Draft version December 27, 2023
Typeset using LaTeX **twocolumn** style in AASTeX631

VLASS Epoch 4 Science Case

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ABSTRACT

We propose extending the VLA Sky Survey (VLASS) to include a 4th epoch. VLASS has proven to be a productive, high-impact astronomical survey with a global user-base of astronomers. A 4th epoch would extend the unparalleled legacy VLASS has achieved in the discovery of slow radio variables and transients, provide new opportunities for multi-wavelength/multi-messenger science, and take advantage of recent upgrades to commensal instruments on the VLA. We recommend that the 4th VLASS epoch be carried out with the same parameters and observational strategy as the previous epochs, namely a full-polarization survey over the full S-band bandwidth (2-4 GHz) providing an angular resolution of 2.5″, sky coverage above -40 degrees declination, and a cadence of 32 months. In order for Epoch 4 to follow the same 32-month cadence as the previous epochs, it would need to be scheduled from October 2025 to June 2027. This time frame is well-aligned with the Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST), which will begin operations in mid 2025. VLASS Epoch 4 is predicted to discover ∼1000 new radio transients, including ∼10 new radio-detected TDEs, ∼30 new radio stars, and dozens of young quasar jets. Beyond new time domain opportunities, the increased depth from a 4th epoch in the stacked image products will reveal ∼800,000 additional sources, including ∼400,000 star-forming galaxies. In this white paper, we review recent scientific highlights with VLASS so far, explore new opportunities with a proposed 4th epoch of the survey, and identify aspects of the implementation in need of further consideration.

1. INTRODUCTION

Wide-field astronomical surveys are essential for discovering rare classes of objects, overcoming the statistical limitations of targeted observations, and expanding the user community of a telescope. The Very Large Array Sky Survey (VLASS; Lacy et al. 2020) originated as a community-driven initiative to carry out a high-resolution, multi-epoch radio survey leveraging the expanded capabilities of the Karl G. Jansky Very Large Array (VLA). VLASS was designed as a 3-epoch radio survey of the entire northern sky visible from New Mexico. The unique combination of panoramic sky coverage (33,885 deg^2), high angular resolution (2.5″), frequency range (2-4 GHz), observing strategy (3 epochs with a cadence of 32 months), and full-polarimetric capabilities of VLASS was chosen to enable new discoveries over a wide range of science topics.

VLASS was originally limited to 3 epochs carried out over a 7-year period from 2017-2024 due to the anticipated

Figure 1. Examples of science highlights from VLASS Epochs 1 and 2. **Stellar explosions:** VLASS revealed a merger-triggered core collapse supernova in a search for slow radio transients (Dong et al. 2021). **Tidal disruption events:** VLASS has increased the number of TDEs with radio detections from ∼1 to hundreds (e.g. Somalwar et al. 2022; Cendes et al. 2023). **Flaring radio stars:** VLASS has identified dozens of new radio stars and provided new insights into topics such as the physics of stellar mass loss in M dwarf (Yiu et al. 2023). In addition, commensal data taken with the VLITE Commensal Sky Survey (VCSS) were recently used to identify magnetically active main sequence stars (Polisensky et al. 2023). **Newborn quasar jets:** A combined search using data from VLASS + FIRST taken a decade or more apart revealed a sample of known optical/infrared quasars with newborn radio jets (Nyland et al. 2020). Graphics credit: NRAO/AUI.

start of construction for the next-generation Very Large Array (ngVLA; Murphy et al. 2018) in the mid 2020's. With ngVLA construction now expected to begin later in the decade, we revisit the possibility of extending the timeline of VLASS to include a 4th epoch. **VLASS Epoch 4 would extend the unparalleled legacy VLASS has achieved in the discovery of slow radio variables and transients, provide new opportunities for multi-wavelength/multi-messenger science, and take advantage of recent upgrades to commensal instruments on the VLA.**

In this white paper, we propose an extension of VLASS to a 4th epoch. We provide an overview of VLASS's impact on the astronomical community so far in Section 2. We discuss future scientific opportunities that are only possible with a 4th epoch of VLASS in Section 3, and review additional science that would be enhanced in Section 4. We make recommendations on the implementation of the survey in Section 5 and discuss the broader impacts in Section 6. We summarize the case for VLASS Epoch 4 in Section 7.

2. THE LEGACY OF VLASS

VLASS was envisioned as a launchpad for the future that would build on previous radio surveys and serve the multi-wavelength and multi-messenger communities well into the next decade. Here, we summarize scientific highlights of VLASS, present citation metrics for VLASS to quantify its scientific productivity and global impact in an objective manner, and review its community impact so far.

2.1. *Scientific Highlights*

In this section, we highlight major scientific advancements enabled by VLASS and discuss its broader impact on the astronomical community. The science case for VLASS is thoroughly described in the VLASS survey description and science case white paper (The VLA Survey Science Group 2016) and the published VLASS description paper (Lacy et al. 2020), and we do not revisit it in detail here. Briefly, VLASS was designed as a broadband, high-resolution, synoptic radio survey to enable forefront science over a wide variety of areas by exploring new temporal, spectral, and spatial domains. VLASS has been particularly successful in advancing our understanding of the dynamic radio sky, including stellar explosions, tidal disruption events, flaring radio stars, and newborn quasar jets. A selection of science highlights with VLASS are illustrated in Figure 1.

2.2. *Comparison to NVSS and FIRST*

Prior to VLASS, NRAO conducted two flagship surveys with the VLA: the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) and the Faint Images of the Radio Sky at

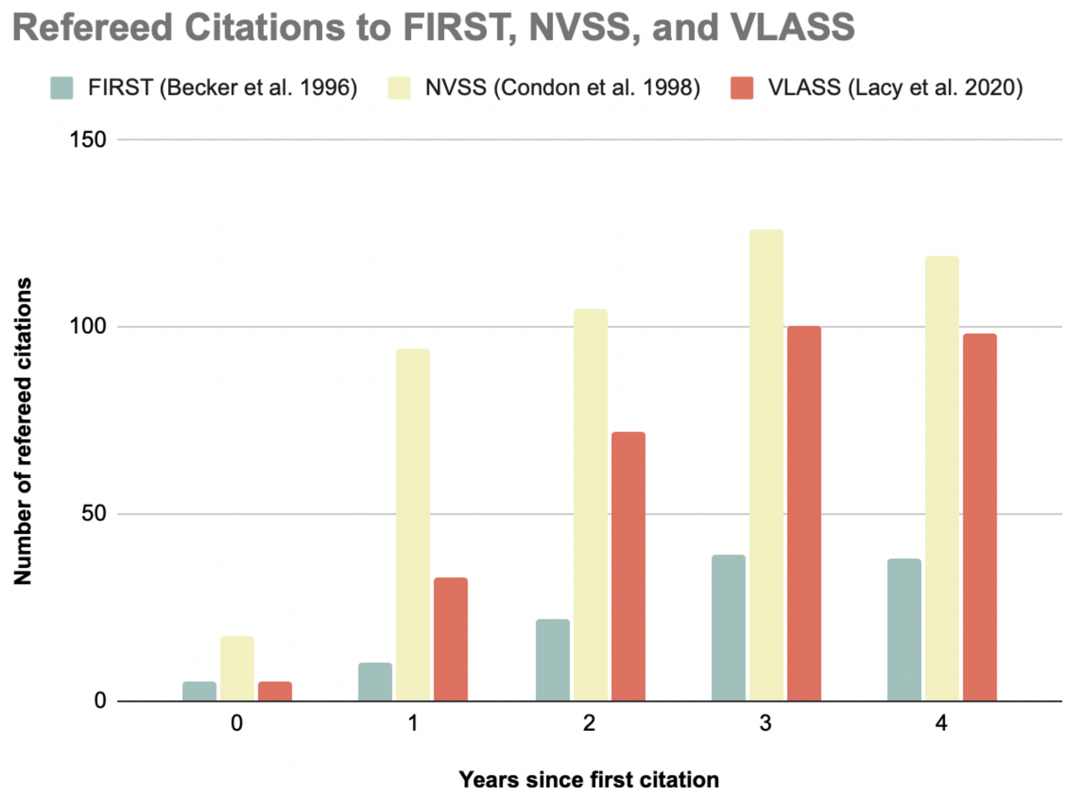

Figure 2. Citation statistics as a function of years since the first citation for the NRAO VLA Sky Survey (NVSS; Condon et al. 1998), the Faint Images of the Radio Sky at Twenty Centimeters (FIRST; Becker et al. 1995), and the VLA Sky Survey (VLASS; Lacy et al. 2020). Data on citations are taken from the Astrophysics Data System and based on an analysis performed in October 2023.

Twenty Centimeters (FIRST; Becker et al. 1995). In the original VLASS survey description and science case paper (The VLA Survey Science Group 2016), the impact of these historical NRAO surveys was reviewed. Based on citation and data usage metrics, both NVSS and FIRST have had a major impact on increasing the scientific productivity of the VLA and expanding its user base compared to PI-driven projects. Currently, the Condon et al. (1998) and Becker et al. (1995) publications on NVSS and FIRST have now accumulated a total of 7,382 citations (6,740 of which are refereed).

Since its publication less than 4 years ago, the VLASS survey description paper, Lacy et al. (2020), has amassed 381 citations (326 of which are refereed). Recently, Lacy et al. (2020) was recognized with an award for being among the top 1% most-cited papers in the IOP publishing portfolio from 2020-2022. We note that in addition to papers that have cited Lacy et al. (2020), $\sim$100 additional papers use VLASS but cite other papers (e.g. the Quick Look catalog paper, Gordon et al. 2020, 2021).

In Figure 2, we compare the citation rate for NVSS (Condon et al. 1998), FIRST (Becker et al. 1995), and VLASS (Lacy et al. 2020) as of the writing of this document. **Figure 2 clearly demonstrates that the scientific productivity of VLASS is comparable to previous NRAO radio surveys, with a citation rate that is considerably higher than that of FIRST.** This settles some concerns that VLASS may not have as much scientific impact as FIRST and NVSS (e.g. Condon 2015).

In Figure 3, we show the global distribution of author and co-author affiliations for papers citing NVSS, FIRST and VLASS over the course of the first 4 years of each survey. This figure shows that the authors of papers using VLASS data are spread over a much wider geographical area compared to FIRST and NVSS over a similar timescale. We note that VLASS appears to be engaging many astronomers from Canada, South Africa, and Australia, which are all involved in the Square Kilometre Array (SKA; Dewdney et al. 2009). On the other hand, early publications using FIRST and NVSS data were primarily written by authors based in the United States. This difference may stem from the increasingly global reach of astronomy in recent years. **The geographically diverse usage of VLASS data so far is a good indicator that VLASS will continue to have a strong and wide-reaching impact going forward.**

2.3. *Community Impact*

Since its inception, a cornerstone of VLASS has been to serve the needs and interests of the astronomical commu-

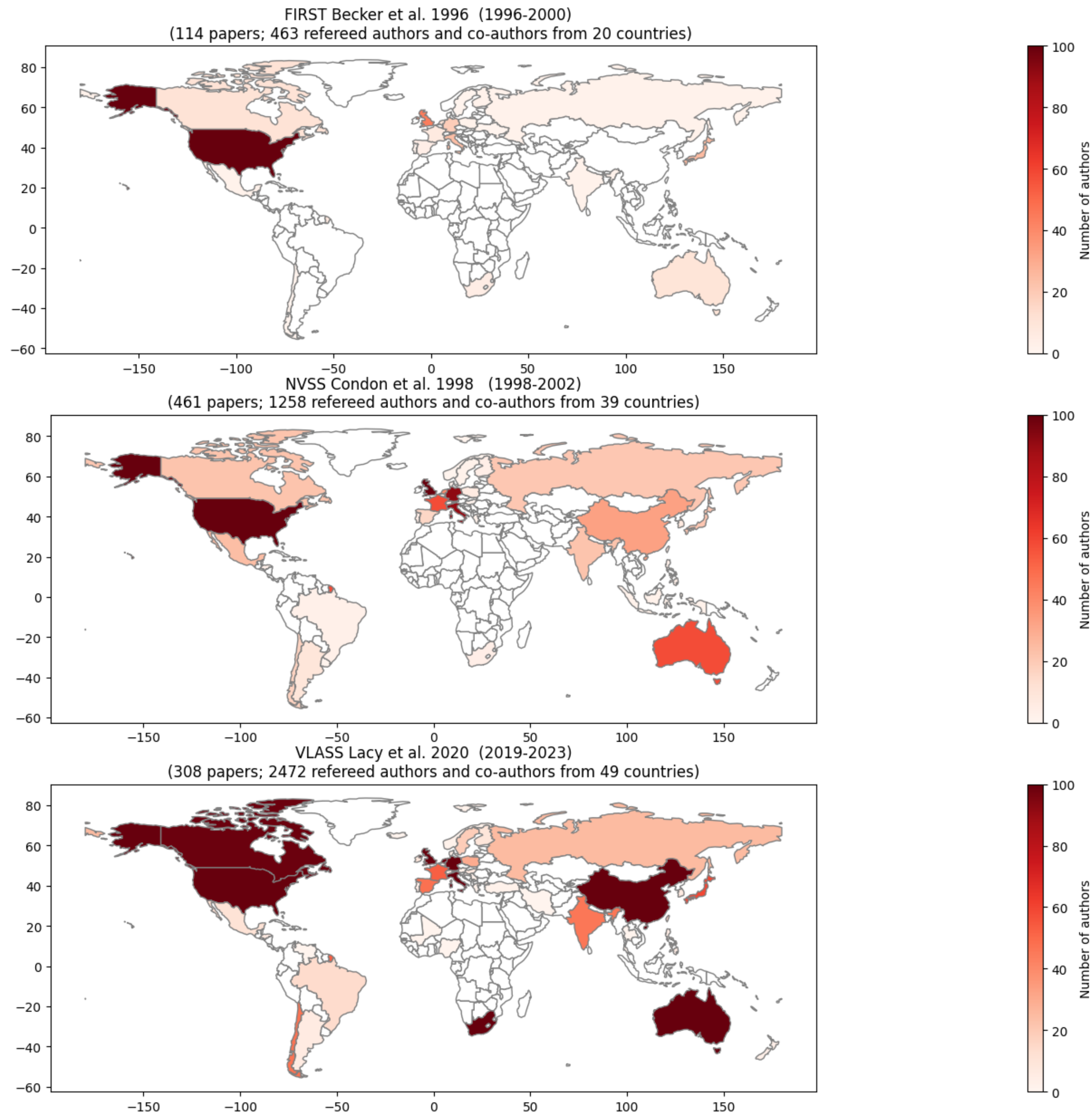

Figure 3. Comparison of the global distribution of authors and co-authors of papers citing FIRST (Becker et al. 1995), NVSS (Condon et al. 1998), and VLASS (Lacy et al. 2020). Data on author affiliations are taken from the Astrophysics Data System and based on an analysis performed in October 2023.

nity. In this section, we describe VLASS's role in supporting the broader astronomical community. Highlights include a hybrid science conference that took place in 2022 as well as educational programs supporting students from under-represented groups.

2.3.1. **VLASS conference**

VLASS science and its broader impacts were recently highlighted at the "VLA Sky Survey in the Multiwavelength Spotlight" conference. This conference was sponsored by NRAO and held in-person in Socorro, New Mexico and also virtually on Zoom from September 7-9, 2022. The goal of

Figure 4. Attendees at the "VLA Sky Survey in the Multiwavelength Spotlight" conference. These astronomers, from all over the world, met to discuss new scientific discoveries as well as opportunities for broader impacts with VLASS.

the conference was to share a diverse range of scientific perspectives, both on the discoveries enabled by VLASS on its own, and on advances made possible through synergy with other multi-wavelength datasets. Over 200 astronomers from around the world participated in the VLASS conference (Figure 4), and the program included over 60 posters, 53 oral presentations, and 3 interactive panel sessions. **This conference demonstrated the high level of interest in the survey among members of the astronomical community at large.**

2.3.2. *Broadening Participation*

The Office of Diversity and Inclusion (ODI) at NRAO has several student programs, educational initiatives, and institutional partnerships intentionally designed to broaden participation of underrepresented populations in STEM fields. These programs offer undergraduate students summer research and training experiences, long-term mentoring, and on-going professional, personal, and financial support. NRAO ODI programs that have focused the use of VLASS as an educational tool for broadening participation include the NINE and RADIAL programs.

- **NINE:** The NRAO National and International Non-traditional Exchange program (NINE[1]) aims to broaden participation of under-represented groups in radio astronomy. Institutions participating in NINE often do not have large physics-astronomy programs, and often no previous experience in radio astronomy research or data analysis. From the start of VLASS when Quick Look imaging became available, VLASS imaging data products were used as a means to expose students to Python, NRAO data products, archive access, and data mining. Participants in NINE workshops bring the computing and development skills back to their home institutions to lead tutorials with fellow students and faculty. In addition to participating in conferences organized by the American Astronomical Society (AAS) and the annual Astronomical Data Analysis and Software Systems (ADASS), NINE program participants have published their findings in conference proceedings via ASP (Beasley et al. 2022; Rodríguez et al. 2022).

- **RADIAL:** Radio Astronomy Data and Image Analysis Lab (RADIAL/footnote[/url[https://superknova.org/radial/]) is a widening participation program run by NRAO in collaboration with the University of Wisconsin-Madison and 14 institutions serving minorities. We provide mentoring and research experiences in data-intensive radio astronomy to students from underrepresented backgrounds. During the on-campus part of their program, RADIAL students are taught the fundamentals of radio astronomy, statistics, and trained

[1] https://go.nrao.edu/nine

in the coding skills necessary for both modern radio astronomy and data science as a whole. Following their research internship, RADIAL students are then supported to present their results at AAS meetings. The large amount of data produced by VLASS has been a key resource for RADIAL, with more than half of the 13 RADIAL students so far having used VLASS in their projects. Continuation of VLASS for a fourth epoch will provide additional data that projects such as RADIAL can continue to draw upon.

3. KEY SCIENCE DRIVERS FOR EPOCH 4

The main science drivers motivating the extension of VLASS to include a 4th epoch are continuing VLASS' legacy of discovery in the dynamic radio sky, exploring new opportunities for multi-wavelength and multi-messenger synergy, and utilizing recent advances in complementary instruments at the VLA. We discuss these topics in further detail in the remainder of this section.

3.1. *The Dynamic Radio Sky*

VLASS was designed to provide a synoptic view of the dynamic radio sky, providing three unique snapshots in time between legacy radio surveys like FIRST and NVSS, and new and future surveys with next-generation radio telescopes, such as the ngVLA and SKA.

As shown in Figure 5, a 4th VLASS epoch would bridge the gap in time between VLASS Epochs 1-3 and upcoming radio time domain surveys with instruments currently under development for the northern hemisphere, such as the DSA-2000 (Hallinan et al. 2019). The extension of VLASS towards the end of the current decade would also allow the deployment of automated transient detection pipelines that are currently under development by Caltech and the Canadian Initiative for Radio Astronomy Data Analysis (CIRADA[2]).

We emphasize that extending VLASS to include a 4th epoch is necessary to enable the identification of new radio transients, and to support the continued monitoring of those detected in prior VLASS epochs. In the following sub-sections, we highlight specific opportunities for science in the radio time domain that would be enabled by VLASS Epoch 4.

3.1.1. *Tidal Disruption Events*

TDEs occur when a star passes within the tidal radius of a supermassive black hole (SMBH) and is ripped apart by tidal forces. During this process, the stellar debris stream is expected to circularize and form a transient accretion disc, with ∼half of the stellar debris gravitationally bound to the SMBH. However, key questions about the timescales of the debris circularization, the nature of the accretion flow, and the possible formation of jets and outflows remain unknown. These questions are informed by multi-wavelength observations, in which radio plays a critical role by tracking the motion of the fastest-moving material (Alexander et al. 2020, and references therein).

Radio emission from TDEs arises from synchrotron radiation produced in shocks generated by the disruption process (either external shocks between outflowing material and the ambient medium, or internal shocks within a jet; e.g. van Velzen et al. 2016; Alexander et al. 2020). Multi-frequency radio observations can be used to determine the energetics and dynamics of outflowing material. Prior to VLASS, prompt radio emission had been discovered in a subset of TDEs, either from powerful on-axis jets (e.g. Sw J1644+57) or from less energetic non-relativistic outflows (e.g. ASASSN-14li). **VLASS enabled the first searches for radio emission in TDEs at late timescales, and directly led to the unexpected discovery that some TDEs "turn on" in the radio years post-disruption, long after the emission at other wavelengths has faded below detectable levels** (Horesh et al. 2021; Cendes et al. 2022, 2023). This discovery has already prompted a flurry of new theoretical work (e.g. Metzger 2022; Matsumoto & Piran 2023; Teboul & Metzger 2023) and has greatly expanded our understanding of the radio diversity of TDEs.

VLASS has also been used to blindly search for TDEs and other nuclear transients in the radio band. This gives an independent constraint on the TDE rate, unbiased by e.g. high extinction in dusty host galaxies that could prevent TDEs in these galaxies from being discovered as optical or X-ray transients. The first results from such searches are promising (Somalwar et al. 2022, 2023b,a) and more results are in prep.

A 4th VLASS epoch would allow the TDE community to fully capitalize on the recently increased TDE discovery rate enabled by ZTF and other optical surveys to better understand the true rates of radio emission in TDEs, particularly at late times. It will also bridge the gap to ngVLA and help ensure that the numerous TDEs expected to be discovered during the first years of Rubin receive unbiased radio follow up (Section 3.3).

3.1.2. *Stellar Flares*

Radio observations of stars trace the plasma conditions and magnetic field properties of stellar magnetospheres and coronae (Dulk 1985) – information that is often unattainable at other wavelengths. Determining the plasma environment of other stars is pertinent if we want to assess the environmental conditions that planets experience around other stars (Callingham et al. 2023).

VLASS has significantly impacted the radio stars and exoplanet field due to its high resolution, sensitivity, and

[2] https://cirada.ca/

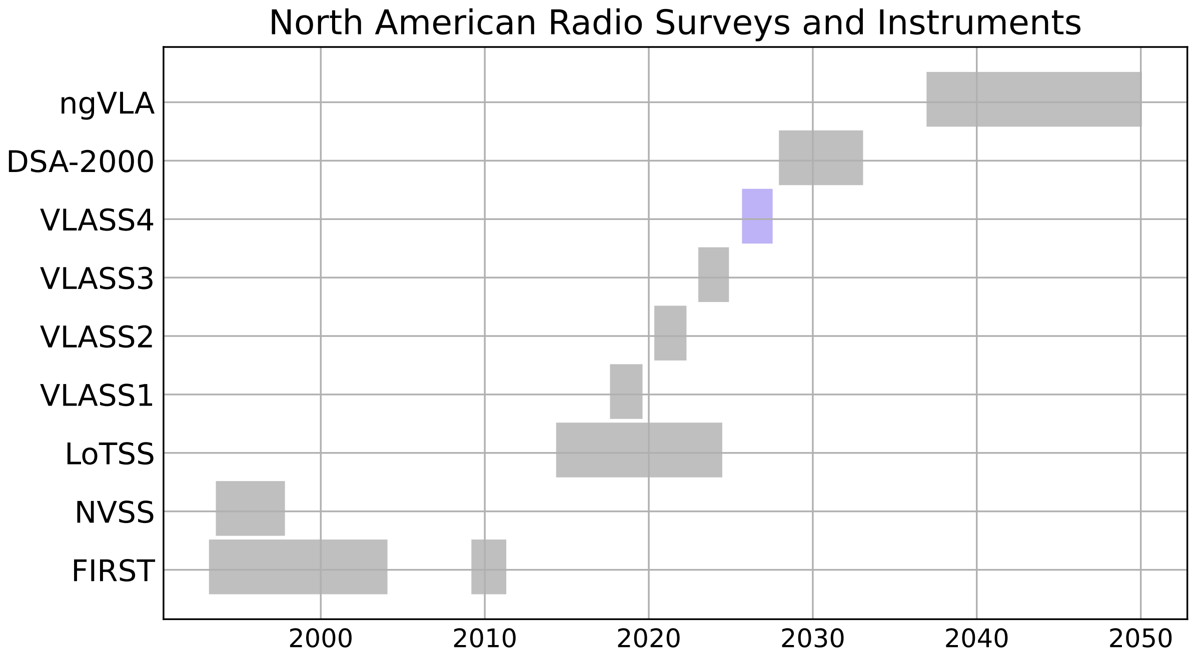

Figure 5. A timeline of selected northern hemisphere radio surveys and/or instruments. References to surveys are provided in the caption to Figure 6. We note that the estimated time range shown for the DSA-2000 is based on the anticipated start of the 5-year-long Cadenced All Sky Survey as reported in Hallinan et al. (2019), but we caution that the start date of 2028 shown in this figure is uncertain and delays are possible. The time range shown for the ngVLA (Murphy et al. 2018) based on the anticipated start of science operations (private comm. with Eric Murphy), but there are no widefield surveys currently planned with the ngVLA. We also note that other radio surveys with SKA precursors and pathfinders are underway or planned for the near future in the Southern hemisphere, such as VAST. VAST is collecting multi-epoch data with ASKAP over the time period of 2019 to 2027 (see Section 3.2). The original VLASS science proposal (The VLA Survey Science Group 2016) provides additional details on other time domain radio surveys.

multi-epoch nature. The combination of these features over a wide-field means VLASS has allowed the unambiguous identification of 70 radio stars, the largest population ever isolated (Yiu et al. 2023).

With such a statistically robust population, Yiu et al. (2023) demonstrated that the population of radio stars at GHz-frequencies is mainly composed of two distinct categories: chromospherically active stellar systems and M dwarfs. The radio detectability of M dwarfs also appeared to evolve with spectral type, with a potential transition in radio detectability around spectral type M4, where stars become fully convective.

Yiu et al. (2023) suggest that the emergence of large-scale magnetic fields in late M dwarfs leads to an increase in radio efficiency. However, such a conclusion is preliminary. Despite having the largest radio star sample ever isolated, more stars are needed to make this conclusion robust. **With another epoch of VLASS, it is expected that ∼30 new stars will be detected, based on the number of detections in each of the VLASS epochs.** Such a large sample would then allow the preliminary conclusion of detectability to be tested.

It remains unclear if late M dwarfs can possess magnetic fields similar to Jupiter – information that is vital to assess if we want to determine if M dwarfs lose mass into their stellar systems like our Sun. VLASS is leading the way in this science and another epoch would cement its legacy of revolutionizing our understanding of stellar magnetospheres.

3.1.3. *Stellar Explosions and their Remnants*

VLASS is an extremely efficient detection engine for the most radio-luminous stellar explosions. Prior to VLASS, there were only ∼10 known supernovae with luminositities $L_\nu \gtrsim 10^{28}$ erg s^{-1} Hz^{-1}), belonging to a rare group of explosions ∼2.5 orders more luminous than the median supernova (Bietenholz et al. 2021).

Preliminary transient searches in VLASS have increased the number of known stellar explosions of this luminosity by a factor of ~ 4, of which $\sim 1/3$ have archival optical counterparts (Dong et al. in prep). Among these events is the nearly 70-year-old SN 1965G (Stroh et al. 2021), which has maintained a flux density of ∼8 mJy in all 3 epochs of VLASS and may be the first century-timescale transient to be discovered outside of our Galaxy. The number of radio-luminous supernovae is continuing to grow in ongoing searches of VLASS Epochs 1, 2, and 3.1 due to the rapid increase in the optical supernova detection rate in modern widefield optical surveys (see Section 3.3).

VLASS has also enabled the discovery of entirely new populations of stellar explosions and remnants, including a merger-triggered supernova (Dong et al. 2021), an orphan γ-ray burst (Law et al. 2018a), and an emerging extragalactic pulsar wind nebula hosted by a dwarf galaxy (Dong & Hallinan 2023).

3.1.4. *Newborn Quasar Jets*

Radio continuum surveys are an important tool for studying the life cycles of jets launched by active galaxies and quasars (e.g. Patil et al. 2022). VLASS has made extensive contributions to our understanding of radio AGN and quasars, including the identification of rare high-z quasars (e.g. Bañados et al. 2023). Compared to other widefield radio surveys with comparable sky coverage and depth (see Figure 6, the parameters of VLASS (high spatial resolution, frequency range, and multi-epoch implementation) make it particularly valuable for studying sources that are compact (e.g. Baldi 2023) and variable, including young radio jets.

Young radio jets associated with active galactic nuclei (AGN) and quasars may exhibit substantial variability due to source expansion and evolution on timescales of years to decades (O'Dea & Saikia 2021, and references therein). Modern radio surveys that record data over multiple epochs with cadences of years or longer are therefore capable of identifying recently-triggered radio jets on the basis of their radio variability. Recently, Nyland et al. (2020) searched for optical- and infrared-selected quasars that had brightened dramatically ($> 2\times$) in the radio between VLASS Epoch 1 and FIRST. These quasars appear to have transitioned from radio-quiet to radio-loud in the past 10-20 years. Simultaneous, multi-band follow-up with the VLA has revealed compact morphologies and peaked spectral shapes that are consistent with young, recently-triggered jets.

The number density of objects found in this VLASS-FIRST comparison is much larger than expected if the typical radio source lifetime is $\sim 10^7$ yr, as inferred from spectral aging of FRII radio galaxies (e.g. Myers & Spangler 1985; Alexander & Leahy 1987), suggesting that only $\sim 1\%$ of radio sources are active for long enough to form large-scale ($\gtrsim 100$ kpc) radio sources. Frequent episodes of short-lived quasar jets could play an important role in galaxy evolution if they contribute to the regulation of star formation rates and SMBH growth over cosmic time.

Continued monitoring of the evolution in the fluxes and radio spectra of these quasars is necessary to test the hypothesis that they are young. Changes in source flux tracked across multiple VLASS epochs will directly constrain the physics of the young jets and their ambient environments (e.g. Ross et al. 2021). Since adiabatic quasar jet expansion is best sampled on $\sim$decadal timescales (e.g. Orienti & Dallacasa 2020), **a 4th VLASS epoch will track the evolution of young jets found in earlier epochs, and enable the identification of dozens more over the $\sim$decadal timescale between Epochs 1 and 3.**

3.1.5. *Changing-look AGN*

Determining the duty cycle, efficiency, and triggering mechanism of supermassive black hole (SMBH) accretion episodes is key to our understanding of SMBH growth and host galaxy co-evolution throughout cosmic time. In the time domain, useful probes of episodic AGN accretion are rare changing-look AGN (CLAGN), which exhibit the appearance or disappearance of broad optical emission lines from high velocity gas close to the SMBH (the broad line region) in response to changes in the accretion state (Elitzur et al. 2014; Schawinski et al. 2015). Over the last 5 years, spectroscopic and time-domain surveys have expanded the number of CLAGN candidates from a few objects to a population of over 100 objects (e.g. Green et al. 2022), with a few hundred new CLAGN from SDSS-V soon to be published.

VLASS Epoch 4 would enable a search for young radio jets launched during the onset of accretion episodes from the expanding population of optically identified 'switching-on' AGN in the era of SDSS-V and LSST. This phenomenon has been observed during multi-wavelength monitoring of CLAGN Mrk 590, which identified fading in the radio and X-rays following a decrease in accretion rate in the 1990s consistent with fading and expansion of shocks in the outflow associated with the former bright state (Koay et al. 2016). Despite this, there are very few other objects with detailed time-domain radio follow-up of CLAGN showing broad-line changes (see Yang et al. 2021, for one such study of a changing-look Seyfert). Previous searches in NVSS and FIRST have estimated radio detection rates of 16% for the small population of CLAGN found prior to SDSS-IV (Yang et al. 2021).

By the time of VLASS Epoch 4, there will be many hundreds of optically identified CLAGN. This will enable detailed population analysis linking the birth of young radio jets and an increase in AGN accretion rate. **VLASS Epoch 4 will provide the first statistical constraints on the radio-loud fraction of CLAGN identified with LSST.** This will provide observational tests for comparison to GRMHD simulations of accretion disk instabilities which can launch jets (e.g. Kaaz et al. 2023) and may provide clues as to the nature of populations of newly radio-bright AGN from radio surveys (Nyland et al. 2020; Wołowska et al. 2021; Zhang et al. 2022).

3.2. *Synergy with New Radio Instruments and Surveys*

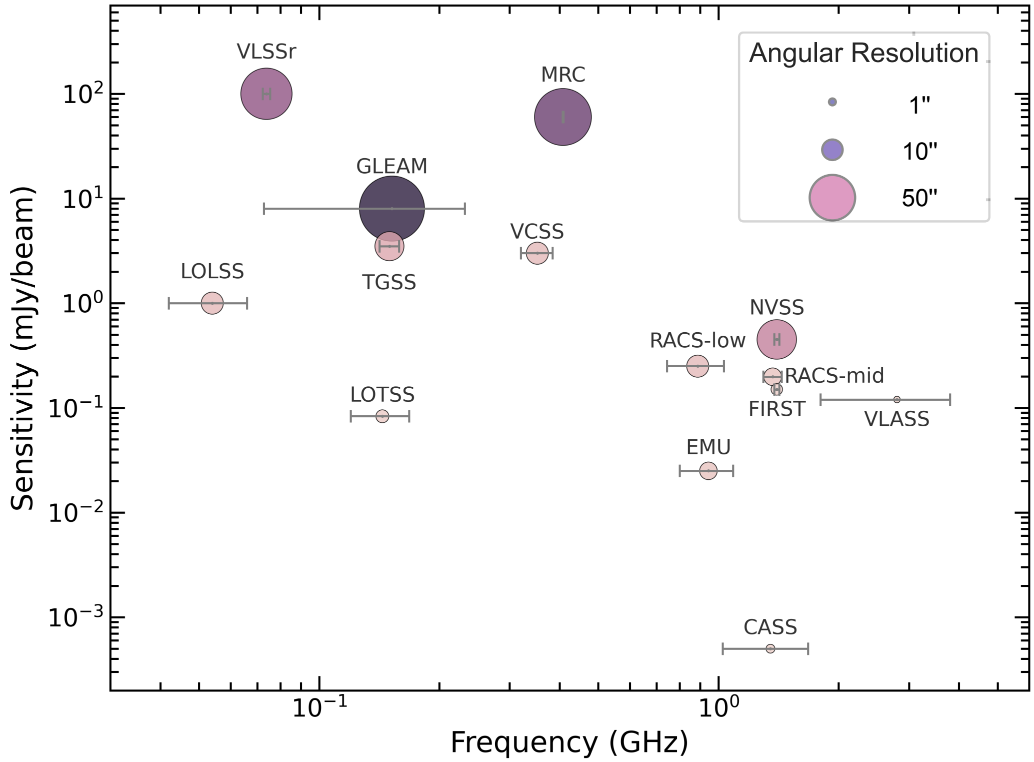

Figure 6. Radio survey frequency vs. sensitivity, adapted from Patil et al. (2020, 2022). Only surveys covering areas larger than 10,000 deg^2 are shown. We plot the nominal $1-\sigma$ sensitivity reported by the survey. The x-axis error bar indicates the bandwidth of the survey, and the size of the colored circle corresponds to the angular resolution. The radio survey acronyms and references are as follows: VLASS: the VLA Sky Survey (Lacy et al. 2020); CASS: Cadenced All Sky Survey (Hallinan et al. 2019); FIRST: Faint Images of the Radio Sky at Twenty-one centimeters (Becker et al. 1995); NVSS: NRAO VLA Sky Survey (Condon et al. 1998); RACS-mid: Rapid ASKAP Continuum Survey in mid band (Duchesne et al. 2023); EMU: Evolutionary Map of the Universe (Norris et al. 2011, 2021); RACS-low: Rapid ASKAP Continuum Survey in low band (McConnell et al. 2020); MRC: Molonglo Reference Catalog of Radio Source (Large et al. 1981); VCSS: VLITE Commensal Sky Survey (Peters et al. 2021); GLEAM: Galactic and Extragalactic All-sky Murchison Widefield Array survey (Hurley-Walker et al. 2017); TGSS: The TIFR GMRT Sky Survey Alternative Data Release (Intema et al. 2016); LOTSS: The LOFAR Two-meter Sky Survey (Shimwell et al. 2019); the VLA Low-Frequency Sky Survey (VLSSr; Lane et al. 2014); LOFAR LBA Sky Survey (LOLSS; de Gasperin et al. 2021).

3.2.1. *The ngVLA*

One of the original goals of VLASS was to establish a reference atlas for follow-up with other instruments, which would include the ngVLA. A 4th epoch of VLASS would provide more robust light curves of variable and transient sources, such as TDEs, for future ngVLA follow-up at much higher frequency, sensitivity, and resolution.

If VLASS were to continue beyond 2028, the transition from the VLA to the ngVLA would need to be considered. VLASS could continue to be executed after the VLA antenna configuration has been fixed in preparation for the construction of the ngVLA. However, this is a topic that warrants additional input from the community and is beyond the scope of this white paper.

3.2.2. *The DSA-2000*

The Deep Synoptic Array (DSA-2000; Hallinan et al. 2019) is a proposed radio survey telescope for the late 2020's that would build on the success of VLASS's synoptic approach to observing the dynamic radio sky. The DSA-2000 is designed to operate at 0.7-2 GHz with 3.5″ resolution. Its Cadenced All Sky Survey (CASS) will observe the northern sky (31,000 deg^2) 16 times over a period of 5 years. VLASS, the CASS, and other radio surveys are compared in Figure 6. The CASS will detect >1 billion radio sources in its continuum sky map with an rms noise of 500 nJy/beam. Over its lifetime, it is forecast to identify $\sim 10^6$ transients, about 1000 times more transients than VLASS captures per epoch (Dillon Dong, Ph.D. thesis). Comparison between 4 epochs of VLASS and the CASS will further bolster the discovery of new transients, increasing the probability of finding rare objects (e.g. compact binary mergers; Dong et al. 2021).

3.2.3. *The ASKAP Variable and Slow Transients Survey*

The Australia Square Kilometer Array Pathfinder (ASKAP) Variable and Slow Transients (VAST) survey will overlap with $\sim$5000 deg^2 of the VLASS survey region in its Equatorial survey (Murphy et al. 2013; Murphy et al. 2021). VAST undertakes monthly cadence observations across two bands centered on 888 and 1296 MHz at a lower resolution than VLASS of 12-20$''$ and with an rms noise of 0.2 mJy beam^{-1} per epoch. The higher cadence of VAST will probe the evolution of radio transients identified in VLASS over shorter timescales. The lower central frequencies of VAST will also provide complementary information about the radio spectrum of sources identified in VLASS. VAST completed a pilot survey from 2019-2021 and commenced the full 4 year survey in December 2022.

3.3. *Multi-wavelength and multi-Messenger Synergy*

The completion of VLASS Epoch 4 in the 2020s would provide an opportunity for overlap with the Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST; Ivezic et al. 2008), as well as space-based surveys such as Euclid (Racca et al. 2016) and the *Nancy Grace Roman* Space Telescope (Akeson et al. 2019).

3.3.1. *LSST*

LSST, which is planned to have first light in early 2025, will survey the southern sky up to declinations of $+12$ degrees in 6 optical bands (ugrizy) with an average cadence of 3-4 days, producing an expected 10 million transient alerts per night. The main LSST survey overlaps the VLASS survey region between declinations of -40 and $+12$ degrees. Three of the four LSST deep-drilling fields overlap with VLASS, meaning that deep optical imaging from LSST will be available for fields with comprehensive X-ray coverage (Ni et al. 2021). This will be enormously beneficial for AGN science with VLASS Epoch 4.

In the much shallower Zwicky Transient Facility optical time-domain survey (Bellm et al. 2019; Graham et al. 2019; Dekany et al. 2020), which reached single epoch limiting magnitudes of g$\sim$21 compared to LSST's g$\sim$24.5, there were already many detections of VLASS radio counterparts to optical transients. For example, of the 33 optical TDEs identified in the first 3 years of the Zwicky Transient Facility (ZTF; Bellm et al. 2019), two were detected in VLASS (Yao et al. 2023).

Of the 235 optically variable disk-emitting AGN in ZTF overlapping with the VLASS survey area, 29 (12.3%) were detected in VLASS (Ward et al. 2023). In addition, a VLASS detection rate of $\sim$ 5.3% was found for optically variable broad-line AGN in ZTF (Ward et al. 2023). Preliminary work on changing-look AGN (CLAGN) identified in time-domain spectroscopy from SDSS-V (Green et al. 2022) and from optical variability in ZTF has found that 12% of CLAGN have radio detections in VLASS and that half of those with detections exhibit $>$10% variability between VLASS Epochs 1 and 2 (Birmingham et al., in prep). 80% of VLASS-detected CLAGN have complementary data from the ASKAP-RACS and ASKAP-VAST surveys which will enable measurement of spectral evolution during the course of VLASS Epoch 4.

The greater depths offered by LSST to probe higher redshifts and fainter transients will provide substantially larger populations of optical transients with which we can search for radio counterparts in VLASS. The multi-epoch radio measurements that VLASS can provide for transient and variable candidates identified with LSST will facilitate statistical analyses on the radio/multi-wavelength source properties for a wide array of transient populations.

3.3.2. *Widefield Surveys with Space Telescopes*

Two new space telescopes offering widefield imaging will provide additional ancillary data that will complement VLASS: Euclid and *Roman*.

• **Euclid:** Following its launch in July 2023, *Euclid* is embarking on a 6-year mission to conduct an all-sky optical/near-infrared survey. Euclid was designed to investigate fundamental open questions in our understanding of cosmology, galaxy evolution, and dark matter and energy by producing a "3D catalog" of billions of galaxies with accurate spectroscopic redshifts.

• **Roman:** *Roman* will map the sky with a spatial resolution that is comparable to the *Hubble* Space Telescope (*HST)*, but will offer a field-of-view over 100 times larger. It is being designed to support a wide range of scientific areas, including the study of dark energy, exoplanet coronography, and time domain astrophysics. *Roman's* wavelength coverage between 0.48 and 2.3 μm and ability to reach a 5σ sensitivity of 26.2 magnitudes at the longest wavelengths in only 1 hr make it ideal fro the study of the impact of radio feedback on high redshift AGN. Grism spectroscopy with *Roman* can help determine the predominant mode of AGN feedback (e.g., Petric et al. 2022), i.e. quasar winds vs. radio jets.

Roman **is scheduled to be launched "no later than mid-2027," and its overlap with VLASS Epoch 4 will depend on the implementation strategy chosen by NRAO** (see Section 5). Regardless of the amount of temporal overlap with Epoch 4, *Roman* will provide extremely valuable information for understanding sources discovered in Epoch 4 (e.g. statistical studies of the hosts of extragalactic transient and variable VLASS sources).

3.3.3. *Multi-messenger opportunities*

VLASS has the potential to detect radio counterparts to transient sources detected via other messengers, such as gravitational waves (GWs), neutrinos, and γ-rays (for a review, see Metzger et al. 2015; Schroeder et al. 2020). **We emphasize that multi-messenger astrophysics is inherently dynamic in nature, and the extension of VLASS to a 4th epoch would therefore increase the likelihood of detect-**

ing a radio counterpart to a signal identified via a non-electromagnetic messenger.

At the time of writing, the third Gravitational-Wave Transient Catalog (GWTC-3; Abbott et al. 2023) has reported a total of 90 candidate compact binary coalescences discovered so far with Advanced LIGO and Virgo. The VLA has demonstrated its ability to identify radio emission associated with such events (e.g., GW170817; Hallinan et al. 2017). No definitive detections of GW events with VLASS have been made so far despite being plausible (Schroeder et al. 2020). VLASS Epoch 4 will extend the time frame for a possible detection of a radio counterpart to a GW event.

Another possible multi-messenger application is localizing neutrinos with astrophysical sources. This field is still in its infancy, though blazars have recently been associated with high-energy neutrino events (IceCube Collaboration et al. 2018). VLASS hasn't identified any neutrino counterparts yet, but a 4th epoch would continue to provide overlap with IceCube.

In conjunction with other radio surveys, VLASS has also proven to be valuable tool for studying Fermi unassociated γ-ray sources (Bruzewski et al. 2023).

In addition to transient sources, VLASS also provides insights into steady sources that are important for understanding the context of multi-messenger studies, such as dual AGN (e.g. Schwartzman et al. 2023; Gross et al. 2023; Walsh & Burke-Spolaor 2023).

3.4. *Commensal Data*

A 4th Epoch of VLASS would provide new data for the commensal projects that benefit from the all-sky observations of VLASS, such as VLITE, COSMIC, and *realfast*.

3.4.1. *VLITE*

The VLA Low-band Ionosphere and Transient Experiment (VLITE[3]; Clarke et al. 2016; Polisensky et al. 2016) is a commensal instrument on the VLA which records data from 18 antennas in a 64 MHz band centered at 340 MHz during nearly all regular telescope operations. Unable to directly correlate OTF observations, during VLASS observations it uses a dedicated correlator mode which collects and correlates roughly 30 seconds of data at 1.5^o intervals in RA. The resulting images and catalogs form the VLITE Commensal Sky Survey (VCSS). The Hierarchical Progressive Surveys (HiPS) for the first epoch of VCSS is available at this site http://archive-new.nrao.edu/vlass/HiPS/VCSS1/Images_vcss1_HiPS with the VCSS1 Bright Source Catalog available at this CIRADA site https://cirada.ca/vcsscatalogue.

The only existing large-area sky surveys at comparable frequencies, such as Texas (Douglas et al. 1996) and WENSS (Rengelink et al. 1997), have considerably lower resolution and/or do not cover the entire northern sky. Thus a primary goal for VCSS is to provide a northern sky model at 340 MHz. Single epoch observations are limited to mJy sensitivity and are incomplete because, as a commensal instrument, VLITE cannot re-observe any failed regions of the sky. Multiple epochs are critical both to increase the sensitivity, and to fill in holes and gaps in the single epoch coverage. A 4th epoch would be useful for both goals – the anticipated 15% increase in sensitivity for regions where all 4 epochs were successful is modest, but for regions where observations have failed in any of the previous epochs (roughly 1% of the sky has no useful data in any epoch as of this writing) the sensitivity increase could be as much as 40%.

As a complement to VLASS, VCSS also provides matched epoch spectral indices, or spectral index limits, providing valuable insight into sources that may be variable either in flux or spectral shape. Particularly for steep-spectrum transient emissions like magnetar pulses and variable pulsars, VCSS provides crucial low-frequency confirmation of time domain behavior. The 3.5^o FoV at 340 MHz results in substantial overlap between each declination row of the higher frequency survey. Consequently, VCSS facilitates the search for variability on various timescales—from minute to hour-long and even spanning days to months. This is achieved by comparing individual correlation center images across declination rows, tracking objects over a significant portion of a tile, and examining objects which appear in the FoV during multiple tile observations. Short timescale interstellar scintillations, interplanetary scintillations from the Solar wind, and long-timescale AGN variability have already been identified in VCSS data (Polisensky, private communication).

Moreover, VCSS serves as a tool for discovering new transient phenomena. While most early-type stars have stable magnetospheres with simple topologies, a subset is predicted to produce incoherent radio emission driven by the centrifugal breakout of stellar wind plasma trapped in the magnetosphere (Townsend & Owocki 2005). Polisensky et al. (2023) searched a catalog of 761 magnetic O, B, and A-type stars for detections in the first two VCSS epochs and reported radio flares from the directions of three hot magnetic stars. A false-association analysis showed a less than 1% probability that these sources were imaging artifacts. Although the VCSS data alone cannot definitively determine the origin of the flares – whether they are produced in the stellar magnetosphere or by magnetically active companions – it does provide candidates for further targeted observation campaigns. **A 4th epoch offers the potential to detect additional candidate stellar flares with VCSS, which could help to shed light on the mystery of whether hot magnetic stars exhibit flaring activity.**

[3] https://vlite.nrao.edu

VCSS is also a powerful tool for discovery of low-frequency radio transients on extended (e.g. years) timescales. Murphy et al. (2017) compared the TGSS and GLEAM sky surveys, revealing a 182 ± 24 mJy transient at 147.5 MHz of unknown origin that faded over a 1-3 year period. The 32 month observing cadence of VCSS epochs makes it well-suited for the detection of such transients. With the addition of a 4th epoch, VCSS will survey a solid angle five times greater than that of Murphy et al. (2017) for radio transients with a flux density greater than $\sim$100 mJy. **Based on the areal density from Murphy et al. (2017), VCSS is expected to detect 1-11 transient in Epoch 4.**

3.4.2. *COSMIC*

The Commensal Open-Source Multimode Interferometer Cluster (COSMIC; Tremblay et al. 2023) offers the first Ethernet-based digital framework on the VLA for rapid, real-time analysis of astronomy data. COSMIC receives a split of the digitized signals from each operational antenna in the array and autonomously processes the data in real-time, with an original goal to search for narrowband (Hz-wide) signals to improve the search for extraterrestrial intelligence (SETI). COSMIC began full operations in March 2023, and commensal observations were conducted during some of the VLASS Epoch 3. The currently operational pipeline during VLASS creates 5 coherent beams and an incoherent sum in recordings every 8 second, therefore observing over 2000 sources per hour with a noise limit of $\sim$850 mJy. By observing a wide range of frequencies and as much of the sky as possible, COSMIC seeks to constrain the prevalence of intelligent beings producing radio signals in the Galaxy, consistent with our understanding of technological communication.

COSMIC is currently made up of an Ethernet-based digital front end utilizing FPGA technologies, a 44 compute node cluster, and $\sim$1 PB of onsite storage. COSMIC uses two 100 Gb Ethernet switches to distribute the packets of data to the compute cluster. The scientific pipelines currently involve calibration with correlation, beamforming, channelization, SETI search, raw voltage storage, and a database of potential signals detected by the search.

VLASS Epoch 4 would allow the mapping of regions of the sky that were missed during science commissioning at the start of Epoch 3 in January to March 2023. Additionally, it is possible that a signal from another civilization could be transient in nature. Therefore, like searches for other periodic signals, covering as much sky over multiple observation campaigns is a benefit to the scientific goals. **Having an Epoch 4 for the VLASS survey, whether immediately following Epoch 3 or in the near future, would therefore be a significant benefit in answering the question "Are we alone?".**

This year, the COSMIC team submitted a proposal to NSF to obtain funding to upgrade COSMIC. Currently, we are capable of processing 1.4 GHz of bandwidth from up to 27 antennas when in beamforming mode. A future goal for COSMIC is to upgrade it to provide multi-casting capabilities to other commensal projects, such as $realfast$ and VLITE, process up the 8 GHz of bandwidth, and increase the sensitivity by increasing the data sampling rate. The benefit of using COSMIC over the current data streams for these other commensal projects would be for improved spectral (2 Hz – 2 MHz) and temporal (ns to s) resolution and, as we utilize commercially available parts, an easier path for upgrades in the future. These upgrades to COSMIC are planned for the 2025 and 2026 calendar years.

3.4.3. *realfast*

realfast is an instrument installed at the VLA to perform commensal, real-time millisecond transient searches (Law et al. 2018b). The search is supported by a 32-node, 64-GPU compute cluster that searches images generated on millisecond timescales. The real-time search will trigger recording of a parallel data stream for later analysis, including localization and radio spectroscopy. The instrument been used for thousands of hours, both in a commensal and primary role. *realfast* re-discovered dozens of known pulsars, several new pulsars or rotating radio transients, as well as nine FRBs. For a complete list of publications from the instrument, see http://realfast.io/publications.

During VLASS, the search has had a sensitivity of 0.4 Jy ms (10σ). The fastest sampling time is limited by the VLA correlator to 18 ms. Its discovery potential during VLASS Epoch 4 is largely defined by its time on sky. In the first 3 epochs of VLASS, *realfast* has identified dozens of pulsars, but no FRBs yet. Based on *realfast* FRB discoveries in other large VLA programs, the expectation is for roughly one FRB discovery per 2 VLASS epochs. **The extension of VLASS to a 4th epoch may therefore enable the survey's first detection of an FRB with *realfast*.** Visibility data from candidate transients (pulsars, FRBs, and more) are made public.

4. ADDITIONAL SCIENCE ENABLED BY A 4TH EPOCH OF VLASS

4.1. *The Faint Radio Sky*

The extension of VLASS to include a 4th epoch will also provide a modest improvement in depth. Specifically, adding an extra epoch of observations to the cumulative VLASS images will reduce the typical rms from $\approx 70\,\mu$Jy/beam (3 epochs) to 60 μJy/beam (4 epochs). In order to estimate the number of additional sources that would be detected with a 4-epoch implementation of VLASS, we used data from the Tiered Radio Extragalactic Simulation (T-RECS, Bonaldi et al. 2019). We assumed a 5σ point source depths at 3 GHz of 350 μJy and 300 μJy for cumulative images based on 3 and 4 epochs, respectively. **We found that a 4th VLASS**

epoch should detect ≈ 5.8 million sources compared to 5 million based on only including data from 3 epochs. However, the additional $800,000$ sources that VLASS Epoch 4 is expected to detect are at a flux density where the dominant radio population is rapidly changing from AGN to star forming galaxies. Based on the T-RECS analysis, **we expect half of these additional sources ($\approx 400,000$) to be star forming galaxies.**

4.2. *Fundamental Reference Sources*

VLASS also supports fundamental reference frame and calibration applications. The forthcoming NRAO/USNO Reference and Flux-density (NURF; Wolfe & Blanchard 2023) survey aims to provide a current catalog of images and fluxes of calibrator sources at multiple frequencies. The NURF program monitors bright, compact radio sources selected to have very long baseline interferometric (VLBI) data available plus detections in VLASS and Gaia.

A key goal of the NURF program is to characterize the dynamic, high-frequency properties of fundamental reference sources in support of preparation for ngVLA calibration needs. Although VLASS samples source emission on different angular scales than VLBI measurements, it provides complementary information to help identify sources that may not be suitable for calibration applications. **A 4th epoch of VLASS would therefore help support calibrator monitoring campaigns like NURF that are important for maintaining databases of fundamental reference sources.**

4.3. *Space Weather Observations*

Another field that stands to benefit from extending VLASS to a 4th epoch is the study of radio propagation effects through the solar wind and coronal mass ejections (CMEs). Understanding the solar wind plasma, in particular the plasma density and magnetic field strength and structure, is critical to understanding the foundational physics of the solar wind (Viall & Borovsky 2020).

A key method for probing these plasma structures involves monitoring background radio sources whose lines of sight (LOS) are located at heliocentric distances of $< 10\,\mathrm{R}_\odot$, and then observing radio propagation effects induced by the solar wind and CMEs. Such propagation effects include angular broadening[4] and Faraday rotation (FR[5]). FR is particularly important because it provides the magnetic field strength and orientation of CMEs shortly after eruption (e.g. see Kooi et al. 2021, 2022), which is important for space weather applications.

Observations of solar wind-induced radio propagation effects require a background "transmitter," such as a pulsar or a radio galaxy, that is linearly polarized[6]. On any given day, there are hundreds of linearly polarized pulsars and radio galaxies near the Sun. Radio galaxies with well-resolved, extended emission are particularly well-suited for solar FR studies, as they provide multiple LOS for measuring the properties of the solar wind plasma.

Previous VLA observations of solar wind and CME-induced radio propagation effects have been performed primarily at L band, where archival survey data from NVSS has been used to select suitable background sources based on their morphological and polarimetric properties (for a review, see Kooi et al. 2022). However, solar FR observations at L band suffer from unwanted solar interference (e.g. solar flares, radio bursts, active regions, the Sun itself, etc.). Higher frequency (i.e. S- and C-bands) observations taken in the A- or B-configurations of the VLA are therefore needed.

Full-polarimetric VLASS data products are a promising resource for developing a new reference database for solar FR studies. VLASS data would dramatically improve source selection for these experiments by providing snapshot images of the source structure, including linear polarization structure for FR experiments, for investigators to evaluate their potential for multiple-LOS observations. Such spatially-resolved information is critical for determining the magnetic field orientation of CMEs. Another improvement enabled by VLASS is the ability to monitor the variable structural and polarimetric properties of background sources. **The extension of VLASS to a 4th epoch would make the survey an even more powerful tool for studies of the solar wind and space weather.**

5. IMPLEMENTATION

The VLASS SSG discussed several possible implementation strategies for a 4th epoch of VLASS. The optimal combination of survey parameters depends on many different factors, including the scientific goals, opportunities for synergy across other instruments and surveys, and the resources available to observatory conducting the survey. Survey parameters were discussed at SSG meetings held over the course of several months. The topics that were debated in preparation for this Epoch 4 white paper were similar to the ones that were raised in the original VLASS proposal, and we refer interested readers there for a detailed review. Examples of

[4] Angular broadening results from turbulent density fluctuations within the solar wind that cause radio sources imaged through the solar wind to appear larger (equivalent to convolving the synthesized beam with an angular broadening power pattern).

[5] FR is the rotation of the plane of polarization of linearly polarized radiation as it propagates through a magnetized plasma. FR is proportional to the path integral of the electron number density and the component of the magnetic field along the LOS to the observer.

[6] Linearly polarized radiation over a broad range of frequencies resolves the $n\pi$ ambiguities in the position angle needed to measure FR.

topics that were considered are described in the remainder of this section.

5.1. *Receiver Band*

There was interest in surveys at alternative frequencies, such as C-band, in order to capture different populations of sources and to constrain the spectral properties of sources discovered previously with VLASS. However, it was noted that this could lead to ambiguities between the radio spectral index and source variability. The SSG therefore concluded that the best way to support continued studies of transient and variable sources would be for VLASS Epoch 4 to be carried out at the same frequency as the previous epochs.

5.2. *Antenna Configuration*

There was some interest in a C-configuration version of VLASS in order to capture diffuse emission that has been missed to due spatial filtering at high resolution. C-configuration data would be valuable for studies of sources such as extended radio galaxy lobes and nearby star-forming galaxies. It was noted that it would beneficial to these science topics to combine the data into a single image with the full resolution, but better sensitivity to extended structure. While this remains an intriguing option, keeping the same configuration is necessary to ensure that measurements of variable sources are measured consistently and accurately.

The SSG also notes that if the start of VLASS Epoch 4 is delayed beyond the standard 32-month cadence, additional factors may also need to be considered, such as the impact of the VLA-ngVLA transition (e.g. a fixed antenna configuration).

5.3. *Sky Coverage and Depth*

Significant changes to the sky coverage and depth of VLASS (e.g. narrow-field/deep vs. wide-field/shallow) were discussed. Deep, narrow-field surveys are valuable for studying faint sources, such as high-z galaxies and quasars. However, the detection of transient and variable sources benefits much more from wide coverage than depth (Metzger et al. 2015). We therefore recommend that the same wide sky coverage of the previous epochs be adopted for Epoch 4. This will allow VLASS to continue to support science at the forefront of our understanding of the dynamic radio sky.

5.4. *Cadence*

VLASS was designed with a 32-month cadence between epochs to be well-matched to the expected rise times of a variety of types of slow radio transients while accommodating the standard 16-month VLA configuration schedule. This cadence has proven to be effective for identifying $\sim$1000 transients per epoch (Dillon Dong, private communication), including tidal disruption events, supernovae, radio stars, and quasar jets.

The SSG discussed two broad options for the Epoch 4 cadence: maintaining the same cadence as Epochs 1-3 or increasing it. VLASS Epoch 3.2 will conclude in October 2024. If VLASS Epoch 4 follows the same 32-month cadence as prior epochs, it would take place from October 2025 to June 2027. Important scientific advantages to this approach were identified, including:

- facilitating systematic time domain searches for radio transients
- leveraging early synergy with LSST, which is scheduled to begin in mid 2025
- uniquely bridging the gap between VLASS Epochs 1-3 and the DSA-2000

However, a longer cadence is also possible. No strong scientific case for delaying the start of Epoch 4 to a longer effective cadence than 32 months was identified. It was noted that it may be beneficial for studying young, adiabatically expanding quasar jets since these sources evolve slowly over years or decades (Orienti & Dallacasa 2020). A longer cadence may therefore be a better filter for identifying candidate newborn quasar jets (e.g. Nyland et al. 2020). We also note that a delayed start to Epoch 4 might facilitate temporal overlap with *Roman* (see Section 3.3).

We also considered operational constraints on the timing of Epoch 4. One advantage of keeping the 32-month cadence the same is maintaining continuity of expertise in the execution and processing of the survey. On the other hand, a delayed start to Epoch 4 may give NRAO more time to deliver high-level data products to the community, including the single epoch (SE) images and full-polarization cubes. The delivery of the SE products was identified by the SSG as an area of concern. The timeline for the delivery of the high-level products has been hampered by data processing delays and technical challenges that were not foreseen before the survey began. We discuss the SE products further in the next sub-section.

Although operational considerations are important, the optimal cadence of VLASS Epoch 4 should be guided primarily by science, with the goal of identifying the best solution for ensuring that the VLA delivers the most high-impact, cutting edge science possible. **We therefore recommend maintaining the standard 32-month VLASS cadence for Epoch 4 if feasible.** This is the best strategy for facilitating systematic time domain searches for radio counterparts to multi-wavelength/multi-messenger transients that will be identified by new instruments and surveys (e.g. LSST).

5.5. *Data Processing*

The increased data processing load to accommodate an additional VLASS epoch will require significant computational and staffing resources to carry out. **The SSG identified key areas of concern about how the data processing at NRAO would be affected by a 4th VLASS epoch.** We provide a summary of these concerns below.

5.5.1. *Quick Look vs. Single Epoch Imaging*

Epoch 4 will leverage the considerable software infrastructure built for Epochs 1–3, including mature pipelines that have already been developed. Nevertheless, the amount of computational and staffing resources needed to process and deliver the Quick Look Epoch 4 products will be significant. Multiple SSG members were concerned that Epoch 4 Quick Look processing would use up all of the available observatory resources (e.g. disk space, processing speed, data analyst time, etc.), thus creating a bottleneck in the timely delivery of the SE products to the community.

The SSG considers the delivery of the SE VLASS products to be extremely important, and advocates for a strategy that enables the Epoch 4 science goals to be achieved without delaying the release of the SE products. We emphasize that this is a complex issue, and the SSG did not reach a unanimous conclusion on its recommendation for how NRAO should proceed. We recommend that this topic continue to be discussed among the SSG, NRAO, and the broader user community.

5.5.2. *Stacked Images*

An additional data challenge for a 4th epoch is that of combining measurement sets into a single stacked image, with the time taken to produce such an image scaling with the number of visibilities used. Astronomers and computer scientists at the University of Wisconsin-Madison are actively working on tackling such problems by leveraging the facilities at the University of Wisconsin's Center for High Throughput Computing (CHTC)[7]. Indeed, there is currently a dedicated search for a postdoc to work specifically on the development and optimization of a pipeline to combine measurement sets from multiple VLASS epochs into full depth stacked images. The work done here will result in mature and robustly tested image combination algorithms already being in place in time for a 4th VLASS epoch. Moreover, the established interest in VLASS at the University of Wisconsin makes it likely that CHTC may be leveraged in the future to help offset the computational needs of processing an extra epoch of observations.

6. BROADER IMPACTS

6.1. *NRAO*

VLASS is the only NRAO program that is working on optimizing the computing cluster usage by running hundreds of simultaneous jobs using the High Throughput Computing (HTC) paradigm that will be essential for ngVLA processing. The VLASS imaging problem is also pushing development of high speed, GPU-enabled gridders that will be needed to solve the wide-field imaging problem for noise-limited imaging with ngVLA at cm wavelengths. VLASS has been pioneering automated QA of imaging projects using both heuristic and machine learning approaches. Again, these techniques will be essential in the ngVLA era. **A 4th VLASS epoch would provide further impetus for the development and optimization of the HTC, QA, and imaging algorithms at NRAO.**

6.2. *Community*

VLASS is also important for NRAO's broader impacts efforts. VLASS data products do not require a detailed knowledge of interferometry to be used scientifically, and are thus ideal for undergraduate or bridge program projects. A 4th epoch of VLASS would provide additional opportunities for engaging students from a diverse range of backgrounds in radio astronomical research. This is important for maintaining and enhancing both interest and expertise in radio astronomy in the ngVLA and SKA eras.

7. SUMMARY

VLASS has proven to be a productive, high-impact astronomical survey with a global user-base of astronomers. We recommend extending VLASS beyond its original 3-epoch timeline to include a 4th epoch. A 4th epoch would uniquely enable new discoveries and scientific advancements in the the dynamic radio source population, provide overlap with new instruments and surveys that are scheduled to begin after the conclusion of Epoch 3 (including LSST), and leverage new upgrades to commensal instruments on the VLA. A summary of key scientific opportunities with VLASS Epoch 4 is provided in Table 1.

A variety of approaches for extending the survey were considered, and key areas of concern were identified. Our overall recommendation to NRAO is that the 4th VLASS epoch be carried out with the same parameters and observational strategy as the previous epochs, namely a full-polarization survey over the full S-band bandwidth (2-4 GHz) providing an angular resolution of $2.5''$ with a cadence of 32 months. If NRAO adopts these recommendations, VLASS Epoch 4 should ideally be scheduled from October 2025 to June 2027.

The SSG was divided on the optimal strategy for processing new data from Epoch 4 while continuing to make progress on the delivery of the SE products from Epochs 1-3 that have been promised to the community. The timely re-

[7] https://chtc.cs.wisc.edu/

Table 1. Key VLASS Epoch 4 Scientific Opportunities

Description	Astro2020 Scientific Priority Area
A total of 1000 new radio transients	Dynamic universe
10 new radio-detected TDEs	Dynamic universe, Drivers of galaxy evolution
Dozens of young quasar jets	Dynamic universe, Drivers of galaxy evolution
Radio-loud fraction of CLAGN	Dynamic universe, Drivers of galaxy evolution
400,000 faint star-forming galaxies	Drivers of galaxy evolution
30 new radio stars (including M dwarfs)	Habitable worlds
New constraints on technosignatures	Habitable worlds

lease of Quick Look images to the community[8] has proven to be a successful strategy for enabling new scientific discoveries with VLASS, particularly in the time domain, and should continue during the 4th epoch. However, the impact of Epoch 4 on the release of the SE products for earlier epochs is a key concern. We recommend that the issue of how to balance observatory resources for releasing VLASS data products be discussed further among the SSG, NRAO, and the broader user community.

We recognize the considerable demands on the NRAO staff that are needed to support VLASS, and we advocate for strategies to streamline the workload as much as possible. We believe the observatory's continued investment in high-impact survey science will help prepare it for challenges that will need to be overcome in the ngVLA era.

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. Basic research in radio astronomy at the U.S. Naval Research Laboratory is supported by 6.1 Base Funding. Construction and installation of VLITE was supported by the NRL Sustainment Restoration and Maintenance fund.

[8] Quick Look images for Epochs 1-3 have been released to the community on a timescale of about month after being observed.

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