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VLASS Science Case Update

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ABSTRACT

The science case for the VLA Sky Survey (VLASS), written before the survey was started, has evolved as VLASS data have become available. In this update, we show how the unique capabilities of VLASS have been used to both expand upon and add to the original science case. VLASS has proved particularly valuable for radio transient studies, with groundbreaking new results on radio emission from gamma-ray bursts, tidal disruption events, supernovae and newly-born AGN jets. We also update the science case for polarization studies, including Stokes V, and discuss some scientific results on radio-loud AGN, and from the commensal VLITE and *realfast* surveys. Finally, we discuss the new science that is likely to emerge from the third epoch of VLASS observations, which should roughly double the number of detected transients, allow follow-up of many sources from the first two epochs, and will include a new commensal all-sky SETI survey.

1. INTRODUCTION

The VLA Sky Survey (VLASS) science case was first outlined in the survey proposal and then summarized in the survey description paper (Lacy et al. 2020) (see Appendix A for citation information). It was based around four key areas: hidden explosions and transient events, Faraday tomography of the magnetic sky through polarimetry, imaging galaxies through time and space, and new Milky Way science. Now that the survey has completed observations for its second epoch, science results are emerging at a rapid rate. Furthermore, observations for the third epoch are to be reviewed in May 2022. We therefore felt it timely to present an update to the science case. Given that observations are only 2/3 complete, and processing of high quality continuum and polarization images has been delayed due to technical difficulties that have only recently been overcome, much of the science has been focused on transients and variables. These were found in the Quick Look image products that are produced 1-2 months after observation (Section 2). Another key set of use cases has emerged from the commensal projects, *realfast* and the VLITE Commensal Sky Survey (VCSS) (Section 3). Although pipelined VLASS polarization products will not be produced until Summer 2022, the polarization science cases have evolved since the original science case was written (Section 4). The survey has also been used for more traditional extragalactic continuum radio astronomy (Section 5), but only a couple of Galactic science papers have emerged (Ruan et al. 2020; Barrett 2022). In this Memo we present some of these early science results and look forward to Epoch 3. **Note that this document is not intended to be a science case for the third epoch, which we consider to have been approved as part of the original survey scope. Rather, the intention of this document is to show that the survey is being used to make new discoveries, that science beyond the original case is being carried out, and to look towards future science opportunities with the existing survey data plus the addition of Epoch 3.**

2. TRANSIENT EVENTS

2.1. *Overview*

The systematic exploration of the time domain radio sky is one of the primary science themes motivating VLASS. The VLASS strategy of covering the whole sky observable by the VLA in three epochs is optimized for the detection of radio transients and variables. VLASS is providing a 100× increase in the number of radio transients detected relative to previous surveys. With > 2000 transients detected in Epoch 2 relative to Epoch 1 and a similar number that have disappeared from Epoch 1 to Epoch 2 (D. Dong, personal communication), early results already confirm that VLASS will transform our understanding of the transient radio sky.

Most of the VLASS radio transients detected to date are opening a unique window on explosive events powered by core-collapse, merger, accretion, or stellar activity. Synchrotron emission from shock interaction is an excellent means to diagnose relativistic outflows and is sensitive to a wider range of Doppler boosting factors than surveys in the γ-ray regime (Piran et al. 2019). This has been demonstrated with the detection of a decades old transient, present in FIRST but absent from VLASS, that is a strong candidate for the first bona fide orphan gamma-ray burst afterglow (Law et al. 2018; Mooley et al. 2022).

2.2. *Tidal Disruption Events*

The tidal disruption of stars by supermassive black holes at the centers of galaxies (TDEs) can also produce a range of relativistic and sub-relativistic outflows that can be sensitively traced in the radio (Alexander et al. 2020). The first radio-discovered TDE was detected in the Caltech-NRAO Stripe 82 Survey (CNSS; Mooley et al. 2016), a precursor to VLASS (Anderson et al. 2020). VLASS has expanded the number of TDEs discovered in the radio, including a decades old transient that has been fading since 1986 that fills the radio luminosity gap between the relativistic, jetted TDEs observed at high redshift, and the sub-relativistic outflows observed in the local universe (Ravi et al. 2022). More recently a candidate relativistic TDE has been discovered in VLASS at a distance of only 340 Mpc (Somalwar et al., in prep), much closer than previously uncovered events. The discovery of this candidate was made by two separate teams working on VLASS, one using comparison of VLASS to the NRAO VLA Sky Survey (NVSS; Condon et al. 1998), and the second using a new technique combining simultaneous VLASS and commensal 340 MHz VCSS data aimed at targeting inverted spectrum dynamically young sources. An unexpectedly very delayed TDE radio flare in ASSASN-15oi was discovered in VLASS by Horesh et al. (2021) four years after the initial event.

2.3. *Supernovae*

Radio transient surveys are also particularly well-suited to identifying populations powered by the interaction of supernova ejecta with dense environments, tracing the often complex mass loss history of massive stars. While optical surveys can identify interaction with dense material in the immediate environment ($\sim 10^{15}$ cm) of the supernovae (e.g. super-luminous Type IIn supernovae), radio surveys at GHz frequencies are biased towards the detection of dense shells of wind material at much greater distances ($\sim 10^{16} - 10^{18}$ cm), tracing pre-supernova outbursts in the centuries prior to core-collapse.

Cross-matching all publicly announced optical supernovae prior to 2020 with VLASS has revealed a sample of 19 heretofore undetected luminous afterglows with properties that do not obey predictions assuming an r^{-2} density profile from a simple continuous wind (Stroh et al. 2021). Consistent with this observation, follow up of extremely luminous radio transients discovered in VLASS and associated with galaxies in the local universe ($<$ 200 Mpc) shows that a substantial fraction have indications of interactions of supernova ejecta with dense winds (Dong et al. in prep.). These discoveries open a new window on studies of common-envelope interaction, which is thought to be an important mechanism for stripping the envelopes of massive stars, and for the production of tight compact binary systems observed in coalescence by LIGO and VIRGO. In one spectacular example (Dong et al. 2021), the radio transient is spatially coincident with an archival X-ray transient detected by *MAXI*, implying a relativistic jet was launched at the time of core collapse. The combination of an early relativistic jet and late-time dense interaction is consistent with expectations for the inspiral of a compact object within the envelope of its companion, leading to a merger-driven core collapse supernova. This type of explosion had been predicted (Chevalier 2012), but never observed before (Figure 1).

2.4. *Newborn Quasar 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). 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 the Faint Images of the Radio Sky at Twenty Centimeters survey (FIRST; Becker et al. 1995). These quasars appear to have transitioned from radio-quiet to radio-loud in the past 10-20 years (Figure 2). Simultaneous, multi-band follow-up with the VLA has revealed compact morphologies and peaked

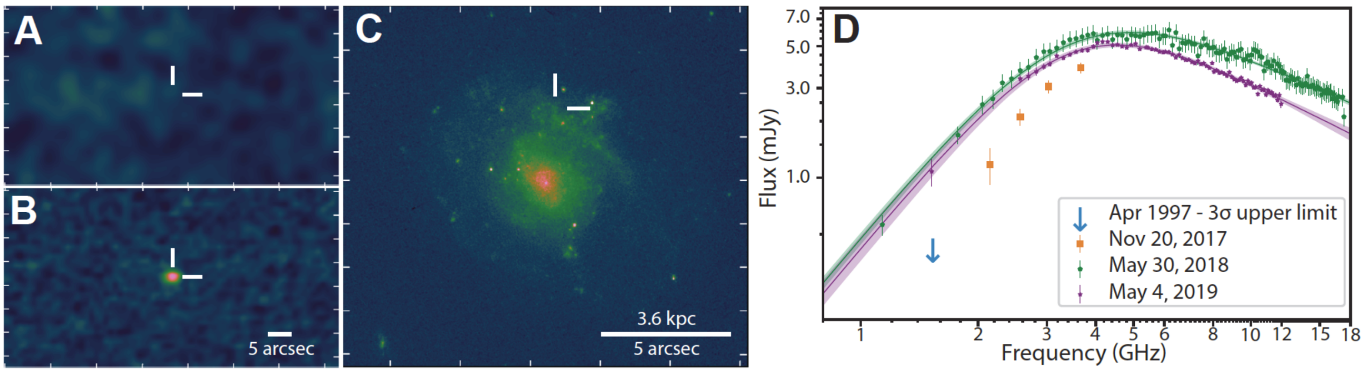


Figure 1. Transient highlight - A merger-triggered core collapse supernova (Dong et al 2021): VT J1210+4956 was a transient discovered in VLASS Epoch 1.1, relative to FIRST, and represents the first discovery of a new class of merger-triggered supernovae. Panel A) Non-detection in the FIRST survey at 1.4 GHz, with a 3σ upper limit of 0.41 mJy on 1997 April 17. Panel B) Detection in VLASS at 3 GHz at 2.7 mJy 20.59 years after the FIRST observation (2017 November 20). Panel C) Optical image of the location of VT 1210+4956 in a star-forming galaxy at a distance of 140 Mpc. Panel D) The radio spectrum of VT 1210+4956 measured from the VLASS discovery observation, and follow-up epochs observed with the VLA (Project 19A-422). The radio emission is consistent with supernova ejecta colliding with a dense shell of material, ejected by a binary interaction in the centuries prior to explosion. We also associate the supernova with an archival X-ray transient, which implies a relativistic jet was launched during the explosion. The combination of an early relativistic jet and late-time dense interaction is consistent with expectations for the inspiral of a compact object within the envelope of its companion, leading to a merger-driven core collapse supernova.

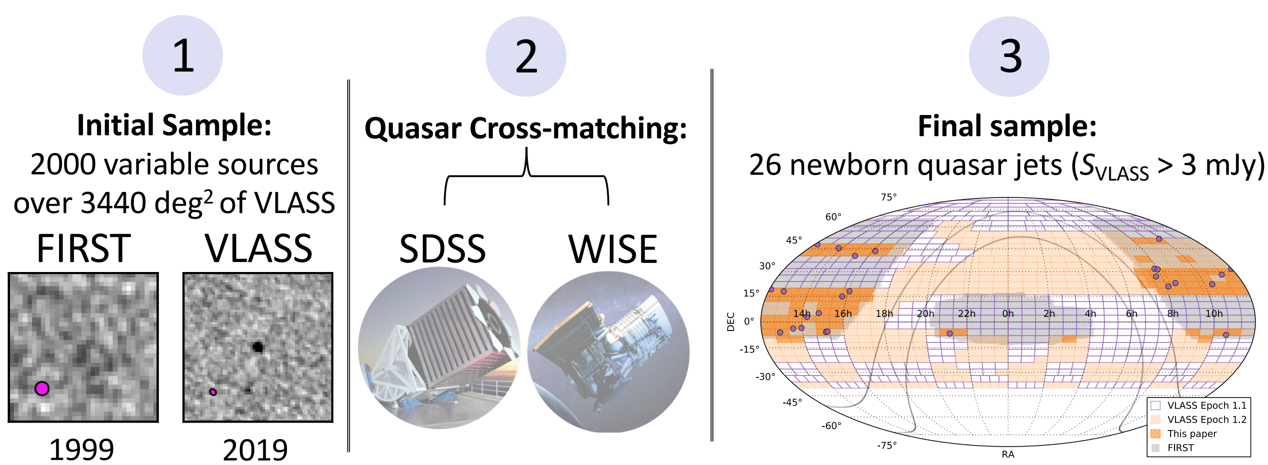


Figure 2. Illustration of the selection criteria from Nyland et al. (2020) used to identify quasars that had switched from radio-quiet to radio-loud between FIRST and VLASS Epoch 1.

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 supermassive black hole 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 (Figure 3). Changes in source flux tracked across VLASS Epochs 1, 2, and 3 will directly constrain the physics of the young jets and their ambient environments (e.g. Ross et al. 2022). In combination with simultaneous multi-band VLA follow-up observations, the 3 epochs of VLASS will test whether beaming, multiple superimposed components (e.g. a restarted jet + fading "lobes"), or transient phenomena (e.g. extreme scattering events) influence the dynamic radio properties of candidate newborn quasar jets.

2.5. *Fast Radio Burst Persistent Radio Sources*

Fast radio bursts (FRBs) are bright, millisecond flashes, which have been seen in galaxies out to cosmological distances.[1] The ~600 FRBs published so far show a bewildering diversity. Some repeat, others are so far one-offs; some repeating FRBs repeat in periodic active windows, others repeat randomly. Some FRBs are in the disks of spiral galaxies, but one has now been found in a globular cluster. Favored models for FRBs center on magnetars (Margalit & Metzger 2018), but many other models are possible (Platts et al. 2019), and there is currently no consensus, nor an understanding of how many different types of sources might need to be explained.

A vital clue to the nature of FRBs is that two FRBs have been associated with *persistent radio sources* (PRSs), which perhaps represent nebulae powered by the FRB mechanism (Law et al. 2022). The first two epochs of VLASS are already being used to search for more PRS: an untargeted search for PRS-like objects across the full VLASS survey (Law et al., in prep.), and a targeted search for PRS at the locations of FRBs detected by CHIME (Ibik et al., in prep.). Dong et al. (in prep; Figure 4) have found a transient with very similar properties to PRSs that is strong candidate for an emerging pulsar wind nebula. Epoch 3 of VLASS will provide key information on the flux variability of PRSs and will allow more sensitive searches for PRSs based on stacked images.

[1] The highest redshift so far seen for an FRB is $z = 0.66$; see frbhosts.org.

2.6. *Time domain science with Single Epoch products*

The delivery of Single Epoch (SE) products will allow further time domain science to be performed. In particular, the spectral evolution of slow transients can be studied between epochs, as can the polarization. In general, polarization variability contains information on the structure of magnetic fields in the jet production region and/or in regions of Faraday rotation around it (Martí-Vidal & Goddi 2021), but has only been studied for a few hundred sources (e.g. Lister et al. 2021), with VLASS we will be able to extend these studies into the tens of thousands.

3. COMMENSAL SCIENCE

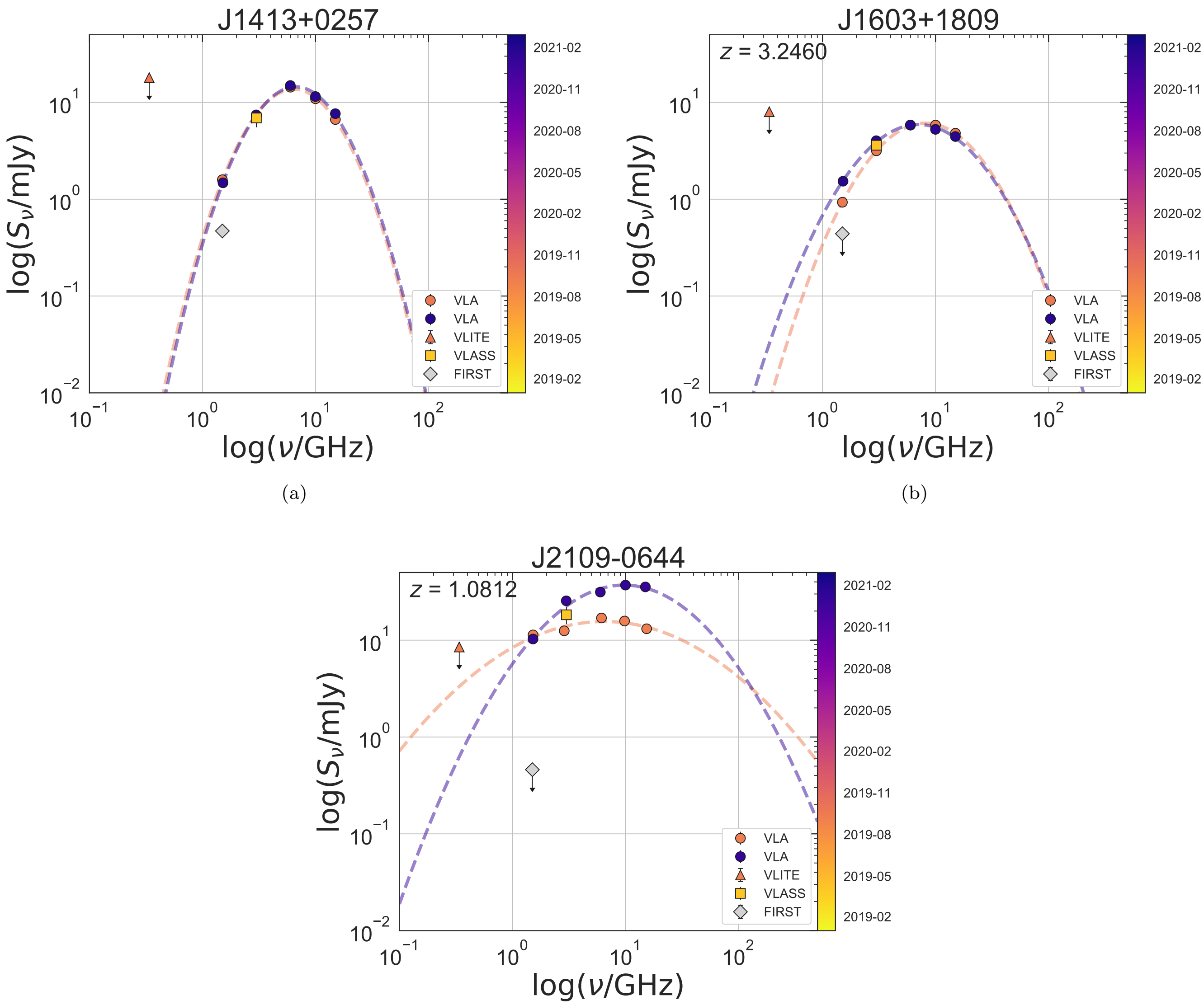
3.1. *realfast*

realfast is a commensal, real-time, fast-transient search system integrated with the VLA correlator. This gives the VLA the ability to search for dispersed transients on a fast (milliseconds) visibility data stream before the standard visibility data (binned in timescales ~seconds) are generated. Commensal operation during VLASS has discovered transient and variable signatures on timescales faster than the correlator integration time. This has also been useful in revealing data problems during VLASS that have resulted in improvements to the correlator and scheduling software.

3.1.1. *FRBs*

realfast is now in full commensal operation for L-, S-, C- and X-band continuum observations. With its real-time operation and access to a slow data stream, *realfast* is uniquely positioned to search for persistent and fast-evolving radio counterparts to FRBs. The slow-sampled data is used to search for both a persistent radio source and/or rapid time-evolving radio emission (seconds to minutes). This feature was first demonstrated for large numbers of FRBs by VLA/*realfast* and has since been designed into Square Kilometre Array (SKA) pathfinders, such as The Australian SKA Pathfinder (ASKAP; Hotan et al. 2021) and MeerKAT (Jonas & MeerKAT Team 2016).

The *realfast* system has made major contributions to our understanding of FRBs. The prototype system was used to make the first precise localization of an FRB, which provided the first direct evidence of FRBs as an



(a) (b) (c)

Figure 3. Multi-epoch, multi-band radio spectra of three candidate young jets fit with curved power-law models (see Nyland et al. 2020 for details). On timescales of a couple of years, the radio spectra of candidate newborn jets may exhibit a) no signs of variability, b) steadily increasing optically-thick flux consistent with expectations for an adiabatically expanding young source, or c) extreme changes in shape indicative of relativistic beaming effects (Nyland et al. in prep.)

extragalactic phenomenon (Chatterjee et al. 2017; Tendulkar et al. 2017; Bassa et al. 2017; Marcote et al. 2017). It is currently the only FRB detector in the world with an angular resolution that allows *every FRB it detects* to be confidently associated with a host galaxy out to $z \sim 1$ (Figure 5).

A central question in the field is: do all FRBs come from the same kind of object or are there multiple kinds of FRB-emitting objects? FRB localization will continue to drive novel discoveries by building large samples of multiwavelength associations. *realfast* has localized seven FRBs, largely through pointed observations of repeating FRBs. Two of these FRBs have persistent radio counterparts that have motivated new models for FRB sources (Niu et al. 2021). These models make predictions for source environment and host galaxy that are not yet well constrained by the small sample of FRB/PRS sources. More examples are needed to measure the luminosity and spectral properties that define their total energy, age, and other properties.

3.1.2. *Pulsars*

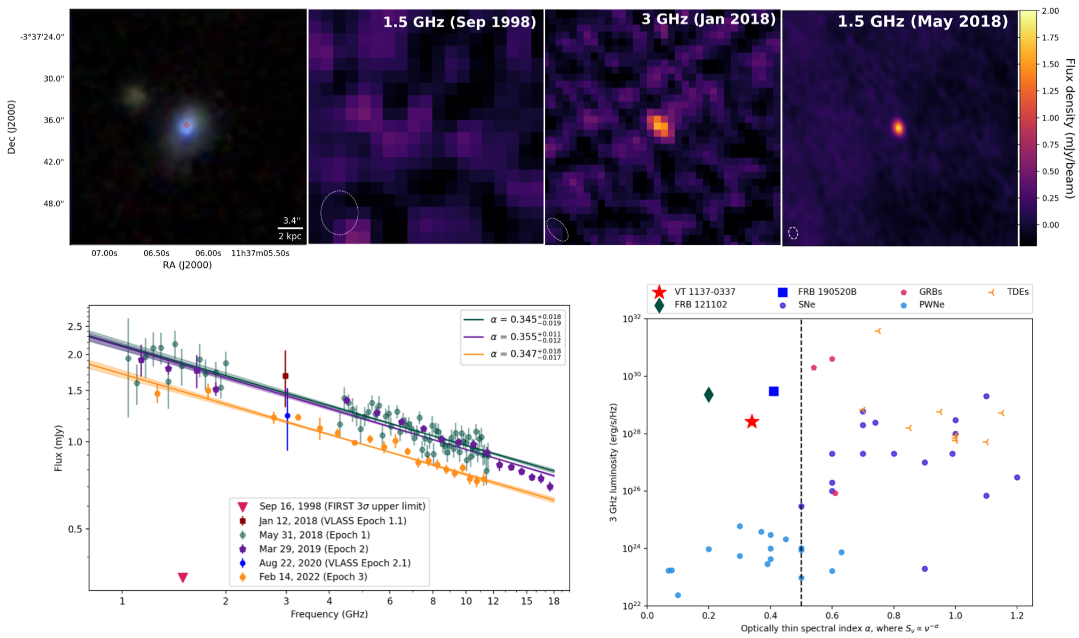


Figure 4. Top: The discovery of VT 1137-0337. From left to right: (1) The position of the transient relative to an SDSS image of its host: a $10^{8.3}$ $M_\odot$ dwarf star forming galaxy, (2) A nondetection in our reference epoch, the FIRST survey, (3) The initial detection image from Epoch 1.1 of VLASS, (4) Confirmation of the transient at the same frequency as FIRST through VLA followup. Bottom: (1) The flat $\nu^{-0.35}$ radio spectrum of VT 1137-0337, which has faded by ≈20% in the 4 years since first detection and shows no indication of spectral structure due to scintillation or AGN variability. (2) VT 1137-0337 in comparison to other transients and flat spectrum sources associated with dwarf galaxies. Among sources left of the dashed line (harder than the $\nu^{-0.5}$ diffusive shock acceleration limit), VT 1137-0337 is the only transient. The source bears a striking resemblance to both known persistent radio sources associated with FRBs

The commensal fast transient search during VLASS has also detected numerous pulsars. Currently, 40 millisecond transients have been found: 35 are identified as known pulsars via sky position and dispersion measure (DM) matches; 5 have DM consistent with galactic sources and are likely to be newly-discovered pulsars. In some cases, only a single pulse is detected, making them candidate "rotating radio transients" (RRATs). The sources have been found via their individual pulses, rather than periodicity searches. This kind of search is much less sensitive than traditional searches, but it selects for pulsars with large pulse-to-pulse variability or mode-changing behavior (Burke-Spolaor & Bailes 2010). Furthermore, VLASS observes from 2–4 GHz, a frequency range that has never been used for an all-sky pulsar survey. These two facts make the VLASS pulsar survey a unique complement and novel view on the Milky Way pulsar population.

3.2. *VLITE Commensal Sky Survey*

The VLA Low-band Ionosphere and Transient Experiment (VLITE; Clarke et al. 2016) is a commensal observing system on the VLA that operates at 340 MHz during nearly all observations that use the Cassegrain focus. VLITE records roughly 6000 hours of data per year and currently operates on 18 antennas. VLITE was modified to enable operation during VLASS. The resulting data acquired in this mode is known as the VLA Commenal Sky Survey (VCSS; Peters et al. 2021).

VCSS observations have been underway since the beginning of VLASS. Data are processed using a modified version of the VLITE data processing pipeline. Low frequency observations have much larger primary beam responses than higher frequencies, thus VCSS produces a set of overlapping snapshots based on the VLASS observing strategy. The snapshots are combined into mosaics with a typical sensitivity of 3 mJy/beam for a single epoch, and a resolution of 20″. All VCSS mosaics are processed through the VLITE Database Pipeline (VDP; Polisensky et al. 2019) into a custom SQL database. The VCSS data products are used for stand-alone science, such as measuring the properties of extended, steep-spectrum sources that VLASS not be detected by VLASS. Together with VLASS, VCSS also provides simultaneous spectral index measurements, which constrains source conditions (e.g. optically-thin vs. optically-thick synchrotron) and ages.

At early times, radio transients provide unique physical information such as ejecta speeds and ambient den-

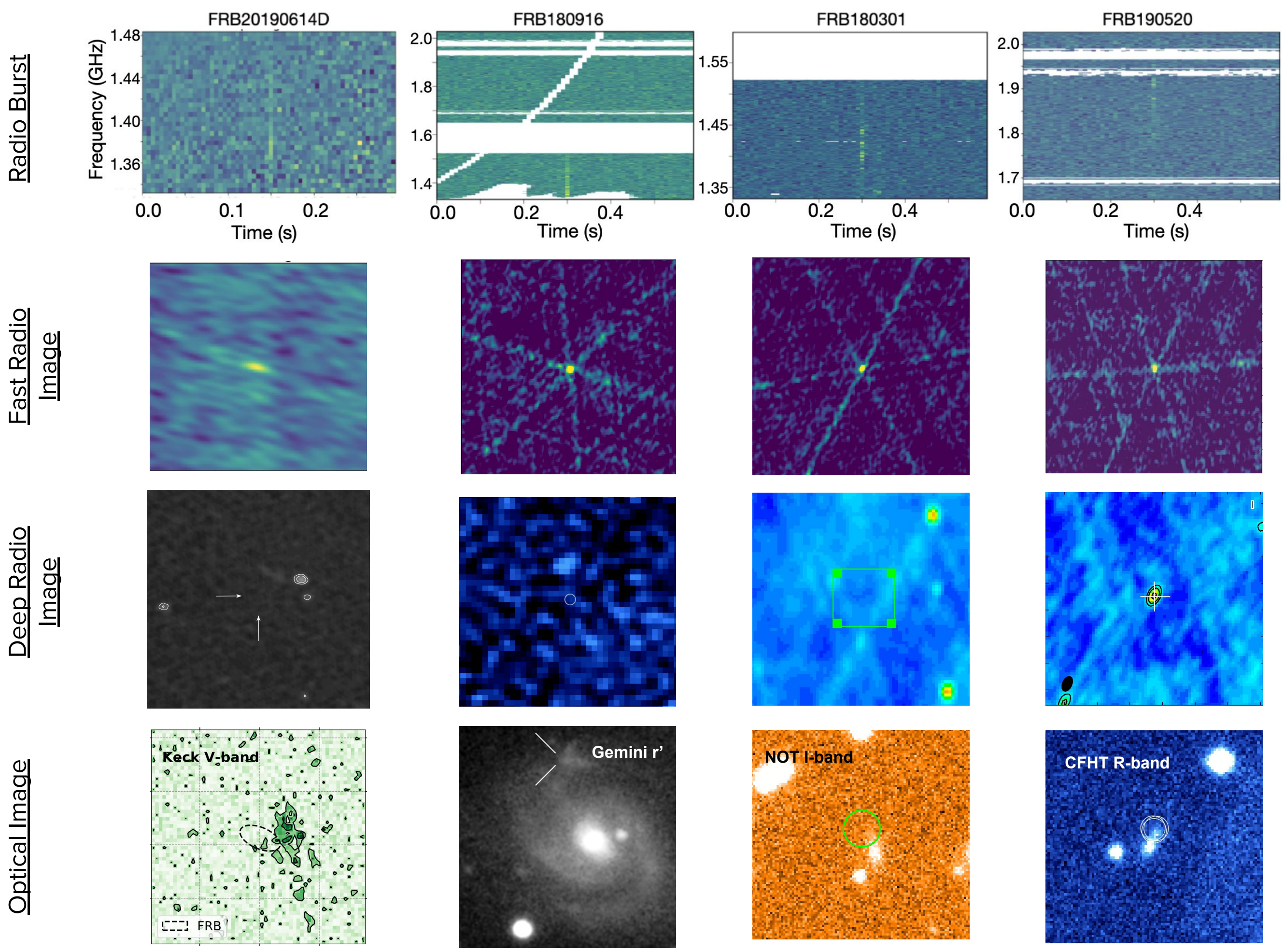


Figure 5. Summary view of four of the seven VLA/*realfast* localizations of FRBs (publications at http://realfast.io/publications/). These detections have helped demonstrate that FRBs live in a wide range of environments, including high and low stellar mass, mergers and isolated galaxies, and hosts with ionization dominated by both star formation and active galaxies.

sity profiles that are key to understanding energetic explosions and their progenitors. The challenge is to identify and study these events before these early signatures fade. The combination of VLASS and VCSS is offering a unique view of young transients, by providing instantaneous 0.3–3 GHz spectral indices for >500,000 sources at each VLASS epoch. Chen et al. (in prep.) have used this data set to derive a comprehensive census of self-absorbed and optically thick (and hence potentially young and rapidly-evolving) transients at the earliest stages of evolution, including a remarkably bright ($\sim$70 mJy) new Galactic nova. Epoch 3 of VLASS and VCSS will not only increase our yield of such sources by 50%, but will let us track the spectral evolution of such sources identified in the first two epochs.

4. POLARIZATION

4.1. *Circular polarization*

A special consideration that has emerged after the original science case was written is whether to store the Stokes V (circular polarization) images that are produced by the pipeline. Initially, it was thought that Stokes V would be of poor quality due to difficulties with on-axis calibration and strong off-axis leakage. The decision was thus taken early in the survey not to store the Stokes V products, saving $\approx$ 30% in storage costs (Stokes V is output by the pipeline by default, so the processing costs are zero). Early tests, however, suggest that the on-axis calibration can be as good as for Stokes Q and U, and that the Stokes V off-axis leakage, though worse than for Q and U, is $\lesssim$ 1% compared to source V, polarizations of up to $\sim$ 10%.

Circularly-polarized emission from stars can be due to intrinsic processes in a single star, or from binary (star-star or star-planet) interactions. It provides information about both the star itself (e.g., single vs. binary) and about the extent to which processes at or near the Sun are similar or dissimilar to those of other stars. Typical polarizations are well above the 1% level (e.g. Hallinan et al. 2007; Villadsen & Hallinan 2019; Vedantham et al. 2020; Quiroga-Nuñez et al. 2020; Pritchard et al. 2021). Pulsars and magnetars also often show circular polarization. It is also possible that new classes of object will be discovered. For example, Wang et al. (2021) find a mysterious transient with strong circular polarization near the Galactic Center. In AGN, circular polarization of $\gtrsim$ 1% is much rarer, however, some low-luminosity AGN show circular polarization (Irwin et al. 2018). All known sources of circular polarization are variable, thus the multi-epoch nature of VLASS is particularly important for this science.

4.2. *Linear polarization*

Polarimetry of compact sources was one of the main original science drivers for VLASS, with the potential to provide unique information on the magnetic fields in both active and star-forming galaxies, and on how these fields have evolved over cosmic time (Mao et al. 2014). In particular, VLASS is a superb complement to lower-frequency polarization surveys such as the Polarization Sky Survey of the Universe's Magnetism (POSSUM; Gaensler et al. 2010) and the LOFAR Two-metre Sky Survey (LOTSS; Shimwell et al. 2022), because it is sensitive to much higher rotation measures (RMs) that are expected to completely depolarize sources in these other data sets. Furthermore, VLASS provides significant sky overlap with both POSSUM and LOTSS, allowing data sets to be combined to perform ultra-broadband spectropolarimetry (see, e.g., Anderson et al. 2016). This makes both VLASS on its own and VLASS in combination with POSSM or LOTSS valuable for identifying Faraday complex souces, where a simple Faraday screen model is insufficient to explain the observed dependence of polarization on wavelength (Anderson et al. 2015).

While polarization processing from VLASS is still in a pilot/testing phase, the Canadian Initiative for Radio Astronomy Data Analysis (CIRADA; www.cirada.ca) has created an extensive software suite for analysis and processing, ready for application to VLASS Stokes cubes. This includes quality assessment and diagnostic tools (which have already been used on pilot cubes), and pipelines to apply rotation RM synthesis and derive RM catalogs. Analysis of pilot cubes has resulted in a detection of around $\sim$ 6 RMs per deg^2, consistent with predictions, and implying a total yield of around 200,000 RMs per epoch.

A relatively unexplored topic is time-variability of AGN polarization, which directly probes physical processes happening close to the central supermassive black hole. Polarization monitoring over decades (e.g., Aller et al. 2017) and/or at milliarcsecond-scale resolution (e.g., Hovatta et al. 2012; Lister et al. 2018) have both been performed for modest samples of hundreds of AGN over a small set of widely spaced frequencies, and mostly only for very bright sources. But, there has never been a large-scale, multi-epoch, broadband spectropolarimetric survey at mJy flux levels. Initial spectropolarimetric results from a small number of sources suggest remarkable, complex variability in Faraday rotation for some AGN (Figure 6; Anderson et al. 2019). However, a much broader phenomenology needs to be established before any meaningful interpretation becomes possible.

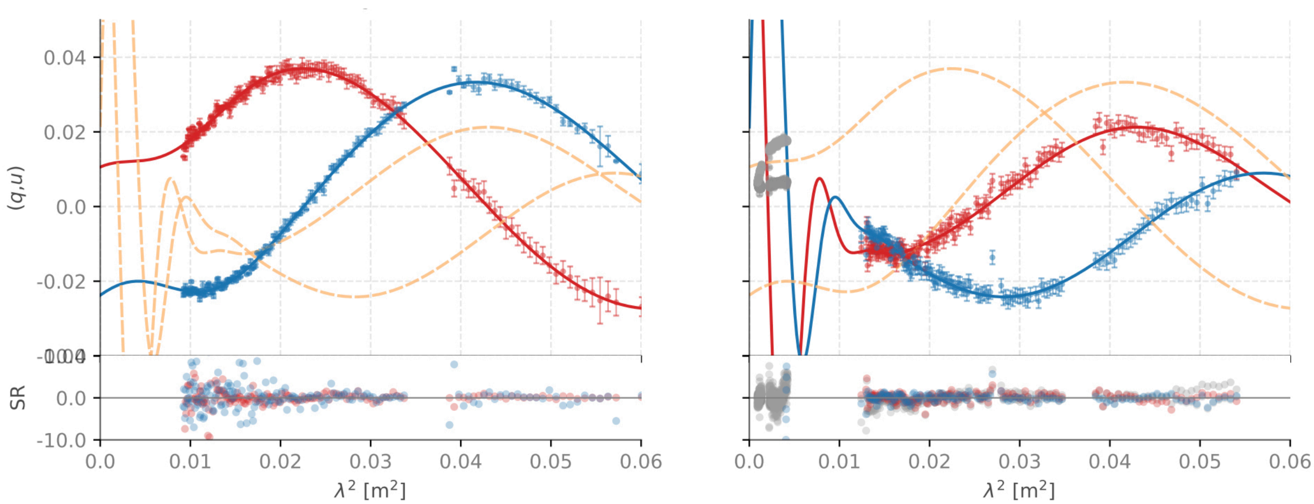


Figure 6. Broadband spectropolarimetric variability of PKS B0454-810 between 2012 (left panel) and 2017 (right panel) (Anderson et al. 2019). Red points represent Q/I, while blue points indicate U/I, with respective best-fit models from a multi-component Faraday rotating source shown as red and blue lines. Orange lines show the best fit at the other epoch, and the lower panel shows the standarized residuals between the data and the model. Substantial variability in frequency-dependent polarization properties is seen between epochs. The source's 1.4 GHz total intensity varied from 0.81 Jy in 2012 to 0.97 Jy in 2017.

5. IMAGING GALAXIES THROUGH TIME AND SPACE

The high angular resolution of VLASS makes it unique among wide-field radio surveys, and VLASS has already been used many times in studies of radio galaxies and other AGN. To give some examples, VLASS data have been used to study the structure and spectra of dust obscured AGN (Patil et al. 2020), AGN in dwarf galaxies (Molina et al. 2021; Ward et al. 2021), and an extended radio jet at $z = 6.1$ (Ighina et al. 2022).

VLASS was not designed with high surface brightness sensitivity as a goal, nevertheless it has proven very useful in the study of extended (angular size $\gtrsim 1'$, corresponding to ≈ 0.5 Mpc at $z = 1$) radio galaxies. VLASS reveals structure in the outer lobes of radio galaxies that would appear unresolved in lower-resolution surveys. Furthermore, VLASS detections of the cores and kpc-scale inner structures of giant radio galaxies have proven of great value for providing optical/IR identifications, and have improved our understanding of the nature of ongoing activity in the cores and inner jets (e.g. Tang et al. 2020; Oei et al. 2022)

A systematic inspection of the entire North Polar Cap region (Decl $> +64°$) in comparison with optical/IR surveys like Pan-STARRS and AllWISE has yielded around 200 new giant radio galaxies with projected size larger than 1 Mpc.[2] In addition, positions for a few thousand candidate extended radio galaxies were logged during a visual inspection of VLASS Epoch 1 Quick Look images of southerly regions not covered by FIRST (Villarreal Hernández & Andernach 2018).

A fraction of these radio galaxies can be spotted semi-automatically by looking for pairs of extended radio sources in VLASS source catalogs (e.g. Gordon et al. 2021) by a selection of a suitable range of mutual orientation angles and those with respect to the axis connecting the source pair. If such pairs are chosen among the "empty islands" in the catalog of Gordon et al. (2021), many of these turn out to be remnant-type radio galaxies of angular size ($< 1'$) not previously recognized in prior large-scale radio surveys. VLASS is also useful in the classification of remnant radio galaxies based on the absence of hotspots in diffuse lobes of previously known radio galaxies.

6. PROSPECTS FOR THE THIRD EPOCH OF VLASS

6.1. *Slow transients*

VLASS observations have already discovered a record-breaking number of transient radio sources, and the breadth of the transient science return from VLASS continues to grow rapidly. Cross-matching of transients detected in VLASS Epoch 2.1 with Pan-STARRS and *Gaia* have produced the largest sample of radio stellar flares ever produced (Ayala et al. in prep.). Given that most of the expected slow transients (SNe, TDEs) fade on timescales of months, the sample of transients between Epoch 2 and 3 will be largely different from those between Epochs 1 and 2, essentially doubling the sample size. Furthermore, for those transients that do persist on timescales of years, Epoch 3 will give a further point on the light curve.

6.2. *Fast transients and SETI*

A third epoch of VLASS improves the science results from *realfast* in three ways: improved sensitivity, an extra epoch to search for events, and a longer time baseline to study changes. The *realfast* system searches for transient events, so new discoveries of FRBs and pulsars are more likely with more time on sky. In fact, *realfast* was fully operational only starting in VLASS Epoch 2, so a third epoch will double the amount of commensal, fast-transient search time on sky. For some science cases, deeper or longer time baselines will improve our understanding of these events or their multiwavelength counterparts. For example, the time variability of FRB PRS counterparts is poorly constrained, but it is a powerful discriminator of FRB source models.

The Commensal Open-Source Multimode Interferometer Cluster Search for Extraterrestrial Intelligence (COSMIC) uses separate feeds from the VLA antennas connected to GPU-based signal analysis hardware to search for extraterrestrial technosignatures.[3] The system is expected to be operational by the start of VLASS Epoch 3 observing, and, by operating in parallel with VLASS, will be able to perform an all-sky SETI search that would not be possible otherwise.

6.3. *Polarimetry*

The multi-epoch polarization data set that VLASS will provide will be unique, since no other all-sky polarization sky survey consists of multiple epochs toward large numbers of sources. Two epochs on their own will provide ambiguous results, since they will not be able to distinguish short-term or fluctuating behavior from secular trends. A third VLASS epoch will be vital to establishing patterns and statistics of polarization variability in AGN.

[2] See presentation by Andernach at https://www.aoc.nrao.edu/events/VLA40th/slides/session9/Heinz-Andernach.pdf.

[3] https://www.seti.org/using-vla-seti

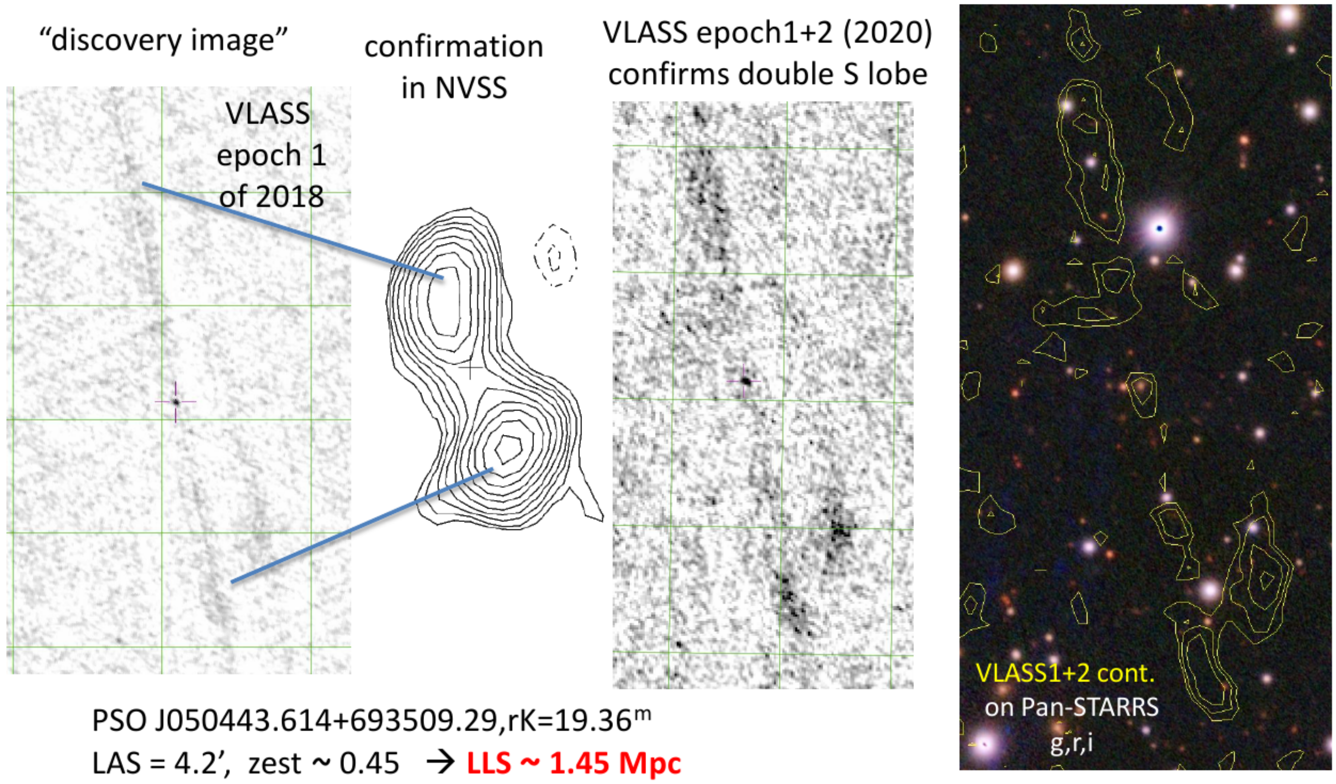


Figure 7. An example of a giant radio galaxy for which the combination of VLASS (epochs 1 and 2), NVSS and deep optical surveys was essential to arrive to its identification. The central crosses on the VLASS and NVSS images indicate the location of the host galaxy.

6.4. *Radio AGN and star-forming galaxies*

For non-variable radio sources, the cumulative imaging products from all three epochs will improve sensitivity by 70% compared to the single epoch products, and the additional *uv* data will also help to suppress artifacts. At the flux density levels corresponding to the limit of VLASS, AGN dominance of the radio source counts is giving way to rapidly rising counts of star-forming galaxies (e.g. Matthews et al. 2021), so even this small sensitivity improvement will be important in terms of increasing the number of star-forming galaxies available for study. The cumulative imaging products will also include tapered lower resolution (≈ 7-arcsec) images that will result in improved sensitivity for low surface brightness objects such as the lobes of giant radio galaxies. For variable AGN, the extra epoch will allow better characterization of AGN variability in the radio. This is especially important for the newborn quasar jets described in Section 2.4, where VLASS Epoch 3 observations can determine if most of them continue to brighten, or whether a fraction of them are fading back into quiescence on timescales of a few years.

7. SUMMARY AND FUTURE DIRECTIONS

VLASS has been very successful in advancing a number of scientific areas. In particular, new results on slow radio transients have already led to new important new insights into gamma-ray bursts, supernovae, TDEs and radio AGN life-cycles. In combination with the commensal *realfast* program, VLASS gives us a unique way to study FRBs and any persistent sources associated with them, which will potentially revolutionize our understanding of these mysterious objects. With the production of pipelined polarization images to start in the summer of 2022, polarization studies, including polarization variability, will open up, completing the synoptic axes of the survey (time, frequency and polarization). VLASS has also been valuable for pointing the way towards future projects such as ngVLA and SKA, both in terms of adding to and refining the science cases of these instruments, and in terms of the scientific and technical developments in wide-field, wide-band imaging algorithms and in high-throughput computing that will be needed to support them.

Looking ahead to Epoch 3, the quantity and quality of multiwavelength survey data complementary to VLASS will continue to improve. Large area ongoing/upcoming sky surveys include multi-epoch optical surveys such as ZTF and LSST, spectroscopic surveys such as DESI and PFS, and space-based surveys such as *eROSITA*, *SphereX* and further *Gaia* data releases. These will be valuable for identifying and obtaining redshifts for both non-varying radio sources and slow transients. Transient identification in VLASS is also likely to improve in Epoch 3 through the refinement of algorithms developed for Epoch 1 to Epoch 2 transient identification. Thus, although it might be argued that Epoch 3 will only double the number of transients found by VLASS, its impact will be enhanced by more than that, both in terms of numbers and in terms of the ability to use new surveys to quickly identify and classify the events.

The NRAO is organizing an upcoming conference to support VLASS science and engage with the community.[4] The conference title is the "Very Large Array Sky Survey in the Multiwavelength Spotlight," and it will take place from September 7-9, 2022, in Socorro, New Mexico, USA as well as virtually. This conference will provide a platform for a diverse range of scientific perspectives, both on the discoveries enabled by the Very Large Array Sky Survey (VLASS) on its own, and on advances made possible through synergy with other datasets.

REFERENCES

Alexander, K. D., van Velzen, S., Horesh, A., & Zauderer, B. A. 2020, SSRv, 216, 81, doi: 10.1007/s11214-020-00702-w

Alexander, P., & Leahy, J. P. 1987, MNRAS, 225, 1, doi: 10.1093/mnras/225.1.1

Aller, M., Aller, H., & Hughes, P. 2017, Galaxies, 5, 75, doi: 10.3390/galaxies5040075

Anderson, C. S., Gaensler, B. M., & Feain, I. J. 2016, ApJ, 825, 59, doi: 10.3847/0004-637X/825/1/59

Anderson, C. S., Gaensler, B. M., Feain, I. J., & Franzen, T. M. O. 2015, ApJ, 815, 49, doi: 10.1088/0004-637X/815/1/49

Anderson, C. S., O'Sullivan, S. P., Heald, G. H., et al. 2019, MNRAS, 485, 3600, doi: 10.1093/mnras/stz377

Anderson, M. M., Mooley, K. P., Hallinan, G., et al. 2020, ApJ, 903, 116, doi: 10.3847/1538-4357/abb94b

Barrett, P. E. 2022, AJ, 163, 58, doi: 10.3847/1538-3881/ac3ed9

Bassa, C. G., Tendulkar, S. P., Adams, E. A. K., et al. 2017, ApJL, 843, L8, doi: 10.3847/2041-8213/aa7a0c

Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559, doi: 10.1086/176166

Burke-Spolaor, S., & Bailes, M. 2010, MNRAS, 402, 855, doi: 10.1111/j.1365-2966.2009.15965.x

Chatterjee, S., Law, C. J., Wharton, R. S., et al. 2017, Nature, 541, 58, doi: 10.1038/nature20797

Chevalier, R. A. 2012, ApJL, 752, L2, doi: 10.1088/2041-8205/752/1/L2

[4] go.nrao.edu/vlass22

Clarke, T. E., Kassim, N. E., Brisken, W., et al. 2016, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 9906, Ground-based and Airborne Telescopes VI, ed. H. J. Hall, R. Gilmozzi, & H. K. Marshall, 99065B, doi: 10.1117/12.2233036

Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, AJ, 115, 1693, doi: 10.1086/300337

Dong, D. Z., Hallinan, G., Nakar, E., et al. 2021, Science, 373, 1125, doi: 10.1126/science.abg6037

Gaensler, B. M., Landecker, T. L., Taylor, A. R., & POSSUM Collaboration. 2010, in American Astronomical Society Meeting Abstracts, Vol. 215, American Astronomical Society Meeting Abstracts #215, 470.13

Gordon, Y. A., Boyce, M. M., O'Dea, C. P., et al. 2021, ApJS, 255, 30, doi: 10.3847/1538-4365/ac05c0

Hallinan, G., Bourke, S., Lane, C., et al. 2007, ApJL, 663, L25, doi: 10.1086/519790

Horesh, A., Cenko, S. B., & Arcavi, I. 2021, Nature Astronomy, 5, 491, doi: 10.1038/s41550-021-01300-8

Hotan, A. W., Bunton, J. D., Chippendale, A. P., et al. 2021, PASA, 38, e009, doi: 10.1017/pasa.2021.1

Hovatta, T., Lister, M. L., Aller, M. F., et al. 2012, AJ, 144, 105, doi: 10.1088/0004-6256/144/4/105

Ighina, L., Moretti, A., Tavecchio, F., et al. 2022, A&A, 659, A93, doi: 10.1051/0004-6361/202142676

Irwin, J. A., Henriksen, R. N., Weżgowiec, M., et al. 2018, MNRAS, 476, 5057, doi: 10.1093/mnras/sty451

Jonas, J., & MeerKAT Team. 2016, in MeerKAT Science: On the Pathway to the SKA, 1

Lacy, M., Baum, S. A., Chandler, C. J., et al. 2020, PASP, 132, 035001, doi: 10.1088/1538-3873/ab63eb

Law, C. J., Connor, L., & Aggarwal, K. 2022, ApJ, 927, 55, doi: 10.3847/1538-4357/ac4c42

Law, C. J., Gaensler, B. M., Metzger, B. D., Ofek, E. O., & Sironi, L. 2018, ApJ, 866, L22, doi: 10.3847/2041-8213/aae5f3

Lister, M. L., Aller, M. F., Aller, H. D., et al. 2018, ApJS, 234, 12, doi: 10.3847/1538-4365/aa9c44

Lister, M. L., Homan, D. C., Kellermann, K. I., et al. 2021, ApJ, 923, 30, doi: 10.3847/1538-4357/ac230f

Mao, S. A., Banfield, J., Gaensler, B., et al. 2014, arXiv e-prints, arXiv:1401.1875. https://arxiv.org/abs/1401.1875

Marcote, B., Paragi, Z., Hessels, J. W. T., et al. 2017, ApJL, 834, L8, doi: 10.3847/2041-8213/834/2/L8

Margalit, B., & Metzger, B. D. 2018, ApJL, 868, L4, doi: 10.3847/2041-8213/aaedad

Martí-Vidal, I., & Goddi, C. 2021, Galaxies, 9, 51, doi: 10.3390/galaxies9030051

Matthews, A. M., Condon, J. J., Cotton, W. D., & Mauch, T. 2021, ApJ, 914, 126, doi: 10.3847/1538-4357/abfaf6

Molina, M., Reines, A. E., Latimer, L. J., Baldassare, V., & Salehirad, S. 2021, ApJ, 922, 155, doi: 10.3847/1538-4357/ac1ffa

Mooley, K. P., Hallinan, G., Bourke, S., et al. 2016, ApJ, 818, 105, doi: 10.3847/0004-637X/818/2/105

Mooley, K. P., Margalit, B., Law, C. J., et al. 2022, ApJ, 924, 16, doi: 10.3847/1538-4357/ac3330

Myers, S. T., & Spangler, S. R. 1985, ApJ, 291, 52, doi: 10.1086/163040

Niu, C. H., Aggarwal, K., Li, D., et al. 2021, arXiv e-prints, arXiv:2110.07418. https://arxiv.org/abs/2110.07418

Nyland, K., Dong, D. Z., Patil, P., et al. 2020, ApJ, 905, 74, doi: 10.3847/1538-4357/abc341

O'Dea, C. P., & Saikia, D. J. 2021, A&A Rv, 29, 3, doi: 10.1007/s00159-021-00131-w

Oei, M. S. S. L., van Weeren, R. J., Hardcastle, M. J., et al. 2022, A&A, 660, A2, doi: 10.1051/0004-6361/202142778

Patil, P., Nyland, K., Whittle, M., et al. 2020, ApJ, 896, 18, doi: 10.3847/1538-4357/ab9011

Peters, W., Polisensky, E., Brisken, W., et al. 2021, in American Astronomical Society Meeting Abstracts, Vol. 53, American Astronomical Society Meeting Abstracts, 211.06

Piran, T., Nakar, E., Mazzali, P., & Pian, E. 2019, ApJL, 871, L25, doi: 10.3847/2041-8213/aaffce

Platts, E., Weltman, A., Walters, A., et al. 2019, PhR, 821, 1, doi: 10.1016/j.physrep.2019.06.003

Polisensky, E., Richards, E., Clarke, T., Peters, W., & Kassim, N. 2019, in Astronomical Society of the Pacific Conference Series, Vol. 523, Astronomical Data Analysis Software and Systems XXVII, ed. P. J. Teuben, M. W. Pound, B. A. Thomas, & E. M. Warner, 441

Pritchard, J., Murphy, T., Zic, A., et al. 2021, MNRAS, 502, 5438, doi: 10.1093/mnras/stab299

Quiroga-Nuñez, L. H., Intema, H. T., Callingham, J. R., et al. 2020, A&A, 633, A130, doi: 10.1051/0004-6361/201936491

Ravi, V., Dykaar, H., Codd, J., et al. 2022, ApJ, 925, 220, doi: 10.3847/1538-4357/ac2b33

Ross, K., Hurley-Walker, N., Seymour, N., et al. 2022, MNRAS, doi: 10.1093/mnras/stac819

Ruan, D., Taylor, G. B., Dowell, J., et al. 2020, MNRAS, 495, 2125, doi: 10.1093/mnras/staa1305

Shimwell, T. W., Hardcastle, M. J., Tasse, C., et al. 2022, A&A, 659, A1, doi: 10.1051/0004-6361/202142484

Stroh, M. C., Terreran, G., Coppejans, D. L., et al. 2021, ApJL, 923, L24, doi: 10.3847/2041-8213/ac375e

Tang, H., Scaife, A. M. M., Wong, O. I., et al. 2020, MNRAS, 499, 68, doi: 10.1093/mnras/staa2805

Tendulkar, S. P., Bassa, C. G., Cordes, J. M., et al. 2017, ApJL, 834, L7, doi: 10.3847/2041-8213/834/2/L7

Vedantham, H. K., Callingham, J. R., Shimwell, T. W., et al. 2020, ApJL, 903, L33, doi: 10.3847/2041-8213/abc256

Villadsen, J., & Hallinan, G. 2019, ApJ, 871, 214, doi: 10.3847/1538-4357/aaf88e

Villarreal Hernández, A. C., & Andernach, H. 2018, arXiv e-prints, arXiv:1808.07178. https://arxiv.org/abs/1808.07178

Wang, Z., Kaplan, D. L., Murphy, T., et al. 2021, ApJ, 920, 45, doi: 10.3847/1538-4357/ac2360

Ward, C., Gezari, S., Nugent, P., et al. 2021, arXiv e-prints, arXiv:2110.13098. https://arxiv.org/abs/2110.13098

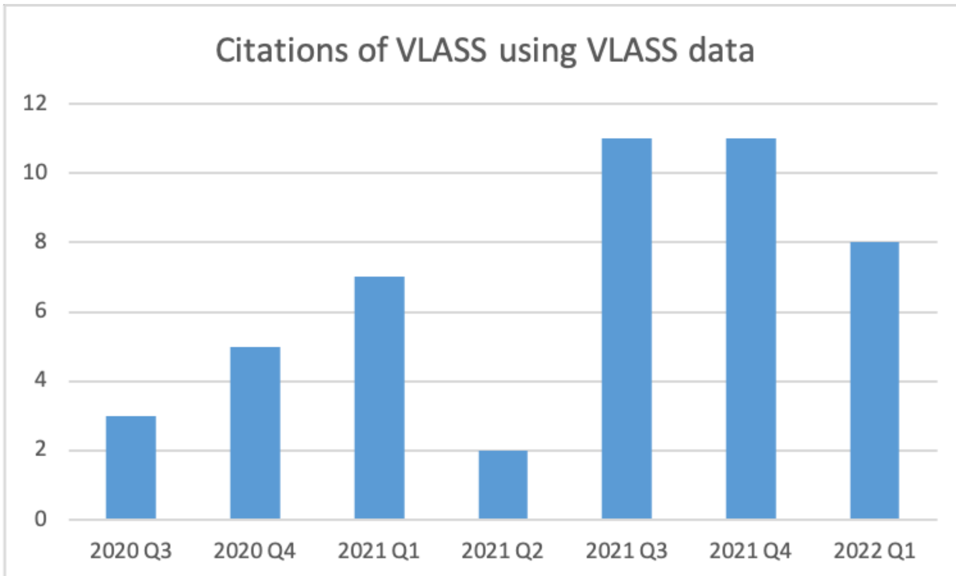


Figure 8. Citations of the VLASS survey paper that use VLASS data by (calendar year) quarter.

APPENDIX

A. CITATION STATISTICS FOR THE VLASS SURVEY DESCRIPTION PAPER

At the current time of writing (June 2022), the VLASS survey paper (Lacy et al. 2020), published in March 2020 has 190 citations on ADS. In common with other survey papers, many of these do not use the survey data, but instead cite the survey paper give their work context, or point towards possible future studies. The NRAO librarian has identified 59 papers that actually use VLASS data. These citations are consistent with a growing uptake of the survey with time (Figure 8).