mosaicking
**Overhead Assumptions:** In the estimates for total observing time, allowance is made for the overhead for slewing, setup, and calibration that will apply to a given component of the survey. We assume that:

<table>
<thead>
<tr>
<th>Assumed Overheads for VLASS by Component</th>
<th>Component</th>
<th>Overhead</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Deep/COSMOS, Deep/ECDFS</td>
<td>25%</td>
<td>5–7 hour blocks, contained calibration</td>
</tr>
<tr>
<td></td>
<td>Deep/E-N1, Galactic</td>
<td>22%</td>
<td>6–8 hour blocks, contained calibration</td>
</tr>
<tr>
<td></td>
<td>All-Sky, Wide</td>
<td>17%</td>
<td>long blocks, shared calibration</td>
</tr>
</tbody>
</table>

These numbers are adopted as guidance in the times given below. Note that the overheads actually used for scheduled hours for the Deep fields are close to these, but are rounded to make the schedules of a sensible length (e.g. rounded to nearest 15 minute duration).

For example, for All-Sky the estimated calibration overhead is 17% and thus the required integration time of 1443 hours is multiplied by the factor 1.17 to arrive at a “clock time” of 1857 hours needed to execute the All-Sky component. This in turn is rounded to 1860 hours to allow for distribution between the cycles in which this component is scheduled (§ 6.3).

In practice, the exact overhead will depend on exactly how the survey components are scheduled and how much calibration can be shared between blocks. The calculations used to arrive at the overheads are presented in the Technical Implementation Plan (TIP) document, and verification of these assumptions are included in the Test Plan described in § 6.8.

### 4.1 All-Sky

**Table 4:** Summary of All-Sky (Tier 1)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Area</td>
<td>33885 deg$^2$, $\delta &gt; -40^\circ$</td>
</tr>
<tr>
<td></td>
<td>23885 deg$^2$ exclusive of Wide</td>
</tr>
<tr>
<td>Cadence</td>
<td>single epoch, spread over 4 cycles</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>$2/'1$ (B/BnA configuration)</td>
</tr>
<tr>
<td>Continuum Image rms (Stokes I)</td>
<td>$\sigma_I \geq 100$ µJy/beam</td>
</tr>
<tr>
<td>Integration Time</td>
<td>1443 hr total (exclusive of Wide)</td>
</tr>
<tr>
<td>Observing Time (17% overhead)</td>
<td>1860 hr total (exclusive of Wide)</td>
</tr>
</tbody>
</table>

#### 4.1.1 Context

The age of survey astronomy is unfolding with the development of sensitive all-sky telescopes in the optical/IR (WISE, Pan-STARRS, PTF, etc.) and at high energies (Swift, Fermi, eROSITA). Ten years from now, LSST will begin constructing the definitive large, deep optical map of the universe. For the past 16 years, the NVSS provided the wider astronomy community with a reliable reference image of the GHz sky. Thanks to the EVLA project, the VLA is positioned to play a similar role in the next decade of astronomy.

We propose that the first tier of VLASS provide a high-resolution radio reference for the entire northern sky$^3$. The All-Sky tier will have an unprecedented combination of resolution and sensitivity with powerful spectral and polarimetric information.

$^3$“All-Sky” for our purposes means the declination range than can be reliably observed by the VLA. This includes the sky north of declination $-40^\circ$, which covers 33,885 deg$^2$, or 82% of the entire celestial sphere.
Figure 8: FWHM resolution required to achieve reliable cross-matches at fainter magnitudes using $r$-band galaxy counts. Two curves are shown for 90% and 95% reliable identifications, and the resolutions of VLASS, ASKAP-EMU and WODAN are shown. This confirms that the SKA pathfinders are at best marginally sufficient for identifications at SDSS/Pan-STARRS depths, while VLASS is usable all the way to $r = 25$.

The spatial resolution of this tier (and all tiers of VLASS) will give astronomers a unique ability to robustly identify radio counterparts to sources at other wavelengths. The synthesized beam will have a FWHM of $2'1$, $\sim 20$ times smaller than the NVSS and 5–7 times smaller the SKA pathfinder surveys EMU and WODAN. In Appendix C we provide a detailed analysis (i.e., the “S/N model of positional accuracy”) that demonstrates that one-third of the optical counterparts to SDSS depth will be false matches using the 95% confidence matching radius required for WODAN. The false counterparts will obviously be an even bigger problem for deeper optical surveys, such as the ongoing DES and HSC surveys and eventually for LSST (Figure 8). Thus, VLASS will be a unique radio resource for the entire astronomical community.

With a survey depth of 100 $\mu$Jy beam$^{-1}$, the All-Sky tier will be $\sim 3$ times more sensitive than the NVSS to sources with $\nu \sim -0.7$ radio spectral indices. In a sense, this makes the All-Sky tier an extension of the FIRST survey. However, by virtue of using $S$ band and its large fractional bandwidth (2–4 GHz), VLASS will produce more reliable images and a richer information for each radio source. Spectral indices and full-Stokes spectro-polarimetric properties will constrain the nature of the radio emission and effects of propagation.

4.1.2 Description

Area and Depth: The All-Sky component will cover $\approx 34,000$ deg$^2$ north of declination $-40^\circ$, which is 82% of the entire celestial sphere down to a 1$\sigma$ rms depth of 100 $\mu$Jy, thus covering the entire VLA-visible sky down to FIRST depth.
Angular Resolution: The All-Sky component will be conducted in B and BnA-array, providing a uniform 2'1 synthesized beam over the entire sky. Such high resolution is necessary for accurate positional matching with existing and forthcoming optical/NIR imaging surveys. This is also a factor at least 5 times finer than what is being delivered by similar all-sky surveys by other SKA pathfinders.

Cadence of Multiple Epochs: The entire sky will be imaged once down to a depth of 100 µJy uniform over the survey area, providing a single high-resolution map and catalog. This all-sky map will provide a critical baseline for all future transient surveys and follow-up of multi-wavelength transient events (e.g., gravitational waves, LSST, etc.).

4.1.3 Survey Science

The All-Sky tier will have impact in many areas of astronomy. Here we highlight the key science enabled by this tier.

Community Science: A prime driver for this tier is to create a set of legacy products that can be used for a very broad range of science by the whole astronomical community. As the entire sky down to -30° declination has already been covered by the Pan-STARRS survey, we can guarantee that the whole VLASS will be utilized for science as soon as it is available, providing this decade’s enhanced version of the powerful FIRST+SDSS combination. The 1700 papers citing FIRST cover topics from galaxies to stars, studying individual sources and whole populations, searching for predicted signatures and finding them serendipitously. The VLASS All-Sky tier will become a top-level community resource for almost every area of astronomy.

Quasar Science: The primary demand that quasar science—at high redshifts in particular—places on a radio survey is for a wide area. Quasars are rare, and the radio-loud sources account for only ~5% of the population as a whole. To SDSS depth, the surface density of optically selected quasars is ~ 43 deg⁻² at 0 < z < 5 (Richards et al. 2006; Ross et al. 2013); of which only ~ 1.4 deg⁻² are at z > 3. Thus only one high-redshift (z > 6), radio-loud quasar is detected per ~ 7 deg² of survey area. Building a large statistical sample of radio sources for demographical studies of, for example, the evolution of radio loudness with redshift (Jiang et al., 2007) requires significant sky coverage.

High-resolution is also important for understanding of radio-loud quasars. The typical spectral index for a radio quasar is \( \alpha \sim -0.5 \). Although this is relatively flat, it still argues for lower frequencies in order to achieve higher sensitivity for a given flux limit. In addition, there are hints that compact, steep-spectrum radio emission may be more prevalent at high redshifts (e.g., Frey et al., 2011). Such sources will be easily detected by planned low frequency (< 1 GHz) surveys with excellent sensitivity; however, these surveys will invariably have poor resolution. Efficient matching of radio sources to surveys at other wavelengths (particularly in the optical) requires ~arcsecond resolution. In this way, a higher frequency VLA survey can provide an essential complement to the low frequency surveys, providing localization of radio sources at a much greater depth than FIRST. This is prerequisite to identifying candidates for spectroscopic campaigns to obtain redshifts, either in the optical/near-IR, or with ALMA.

Polarization Science The All-Sky tier provides the first arcsecond-resolution, all-sky survey of polarization at any frequency. By observing at higher frequencies and high spatial resolution, depolarization effects will be dramatically reduced compared to all previous surveys. The uniquely large fractional bandwidth gives sensitivity to larger Faraday depths (>10⁵ rad m⁻²) and extended.

---

4We will examine the possibility of dividing All-Sky into two epochs to increase VLASS transient science. We will do this if OTF tests for fast slew rates show feasibility, and robust testing assures no degradation of final image quality, polarization, or spectral results from short multiple epoch imaging.
structures in Faraday depth space. This opens the possibility of discovering entirely new populations of polarized sources (e.g., in very turbulent environments: inner regions of jets, starbursts, etc.). The combination of VLASS with the POSSUM/WODAN surveys will create a powerful lever arm to study magnetic fields in Faraday-complex sources, the Galaxy, and potentially the intergalactic medium.

**Time Domain Science:** From the point of view of the dynamic radio sky, the VLASS All-Sky tier will provide a unique snapshot of the Universe some 20 years after the FIRST survey. With its depth, area, and angular resolution, these observations will provide a new launching point for future surveys as well as the targeted follow-up of events triggered by a new suite of multi-wavelength (radio, infrared, optical, X-ray and $\gamma$-ray) and multi-messenger (cosmic ray, gravity-wave) facilities.

<table>
<thead>
<tr>
<th>Table 5: Summary of Wide (Tier 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>Total Area</td>
</tr>
<tr>
<td>Cadence</td>
</tr>
<tr>
<td>Angular Resolution</td>
</tr>
<tr>
<td>Continuum Image rms (Stokes I)</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Integration Time</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Scheduled Time (17% overhead)</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

### 4.2 Wide

#### 4.2.1 Context

Where the All-Sky tier is driven by inclusivity, the Wide tier is driven by matching radio survey depth to ongoing large-area optical surveys. Multi-wavelength photometry and spectroscopic surveys tend to be concentrated in the SDSS/DESI area. Deeper radio data in this region will thus make an unique and immediate impact. This region includes overlap with the deep photometric surveys from LSST, the Dark Energy Survey (DES) and Hyper-Suprime Cam (HSC), with depths of $i=26.8$, 25.3, and 25.9, respectively—an order of magnitude deeper than Pan-STARR5.

In these regions, the high resolution afforded by VLA is particularly critical. At the limits of the DES, HSC, and LSST surveys there are 5, 8, and 14 galaxies in an ASKAP beam. More sensitive observations expected from EMU/Wodan will also be compromised by association ambiguity, resulting in a high probability of misidentifications (see Appendix C). By using B configuration at S-band, VLASS will find $\lesssim 1$ galaxy counterpart per beam, which aids identification without resolving out extended radio sources.

The Wide tier will cover roughly a third of the sky to a depth of 50 $\mu$Jy. This allows the detection of a statistically significant number of objects in source populations that are moderately fainter than the FIRST detection limit. This improved sensitivity, in combination with the high-resolution polarization measurements, contemporaneous spectral indices, and higher frequency data, will provide a legacy dataset with maximal public utility.
Figure 9: Left: Radio luminosity vs. redshift. The dashed line indicates a division between radio-loud and radio-quiet quasars according to the radio luminosity (e.g., Goldschmidt et al., 1999). Radio upper limits are shown by arrows (offset downward slightly from the actual limits and sparse sampled for clarity). The depth of VLASS Wide tier (as indicated by the red line) allows us to push the redshift limit of radio-loud completeness from \( z = 2.7 \) to \( z > 4 \). Right: Radio loudness (as measured by the ratio of radio to optical flux) vs. i-band magnitude. The dashed line shows the traditional division between radio-loud and radio-quiet quasars of \( \log(R)=1 \). Upper limits are given as arrows (offset downwards slightly and for clarity). The solid red line shows the improvement that results from VLASS Wide tier. Not only will we be complete to radio-loud quasars to \( i = 19.9 \), combining with the deep optical data will allow us to study the most radio-loud objects to \( i \sim 24 \) over a significant fraction (\( \sim 30\% \)) of the sky.

4.2.2 Description

Area and Depth: The Wide component will cover \( \approx 10,000 \text{ deg}^2 \) down to a 1\( \sigma \) rms depth of 50 \( \mu \)Jy, covering the bulk of the 14,000 deg\(^2\) area being targeted by the Dark Energy Spectroscopic Instrument (DESI), which will obtain optical spectra for tens of millions of galaxies and quasars, constructing a 3-dimensional map spanning the nearby universe to 10 billion light years.

Angular Resolution: Like All-Sky, Wide will be conducted in B-array, providing a uniform 2\( \prime \) beam synthesized beam over the entire field. This resolution is necessary to provide accurate positional matching with existing and forthcoming optical/NIR imaging surveys.

Cadence of Multiple Epochs: Wide will be carried out in 4 epochs, each reaching a 1\( \sigma \) rms of 100 \( \mu \)Jy to enable the transient science described above.

Choice of fields: By focusing on the area of sky with the best spectroscopic coverage, we will maximize the return of these VLA data. The logical footprint for the Wide tier is thus the DESI area, that has already been heavily covered by SDSS-I/II/III spectroscopy (2.2M spectra in all, including 440k quasars, 1.47M galaxies, and 260k stars) and will be covered in the near (and not quite so near) future by SDSS-IV, HSC, and DESI itself. This will allow HSC (and DESI) spectroscopic targeting based on VLASS. The bulk of this area is in the North Galactic Cap, but includes a significant region towards the South Galactic Cap where the extremely high spectral density (and multi-wavelength coverage) of SDSS Stripe 82 is particularly attractive (representing about 3\% of the Wide tier coverage). Figure 10 shows the approximate area that we propose to cover with Wide.
4.2.3 Survey Science

All of the extragalactic science enabled by the All-Sky tier will be strengthened by the Wide tier, but this tier also allows a host of new investigations. The Wide tier will capitalize on the investigations done with the FIRST survey by concentrating on the same area, but probing to fainter flux limits.

Star forming galaxies: Current surveys fail to provide a large sample of low-z galaxies with well-established polarizations over a wide range in starburst luminosities. The Wide tier will detect (unresolved at 5σ) luminous star forming galaxies (i.e., Luminous Infrared Galaxies; LIRGs) out to $z \sim 0.15$ (LIRGs) and rarer ultra-luminous infrared galaxies (ULIRGs) out to $z \sim 0.5$. By surveying a representative volume of the low-redshift universe, this tier will provide a good baseline sample of relatively nearby objects with which to compare the higher-redshift objects probed by the Deep tier.

Time Domain Science: The Wide component will be carried out in four distinct epochs, each spanning around 4 months with approximately 12 months in between. This will enable the discovery of emerging long-duration events due to the afterglows from supernova explosions, binary neutron star mergers, and tidal disruption of material falling into supermassive black holes. The Wide survey area encompasses the best-studied large region of the northern sky, and thus at these depths, a transient event should easily be identified with and located within a known optical/infrared host galaxy, providing critical input for prompt identification of the most interesting events for follow-up.

Quasar Science: The FIRST survey detects barely 10% of SDSS quasars, requiring stacking analyses for the vast majority of sources. That is a real problem, as only about 10% of quasars are formally “radio-loud”, leaving us with a very biased view of the radio properties of quasars, as well as many unanswered questions. By extending VLASS depth to 50 μJy, that fraction would increase to ~20%, which would crucially allow the detection of radio-quiet (but not radio-silent!) quasars that FIRST generally does not probe. While VLASS will not be as sensitive as FIRST to extended sources, Ivezić et al. (2002) find that complex sources only account for 15% of the SDSS...
quasar sample. Moreover, Hodge et al. (2011) report on A-array observations (i.e., with better resolution than FIRST) to 3x the depth of FIRST in SDSS Stripe 82 and found that 97% of known SDSS quasars are recovered in the higher resolution data. According to White et al. (2007, Figure 3), Wide should provide a 5 \( \sigma \) detection for up to \( \sim 20\% \) of SDSS quasars.

**Table 6: Summary of Galactic (Tier 2)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Area</strong></td>
<td>3160 deg(^2)</td>
</tr>
<tr>
<td></td>
<td>(560 deg(^2) in Galactic bulge, (-10^\circ &lt; \ell &lt; 10^\circ,</td>
</tr>
<tr>
<td></td>
<td>2600 deg(^2) in Galactic plane, (-20^\circ &lt; \ell &lt; -10^\circ) and</td>
</tr>
<tr>
<td><strong>Cadence</strong></td>
<td>4 epochs, separated by at least 12 months</td>
</tr>
<tr>
<td><strong>Angular Resolution</strong></td>
<td>0.76 (A configuration)</td>
</tr>
<tr>
<td><strong>Continuum Image rms (Stokes I)</strong></td>
<td>(\sigma_I = 50 \mu Jy/beam) combined (with All-Sky)</td>
</tr>
<tr>
<td></td>
<td>(\sigma_I = 114 \mu Jy/beam) per-epoch (exclusive of All-Sky)</td>
</tr>
<tr>
<td><strong>Integration Time</strong></td>
<td>917 hr total in region</td>
</tr>
<tr>
<td></td>
<td>688 hr in addition to All-Sky,</td>
</tr>
<tr>
<td></td>
<td>172 hr additional per epoch</td>
</tr>
<tr>
<td><strong>Scheduled Time</strong></td>
<td>840 hr (in addition to All-Sky)</td>
</tr>
<tr>
<td>(22&amp; overhead)</td>
<td>210 hr additional per epoch</td>
</tr>
</tbody>
</table>

### 4.3 Galactic

#### 4.3.1 Context

In recent years, IR surveys of the Galaxy have dramatically improved in resolution and sensitivity, which has improved our understanding of the life cycle of stars and gas in the Milky Way. Surveys have been made with *Spitzer* (GLIMPSE; Benjamin et al., 2003; Churchwell et al., 2009) and (MIPS-GAL; Carey et al., 2009), *Herschel* (Hi-GAL; Molinari et al., 2010), and ground-based facilities (Lucas et al., 2008, UKIDSS). An effort to complement that in the radio domain is the CORNISH survey, a 5 GHz counterpart to GLIMPSE. CORNISH sampled a longitude range of 10 to 60 degrees and \( \pm 1^\circ \) in latitude at arcsecond resolution (Hoare et al., 2012). CORNISH demonstrated yet it had a fairly restricted survey area, and omitted both the Galactic bulge and center, two unique regions for understanding the interplay between the stellar and interstellar medium. Recently, a follow up survey to CORNISH, GLOSTAR (VLA/14A-420; PI. Menten), has begun observing the Galactic plane with the new wideband C-band receiver using multiple configurations and targeting a latitude range of \( \pm 1^\circ \) in the Galactic plane. Expanding to \( \pm 5^\circ \) in Galactic latitude enables a reach to more nearby star-forming regions. As Figure 6 demonstrates, the distribution of detected planetary nebulae occurs throughout this latitude region. The Galactic area was expanded to include a large section of the Bulge, where the older stellar population can provide a rich yield of pulsars, especially the unusual ones which are important for probes of extreme physics.

VLASS is an opportunity to systematically survey the entire Galactic plane and bulge regions in a way that complements existing IR surveys. The time investment is incremental, as it builds on the All-Sky tier. It also allows high-resolution images be made in the most confused part of the sky by observing in A configuration.
4.3.2 Description

Area: The Galactic component will cover 3160 deg$^2$ defined by a longitude range of $-20$ to $260$ degrees, and a latitude range of $+/-5$ degrees (this latitude range will provide exceptional coverage of sources in the Galactic plane, overlapping with many infrared surveys of this region and provide significantly more survey area than many radio surveys of the Galactic plane). In addition, our Galactic component includes a special extension in latitude to include the “Bulge region,” a region defined to be between longitudes of $5^\circ$–$10^\circ$ and $-5^\circ$ to $-10^\circ$, additional latitude coverage up to $\pm14^\circ$ (a corner goes below declinations of $-40^\circ$ and will be out of reach).

Resolution and Need for A-array: In order to carry out the optimum Galactic science described below, sub-arcsecond A-array resolution is critical. Most major Galactic surveys at other wavelengths (X-ray, optical, infrared, far-infrared and millimeter) have spatial resolutions of $\sim1''$, and so for source identification and classification, the addition of A-array observations will make VLASS-Galactic component much more useful by astronomers across the electromagnetic spectrum. In turn, this will allow VLASS to have much higher legacy value among all astronomers interested in Galactic science.

Requested Sensitivity: The requested final sensitivity in the region described above is 50 $\mu$Jy, which includes A-array data that will be added to the B-array coverage of the Galactic plane and bulge included in the All-Sky mapping (the B-array alone will get to an rms of $\sim100$ $\mu$Jy).

Multiple Epochs: At a final depth of 50 $\mu$Jy, we can easily get at least 4 epochs, based on the imposed data rate limitation for OTF of 25 MB/s. Factoring in the true usable bandwidth and the elevation dependent $T_{sys}$, it is likely that we will obtain at least 6 epochs on the bulge. Multiple epochs will be very important for transient science (many of the above sources, in particular the stellar sources and stellar systems) in the Galaxy.

4.3.3 Survey Science

Discovering Unusual Pulsars: Galactic pulsars can be identified via their steady continuum emission. This can be used to target systems for traditional, deep time-domain searches for pulsations. This hybrid imaging/periodicity search method is sensitive to systems that are hard to find in traditional searches, such as compact neutron star binaries, highly scattered millisecond pulsars, and pulsars with spin periods less than a millisecond (should they exist). Identifying candidate pulsars requires a high spatial resolution of the Galactic plane at relatively low frequency.

Use planetary nebulae to map Galactic structure: Radio emission from planetary nebulae can trace Galactic structure out at large distances, since they are bright and techniques have been established to measure their distances well. Nearly all known PNe within a few kpc are detected in NVSS. Given that, we expect to detect all PNe in the catalog of Zijlstra et al. (1989) out to 30 kpc for a conservative (20$\sigma$) detection limit of 0.1 mJy. New detections will require follow-up observations in recombination lines to measure distances.

Thermal and Non-thermal radio emission from YSOs: The increased sensitivity of the VLA, combined with the large area coverage of the Galactic Plane tier, will be able to increase the numbers of radio-detected objects, perhaps up to a factor of 4 (see Ortiz-Leon et al., 2013, for early EVLA results). Temporal variability is an important factor affecting the radio emission, and motivates multiple epochs for detections. High spatial resolution observations of young stellar objects are needed for classification, and a large in-band frequency coverage constrains the spectral index to determine thermal or nonthermal emission. The fraction of objects detected in previous pointed centimeter wavelength observations varies with mass and evolutionary phase, but is low, 10-50% (see discussion in Osten & Wolk, 2009).
### Table 7: Summary of Deep (Tier 3)

<table>
<thead>
<tr>
<th>Field</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
</table>
| COSMOS  | Total Area                                      | 2 deg², centered at 10°00'28'', +02°12'21"
|         | Cadence                                        | 4 epochs of 4 month duration spaced by 12 months (approx.) 10 passes per epoch |
|         | Total Tier 3 Integration Time                   | 234 hr                                                                |
|         | Scheduled Time (25% Overhead)                   | 300 hr                                                                |
|         | Per Epoch                                      | 75 hr total (7.5 hr per pass)                                         |
|         | Previous data                                  | 302 hr of Archival observations (12B-158)                            |
|         | Continuum Image rms (Stokes I)                  | $\sigma_I = 1.5 \mu Jy/beam$ combined (w/ previous) $\sigma_I = 4.5 \mu Jy/beam$ per new epoch $\sigma_I = 10 \mu Jy/beam$ per new pass |
| ECDFS   | Total Area                                      | 4.5 deg², centered at 03°32'28'', -27°48'30"
|         | Cadence                                        | 4 epochs of 4 month duration spaced by 12 months (approx.) 92 passes per epoch |
|         | Total Tier 3 Integration Time                   | 1570 hr                                                               |
|         | Scheduled Time (25% Overhead)                   | 1960 hr                                                               |
|         | Per Epoch                                      | 490 hr total (5 hr per pass)                                          |
|         | Continuum Image rms (Stokes I)                  | $\sigma_I = 1.5 \mu Jy/beam$ combined $\sigma_I = 3 \mu Jy/beam$ per epoch $\sigma_I = 30 \mu Jy/beam$ per pass |
| ELAIS-N1| Total Area                                      | 3.5 deg², centered at 16°08'44'', +56°26'30"
|         | Cadence                                        | 4 epochs of 4 month duration spaced by 12 months (approx.) 39 passes per epoch |
|         | Total Tier 3 Integration Time                   | 937 hr                                                                |
|         | Scheduled Time (22% Overhead)                   | 1131 hr                                                               |
|         | Per Epoch                                      | 282.75 hr total (7.25 hr per pass)                                    |
|         | Continuum Image rms (Stokes I)                  | $\sigma_I = 1.5 \mu Jy/beam$ combined $\sigma_I = 3 \mu Jy/beam$ per epoch $\sigma_I = 19 \mu Jy/beam$ per pass |

### 4.4 Deep

#### 4.4.1 Context

There are three main reasons why VLASS contains a deep tier:

1. A deep tier allows objects of similar luminosity to those in the complementary, shallower but wider tiers to be observed at much greater distances and larger look-back times. This provides an essential lever arm to disentangle the effects of differing luminosity from the effects of cosmic evolution of the source population being studied.

2. The Deep tier will be observed with a higher cadence than the Wide and All-Sky tiers, allowing studies of variability and transient phenomena on shorter timescales than possible in a wide survey. A deep survey also enables the study of entirely distinct transient populations than those detected in a wide survey, while additionally allowing transient populations detected in both deep and wide surveys to be studied at a range of flux density levels to investigate their evolution.
Figure 11: The VLASS-Deep selection function (5σ) for unresolved star-forming galaxies in units of limiting star formation rate. For comparison, we over plot the selection function (dotted line) of the GOODS-Herschel 100 μm (5σ) data, which are some of the deepest Herschel far-infrared extragalactic survey data ever taken, covering a total of ≈320 arcmin$^2$ in GOODS-N+S (i.e., more than 100× less area than VLASS-Deep; Elbaz et al., 2011; Magnelli et al., 2013). One beyond $z \sim 2$, the VLASS data are actually more sensitive to star-forming galaxies than the ultra-deep Herschel imaging. We additionally show the selection function (dashed line) for Herschel/SPIRE 250 μm (5σ) data, as these data are available for the full VLASS-Deep 10 deg$^2$.

3. The Deep tier provides a reference “truth” image for the Wide and All-Sky tiers where they overlap, allowing accurate assessment of completeness and reliability.

To date, the combined area of all extragalactic deep fields at $\lesssim 2 \mu$Jy at S-band (or equivalent) constitutes <3 deg$^2$. Given that star formation is environmentally dependent, any investigation on the evolution of star-forming galaxies requires that we be able to probe them over the full range of cosmic environments (e.g., from rich clusters to voids). And, by having multiple fields covering such large areas, such survey will be able to overcome/test any remaining cosmic variance effects. As already shown above, we have chosen 10 deg$^2$ as the full survey area of Deep as this is the only way to both reduce the Poisson uncertainty for deriving statistically meaningful luminosity functions for star-forming galaxies (see Figures 3), as well as to reduce sample variance due to large-scale structure (see Figure 4), which is critical for developing our understanding of the link between star formation, galaxy mass and environment.

4.4.2 Description

Area and depth The Deep component of VLASS will cover 10 deg$^2$ to an rms depth of 1.5 μJy in three well-separated fields to help mitigate against cosmic variance effects. At a depth of 1.5 μJy we will be sensitive to L$^*$ galaxies out to $z \sim 2$ (e.g., Gruppioni et al., 2013, see Figure 11).
Figure 12: Multi-wavelength coverage maps of ECDFS (left) and EN1 (right), showing the wealth of degree-scale imaging over each field.

At this depth, VLASS-Deep is as sensitive to obscured star formation as the deepest Herschel survey data taken (i.e., GOODS-Herschel; Elbaz et al., 2011; Magnelli et al., 2013), but will cover more than $100 \times$ the area with $10 \times$ better angular resolution. Furthermore, a $7.5 \mu Jy/\text{bm}$ ($5\sigma$ detection threshold) corresponds to a star-formation rate of $\sim50$ solar masses per year at $z = 1.5$. Given that the luminosity function for star-forming galaxies is relatively steep, the increase in source density is significant when compared to the current VLA survey over the COSMOS field. e.g. in the redshift slice $z = 1.4 - 1.5$, there are $\sim250$ vs $\sim450$ star-forming galaxies per deg$^2$ for 2.5 $\mu Jy$ rms vs 1.5 $\mu Jy$ rms, respectively.

Angular Resolution Sub-arcsecond resolution (A-array in S-band) is needed in order to both make reliable identifications of faint star-forming galaxies, and measure the sizes star-forming galaxy disks to enable weak-lensing science, as well as for a comparison with optical sizes. We note that in addition to robustly-weighted maps, we will take advantage of the centrally-dense A-array to investigate completeness issues, by making $uv$-tapered versions of our maps that should improve the brightness temperature sensitivity by a factor of $\approx3$.

Cadence of multiple epochs Deep will have $\approx4$ epochs, each reaching an rms of $\sim3 \mu Jy$.

Choice of fields Our field selection includes 4.5 deg$^2$ in the Extended Chandra Deep Field South (ECDFS), 3.5 deg$^2$ in the ELAIS-N1 (EN1) field and 2 deg$^2$ in the COSMOS field. The chosen footprints for ECDFS and EN1 are largely based on the available deep NIR/VIDEO and warm Spitzer/SERVS data (see Figure 12). In Table 8, we provide a detailed list of the available ancillary data for our largest field, ECDFS; however, all three fields have medium-deep multi-wavelength data in X-ray through infrared bands, with typical 5$\sigma$ depths of $r_{AB} \sim 25$ and $K_{AB} \sim 23$ in the optical/near-IR, mid-infrared depths of $S_{4.5} \approx 2\mu Jy$ and $S_{24} \approx 300\mu Jy$, and Herschel SPIRE data to $S_{250} \approx 30\mu Jy$. Much of multi-wavelength COSMOS data (imaging/cutouts, catalogs, etc.) is already readily available from IPAC/IRSA$^5$. In addition, COSMOS has an existing S-band VLA survey to 2 $\mu Jy$, which will be augmented with VLASS-Deep imaging. EN1 has 0.1deg$^2$ to 1$\mu Jy$ sensitivity in C-band, and 1.1deg$^2$ to 7$\mu Jy$ at 610MHz, allowing us to obtain spectral indices for some fraction of the survey objects. While we prioritized southern fields due to visibility to ALMA, along with having slightly better optical/NIR data, our second southern field choice, XMM-LSS,

$^5$http://irsa.ipac.caltech.edu/Missions/cosmos.html
Table 8: Current/Scheduled 1–10 deg\(^2\) Multi-Wavelength Coverage of the W-CDF-S

<table>
<thead>
<tr>
<th>Band</th>
<th>Survey Name and Solid-Angle Coverage</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio</td>
<td>Australia Telescope Large Area Survey (ATLAS; 3.7 deg(^2))(^a)</td>
<td>15 (\mu)Jy rms depth at 1.4 GHz</td>
</tr>
<tr>
<td></td>
<td>MIGHTEE Survey (Scheduled; 4.5 deg(^2))(^b)</td>
<td>1 (\mu)Jy rms depth at 1.4 GHz</td>
</tr>
<tr>
<td>FIR</td>
<td>Herschel Multi-tiered Extragal. Survey (HerMES; 0.6–11 deg(^2))(^c)</td>
<td>5–60 (\mu)Jy depth at 100–500 (\mu)m</td>
</tr>
<tr>
<td>MIR</td>
<td>Spitzer Wide-area InfraRed Extragal. Survey (SWIRE; 6.6 deg(^2))(^d)</td>
<td>3.6–160 (\mu)m</td>
</tr>
<tr>
<td>NIR</td>
<td>Spitzer Extragal. Representative Volume Survey (SERVS; 4.5 deg(^2))(^e)</td>
<td>2 (\mu)Jy depth at 3.6 and 4.5 (\mu)m</td>
</tr>
<tr>
<td></td>
<td>VISTA Deep Extragal. Observations Survey (VIDEO; 4.5 deg(^2))(^f)</td>
<td>(ZYHK_s) to (m_{AB}) \approx 23.5–25.7</td>
</tr>
<tr>
<td>Optical</td>
<td>Dark Energy Survey (DES; 9 deg(^2) in 3 W-CDF-S fields)(^g)</td>
<td>Multi-epoch griz; (m_{AB}) \approx 28 co-added</td>
</tr>
<tr>
<td>Photometry</td>
<td>Pan-STARRS1 Medium-Deep Survey (PS1MD; 7 deg(^2))(^h)</td>
<td>Multi-epoch grizy; (m_{AB}) \approx 26 co-added</td>
</tr>
<tr>
<td></td>
<td>VST Optical Imaging of CDF-S and ESI (VOICE; 4.5 deg(^2))(^i)</td>
<td>Multi-epoch ugriz; (m_{AB}) \approx 26 co-added</td>
</tr>
<tr>
<td></td>
<td>SWIRE optical imaging (6.6 deg(^2))(^j)</td>
<td>ugriz; (20,000) visits total</td>
</tr>
<tr>
<td></td>
<td>LSST deep-drilling field (Planned; 10 deg(^2))</td>
<td>(ugrizy)</td>
</tr>
<tr>
<td>Optical/NIR</td>
<td>Carnegie-Spitzer-IMACS Survey (CSI; 6 deg(^2))(^k)</td>
<td>(40,000) redshifts, 3.6 (\mu)m selected</td>
</tr>
<tr>
<td>Spectroscopy</td>
<td>PIRSm Multi-object Survey (PRIMUS; 1.95 deg(^2))(^l)</td>
<td>(20,800) redshifts to (m_{AB}) \approx 23.5</td>
</tr>
<tr>
<td></td>
<td>VLT MOONS Survey (Scheduled; 4.5 deg(^2))(^m)</td>
<td>(80,000) redshifts</td>
</tr>
<tr>
<td>UV</td>
<td>GALEX Deep Imaging Survey (7 deg(^2))(^o)</td>
<td>(Depth) (m_{AB}) \approx 25</td>
</tr>
</tbody>
</table>


appears to be impractical due to RFI issues as it sits in the Clark satellite belt. We note though, having a northern field both helps with practical scheduling constraints, and will deliver a better behaved beam.

4.4.3 Survey Science

Star-forming galaxies: While the Wide tier will detect luminous star forming galaxies out to \(z \sim 0.15\) (LIRGs) or \(\sim 0.5\) (ULIRGs), we need the Deep tier to find them at \(0.5 < z < 4\) to study the evolution of the radio properties. The proposed deep fields have Herschel data that is sensitive to ULIRGs at \(z \sim 2\), but which is of low spatial resolution, making unambiguous identifications difficult. Radio data with good angular resolution is required as the bridge to cross-identify the Herschel sources with the deep near-infrared data in these fields (from Spitzer and VISTA surveys). The primary beam of ALMA is too small to make it an efficient survey instrument, so the VLA is needed. The deep component of VLASS will allow us to ask key questions about the evolution of the luminous starburst population as a function of redshift and environment, in particular magnetic field evolution (through both polarization studies and a careful comparison of the far-infrared-radio correlation for objects of equivalent luminosity).

Clustering and large-scale structure at high redshifts: The clustering properties of luminous star forming galaxies and radio-quiet/intermediate AGN can give valuable information on the masses of their underlying dark haloes. Making accurate measurements of the two-point correlation function, and conducting halo occupation distribution analyses, provides information on the underlying dark matter distribution in these regimes. To sufficiently constrain the two-halo clustering signal at large scales, where one moves from the non-linear to linear regime, requires structures to be fully sampled on \(> 2 - 3\) Mpc scales in angular space. Consequently, the \(\sim 50 - 60\) Mpc dimensions required to sample these large scales equates to a linear dimension of the survey of
Weak lensing: The two crucial observational parameters that determine the quality of weak lensing measurements are the survey depth and angular resolution. An angular resolution \( \theta \text{res} < 1'' \) is required in order to facilitate the accurate measurement of typical galaxy shapes at redshifts \( z \sim 1 \). The choice of A-array at S-band (\( \theta \text{res} = 0.65'' \)) is therefore well suited for weak lensing. In terms of survey area, a simple optimization procedure designed to maximize the signal-to-noise of the weak lensing measurement yields an optimal survey area of order \( \sim 10 \text{deg}^2 \). Thus the array configuration and survey area envisaged for the Deep component is extremely well suited for weak lensing science.

AGN and implications for galaxy formation: Radio jets are probably the key to understanding feedback processes in galaxy formation. Although strong “quasar mode” feedback is easy to find in the form of winds and powerful jets powered by the most luminous AGN, the duty cycle of such activity is so small (\( \sim 10^{-2} \) even in massive objects at the epoch of peak of quasar activity). Jets and winds of relatively low kinetic luminosity are probably responsible for providing the bulk of AGN feedback outside of quasar outbursts in a “maintenance mode”, whose characteristics are currently poorly understood. Measuring the AGN radio luminosity function down to the lowest AGN luminosities, where it merges with the radio luminosity function of starbursts is therefore essential. While the Wide tier will allow us to obtain a good baseline at low redshifts, the Deep component is needed to push out to \( z \sim 1 - 2 \), where feedback needs to be most active to prevent galaxy growth.

Quasar science: Although SDSS-III/BOSS targeted FIRST sources nearly 3 magnitudes deeper in the optical than the main SDSS survey, a paltry 4% of BOSS quasars appear in the FIRST catalog (Páris et al., 2014). Clearly, a next-generation survey is needed to explore the radio properties of these large quasar samples. While All-Sky and Wide will more than double the number of SDSS quasars detected in the radio (not just radio loud), only with the Deep tier will we detect the vast majority of radio-quiet quasars in the radio. Not only will Deep provide truth tables that will inform what limitations the Wide tier has, but achieving this greater depth is important to determining whether this (quiet) radio flux is intrinsic to the AGN or is due to star formation (e.g., Kimball et al., 2011b; Condon et al., 2013b; Zakamska & Greene, 2014). As with the fluxes, spectral indices in the Deep tier will act as truth tables for the Wide and All-Sky tiers. At the rms of Deep, we can hope to measure relatively accurate spectral indices for quasars as faint as 52 \( \mu \text{Jy} \), which generally represents a radio-quiet quasar. At the limit of the good spectral indices for Wide, the error on the Deep spectral indices will have statistical errors as small as \( \Delta \alpha \pm 0.003 \). The Deep tier will provide a small area where we are complete to SDSS quasars at all redshifts and to the depth of the imaging data. The Deep fields have also been targeted as part of a spectroscopic survey of luminous mid-infrared selected AGN (Lacy et al., 2013), so radio luminosities of dust reddened AGN and quasars will also be obtained to compare to the normal quasar population.

Time Domain Science: The Deep Tier fields will be observed in 40–392 passes in each of four A-configuration cycles spread throughout the 5-year span of the survey, sampling the transient and variable radio sky in these areas with cadences from days to years. This in turn will enable the measurements of the variability of the AGN population on these timescales, probing both intrinsic and propagation induced dynamic phenomena. The Deep data stream will also open up the deep radio sky for the discovery and characterization of intermediate and long duration transients from lower luminosity events or at greater distances than in the Wide tier in fields that are and will continue to be well-studied throughout the wavelength spectrum.
5 Data Products

The VLASS data products are described below. Products are broken into classes of “Basic” and “Enhanced,”. The Basic Data Products for VLASS are those that will be produced by NRAO using standard (or soon to be standard) data processing systems, or modest extensions thereof. NRAO will assume responsibility of producing and providing the basic products and will carry out the necessary quality assurance. The BDP have been defined to be a set of products from which the community can derive the science outlined in this proposal, requiring modest post-processing on the user’s part. Enhanced Data Products require extra resources or involve specialized domain expertise, so they will be left for community members to define and produce. These would clearly enhance the utility of the survey and enable further science, but are beyond the anticipated resources of NRAO to carry out.

5.1 Basic Data Products

The Basic Data Products (BDP) of VLASS consist of

1. raw visibility data;
2. calibration data and process to generate calibration products (current best version as well as past released versions maintained in Archive);
3. quick-look continuum images;
4. single-epoch images;
5. single-epoch basic object catalogs;
6. cumulative VLASS images; and
7. cumulative VLASS catalog.

The resources for processing, curating, and serving will be provided by NRAO (§5.3). Teams led by NRAO, but including external community members where possible, will carry out the activities required for the processing and Quality Assurance (QA) of the products. Table 9 summarizes the components of each data product and the time scale for their production. Specific details of individual BDP are described below.

**Raw Visibility Data** The raw visibility data for VLASS will be stored in the standard VLA archive. These data will be available immediately after observation with no proprietary period. As VLASS is being observed using standard data rates (25 MBps maximum averaged over the project) there are no special resources required for the storage and distribution of these data.

**Calibrated Data** VLASS data will be processed using a modified version of the normal CASA-based calibration pipeline. By the time of the VLASS observations, the VLA pipeline will have the requisite functionality to process VLASS data (full polarization, many individual target fields generated in OTF mode). The VLA pipeline is currently run on most VLA observations and is well tested. VLASS will use a version specifically tested on VLASS pilot observations.

Once the pipeline has run and after QA assessment, users will gain access to the calibrated data from the Archive. Archiving the calibrated visibility data themselves would double the required data volume, which is too costly. Instead, VLASS will archive calibration products and maintain scripts to generate the calibrated dataset. Scripts to apply calibration products will be based on CASA. Upon first processing of a Scheduling Block, the calibrated data will be available for a short time for transfer to subsequent processing teams.
Table 9: VLASS Basic Data Products

<table>
<thead>
<tr>
<th>Data Product</th>
<th>Components</th>
<th>Production Time Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Visibility Data</td>
<td>standard VLA data</td>
<td>Immediate</td>
</tr>
<tr>
<td>Calibrated Data</td>
<td>Final Calibration Tables, Pipeline Control Script, Flagging Commands, QA Reports &amp; Plots, Calibration Sky Models</td>
<td>1 Week after Observation</td>
</tr>
<tr>
<td>Quick-Look Images</td>
<td>Stokes IV Images, Stokes IV Noise Images</td>
<td>48 hr</td>
</tr>
<tr>
<td>Single-Epoch Images</td>
<td>Stokes IQUV images: Calibrated beam-corrected and rms noise, Spectral Index and uncertainty images for Stokes I (generated using Multi-Frequency Synthesis)</td>
<td>2 mon. for Tiers 1 &amp; 2</td>
</tr>
<tr>
<td></td>
<td>Position, and uncertainty (centroid of Stokes I emission), Peak Brightness in Stokes IQUV and uncertainty, Flux Density in Stokes IQUV and uncertainty, Spectral Index at Peak Brightness (Stokes I) and uncertainty, Integrated Spectral Index (Stokes I) and uncertainty</td>
<td>6 mon. for Tier 3</td>
</tr>
<tr>
<td>Single-Epoch Basic Object Catalog</td>
<td>Calibrated beam-corrected Stokes IQUV images, rms noise images for the Stokes IQUV images, Spectral Index and uncertainty images for Stokes I</td>
<td>Within 6 mon. for Tiers 1 &amp; 2</td>
</tr>
<tr>
<td></td>
<td>Position, and uncertainty (centroid of Stokes I emission), Peak Brightness in Stokes IQUV and uncertainty, Flux Density in Stokes IQUV and uncertainty, Spectral Index at Peak Brightness (Stokes I) and uncertainty, Integrated Spectral Index (Stokes I) and uncertainty</td>
<td>Within 1 yr for Tier 3</td>
</tr>
<tr>
<td>VLASS Images</td>
<td>Calibrated beam-corrected Stokes IQUV images, rms noise images for the Stokes IQUV images, Spectral Index and uncertainty images for Stokes I</td>
<td>With Single-Epoch Images</td>
</tr>
<tr>
<td>VLASS Catalog</td>
<td>Position, and uncertainty (centroid of Stokes I emission), Peak Brightness in Stokes IQUV and uncertainty, Flux Density in Stokes IQUV and uncertainty, Spectral Index at Peak Brightness (Stokes I) and uncertainty, Integrated Spectral Index (Stokes I) and uncertainty</td>
<td>With VLASS Images</td>
</tr>
</tbody>
</table>

**Quick-Look Images** The identification of transient and variable objects is a key VLASS science goal. The Transient Working Group has set the requirement to generate images within 48 hr of data acquisition, with a goal of 24 hr. The Quick-Look Stokes I and V images will be constructed through mosaicking, and there will also be a corresponding rms sensitivity (noise) image.

**Single-Epoch Images** These fully calibrated and quality-assured images below will be produced using a specialized CASA-based Imaging Pipeline and served from the Archive. This pipeline will be developed by the NRAO staff, with the involvement and guidance of active community members.

**Single-Epoch Basic Object Catalogs** Results from previous analyses (e.g., Huynh et al. 2012) and tests on the VLASS images will be used to determine the optimal means to identify sources within the VLASS images. The software (or software packages) that produce the optimal results will be used to produce a Basic Object Catalog from the VLASS images.

**VLASS Images** These images will be produced in a similar manner as for the Single-Epoch Images, but using all epochs, and would serve to be the final set of VLASS images. Sufficiently strong variable sources will be taken into account during the imaging.

**VLASS Catalog** These would be produced in a manner similar to the Single-Epoch Basic Object Catalog but would serve to be the complete catalog for VLASS.
5.2 Enhanced Data Products

The Enhanced Data Products (EDP) are those that require additional resource and/or more domain expertise, and so will be defined and produced by the VLASS community outside the NRAO. These data products will require external support to define, produce, and validate. However, these products are seen as essential to the VLASS science case, so both BDP and EDP (where practical) will be curated and served by the NRAO. Enhanced Data Services (EDS, §5.3) will be required for curation and distribution of EDP beyond the capabilities of NRAO to support.

Some examples of EDP include (but are not restricted to):

1. Transient Object Catalogs and Alerts
2. Rotation Measure Images and Catalogs
3. Improved Object Catalogs
4. Light curves (intensity and polarization) for objects and/or image cutouts
5. Catalogs of multi-wavelength associations to VLASS sources

Beyond requiring extensive domain expertise, these areas are also ideal for nucleating multi-wavelength community groups and resources to work with and enhance VLASS.

A special case is the support for commensal observing at P-band (230–470 MHz) using the VLITE system. There is no NRAO processing or archive support currently budgeted for VLITE data products, and thus use of VLITE with VLASS should be considered as a EDP (and EDS) provided in partnership with NRL.

Other areas for EDP will undoubtedly become apparent. Once the survey is approved, we will take proposals for new EDP to be included in the list above. Criteria for including EDP in the VLASS archive will be relevance to the VLASS science case and cost of curating and serving the products. As an incentive to include EDP in the VLASS archive, we ask that the NRAO encourage authors that use EDP to acknowledge groups that produced them.

5.3 Enhanced Data Services and the VLASS Archive

A comprehensive survey like VLASS will produce a diverse set of data products and will require a full-featured archive to serve it to the public. A baseline plan is to serve products from a website hosted by the NRAO. This site will feature basic search capabilities of catalogs and products, as has been done for FIRST\(^6\) and NVSS\(^7\). Previous VLA surveys only provided catalogs and images, so at a minimum VLASS will extend that search capability to visibility data, calibration products, and deep/multi-epoch images. The NRAO will also provide data analysis scripts to apply calibration to raw data.

However, astronomy is increasingly a multi-wavelength discipline with a diverse set of tools for comparing observations from different observatories. If the VLASS archive exists only as a stand-alone NRAO-hosted service, it would not be as useful as one integrated with the tools available at places like IPAC\(^8\) or the Virtual Observatory \(^9\).

We are investigating options for having catalogs and/or images served by organizations outside the NRAO. This would extending the reach of VLASS outside the radio community and open access to powerful tools for multi-wavelength analysis. The VLASS community, including the co-authors of the VLASS proposal, will be writing an NSF proposal to support VLASS data analysis.

\(^6\)http://sundog.stsci.edu/cgi-bin/searchfirst
\(^7\)http://www.cv.nrao.edu/nvss/postage.shtml
\(^8\)http://www.ipac.caltech.edu
\(^9\)http://www.us-vo.org
and a more effective archive. These Enhanced Data Services will greatly augments the utility of
VLASS and its basic and enhanced data products to the wider astronomical community.

Another area that would be greatly improved through EDS is the capability for “processing on-
demand” (POD) of images or image cubes. [GTR: Amy asks if this includes forced photometry?] This would alleviate storage volume concerns, and enable more flexible angular and spectral res-
olution of the resulting products. We expect to utilize the NSF XSEDE network for modest use of
POD-like processing for the pipeline. Fully enabled POD for VLASS could be carried out through
partnerships with NSF supercomputing centers or with DOE science labs. Exploration of these
options will commence upon approval by NRAO for VLASS.

As noted above, data archive and distribution support for commensal observing at P-band
(230–470MHz) using the VLITE system is not currently budgeted for support by NRAO. Archive
serving of VLASS should be considered as a EDS provided in partnership with NRL.

6 Implementation Plan

Here we present an overview of the implementation plan and observing logistics. Details of the
observations and observing plan are given in the VLASS Technical Implementation Plan (TIP)
document. The TIP will be reviewed internally by NRAO as a Conceptual Design Review prior to
the VLASS Science Review. The CoDR report will be provided to the science reviewers.

6.1 Mosaic Observing Patterns

In order to carry out VLASS, we will need to observe the sky using a large number of mosaicked
pointings of the VLA. At 2–4 GHz, the VLA has a field-of-view given by the primary beam re-
sponse of the 25-meter diameter antennas. This approximately follows a Gaussian response, with
a full-width at half-maximum (FWHM) given by

\[ \theta_{\text{FWHM}} \approx 45' \left( \frac{1\text{GHz}}{\nu} \right) \]  

at observing frequency \( \nu \), and thus over the S-band the FWHM varies from 22.5' at 2 GHz to
11.25' at 4 GHz, with FWHM of 15' at 3 GHz mid-band. In order to optimally cover a given
sky area in an efficient manner, the array must either conduct a raster scan using “on-the-fly”
mosaicking (OTFM), or tile the area with a number of discrete pointings in a hexagonal packed
configuration (“Hex-pattern Mosaicking”). The choice between these techniques is determined by
the extent to which the extra overhead (from 3 to 7 seconds) needed to move the array and settle at
each pointing in the discrete hex-pattern mosaic becomes a burden on the observations, and thus
OTFM is favored.

The techniques of OTFM and Hex-pattern Mosaicking and the calculations and procedures
needed to set these up are described in the Guide to VLA Observing: Mosaicking section. The
salient features are

OTFM: There is very little move-and-settle overhead as the array is in continuous motion
over a row of a raster with only a small startup (~10–15 sec) at the start of a row. In OTFM
the phase center of the array is discretely stepped on timescales of a few seconds or longer, so
no phase smearing of the images results. However, because the primary beam response pattern
is moving with respect to the sky, there are errors introduced in the amplitudes by the moving
beam in a single visibility integration time. Short correlator “dump” times are required, ideally
10% or less of the time it takes to cross the FWHM of the primary beam (0.5 seconds or less for
Tiers 1 and 2). This in turn increases data rates from those otherwise required. The secondary
cost of OTFM occurs in the imaging process, where the effects of the moving primary beam over
the time at which the phase center is fixed must be compensated for by the imaging algorithm at significantly increased computational cost over that required for a similar observation taken with a fixed pointing center. This is currently done by the CASA software package in its clean deconvolution task. This has been used successfully in the S-band Stripe82 program of 13B-370 (PI: Gregg Hallinan), and has produced images of comparable quality to those using a traditional hex-mosaic (see below). However, OTFM has not yet been demonstrated for polarimetry. More detailed testing of the efficacy and efficiency of the use of the CASA imaging for OTFM is part of the testing plan given below. For the purposes of this plan, we will assume that OTFM datasets can be imaged with sufficient accuracy to be practical for the depths (and dynamic ranges) required for the Tier 1 and 2 observations, including polarimetry.

Hex-pattern Mosaicking: It takes the VLA 3–7 s (depending on the direction of motion in azimuth-elevation coordinates, usually around 6–7 s if not optimized) to move and settle between nearby pointings. In order to keep the overhead from this motion to be 25% or less, one needs to spend at least 28 s integrating on each pointing. For a hex-pattern, each field gets 67% of the total integration time desired on-sky, so observations where the VLA Exposure Calculator\(^\text{10}\) indicates an on-source time of 42 seconds or less will incur significant overhead if not done with OTFM. For VLA S-band, the calculated exposure time is 7.7 seconds at a rms image sensitivity of 100 µJy/beam, and thus observations desiring a depth shallower than around 43 µJy/beam in a single pass will prefer OTFM. Thus, our Tier 1 and 2 observations with single-pass depths > 100 µJy will require OTFM, which the deep Tier 3 observations (single-pass depth < 34 µJy/beam) can be carried out with straightforward Hex-pattern Mosaicking. Note that it is in principle possible to arrange the order in which the fields are observed to make the motions to be predominantly in the elevation axis which damps the telescope settling, and has been shown to lose only 3–4 seconds. However, this optimization is dependent on the local time at which the observations are made requiring restricted LST scheduling blocks, and is difficult to arrange over large areas of the sky. We will try where possible to use this optimization to further reduce overheads in the Tier 3 mosaics.

6.2 Scheduling Considerations

The Jansky VLA is normally operated using a “Dynamic Scheduling Queue” where the individual Scheduling Blocks (SBs) are created in the VLA Observing Preparation Tool (OPT) to be able to be executed in a prescribed range of LST, and submitted to the VLA Scheduler software (OST) to be queued up for observation by the array in a manner dictated by weather and priority. It is our intent that the Tier 3, along with some of the Galactic Plane Tier 2) observations, where possible for each pass, be observable using standard Dynamic Scheduling. This requires that these blocks contain sufficient calibration to stand alone or be boot-strapped from other VLASS SBs executed nearby in time.

For Tier 1 and most of Tier 2, it would be advantageous to construct the schedules in large blocks to be observed at specific LST start times. This would allow maximum efficiency in calibration and control of slewing (e.g., telescope wraps). In practice, due to considerations such as the ability to allow interrupts for target-of-opportunity observations, and fault tolerance (e.g., for power outages, weather, etc.), the schedule will need to be broken in to modestly sized blocks. The most straightforward plan is to make sets of SBs for submission (see below) and submit only a day ahead.

VLASS will ultimately consist of many SBs that will be submitted through the OPT for execution. It will be impractical to use the VLA OPT in standard interactive mode to construct the thousands of hours of schedules for thousands of pointings that must be in the Source Catalog Tool. Instead, we will create some lightweight software in Python to construct the ascii lists that

\(^{10}\)https://science.nrao.edu/facilities/vla/docs/manuals/propvla/determining/source
the OPT and SCT can read. This feature has been used by the 13B-370 Stripe-82 observers (mainly Caltech graduate student Kunal Mooley) with success to schedule those observations. Our plan is to use and modify as needed the Python code developed for that project. These scripts and code would be made available to the community for their own use for similar surveys.

To carry out the day to day scheduling and monitoring of VLASS, we propose an “Astronomer on Duty” (AoD) who will keep track of what SBs are ready to observe, make sure they are submitted, make sure that they run, and make any modification necessary (e.g., due to TOO or weather interrupts). This duty would be rotated and would be the point of contact with the NRAO Data Analysts who would be handling the general logistics of scheduling, data transfer, and pipeline processing.

**Target-of-Opportunity Interrupts:** For the long-block observations in Tiers 1 and 2 (and some of Tier 3), provision will be made for the possibility that observations will be interrupted for time critical TOO programs (e.g., for triggered transient observations). There is currently no mechanical provision in the way schedules are constructed or executed for the suspension and restarting of schedule blocks. Therefore, the most straightforward implementation is to break all schedules into blocks of 2–3 hours in length, and to allow TOO interrupts to simply stop the execution of the current schedule and possibly pre-empt the execution of the following one or more SBs. After TOO observations are complete, the VLASS schedule would resume with the next appropriate block. The AoD would be informed of this interruption, and would examine the archive record to determine the missing observations and construct a “make-up” SB to be run at the first appropriate opportunity. The plan for the construction of schedules (see below) will take this need into account.

### 6.3 Overall Observing Schedule

VLASS as proposed requires just under 9000 hours of scheduled observing, which we propose will be carried out over the course of 4 cycles of VLA in its A and B configurations, spanning a total of 5 years (64 months). The cycles start with an additional A-configuration tacked onto the beginning of semester 2015B (which would normally transition to D from the A configuration of 2015A). We assume the array follows the current standard cycle order of B followed by A. We also assume that each configuration is the current 4-month duration, but note that accommodating VLASS could involve extending some of the durations in the more loaded sessions.

In this scenario VLASS is a 5-year survey with a scheduled total of 8963 hours of observing spanning parts of 5 cycles spanning a total of 64 months or more (if we keep to 4 months per cycle minimum):

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Config</th>
<th>All-Sky</th>
<th>Wide</th>
<th>Galactic</th>
<th>COSMOS</th>
<th>ECDFS</th>
<th>ELAIS-N1</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B</td>
<td>465</td>
<td>706</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1171.0</td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>0</td>
<td>0</td>
<td>222</td>
<td>75</td>
<td>490</td>
<td>282.75</td>
<td>1069.75</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>465</td>
<td>706</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1171.0</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>0</td>
<td>0</td>
<td>222</td>
<td>75</td>
<td>490</td>
<td>282.75</td>
<td>1069.75</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
<td>465</td>
<td>706</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1171.0</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>0</td>
<td>0</td>
<td>222</td>
<td>75</td>
<td>490</td>
<td>282.75</td>
<td>1069.75</td>
</tr>
<tr>
<td>4</td>
<td>B</td>
<td>465</td>
<td>706</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1171.0</td>
</tr>
<tr>
<td>4</td>
<td>A</td>
<td>0</td>
<td>0</td>
<td>222</td>
<td>75</td>
<td>490</td>
<td>282.75</td>
<td>1069.75</td>
</tr>
<tr>
<td>Tot</td>
<td>1860</td>
<td>2832</td>
<td>888</td>
<td>300</td>
<td>1960</td>
<td>1131</td>
<td>8963.0</td>
<td></td>
</tr>
</tbody>
</table>

Note: The All-Sky allocation is placed into the relevant B configuration, but we plan to observed the southernmost regions of the survey in the BnA hybrid to form a more circular synthesized beam comparable to that for higher declinations.
This starts in May 2016 and follows the standard cycle schedule (BADC), completing at the end of 2020 (or early 2021). We assume that each configuration is the current 4-month duration, but note that accommodating VLASS could involve extending some of the durations in the more loaded sessions. The B-configuration All-Sky (excluding the Wide area) has a single epoch per field with the fields distributed in four cycles.

6.4 Calibration

The goal of the VLASS Calibration process is to determine, on the basis of a priori factors and from observations of standard calibration sources, the corrections to the raw data amplitude, phase, and visibility weights to be applied to the data. This process also determines the flags that are needed to remove bad data due to instrumental faults, RFI, and other causes of error. When applied to the VLASS data, this calibration will allow the production of images in the next processing stage. This process only includes the derivation of the complex gain and bandpass calibration factors known through previous measurements or determined by the observations of calibrators and transferred to the VLASS target observations. The self-calibration of VLASS data is included in the Imaging stage of processing.

VLASS data will be processed using a modified version of the normal CASA-based VLA calibration pipeline. By the time of the VLASS observations, the VLA pipeline will have the requisite functionality to process VLASS data (full polarization, many individual target fields generated in OTF mode). The VLA pipeline is currently run on most VLA observations and is well tested. VLASS will use a version specifically tested on VLASS pilot observations.

As mentioned earlier when discussing Data Products, it is more efficient to store the calibration tables, flags, and pipeline commands and the create the calibrated dataset upon request from the archive, rather than to store both raw and calibrated datasets. Should it be deemed appropriate and possible, we might consider also archiving off-site the full calibrated dataset (e.g., through Enhanced Data Services by a community partner).

6.5 Imaging

VLASS is at its heart a wide-band continuum imaging survey. The science goals of the survey are predicated on the ability of the instrument and data processing to deliver images of sufficient quality to be able to identify objects and measure the salient properties (e.g., flux density, position, spectral index, polarization, light curve). In order to keep up with the observing, the VLASS Imaging Pipeline must be able to process and image the data at a rate commensurate with the observing rate. This will be effected through the parallel image processing of sub-mosaics on NRAO-based clusters or externally provided systems (e.g., through XSEDE).

There are three imaging processes that need to be handled by the pipeline:

- Quick Look (QL) imaging triggered after every scheduling block is observed (e.g., for transient identification)
- per-epoch imaging triggered after the last observation each configuration
- cumulative imaging triggered after each epoch beyond the first, incorporating all previous data

For each of these, there are three kinds of images that may be produced:

- Wide-band (2–4GHz) continuum images
- Full-resolution (2MHz channels) image cubes
Coarse-resolution (128MHz spectral windows or similar) image cubes

Imaging is done in all Stokes parameters (IQUV) for polarimetry capability.

Continuum imaging can include higher-order Taylor terms in the spectral dimension (e.g., spectral index, spectral curvature) depending on image depth (e.g., for processing beyond the Quick Look). CASA has Multi-Frequency Synthesis (MFS) algorithms for this that have been used in past programs, and further development of these capabilities is underway. Full-polarimetric imaging is a key part of VLASS, and the use of accurate polarized “primary beam” maps of the VLA field-of-view during imaging and analysis are critical to the production of science ready images. Self-calibration (through the use of previous sky models as well as true self-calibration from iterative imaging) is also an integral part of the image processing.

We assume for all image size calculations that in the ideal case the images will be pixellated at a sampling level 0.4 of the (robust weighted) resolution at the highest frequency of the band (4 GHz), rounded to a convenient value. For A-configuration, this is 0.2″ (resolution 0.49″ at 4GHz), giving 324Mpix per square degree. For B-configuration, this is 0.6″ (resolution 1.58″ at 4GHz), or 36Mpix per square degree. In practice we will refine this based on imaging performance and we may be able to get by with less oversampling. In addition, individual sub-images will likely need some amount of extra padding to accomodate odd shapes. Overall we should treat these estimates as reasonably conservative, uncertain at the around the 25% level. However, this optimal level of resolution leads to large image archive sizes (see §6.7) and thus a key issue for testing is the determination of the lowest acceptable resolution in the images and image cubes that will still enable the key science with the Basic Data Products. It may be possible to reduce the image data volumes by significant factors (2–8) in this manner. In addition, image compression algorithms (lossless and lossy) can also improve storage efficiency and will be investigated in the Test and Development Program.

The image cubes are needed as input to more advanced processing for Rotation Measure determination, spectral line surveys, and more detailed SED modeling of sources. Most of these would be provided as Enhanced Data Products and Services. Note that the storage and distribution of the large full-resolution cubes will be a challenge for the archive (see §6.7), and options for external hosting and “on-demand” image processing should be explored (e.g., as an Enhanced Data Service). As a fallback we would carry out compression through a combination of reduced angular resolution (e.g., 0.3″, Nyquist at 3GHz) and spectral resolution (average 8 channels, 32MHz).

6.6 Image Analysis and Sky Catalogs

The main image analysis task for VLASS is the production of the basic object catalogs for the Quick-Look and standard images.

A good study of the performance of radio continuum image source finders is Hancock et al. (2012MNRAS.422.1812H), which considers the available options in the context of ASKAP. The upshot is that there are options available that should have acceptable performance for the basic catalogs for VLASS. Note that inclusion of the spectral index images and polarimetric images from VLASS will likely require some extensions to these source finders, which in turn will require some developer or astronomer time.

Also available as a proof of concept is the source finding carried out for the VLA Stripe-82 surveys by Mooley et al. (2014, in preparation). There is also a comprehensive discussion in Mooley et al. (2013) in the analysis of archival VLA ECDFS multi-epoch data. It is our current assessment that one or more of these methods will be suitable for the basic catalogs from VLASS.

More advanced catalogs and source finding algorithms could be developed and produced as an Enhanced Data Product.
6.7 Archiving and Data Distribution

The primary interface that the user community will have to VLASS is through the archive and data distribution system. Raw data will be served via the normal VLA archive, available with no proprietary period as soon as it has been ingested into the archive system.

The archive, or at least some archive, will have to also serve the VLASS data products as described above. It is the responsibility of NRAO and VLASS to make the Basic Data Products available through this archive mechanism. Enhanced Data Products may or may not be made available through the NRAO-hosted VLASS archive, this will need to be negotiated and is largely dependent upon resources required. The VLASS products, either in basic form or further processes, may also be made available via alternative Enhanced Data Services.

The estimated data volumes required for storage of the VLASS data and data products, and resources need to support these, are given in the Technical Implementation Plan.

6.8 Test and Development Plan

There are a number of issues related to VLASS that must be addressed before the survey can be observed on the telescope. As part of the TIP, we propose a VLASS Test & Development Program leading up to and through the survey start, for example through small test observations or through larger pilot observations, or through analysis of archival data from previously observed projects such as Stripe-82 13B-370. These will require significant astronomer resources to carry out, and thus we are unable to fully prosecute this program before submission of the VLASS proposal — approval for the observation of VLASS would be necessary before allocating the resources to carry out this test program. There would be a final critical technical design review before survey observations commence, and that point we will have dealt with the high and medium risk issues sufficiently to proceed.

For example, a key item is the development and testing of the pipelines for VLASS. These will be based on the general VLA pipelines that are now being deployed and used, tuned for VLASS specific cases. Testing on suitable projects (current and archival) will be an important aspect to pipeline test and development. Other key test elements include:

- Tests of RFI occurrence, RFI flagging efficacy, bandwidth losses to RFI in VLASS sky coverage area
- Tests of wide-band wide-field polarimetry
- Assessment of effects of source variability (intensity and polarization) on deeper static-sky imaging performance
- Tests of fast slew and correlator dump rates to enable multi-epoch All-Sky
- Tests of Imaging errors from OTF scanning (continuum intensity and polarimetry)
- Assessment of Imaging performance for deep mosaicked fields (continuum intensity and polarimetry) based on archival data
- Assessment and improvement of calibrator source lists for VLASS

Many of these are currently being carried out by VLA staff and resident observers as part of the normal development and science support, and by the user community in their research activities. However, new resources (additional staff, post-doc, or student time, computing, and telescope test time) will be required to fully implement this plan before the start of VLASS.

More details on the VLASS Test and Development Program are given in the Technical Implementation Plan.
7 Education and Public Outreach

The activities of communication, education and outreach cover a very large, and often overlapping, sets of activities, which, however, present interesting opportunities for dissemination. We discuss how VLASS science, results and data will be publicized and made available to interested persons. Wherever possible, we leverage off existing infrastructure and resources, adopting and adapting as necessary. The overall objective is to disseminate VLASS science, results and data to the widest audiences.

7.1 Audiences

We identify these unique audiences for VLASS, each with its own style of communication and interaction, and grouped into 4 categories:

7.1.1 Scientists

- experienced radio astronomers, experts at analyzing radio data
- novice radio astronomers, content experts but who many have little to no experience with retrieving and analyzing radio data
- Professional astronomers are primarily interested in how VLASS products can be used to further their research objectives.

For expert radio astronomers, access to the data and calibrated products is relatively easy, as is the analysis. For astronomers who are familiar with other methods of data acquisition (optical telescope spectra and images) or delivery methods (e.g., calibrated HST or Chandra data products) figuring out how to obtain, manipulate and understand and integrate unaccustomed data structures can be challenging. Thus, the first group is likely satisfied with access to a catalogued database. The second group would prefer to have calibrated data products in a form they can use with their familiar tools, for example a FITS image of the M87 Halo in 90 cm continuum halo (Image courtesy of NRAO/AUI and F.N. Owen, J.A. Eilek and N.E. Kassim). This group is keenly interested in timely updates - for example, the most recent data release. Methods of communication include email newsletters, the Astronomers Facebook Group, The American Astronomical Society, and similar venues.

7.1.2 Staffers, Managers

- NRAO directorate and upper management
- AUI officers and board of trustees
- Funding agency program officers
- Congressional staff

Members of this audience are probably most interested in receiving encapsulated information e.g., progress reports, press releases, summary of results.
7.1.3 Educators

- Teachers in accredited K-12 schools, 2 and 4 year colleges
- Informal science educators, e.g., after school programs, science centers, planetaria and so forth
- Disseminators of information, e.g., journalists, bloggers

This grouping has teachers who serve a variety of demographics, namely pre-college and undergraduate students in formal educational institutions, subject to curriculum requirements. Informal science educators serve students, but also include families as well as the general public. The needs for this group as a whole are easily accessible materials, with appropriate pedagogical backing.

7.1.4 General public

The broadest category which includes people of all ages, interest level and residency (US, international and so forth). The public is far from monolithic, with very wide range in age, education level, socioeconomic status and preferred means of obtaining information.

7.2 Social media and communication

Interest in science and astronomy among the general public has been on the rise and is at least partly facilitated by the ease of sharing information and engaging with scientists using social media. The Very Large Array Sky Survey can build on the existing audience and practices of NRAO social media and rely on the breadth of expertise and personalities working with the project.

Examples of active NRAO social media accounts (as of 7/9/2014):

- Facebook - https://www.facebook.com/TheNRAO - 40,041 likes
- Twitter - https://twitter.com/thennrao - 5186 followers

A sound social media project includes defining clear goals for the communications, picking which specific platforms to use, and ensuring regular posting and interaction with the community (Bohon et al. 2013). Though some of the work of VLASS can be worked into the existing framework of NRAO social media projects, work from VLASS’s many participants would be appreciated as well. This would particularly be true of the NRAO’s Facebook presence, which is by far its largest audience.

One model for additional participation is to have a weekly “host” of a twitter account that uses the week to communicate their particular aspect of the science being done with VLASS. Examples of such accounts already in use are @realscientists (https://twitter.com/realscientists), @WetheHumanities (https://twitter.com/WetheHumanities), and @astrotweeps (https://twitter.com/astrotweeps). Other collaboration members who are already active on social media can use a specific hashtag to join the conversation. To date, we have adopted the simple hashtag #VLASS.

Another outlet for VLASS news and communication would be in blog form so that long format stories can be told. Such a blog would be modeled after the CANDELS Blog (http://candels-collaboration.blogspot.com/). This site has two editors who ensure that new and relevant content is posted on a regular basis. These editors invite members of the collaboration to submit posts on their specific science, their role in the survey, biographical profiles, or explainer articles on
broad and basic scientific concepts. A blog hosted by Wordpress.com is free and is easy to use for collaborative projects. The URL vlass.org is also available (that is, has been privately reserved) for use for either this blog or for a broader public website if desired.

Although it is now considered an “old” form of web communication, emails lists are still a popular method of communication as it ties directly into the users daily email routine and does not require visiting an external app or site. Email lists can also be audience specific (as in separate lists for teachers, general public, and professional astronomer) and are opt-in by the user. At the very least, a periodic email list should be made available for professional astronomers interested in the status of the survey and its data products.

All of these methods of communication have little to no cost for the accounts but incur costs in the person-hours to develop content and communicate with the community.

### 7.3 Examples of Community Educational Outreach Activities

#### 7.3.1 Picture of the Week

Each epoch of VLASS data acquisition lasts approximately 8-12 weeks. Starting with the first week, VLASS should release a picture of an interesting object, along with explanatory material and a press release delivered through as many channels as possible to maximize exposure. The very first image could be simply a ‘pretty picture’ just to get started, though thereafter in addition to being good looking, the POTW should be of scientific interest, whether as a unique object or one that demonstrates a specific instrument capability. In this category are the “most”: distant, brightest, faintest, dusty, nearest, resolved etc. VLASS scientists pick the targets ahead of time, reduce the data and generate the ‘picture’. Someone expert in visualization will need to work with VLASS scientists on these pictures. This is very similar to the way HST among others, generate interest in its surveys (PHAT, Frontiers Fields) and attract attention.

#### 7.3.2 Citizen Science

Public participation in science has grown in the last few years with access to new technologies and data sharing techniques. Projects range in participant involvement from collection of data (e.g., variable star observations) to web-enabled classification and data analysis (e.g., Galaxy Zoo, CosmoQuest) to passive use of computing resources (e.g., SETI@home). With the exception of projects that just use computing resources with no human intervention, citizen science projects tied to large surveys such as VLASS are best suited for problems that need human interaction through simple tasks that cannot be handled automatically by a computer. Searching for transients that might be missed by traditional source finding techniques is one such application of a citizen science task.

Audiences: general public, with access to the internet. Can also tie into K-12 education with appropriate teacher materials.

#### 7.3.3 Science Stories

An ongoing VLASS blog, where VLASS personnel contribute individual entries, can generate and sustain interest in the survey. Individual stories could include descriptions (by the parties involved) of the deliberations undertaken to arrive at the final survey plan, life of an astronomer during the week of, and the like. New postings are advertised via social media apps, email, on the web page. Readers can post comments (moderated, of course).

Audiences: all
7.3.4 Education Activities

Here, the objective is to take advantage of existing resources at NRAO, its partner institutions (RIT, CalTech) and extant networks (e.g NightSky Network), to share VLASS science in ways that are compatible with the objectives of formal and informal educators. Partnerships with other national and international institutions with experience in this area (International Astronomical Union’s Office for Astronomy Development, Galileo Teacher Training Program) would be helpful as well. Audiences: K-12 and Higher Education

8 Summary

The proposed VLASS definition comprises a cohesive and aggressive science program that will benefit the entire astronomical community, deliver unique forefront scientific discovery, and keep its legacy value well into the SKA-era. The scientific legacy, impact, and efficiency of deep and all sky surveys are clearly established - from the Hubble Deep Fields to GALEX to NVSS/FIRST to Sloan and the next US optical/NIR ground-based priority LSST. The proposed VLASS finds its place within this tried and true tradition of modern astronomy. Analysis of the statistics from NVSS and FIRST (as with the Hubble Deep Fields) clearly indicate that the impact on PI science from these kinds of community surveys is positive, as might seem counterintuitive. This is true not only in terms of the extensive usage of these data by wide swatches of the community, resulting in startlingly high publication rates, but also due to the new inquiry driven PI science they enable, that could not otherwise have been conceived or survived the proposal process without the critical enabling data and demonstration science from the surveys. The proposed VLASS will continue the integration of radio astronomical data into the multi-wavelength astronomical community, putting the U.S. broad astronomical community in an optimum position to make substantial use of the SKA when it comes online.

References


—. 2013b, Astrophysical Journal, 768, 37


de Zotti, G., Massardi, M., Negrello, M., & Wall, J. 2010, Astronomy and Astrophysics Reviews, 18, 1


Farnsworth, D., Rudnick, L., & Brown, S. 2011, Astronomical Journal, 141, 191


Heckman, T. M., & Best, P. N. 2014, Annual Reviews of Astronomy and Astrophysics, 52, 589


—. 2011b, Astrophysical Journal Letters, 739, L29


Lovell, B. 1963, Nature, 198, 228


—. 2013b, Astrophysical Journal, 778, 18


Murphy, E. J. 2009, Astrophysical Journal, 706, 482


Peterson, J. R., & Fabian, A. C. 2006, Physics Reports, 427, 1
Silk, J. 2013, Astrophysical Journal, 772, 112


Urry, C. M., & Padovani, P. 1995, Publications of the ASP, 107, 803


Appendix

A Motivation and Process

In July 2013 NRAO announced that it would consider a new radio sky survey using the Karl G. Jansky Very Large Array (VLA), after several members of the community approached the NRAO Director suggesting that it was time to think about a follow-on from NVSS and FIRST. These two surveys were ground-breaking in their time, but in the twenty years since their execution both the capabilities now available on the VLA following the Expanded VLA (EVLA) Construction Project, and the wealth of surveys, extant and planned, at other wavelengths that require arcsecond localization of associated radio emission, make necessary the consideration of a new radio survey. In particular, the availability of On-The-Fly (OTF) mosaics and the wide fractional bandwidth of the VLA provide the fast mapping speed, increased continuum sensitivity, and instantaneous spectral index information that would simply not have been possible prior to the improvements provided by the EVLA.

Given the potential impact a large survey would have on the use of the telescope, both in terms of the large-scale survey science that is simply not possible through the regular peer-review process, and on the resulting reduction in the availability of time for regular PI science should a large survey proceed, the survey science and definition had to be proposed and reviewed by the community. A process was therefore defined that would result in a community-led recommendation being provided to the NRAO Director, with NRAO facilitating the process. The process included, from the start, open international participation in the development of a VLA Sky Survey (VLASS) Proposal, with the final deliverables being public data and data products. Should the Proposal pass its Community Review, NRAO would implement the survey, deliver basic data products, and support the community with higher-level data products as resources allow.

In preparation for a VLASS Science Planning Workshop held January 5, 2014 at the 223rd American Astronomical Society meeting in Washington, D.C., White Papers (WPs) were solicited from the community through the NRAO eNews, and a Scientific Organizing Committee (SOC) was convened to review the WPs and define the agenda of the Workshop. A total of 22 WPs were received, with contributions from 180 unique authors. It is interesting to note that of these authors, approximately 20% were not users of NRAO telescopes, and do not appear in the NRAO User Database (i.e., they have never been on a proposal to use an NRAO instrument, either as co-I or PI, nor have they registered in the User Database for any other reason). Therefore, the act of soliciting the WPs, in and of itself, already attracted interest from a broader community than the “traditional” radio astronomy community. The Workshop attracted ≈50 attendees, and comprised morning talks followed by afternoon discussion. Areas for debate became apparent, and some possible avenues for the survey began to be ruled out (such as a large-scale, high-frequency survey).

Following the Workshop, the SOC was responsible for defining the process by which the VLASS Proposal would be developed. In February 2014 the Survey Science Group (SSG) was formed comprising several working groups (WGs), open to the entire community, and advertised in multiple eNews articles. The WGs topics were:

- Galactic
- Extragalactic
- Transients and Variability
- Programmatics
- Communication/Education/Outreach
- Technical
Each working group was led by two co-chairs, with the co-chairs comprising the SSG Governing Council. The SSG Governing Council itself had two co-chairs (Stefi Baum and Eric Murphy). Contributions to the WG discussions were enabled through the NRAO Science Forum,\(^\text{11}\) with material also posted on the NRAO Public Wiki,\(^\text{12}\) along with other methods of group communication such as Google Groups, as defined by the co-chairs of the individual WGs. In this way, contributions to the discussion on these WGs was expanded well beyond the original authorship of the WPs.

The process by which the VLASS survey definition proceeded from this point is worth documenting, as it may serve to guide the development of future surveys. Initially, the three scientific WGs (Galactic, Extragalactic, and Transients/Variability) were asked by the SSG Council co-chairs to specify their “ideal” survey designs, supported by key science goals. A “virtual face-to-face” meeting was then used to assess areas of commonality between the elements of the proposed surveys (frequency band, array configuration) and to identify areas that needed further discussion (number of epochs, depth of each epoch, monolithic vs. tiered). At this stage, the focus of the Galactic working group on thermal science, and therefore on higher frequencies than the Extragalactic or Transient WGs and with much less baseline understanding of the nature of the Galactic sky at those frequencies, led to difficulties defining a coherent survey that would justify being part of VLASS rather than being proposed as a Large program through the regular NRAO proposal process. In all three cases, the “ideal” survey (for each WG) would have far exceeded the time. For example the Galactic WG wanted both high and low frequency, while transients wanted many more epochs than possible. Extragalactic ideally would like 5 tiers if decreasing area, but increasing depth (the areas being roughly categorized as All-sky, SDSS/FIRST/DESI footprint, DES+HSC footprint, SDSS Stripe 82, a few of the LSST deep drilling fields, and an Ultra-deep field) from the depth of FIRST down to \(\sim 0.5 \mu\text{Jy}\). With this lack of consensus, the SSG Council co-chairs proposed a baseline all-sky, S-band, B-config, survey of \(\sim 8500\) hours, with the WGs proposing tradeoffs in time/area coverage needed to achieve their key science goals. The VLASS Proposal is the outcome of this process, and represents contributions from more than 200 astronomers over a 9 month period from November 2013 through July 2014.

B Impact of VLASS Sky Survey on Overall EVLA Science: The High Impact of Surveys

The time committed to the proposed VLASS will reduce the time available for other VLA programs. However, we argue that the time spent on large VLA surveys has effects that increase the net science coming from the VLA:

1. VLA sky surveys have a science impact per observing hour that is demonstrably greater than the average VLA observing program. This is at least partly because surveys expand the usage of radio data beyond the usual radio astronomy community.

2. Once VLA sky survey products are available, many science projects that require pointed observations of a sample of objects (e.g., to measure spectral indices for a sample of quasars) can be carried out directly from the catalogs rather than requiring an observing proposal. That reduces the time requested for such observing proposals and so increases the time available for other projects.

3. The sky survey products themselves will become a key resource for radio astronomers in identifying targets and projects for followup proposals. That also leads to an increase in the science done by enabling projects that are not possible without the inputs from a sky survey.

\(^\text{11}\)https://science.nrao.edu/forums/viewforum.php?f=59
\(^\text{12}\)https://safe.nrao.edu/wiki/bin/view/VLA/VLASS
The existing VLA sky surveys, NVSS (Condon et al., 1998) and FIRST (Becker et al., 1995; White et al., 1997), provide powerful evidence that the telescope time dedicated to these surveys repays the investment many times over. Below we present some statistics on the usage of the FIRST survey data and on the impact of FIRST and NVSS as measured by publications and citations.

B.1 FIRST survey data usage

The FIRST image server\(^{13}\) provides JPEG or FITS cutouts extracted from the FIRST survey at user-specified positions. Here are some statistics about its usage:

- During the last 18 months the FIRST cutout server has delivered on average more than 7,500 image cutouts every day.
- Each image served is equivalent to a three-minute VLA observation (the exposure time required to reach the FIRST depth); thus, our image server issues the equivalent of a 3-minute VLA observation every 12 seconds.
- Every 10 days the FIRST cutout server distributes snapshots with a total exposure time equal to the entire 4000 hours invested in the FIRST survey.

By creating a legacy dataset that covers as much of the sky as possible, we can vastly expand the user community (and scientific productivity) of the VLA. This is the single most important reason to do an all-sky survey.

B.2 NVSS/FIRST publications & citations

Publications and citations are the best objective measures we have of scientific impact. While there are lots of caveats (e.g., papers in fashionable fields collect more citations), every other measure of productivity is even less objective and harder to evaluate. In this section we discuss the publication statistics for the FIRST and NVSS surveys. The results strongly support the value of these surveys both in absolute terms and in comparison to other VLA projects.

There are three basic papers that define the FIRST and NVSS survey data products:

- FIRST images: (Becker et al., 1995)
  - 1311 citations
- FIRST catalogs: (White et al., 1997)
  - 587 citations
  - 1722 citations combined with Becker et al.
- NVSS images & catalogs: (Condon et al., 1998)
  - 2675 citations

Combining the FIRST and NVSS papers, there are a total of 3550 citations (3132 refereed citations). These 3 papers are ranked #1, #2, and #11 in citations among all VLA publications.

These papers are highly cited not just among VLA publications, but among all astronomy papers. Of the most-cited papers published since 1995, the NVSS paper is #16 and the Becker et al. paper is #67. Other than WMAP papers, the only other “radio astronomy” papers to crack the top

\(^{13}\)http://third.ucllnl.org/cgi-bin/firstcutout
100 are #29 (Urry & Padovani, 1995, ‘Unified Schemes for Radio-Loud Active Galactic Nuclei’
) and #63 (Kalberla et al., 2005, “The Leiden/Argentine/Bonn (LAB) Survey of Galactic HI”
).

There are a few exceptions, but we can generally treat the list of citing papers as an indication
of the usage of VLA survey data. The 3522 papers in ADS that cite NVSS and/or FIRST (as of 2014
March 29) have a total of 9086 unique authors. There could be some double-counting here, since
some authors publish using more than one version of their name-initials; but even if we compare
only last names, there are still 6925 unique authors among these papers. There are 1876 unique
first authors on these papers, or 1666 unique first authors using unique last names only. So, if
anything, these citation numbers underestimate the usage of the survey data.

The NRAO database includes a total of ~ 6200 users (G. Hunt, private communication). That
includes almost everyone who has ever been on a radio proposal. It is clear that the community
using NVSS/FIRST data is considerably larger than the community of radio telescope users. By
every measure, the impact of FIRST plus NVSS is large compared to other VLA observations.
According to the NRAO publications database, there were 192 refereed VLA papers per year over
the decade 2000–2009. (We used those years because the VLA publication rate has dropped a little
since 2010.) For comparison, over that same period there were 262 refereed publications per year
that cited FIRST and/or NVSS. Thus, there is very strong evidence against the argument that the
science out of the VLA is negatively impacted when surveys displace regular proposals. Surveys
will enhance science at the VLA, just as they have at every other modern observatory. That is why
more and more time at all major observatories is being dedicated to large surveys.

B.3 Will VLASS have the same impact as FIRST & NVSS?

Both the publications and data usage provide extremely strong support for the proposition that
time invested in VLASS will be repaid many times over. The impact of NVSS and FIRST is demon-
strably much greater than the impact of the displaced VLA science proposals. Moreover, after a
few years the time invested in the survey pays for itself by freeing up observing time that would
otherwise have been spent on survey-like observations of samples of objects or of small sky ar-
 eas. And the survey data multiplies the value of other VLA observations by providing ancillary
data at a different epoch, frequency, and resolution that can be used in conjunction with new ob-
servations. Many current VLA proposals begin with samples that are derived from the existing
surveys. From every point of view, the investment of time in VLASS increases the overall scientific
productivity of the VLA.

Some have argued that FIRST and NVSS were unique, and that a new VLA sky survey will
not have the same impact because it will not have the unique and long-lasting legacy value in the
face of the oncoming SKA pathfinders (and the SKA itself). We see two strong counter-argument
to this view. First, the resolution of the VLASS is an essential difference that puts VLASS in a class
by itself (§C). WODAN and ASKAP-EMU will surely spawn some great science on radio source
properties. However, astronomers attempting to identify radio sources with even moderately
deep observations at visible or infrared wavelengths will use VLASS.

Secondly, we have a clear counter-example to the argument that the survey must be “abso-
lutely unique” compared to any existing or planned future survey. Consider the NVSS and FIRST
themselves: They were carried out at the same time, with the same telescope and receivers. They
observed at the same frequency. The sky covered by FIRST was also completely covered by NVSS.
FIRST is only about 2.5 times deeper than NVSS for point sources, and the sensitivity difference is
even less for extended sources. And yet both FIRST and NVSS have thrived, and both have had a
demonstrably large impact on radio and multi-wavelength science. How can that be?

The answer is that the higher resolution of FIRST (with a beam 8 times smaller than NVSS)
is essential in doing cross-matches to SDSS and other deep imaging observations. Science with
NVSS depends on its larger sky coverage and good sensitivity to large-scale emission that come
from a low-resolution survey. Even though these surveys were carried out and released essen-
tially simultaneously, and even though they had many characteristics in common, it took only one difference — resolution — to distinguish them and make them both widely used to this day.

While we agree that it is important to consider VLASS in the context of current planned surveys and not to duplicate those surveys, we definitely do not agree that it is necessary to push to the extreme limits of the VLA parameter space (e.g., very high frequencies and the highest possible spatial resolution) in order to distinguish it from coming low-frequency, low-resolution surveys by the SKA pathfinders. NVSS and FIRST have had a huge impact on astronomy, and they have succeeded in vastly expanding the community of users of radio data. VLASS will surely have a comparable impact.

C The “S/N model” of Positional Accuracy

A long-standing notion has been that as the signal-to-noise ratio (S/N) increases, much better positional accuracy is obtained, so that high angular resolution is not needed for reliable identifications at visible or near-infrared wavelengths. The prediction of what we will call the “S/N model” is that as the flux density increases, the positional error will decrease as $1/S/N$, allowing the optical counterpart to be matched. Specifically, the NVSS catalog description (Condon et al., 1998) gives this formula for the noise in RA or Dec for point sources:

$$\sigma_{1D} = \theta / (S/N \sqrt{2 \ln 2}) .$$

(3)

Here $\theta$ is the resolution FWHM (45\arcsec for NVSS) and $S/N$ is the signal-to-noise ratio. Note that this noise equation already has been increased by an empirical factor of $\sqrt{2}$ compared with the theoretical equation “to adjust the errors into agreement with the more accurate FIRST positions” (quoting the NVSS catalog description14). This predicts $\sigma_{1D} \sim 7.6''$ at the catalog detection limit ($S/N = 5$) and $\sigma_{1D} \sim 1''$ at a flux density of 18 mJy/beam.

The positional scatter in Equation (3) is a 1-dimensional uncertainty, giving the error in either RA or Dec. In a 2-D distribution, many values will scatter outside the 1σ circle. The 90% confidence separation limit $\sigma_{90}$, which is typically more appropriate for catalog matching, is a constant factor $\sqrt{2 \ln 10}$ times larger than $\sigma_{1D}$:

$$\sigma_{90} = \frac{\theta}{S/N} \sqrt{\ln 10 \over \ln 2} .$$

(4)

With that increase it is necessary for the NVSS flux density to exceed 40 mJy/beam ($S/N = 85$) to reduce the predicted separation error to 1''.

The above positional accuracy applies to perfect point sources (and perfect data). But how well does it work for real data? We assess the accuracy of the S/N model using a comparison of the FIRST and NVSS data. The NVSS resolution is 45'' FWHM. The FIRST resolution is 5.4'' FWHM. As a large-scale test, we selected a sample of all the FIRST sources that have an SDSS match within 0.7'' and that have an NVSS match within 100''. We restricted the sample to sources with FIRST peak flux densities greater than the 2.5 mJy NVSS detection limit. For all these ~ 95,000 sources, we computed the distance to the nearest NVSS source. The important thing about this sample is that the FIRST source matches the optical source position. That means that if NVSS is to identify the same counterpart, it needs to have a position close to the FIRST source position. There may be several FIRST source components associated with a single NVSS source, but only the FIRST sources that match optical counterparts are included.

How do the positional errors of the S/N model compare with reality? To test this, Figure 13 shows the distance between the NVSS and FIRST positions as a function of the NVSS flux density. The positional differences do tend to decrease as the flux densities increase. The blue line shows

14http://www.cv.nrao.edu/nvss/catalog.ps

59
Figure 13: Position difference between NVSS and FIRST positions as a function of NVSS flux density. The sample includes only objects that have a close SDSS counterpart to the FIRST source position (within 0.7″).

- **Blue line:** Theoretical 90% confidence separation limit computed using the S/N model.
- **Red histograms:** (from bottom to top) the 50, 90, 95, and 99% confidence limits, computed by determining the actual separations in each bin. While the 50% curve behaves approximately as expected, the tail of the distribution is clearly non-Gaussian and has many more distant outliers than expected based on the 90% prediction.

The 90% confidence separation limit $\sigma_{90}$ from Equation (4), simply assuming that all objects are point sources with the median NVSS rms value. The red histogram shows the empirical 50, 90, 95, and 99% confidence separation limits as a function of flux density, computed by determining the relevant percentile of the actual separations in each bin. The computed separation has been corrected for the effects of chance nearby NVSS associations. The actual 90% confidence radius is flat all the way past 100 mJy, and it is much larger than the predicted 90% curve. The empirical separation distribution has many more distant outliers than expected from a Gaussian distribution.

In short, to find 90% of these counterparts using the NVSS positions, it is necessary to use a matching radius of approximately 7″ (≈ 0.15$\theta$) even for sources that are 100 times the rms noise level. The theoretical S/N model predicts that the positions ought to be much more accurate than that ($\sigma_{90} = 0.8″$). To include 95% of the counterparts requires a matching radius of 15″ (≈ 0.3$\theta$), while getting 99% of the counterparts requires matching out to 39″ (≈ $\theta$).

**Why are the low-resolution positions so inaccurate?** — Why are the inaccuracies in the positions so much greater than the S/N model predictions? Real radio sources are not symmetrical objects. They have lobes, jets, cores; star-forming galaxies have spiral arms; and there can be confusion where multiple radio sources get mixed together in the low resolution beam. A low resolution survey does indeed provide a measurement, with high accuracy, of the mean flux-weighted position as the S/N increases. **However, the flux-weighted centroid is often not where the optical counterpart lies.** In many cases, the counterpart is associated with some sharp structure within the radio source, and that structure may be far from the flux-weighted center.
**Figure 14:** Left: Probability of a false match in Pan-STARRS as a function of Galactic latitude. The actual density of PS1 objects was used to calculate the likelihood of a false counterpart within the 95% confidence radius. The plot shows probabilities both for the WODAN 15′′ resolution (blue) and VLASS S-band 3′′ resolution (red). Over most of the extragalactic sky ~ 10% of WODAN-PS1 cross-matches will be chance coincidences, compared with < 1% of VLASS-PS1 matches. VLASS positions are sufficient for reliable identifications even close to the Galactic plane. Right: FWHM resolution required to achieve 95% cross-match reliability in Pan-STARRS as a function of Galactic latitude. In the extragalactic sky (|δ| > 30°) a resolution better than 10′′ is required. WODAN does not have the required resolution; ASKAP-EMU just reaches this limit but will not cover most of the northern sky. The VLASS S-band survey easily meets this requirement.

**Effect on optical identifications** — This analysis shows that matching at the 45′′ resolution of NVSS requires a matching radius of 7′′ = 15% of the NVSS FWHM resolution. Our experience with the FIRST survey is that an even larger radius is required: to get a reasonably complete list of optical identifications we had to use a matching radius of 2′′ ~ 40% of the FIRST FWHM resolution. We argue that is a universal requirement for radio sources: at least for sources down to the sub-mJy regime, the matching radius that is required for realistic radio source morphologies is at least 15% of the FWHM resolution. Achieving 95% complete identifications requires a radius 30% of the FWHM resolution. The resolution for WODAN (which will survey the northern sky accessible to the VLA) is of order 15 × 17′′, while the resolution for ASKAP-EMU is 10′′. For 95% completeness, WODAN will therefore require an optical matching radius of 4.8′′ and ASKAP-EMU will require 3′′. A cross-match between SDSS and FIRST shows that 19% of FIRST sources have a false (chance) SDSS counterpart within 4.8′′. For comparison, 33% of FIRST sources have a true match within 2′′. The conclusion is that one-third of the optical counterparts at SDSS depth will be false matches when using a 4.8′′ matching radius.

The number of false matches can be reduced somewhat by doing a careful analysis of the likelihood of association as a function of separation, but when the starting point is contaminated by 33% of false matches, the final list of identifications will not be complete or reliable. The false matching problem will only get worse for deeper optical/IR data. For example, Pan-STARRS is about 1 magnitude fainter than SDSS in the red and also goes into the Galactic plane where the source density is much higher, so it demands better resolution. We have used the measured density of PS1 sources on the sky to compute the likelihood of false identifications in PS1 as a function of Galactic latitude. The left panel of Figure 14 compares the WODAN and VLASS (S-band B-configuration) surveys. For WODAN, 10% of sources even in the extragalactic sky (|δ| > 30°) will have a spurious counterpart in PS1. For many purposes that is an unacceptable level of contamination. In contrast, VLASS has only a < 1% contamination rate in the extragalactic sky,
and is usable even in the densest parts of the Galactic plane. The right panel of Figure 14 turns this around and asks what FWHM resolution is required to achieve a 95% reliability (∼2σ) in matches to the PS1 catalog. At |δ| > 30° a FWHM resolution of 11″ is required. That is significantly higher resolution than WODAN and slightly higher than ASKAP-EMU will achieve, but is easily satisfied by VLASS. In fact, VLASS with a resolution of 3″ has 95% confident PS1 matches over 99% of the current PS1 catalog area, with only the most crowded areas of the Galactic plane requiring higher resolution.

The next generation of optical/IR surveys will be deeper than Pan-STARRS. Figure 8 shows the resolution required as a function of magnitude using the r-band galaxy counts from the CFHTLS-D1 1 deg² survey (Jarvis, private communication). Since this does not include stars or redder galaxies, it is more optimistic (and less realistic) at the Pan-STARRS limit, but it shows the resolution required for deeper identifications. For 90% reliable identifications, VLASS can be used to r = 27.2, ASKAP-EMU to r = 25.3, and WODAN to r = 24.3. For 95% reliable identifications, the magnitude limits are 25.7 (VLASS), 22.9 (ASKAP-EMU), and only 21.8 (WODAN). The SKA-precursor surveys are usable at the depth of SDSS and Pan-STARRS in the extragalactic sky, but fall well short of the required resolution at fainter magnitudes and in the crowded Galactic plane. VLASS, by contrast, is useful at least to r = 26.

The bottom line is that we need high resolution to get the accurate positions required for optical identifications. Deeper radio imaging is not a substitute for the necessary resolution. VLASS will be the survey of choice for multi-wavelength science, and an all-sky VLASS will have a long and useful life even after the SKA-precursor surveys are complete.

D Additional Science Enabled by VLASS

Below we identify science that will be enabled by VLASS in addition to the key science themes discussed in the main text of the proposal.

D.1 Extragalactic Science

The Physics of Galaxy Clusters:
Clusters of galaxies are the largest gravitationally bound systems in the universe, and are dominated by dark matter (∼80%). Clusters are thought to form hierarchically, with smaller galaxy clusters merging to form bigger ones. This process continues at the present time. Only a tiny fraction of a cluster’s mass is in the form of stars in galaxies (∼3–5%), while the rest (∼15–17%) comprises the intracluster medium (ICM), which is a diffuse hot (10⁷–10⁸ K) gas detected in X-ray observations by its thermal bremsstrahlung and highly-ionized line emission. Radio observations play a key role in understanding the physics of galaxy clusters and the role of the intracluster environment in galaxy evolution. The proposed VLASS observations are particularly suited to (i) Study the interaction and feedback between the ICM and relativistic plasma from AGN, (ii) Determine the properties of cluster-wide magnetic fields, and (iii) probe cluster weather and turbulence through tailed radio galaxies. In addition, the high-resolution VLASS observations will enable the removal of compact sources from lower resolution images that are used to study large-scale diffuse radio emission in clusters (Feretti et al., 2012).

AGN Feedback. The hot gas in the center of relaxed clusters has a relatively high density (∼10⁻² cm⁻³), which implies short radiative cooling times that should lead to strong cooling flows. However, only weak cooling is observed and thus some feedback source to heat the cool core is required. At present, it is hypothesized that the source of heating in cool-core clusters is the AGN activity of the brightest cluster galaxy at the center (e.g., Peterson & Fabian, 2006). The details of this process are still far from being understood.
The radio feedback is thought to work through radio lobes which inflate bubbles (X-ray cavities) in the thermal gas, driving weak shocks and sound waves through the ICM. These bubbles are expected to detach and buoyantly rise through the ICM after the central AGN activity decreases. In addition to the energy injection, these rising bubbles provide a means of seeding the ICM with magnetic fields and relativistic particles. X-ray observations are only able to easily detect small cavities near the plane of the sky at relatively small distances from the cluster core. Larger cavities farther from the core, where the ICM is more diffuse, as well as those at small angles from the line of sight do not provide sufficient contrast for detection in even moderately deep X-ray observations. On the other hand, radio observations provide methods to place observational limits on the energy injected into the ICM by AGN feedback by tracing the complete kinetic feedback history of the ICM over multiple AGN outburst cycles. Despite the many uncertainties, the study of the radio spectrum in the aged and active components provides critical information on the cycles of activity of, and the total energy output delivered into the ICM throughout the cluster lifetime (e.g., Giacintucci et al., 2012).

**ICM Magnetic Fields**  The study of polarized radio emission from cluster and background sources indicates that magnetic fields are ubiquitous in clusters. However, very little is known about the strength and structure of these fields and the origin of these fields is still being debated. Studies of the polarization fraction through Rotation Measures of both cluster and background sources provide a way to determine the properties of ICM magnetic fields (e.g., Bonafede et al., 2010). Such a study is difficult to perform for individual clusters given the limited amount of polarized sources available. VLASS will provide a very large sample of polarized sources allowing binning the results for a large number of clusters.

**Cluster Weather and High-\(z\) Clusters**  Narrow and Wide Angle Tailed radio galaxies (NATs and WATs, respectively) are the most spectacular examples of radio emission from elliptical galaxies. Their shape is the signature of galaxy cluster membership, and is explained as the combination of motion of the hosting galaxy within the cluster and ICM bulk gas motion (e.g., Blanton et al., 2000). Spectral studies along the tails provide estimates of the age of the radio plasma, which in turn can be used to infer the galaxy velocity within the cluster, and information on the dynamical state of the cluster and the ICM. Due to their unique association with dense environments, NATs and WATs can readily be used to identify high-\(z\) galaxy clusters (Wing & Blanton, 2011). High-\(z\) clusters require significant observational efforts for detection in the X-ray and optical bands, while they are fairly accessible with high resolution (arcsecond scale) radio observations. In this way, wide radio surveys that discover WATs and NATs nicely complement the ongoing surveys that exploit the redshift-independent surface brightness of the Sunyaev-Zel’dovich effect, which is now being used to locate previously-unknown clusters at high-\(z\).

**D.2 Galactic Science**

The following classes of sources are likely to be found by VLASS, but are not considered to drive the survey design.

**Thermal Emission from Stellar Winds**  The thermal emissions from massive stars exhibit rising spectra, with \(F_\nu \propto \nu^\alpha\), with \(\alpha \sim 0.6\) for free-free emission from an ionized wind. For massive stars, this wind emission is formed further out in the wind than other diagnostics like H\(\alpha\) or X-ray emission, so has different sensitivities to wind clumping and porosity. While the overall effect of this mass loss from hot stars is also important to a better understanding of how this matter interacts with its environment, the radio wind emission diagnostic is important to a detailed investigation of the wind flows of individual stars, particularly
for comparison with measurements at other wavelengths. There are fewer radio-detected massive stars than the total number known: Rubin et al. (1962) catalogued \( \sim 1300 \) O–B5 stars within 3 kpc of the Sun within \( \pm 5^\circ \) in Galactic latitude. There are only about 65 O–B2 stars with radio detections (Benaglia, 2010), and \( \approx 70\% \) of these show thermal emission. It is likely that radio-detected hot thermal wind sources will be among the sources detected in VLASS.

**Symbiotic Stars** The outflows associated with accreting white dwarf systems (novae, symbiotic systems) produce thermal radio emission, but radio emission has not traditionally been the vehicle for detecting these objects. VLASS can identify additional candidates in these two classes; radio measurements are key to constraining the ejected mass and thus the characteristics of the explosion and the evolution of the white dwarf.

**Thermally-Emitting Novae** Approximately 35 Galactic novae explode each year, with about half of them occurring in the Galactic bulge (Darnley et al., 2006). Most novae are detected in the optical, and due to the effects of dust and optical incompleteness, usually only about a quarter of the total number are detected.

**Radio Emission from Massive Star Stellar Winds** About 30% of hot stars with radio detections display evidence of nonthermal spectra, with \( \alpha \lesssim 0 \); the nonthermal emission is interpreted to be synchrotron emission from colliding winds of a massive star binary (Benaglia, 2010). There is no consensus about formation mechanisms to produce nonthermal radio emission from single OB stars. Recent results indicate that magnetic fields play a heretofore unrealized role in channeling wind emission (Wade et al., 2012), with 6.5% of O and B stars surveyed exhibiting evidence of magnetic fields in their optical spectra.

**X-ray Binaries (XRBs)** Radio and X-ray measurements of stellar-mass black hole and neutron star binaries in a variety of states reveal a power-law relationship \( L_R \propto L_X^{0.6} \) between these emissions (Miller-Jones et al., 2011), illustrating the fundamental coupling between accretion processes (revealed by the X-ray emission) and the presence and action of a jet (probed by radio emission). More generally, there is also a “fundamental plane” relation for black holes, relating their X-ray emission, radio emission, and the mass of the black hole. New XRBs are identified when they go into an outbursting state, and VLASS will provide an immediate measure (or constraint) on the properties of system.

### D.3 Time Domain Science

Below we identify a number of additional scientific opportunities in time domain science that will be addressed by VLASS, and expand on some of the themes already discussed in Section 3.1.

**Supernovae** A comparison of the star formation rate and supernova discovery in the local universe implies that as many as half of the supernovae remain undetected in the traditional optical searches, largely due to extinction via dust obscuration. This has far reaching consequences for models of stellar and galaxy evolution. Synoptic radio surveys, unaffected by dust obscuration, offer a means to reveal the radio afterglows of the core collapse supernovae population (type II, Ib and Ic) (Gal-Yam et al., 2006). Furthermore, Soderberg et al. (2010) and Margutti et al. (2013b) have confirmed that the nearby, subluminous class of GRBs may generate relativistic ejecta yet lack high-energy mission, implying an additional population of energetic radio afterglows detectable in radio surveys, occupying the gap in energy and ejecta velocity between supernovae and GRBs (Figure 15). Conversely, deep follow-up observations of type Ia supernovae suggest that population does not produce bright radio afterglows, likely reflecting the distinct environment of such events. As
Figure 15: Kinetic energy in the fastest moving ejecta is plotted against shock wave speeds and compared for SNe and GRBs. It can be seen that the normal supernova shock wave carries a few orders of magnitude less energy than a GRB shock wave. Similar to the velocity space, energy distribution of SN and GRBs also appear bimodal. Events similar to SN 2009bb populating this parameter space remain to be discovered Margutti et al. (2013a); Soderberg et al. (2010)).

Figure 2 shows, VLASS will probe sufficient volume to rigorously constrain the rate of core collapse radio supernovae in the local universe.

**Orphan Afterglows of Long Gamma-Ray Bursts:** Long duration GRBs are a sub-class of type Ibc supernovae that produce a highly relativistic, collimated outflow powered by a central engine, thought to be an accreting black hole or neutron star. As might be inferred by their name, GRBs are predominantly discovered by space-based wide-field gamma-ray observatories. Detailed follow-up of exemplar candidates is carried out from X-ray to radio wavelengths, with radio observations, once again, key to establishing calorimetry of the explosion. Due to the highly collimated nature of the emission at gamma-ray wavelengths, only those bursts that are collimated in the direction of Earth are detected. Best estimates suggest this corresponds to a small fraction of the true GRB event rate, dependent on the typical opening angle of the collimated jet, with very poor constraints on the latter. The late time radio afterglow of such events, on the other hand, is largely symmetric, providing a means to directly constrain the true rate of GRBs (Cenko et al., 2013). Detection of a population of such “orphan afterglows” would provide an observational measure of the beaming fraction of GRBs. Indeed, given the current degree of uncertainty, even upper limits on this value would be a powerful constraint on models. In assessing the potential impact of VLASS is broaching this problem, we note that a very large degree of uncertainty in the true rate precludes a meaningful prediction, although we include an estimate for the expected rate based on the recent work of Ghirlanda et al. (2014) in Figure 2.
Stellar Flares and Coronal Mass Ejections: Many classes of stars produce flares that are several orders of magnitude more luminous and frequent than any produced on the Sun, including young stellar objects, active M dwarfs and certain classes of tight binaries (eg. RS CVn systems). Such activity dominates the star’s output over much of the electromagnetic spectrum, governs its angular momentum evolution and can also have a profound impact on the planetary systems orbiting such stars. In the latter case, higher X-ray and ultraviolet irradiation can lead to heating of the upper planetary atmosphere, resulting in photochemical reactions leading to significant atmospheric loss. In particular, studies of terrestrial planets in the habitable zone of M dwarfs, possibly the most abundant Earth-like planets in the solar neighborhood (Dressing & Charbonneau, 2013), suggest that large flares and coronal mass ejections (CMEs) may potentially lead to catastrophic loss of the atmosphere of such planets (Khodachenko et al., 2007; Lammer et al., 2007).

Radio bursts are a powerful means to detect and characterize flares and CMEs on the Sun and studies of radio bursts from nearby active stars can be similarly used to probe the local environment of impulsive flare and CME events with the potential for groundbreaking insight into the bulk motion of plasma in stellar coronae. Extremely bright bursts up to 1 Jy (Lovell, 1963) have been detected for decades from nearby M dwarfs, at luminosities that are up to 5 orders of magnitude more intense than any equivalent solar bursts. In more recent years, dynamic spectroscopy of stellar radio bursts has been carried out using the Very Large Array (VLA), Effelsberg, Jodrell Bank and Arecibo radio observatories (Osten & Bastian, 2006, and references therein). In the case of the detected stellar radio bursts, the luminosities are orders of magnitude brighter than anything detected from the Sun, highlighting that the coronae possessed by active stars are very different to the solar corona. The radio emission properties clearly indicate coherent processes, probably associated with plasma radiation or electron cyclotron maser emission, the former providing direct measurement of plasma densities and the latter direct measurement of magnetic field strengths, while broadband dynamic spectra of bursts provide information of the size and extent of the associated stellar coronae. Studying the coronae of such active stars provides a laboratory to investigate physical regimes unavailable with spatially detailed studies of our low-activity Sun. Furthermore, such bursts potentially provide direct insight on the density, velocity and energetics of mass ejection from stellar coronae and the associated impact on planetary atmospheres.

Active stars also produce large incoherent flares (Osten et al., 2005), due to gyrosynchrotron radiation associated with the same nature of magnetic reconnection events that produce bright coherent bursts. Insufficient data exists on the relationship between the incoherent and coherent flare emission, but this can be probed by VLASS and VLITE/LOBO with the former probing the higher frequency incoherent emission and the latter probing the coherent emission more frequently confined to lower frequencies. The degree of circular polarization is often a good distinguishing characteristic between the incoherent and coherent emission. The measured rate of flares from active stars in previous surveys (Mooley et al., 2014) suggests that flares from M dwarfs in particular will prove to be one of the most frequent transient events detected by VLASS, with potentially 100s of events recovered in the All-Sky and Wide tiers of the survey.

Substellar Auroral Emissions: A dozen or so low mass stars and brown dwarfs have been found to be radio sources in the last decade (Antonova et al., 2013, and references therein). A subset of these objects have been the subject of lengthy follow-up campaigns that have revealed the presence of 100% circularly polarized, periodic pulses, with the pulse period typically 2-3 hours and consistent with rotation (Hallinan et al., 2007, 2008; Berger et al., 2009). This radio emission is thought to be electron cyclotron emission produced at the electron cyclotron frequency, in the same fashion as that detected from the auroral regions of the magnetized
planets in our solar system. As is the case for such planets, it enables very accurate measurement of magnetic field strengths and rotation periods and has led to the confirmation of kilogauss magnetic fields in large-scale configurations for ultracool dwarfs. Indeed, radio observations have been the only method thus far capable of direct magnetic field measurements for L dwarfs; Zeeman broadening measurements are inhibited by the difficulty in obtaining high resolution spectra of these cool, dim objects (Reiners & Basri, 2007).

Most recently Route & Wolszczan (2012) found the coolest radio brown dwarf yet detected, with the detection of radio pulses from the 900K T6.5 dwarf, 2MASS J10475385+2124234. Individual pulses were detected from this object in multiple short duration observations with the Arecibo observatory, resulting in a confirmed magnetic field strength of at least 1.7 kG near the surface of this extremely cool object. This significant discovery highlights the unparalleled diagnostic potential of radio observations of brown dwarfs, and their importance in constraining dynamo theory in the mass gap between planets and stars. VLASS will be the first survey with the depth to blindly detect brown dwarfs in both quiescence and outburst. The detection of late L, T and Y dwarfs would be of particular significance for ongoing empirical measurements of magnetic fields in this regime.

**Galactic Center Radio Transients:** Blind surveys of the Galactic Center region with the VLA have been used to search for radio transients with a considerable degree of success (Hyman et al. (2002, 2005, 2009), see Figure 16). Most notably, a blind search program using the Very Large Array (VLA) at 330 MHz (90 cm) identified a mysterious, bright, pulsing source towards the Galactic Center inconsistent with any known class of radio source, labeled GCRT J1745-3009 (Hyman et al., 2005). 100% circularly polarized 1 Jy bursts of duration ten minutes each, reoccurring with period of 77 minutes, were detected in a 7 hours of VLA data taken in September 2002. In multiple follow-up observations, the transient was detected in two more epochs of observations with the Giant Metre-Wave Radio Telescope (GMRT) in 2003 and 2004, with flux levels greatly reduced relative to the original detection. At the last known epoch of emission detected in 2004, the source exhibited an unusually steep spectrum with $\alpha = -13 \pm 3$ ($S(\nu) \propto \nu^\alpha$). Very high circular polarization has also been reported. GCRT J1745-3009 may be as close as 180 pc to the Galactic Center but limits on distance, and thus brightness temperature, are otherwise weak. For distances $d < 70$ pc from the Earth, the radio flux density constrains its brightness temperature to exceed the limit for incoherent synchrotron radiation thus requiring a coherent emission mechanism. The high circular polarization, spectral characteristics and intrinsic beaming of the emission support the assertion of coherent radio emission for this new class of radio source, christened “burper” (Kulkarni & Phinney, 2005). We note that the 100% circularly polarized nature of the bursts from GCRT J1745-3009 favors parallel searches for transients in Stokes V where the galactic contribution will be reduced by many orders of magnitude relative to unpolarized Stokes I images.

No counterpart was identified in observations at other wavelengths, largely due to the poor localization of the position of the transient in radio data. It remains unclear whether GCRT J1745-3009 is intrinsically close to the Galactic Center or rather simply lies in the direction of the Galactic Center; the latter case being feasible due to the biased nature of the survey, for which blind searches for transients were restricted to the Galactic Center. Proposed counterparts include a nulling pulsar, a double pulsar, a transient white dwarf pulsar, a precessing radio pulsar or a nearby pulsing brown dwarf or low mass flare star.

A second Galactic Center radio transient source (GCRT J1742-3001) was detected in multiple epochs of a 235 MHz transient monitoring program with the GMRT in 2006 and 2007 (Hyman et al., 2009). This was a very different class of radio transient, observed to brighten over a period of a month to a maximum of 100 mJy before fading in the subsequent 6 months.
Figure 16: The diversity of the light curves for transients toward the Galactic center Hyman et al. (2002, 2005, 2009). The transient GCRT J1745-3009 burst several times (duration \(\sim 10\) minutes) during a 6-hr observation, with subsequent bursts detected over the next 1.5 yr; GCRT J1742-3001 brightened and faded over several months, preceded 6 months earlier by intermittent bursts; and GCRT J1746-2757 was detected in only a single epoch. None of these objects has been identified nor has a multi-wavelength counterpart been found. The background image is the Galactic center at 330 MHz. Figure taken from Lazio et al. (2009).

Once again, a very steep spectrum \(\alpha = -2\) was inferred. Discovering the frequency, nature and progenitors of these new classes of radio transients will open up new population of exotic objects to astrophysical study with the possibility of such transients being due to previously undetected populations of neutron stars being a particularly exciting possibility. The detection of two new classes of transient in very limited blind searches towards the Galactic Center speaks to the huge potential for discovery associated with monitoring this region of the sky. VLASS will easily probe much deeper than any previous Galactic Center transient surveys. In particular, considering the steep negative spectrum confirmed for GCRT J1745-3009 and GCRT J1742-3001, the possible inclusion of VLITE/LOBO will be key to probing these particular populations as results from previous surveys suggest that the rate of detected transients would be \(\sim 0.2/\text{hr}\) with the upgraded VLA (Hyman et al., 2009).