

Astrophysical Origins of Quasar Variability at Radio Frequencies

DR. KRISTINA NYLAND

*Radio/IR/Optical Sensors Branch
Remote Sensing Division*

December 28, 2023

DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.

REPORT DOCUMENTATION PAGE

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION

1. REPORT DATE 28-12-2023		2. REPORT TYPE NRL Memorandum Report		3. DATES COVERED	
				START DATE 08-11-2021	END DATE 07-11-2022
4. TITLE AND SUBTITLE Astrophysical Origins of Quasar Variability at Radio Frequencies					
5a. CONTRACT NUMBER		5b. GRANT NUMBER		5c. PROGRAM ELEMENT NUMBER NISE	
5d. PROJECT NUMBER		5e. TASK NUMBER		5f. WORK UNIT NUMBER N20Y	
6. AUTHOR(S) Dr. Kristina Nyland					
7. PERFORMING ORGANIZATION / AFFILIATION NAME(S) AND ADDRESS(ES) Naval Research Laboratory 4555 Overlook Ave SW Washington, DC 20375-5320				8. PERFORMING ORGANIZATION REPORT NUMBER NRL/7210/MR—2023/1	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Naval Research Laboratory 4555 Overlook Ave SW Washington, DC 20375-5320			10. SPONSOR / MONITOR'S ACRONYM(S) NUMBER NRL-NISE		11. SPONSOR / MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION / AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A. Approved for public release, distribution is unlimited.					
13. SUPPLEMENTAL NOTES Karles Fellowship					
14. ABSTRACT At radio frequencies, precise measurements of the fluxes and positions of thousands of quasars form the basis of the celestial reference frame (CRF). The CRF is an important navigational asset to the Navy. However, changes in quasar fluxes or positions over human timescales ranging from minutes to years pose a persistent challenge to the accuracy and reliability of the CRF. Despite the importance of quasars, our understanding of the physical drivers of quasar variability remains incomplete. My research focuses on investigating the link between quasar variability at radio frequencies and the properties of the quasar, host galaxy, and ambient environment. In this report, I will discuss the astrophysical implications of my research for our understanding of quasar jet life cycles and galaxy evolution, as well as how this work supports Navy interests.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT		18. NUMBER OF PAGES
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U	SAR		20
19a. NAME OF RESPONSIBLE PERSON Kristina Nyland				19b. PHONE NUMBER (Include area code) (202) 767-8682	

This page intentionally left blank.

CONTENTS

EXECUTIVE SUMMARY	E-1
1. INTRODUCTION	1
1.1 Quasars and Active Galaxies	1
1.2 Identifying Young Jets	2
1.3 The Very Large Array Sky Survey	4
1.4 A New Sample of Young Jets.....	4
1.5 Implications for Galaxy Evolution	5
1.6 Navy Relevance	5
2. NEW RESEARCH	6
2.1 Radio Spectral Variability	6
2.2 Re-started Jets	7
2.3 Quasar Host Galaxy Properties	7
3. SERVICE	8
3.1 VLASS Conference	8
3.2 Astronomy and Astrophysics Talk Series	8
3.3 Student Mentoring	10
3.4 STEM Outreach.....	10
4. FUTURE WORK	11
4.1 Radio-frequency Monitoring	11
4.2 Very Long Baseline Interferometry	11
5. SUMMARY	11
ACKNOWLEDGMENTS	12
REFERENCES.....	12

FIGURES

1	<p>The cosmic history of the universe from the big bang to the present day. The key epoch of “cosmic noon” ($z = 1 - 3$), when the universe was 1-6 billion years old and galaxies and supermassive black holes were growing rapidly, is indicated. We know that large-scale (100’s of kpc) jets and lobes at low redshift release enough energy to regulate star formation. However, the importance and impact of small-scale jets at cosmic noon and beyond remains unknown.</p>	1
2	<p>Left: Artist’s illustration (not to scale) of a quasar host that was radio-quiet when observed by FIRST (1.4 GHz), but was recently discovered to be radio-loud in VLASS (3 GHz) 10–20 years later. Right: Example images showing the absence of radio emission in FIRST and the presence of a bright, compact source in VLASS. Credits: Sophia Dagnello, NRAO/AUI/NSF, and Kristina Nyland.</p>	2
3	<p>Cartoon illustration of the characteristic spectral shapes of an old (large-scale; with ages of millions of years) vs. young (compact; with ages of thousands of years or less) radio AGN. On the left, the diffuse lobes of extended radio galaxies like the example shown in the inset image (Centaurus A) are optically-thin and follow a simple power-law shape. Young sources, like the example artist’s impression shown on the right, typically have ages of thousands of years or less and are thus compact. The high number densities of synchrotron-emitting electrons in compact radio AGN lead to absorption and characteristic peaked radio spectral shapes.</p>	3
4	<p>The selection criteria for the sample presented in Nyland et al. [1]. The final 3 mJy beam^{-1} cut in flux serves to rule-out optically-thick sources that were steady between FIRST and VLASS. Figure adapted from [2].</p>	5
5	<p>Multi-epoch, multi-band radio spectra of three candidate young jets fit with curved power-law models (see [1] 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.).</p>	6
6	<p>Image cutouts for sources with 150 MHz data available from LOTSS DR2 [3]. Each cutout has a width of $2'$. The restoring beam has dimensions of $6'' \times 6''$, and is illustrated by the white circle in the lower-left corner of each image.</p>	7
7	<p>Examples of the rest-frame optical morphologies from my recent Cycle 22 <i>HST</i> WFC3/IR pilot imaging program. Quasar-host decomposition has not yet been applied. The 2 lower-redshift sources in the left and center panels show clearly extended morphologies well suited to the observing capabilities of <i>HST</i>. In the center panel, J0742+2704 has a faint tidal tail indicative of recent merger activity.</p>	9

EXECUTIVE SUMMARY

The objective of this project is to gain new insights into the physics of radio-variable quasars, including CRF sources that play an important role in positioning, navigation, and timing.

This page intentionally left blank

ASTROPHYSICAL ORIGINS OF QUASAR VARIABILITY AT RADIO FREQUENCIES

1. INTRODUCTION

1.1 Quasars and Active Galaxies

The centers of most massive galaxies harbor a supermassive black hole (SMBH) weighing millions to billions of solar-masses. Although SMBHs do not emit any light directly, electromagnetic radiation is emitted during the process of SMBH accretion. An actively feeding SMBH, or “quasar,” may shine thousands of times brighter than an entire galaxy. A subset of all quasars ($\sim 1 - 10\%$) are detected at radio frequencies, and are referred to as being “radio-loud” [4]. The radio emission detected in these quasars originates from bipolar “jets” of plasma produced by synchrotron-emitting electrons accelerated to relativistic speeds by strong magnetic fields near the SMBH.

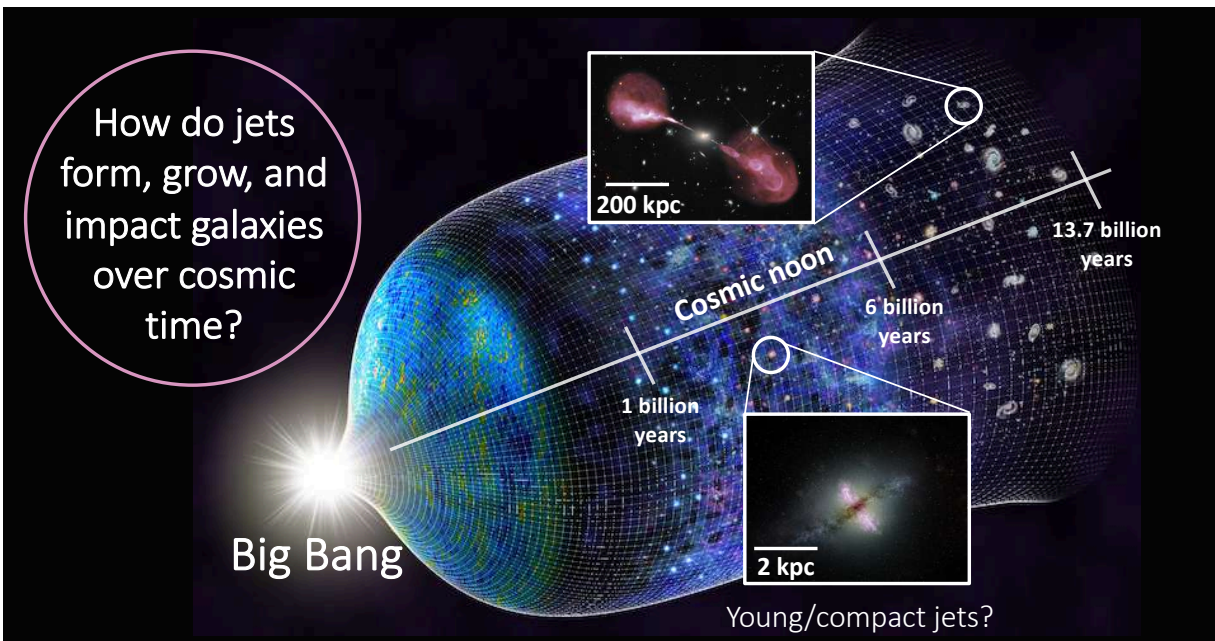


Fig. 1—The cosmic history of the universe from the big bang to the present day. The key epoch of “cosmic noon” ($z = 1 - 3$), when the universe was 1-6 billion years old and galaxies and supermassive black holes were growing rapidly, is indicated. We know that large-scale (100’s of kpc) jets and lobes at low redshift release enough energy to regulate star formation. However, the importance and impact of small-scale jets at cosmic noon and beyond remains unknown.

Over millions of years, quasar jets may grow to large-scales (10’s to 1000’s of kpc), extending far beyond the stellar extents of their host galaxies. The energy released by large-scale quasar jets and lobes is believed

to regulate galactic star formation rates by heating reservoirs of gas in the intracluster medium (ICM). This inhibits the formation of cooling flows, which would otherwise condense and lead to the formation of new stars [5]. This mode of feedback is prevalent among massive galaxies residing in dense environments at low redshifts. However, the role of jet-driven feedback in other types of environments, such as in gas-rich galaxies at $z > 1$, has yet to be fully explored (Figure 1).

Recent observational studies suggest that compact ($\lesssim 1$ kpc) jets are common, perhaps outnumbering classical large-scale sources at cosmic noon ($z = 1 - 3$; e.g. [6]). Compact jets may be associated with youth (i.e. jets launched within the past $\sim 10^4$ years), a low intrinsic jet power, interaction/confinement with a dense interstellar medium (ISM), or shorter jet lifetimes [1, 7, 8]. Furthermore, simulations predict that young quasar jets residing in gas-rich galaxies are also capable of influencing the star formation rates/efficiencies of galaxies [9]. This raises the possibility that jet-driven feedback on ISM scales may play a significant role in the regulation of SMBH growth and stellar assembly. Improved observational constraints on the rate at which quasars form new jets are thus needed to test this possibility.

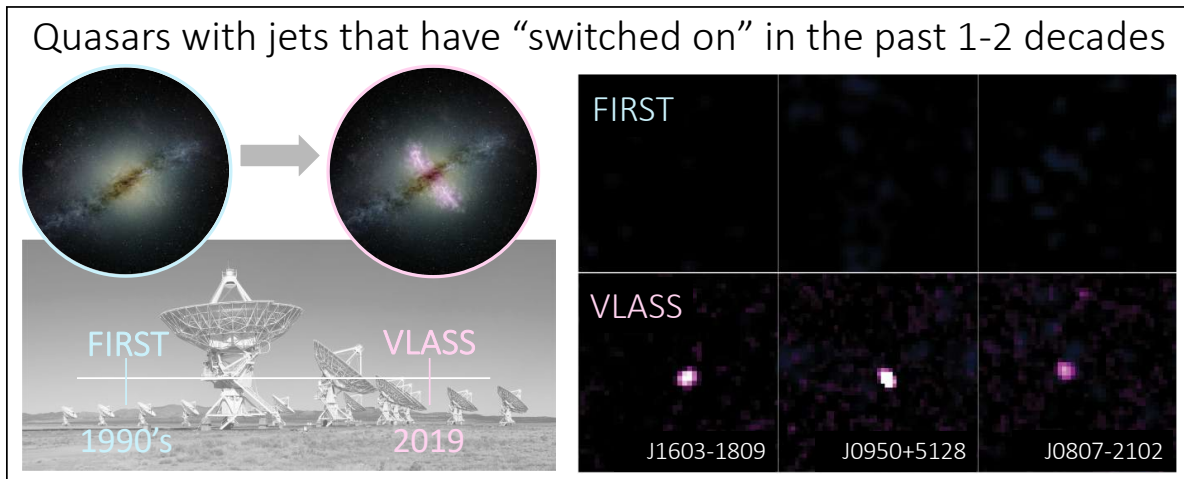


Fig. 2—**Left:** Artist’s illustration (not to scale) of a quasar host that was radio-quiet when observed by FIRST (1.4 GHz), but was recently discovered to be radio-loud in VLASS (3 GHz) 10–20 years later. **Right:** Example images showing the absence of radio emission in FIRST and the presence of a bright, compact source in VLASS. Credits: Sophia Dagnello, NRAO/AUI/NSF, and Kristina Nyland.

1.2 Identifying Young Jets

Systematic studies of young jets, and the properties of the galaxies in which they reside, are of fundamental importance for improving our understanding of the life cycles of radio jets and their connection to galaxy evolution. Young radio jets may be identified on the basis of their radio morphologies, spectral shapes, or variability. I provide additional details on these selection methods in the remainder of this subsection.

1.2.1 Source morphology

The most direct way to identify young/compact jets is by spatially resolving their morphologies with high angular resolution imaging. However, this is only possible for jets with orientations in the plane of the sky (i.e. jets without significant Doppler beaming). The high observing cost of milliarcsecond-scale

observations is a further limiting factor. For instance, a 10 pc-scale radio jet at $z = 1$ has an angular size of 1 milliarcsecond. Observations utilizing the technique of very long baseline interferometry (VLBI) are thus necessary to achieve such high angular resolution. Currently, there are no blind, widefield, radio surveys with sufficient spatial resolution for the systematic identification of young quasar jets based on directly resolved morphologies. This technique is thus best suited for confirming candidate young jets identified using different strategies better suited to unbiased searches.

Radio Spectral Shapes and AGN Life Stages

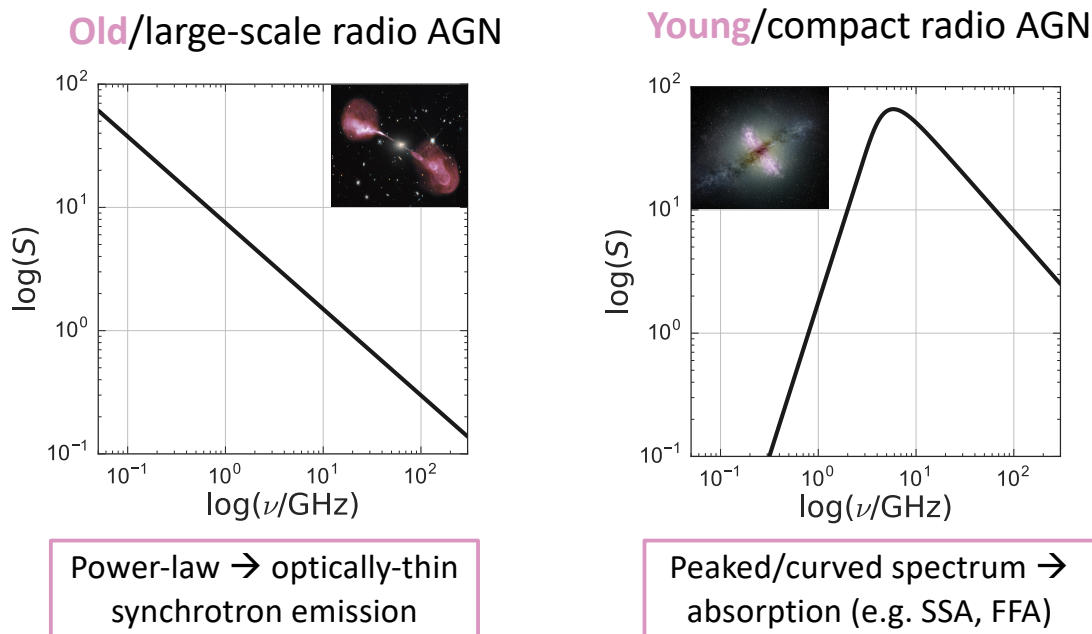


Fig. 3—Cartoon illustration of the characteristic spectral shapes of an old (large-scale; with ages of millions of years) vs. young (compact; with ages of thousands of years or less) radio AGN. On the left, the diffuse lobes of extended radio galaxies like the example shown in the inset image (Centaurus A) are optically-thin and follow a simple power-law shape. Young sources, like the example artist’s impression shown on the right, typically have ages of thousands of years or less and are thus compact. The high number densities of synchrotron-emitting electrons in compact radio AGN lead to absorption and characteristic peaked radio spectral shapes.

1.2.2 Radio spectral shape

If broadband (or multi-band) radio continuum data are available, young jets may be readily identified by their signature peaked/curved radio spectral shapes, which arise due to absorption (Figure 3). Most peaked-spectrum radio sources may be modeled by synchrotron self-absorption (SSA), in which the absorption is caused by the high number density of non-thermal, synchrotron-emitting electrons. Free-free absorption, in which the absorption is due to a high density of thermal electrons [10], may also produce spectral curvature (e.g. in the case of a jet interacting with a dense ionized medium). By systematically combining measurements from radio surveys spanning a wide range of frequencies, samples of candidate young jets may be constructed (though differences in survey spatial resolutions and observing epochs may complicate the interpretation of such candidates; see [11]).

1.2.3 Radio variability

Young and compact jets are well known to exhibit variability over a wide range of timescales. Radio jet variability timescales range from seconds to years depending on the origin of the variability. Rapid variations are typically associated with propagation effects, such as scintillation or plasma lensing. Intrinsic radio jet variability tends to occur over longer timescales (i.e. weeks to years), and may arise from mechanisms such as internal shocks along the jet, variable doppler boosting (due to jet re-orientation), or adiabatic expansion of a growing jet [1, 12–14].

1.3 The Very Large Array Sky Survey

Historically, the limited sensitivities, angular resolutions, bandwidths, and observing cadences of sky surveys with radio telescopes have limited systematic searches. Modern radio surveys, such as the Very Large Array Sky Survey (VLASS; [15]), have enabled new strategies for searching for young jets. VLASS is a multi-epoch radio survey of the entire northern sky visible from New Mexico. VLASS was designed in response to a community-driven effort to carry out a synoptic radio sky survey using the Karl G. Jansky Very Large Array (VLA). The unique combination of panoramic sky coverage, high angular resolution, multi-epoch observing strategy, and full-polarimetric data products of VLASS was chosen to provide opportunities for new discoveries over a wide range of science topics. VLASS has provided important new insights into gamma-ray bursts, supernovae, tidal disruption events (TDEs), and radio jets associated with quasars and active galaxies.

1.4 A New Sample of Young Jets

VLASS has also enabled a game-changing advancement in the search for young jets in the time domain. As illustrated in Figure 2, young jets may be identified by comparing data from modern radio surveys, such as VLASS, and historical ones, like the Faint Images of the Radio Sky at Twenty Centimeters (FIRST; Becker et al. 16), that were carried out years or decades apart. VLASS is still in progress, but emerging young quasar jets with characteristic peaked radio spectral shapes have already begun to be identified by comparing data from VLASS Epoch 1 taken from 2017–2019 and the Faint Images of the Radio Sky at Twenty Centimeters (FIRST; Becker et al. 16) taken from 1993–2011. Nyland et al. [1] have identified a sample of 26 quasars with jets that have brightened dramatically in the radio in the past 1–2 decades based on a comparison between FIRST and VLASS covering $\sim 3400 \text{ deg}^2$.

The initial selection targeted compact sources $> 1 \text{ mJy}$ in VLASS Epoch 1 (2017–2019) that were below the 5σ detection threshold ($< 0.75 \text{ mJy}$) of the 1.4 GHz FIRST (1993–2011; Becker et al. 16) survey. To select candidate radio quasars with variable radio emission, the radio transient candidates were cross-matched within a radius of $1''$ with the spectroscopically-verified quasars in SDSS DR14 [17]. VLASS fluxes were then limited to values $> 3 \text{ mJy}$ in order to rule-out steady but optically-thick sources with spectral indices up to $\alpha = 2.5$ (where $S \sim \nu^\alpha$). These sources would have previously been classified as radio-quiet based on their upper limits in FIRST, but they are now consistent with radio-loud quasars (e.g. [4]) based on their VLASS luminosities of $L_{3\text{GHz}} = 10^{40-42} \text{ erg s}^{-1}$. The Nyland et al. [1] sample of 26 radio-variable quasars includes 13 broad-line quasars (SDSS; Pâris et al. 17) with redshifts of $0.2 < z < 3.2$, bolometric luminosities of $\log(L_{\text{bol}}/\text{erg s}^{-1}) \approx 45.2 - 46.8$, and virial SMBH masses of $\log(M_{\text{SMBH}}/M_\odot) \approx 8 - 9.7$ [18].

Simultaneous VLA follow-up observations from 1–18 GHz revealed high variability amplitudes (100% to $> 2500\%$) at 1.4 GHz compared to FIRST, variability timescales longer than a few months at 3 GHz

compared to VLASS, sizes $< 0.1''$ ($\lesssim 1$ kpc) at 15 GHz, and curved radio spectra peaking at $\sim 5\text{--}10$ GHz (Figure 5, [1]). These radio properties are consistent with young radio sources (e.g., gigahertz peaked spectrum sources; [19]). The long-term radio variability is thus likely associated with pc-scale jets that were launched within the past few decades, possibly associated with a state transition of the SMBH, making these sources among the youngest radio jets known. [20].

1.5 Implications for Galaxy Evolution

The sky density of young jets discovered so far suggests that intermittent episodes during a quasar's life in which short-lived radio jets are (re-)triggered may be common at $z \sim 1 - 3$. The cumulative effects of these brief episodes in which small jets are present may be important for galaxy evolution if they contribute to the regulation of star formation rates and supermassive black hole growth over cosmic time. Continued monitoring with future epochs of synoptic radio surveys like VLASS will provide new insights into the role of jet triggering and feedback in influencing galaxy evolution.

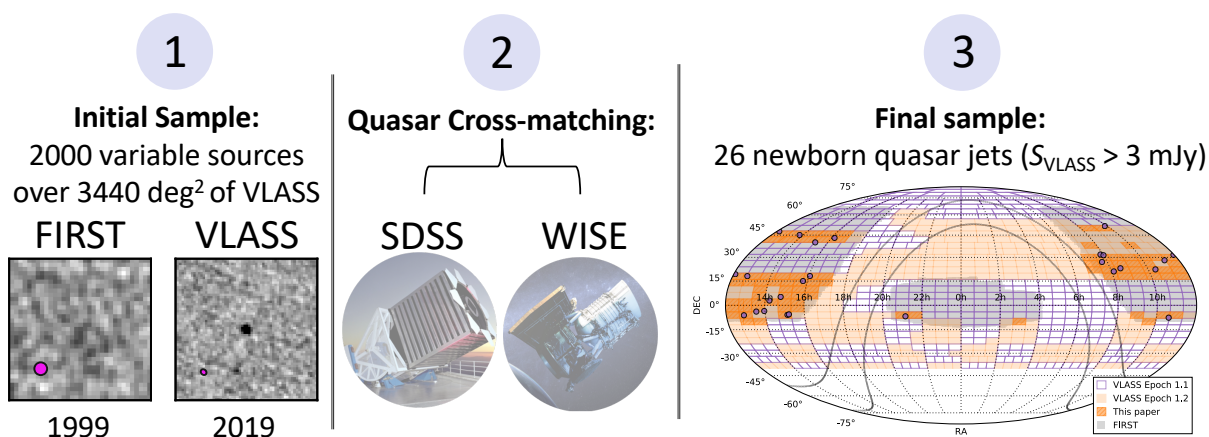


Fig. 4—The selection criteria for the sample presented in Nyland et al. [1]. The final 3 mJy beam^{-1} cut in flux serves to rule-out optically-thick sources that were steady between FIRST and VLASS. Figure adapted from [2].

1.6 Navy Relevance

Owing to their great cosmic distances, quasars serve as cosmic “beacons.” At radio frequencies, precise measurements of the fluxes and positions of thousands of quasars form the basis of the celestial reference frame (CRF). The CRF is an important navigational asset to the Navy. However, changes in quasar fluxes or positions over human timescales ranging from minutes to years pose a persistent challenge to the accuracy and reliability of the CRF [1]. Maintaining and improving the CRF therefore requires regular quasar monitoring to determine the stability of the fluxes and positions, and identify any deviant sources that could lead to vulnerabilities with navigation or communication. My research supports these Navy interests by focusing on the link between quasar variability at radio frequencies and the properties of the quasar, host galaxy, and ambient environment.

2. NEW RESEARCH

2.1 Radio Spectral Variability

Multi-band radio spectra constrain the underlying emission mechanisms (thermal vs. non-thermal) and physics (e.g. synchrotron self absorption or free-free absorption) of jets.

Spectral modeling was performed following the procedure described in Patil et al. [11] and examples are shown in Figure 5. The radio spectra of candidate newborn jets show a variety of behaviors on timescales of 1-2 years. Three different categories were found: 1) no signs of variability, 2) steadily increasing optically-thick flux consistent with expectations for an adiabatically expanding young source, or 3) extreme changes in shape indicative of relativistic beaming effects (Nyland et al. in prep.).

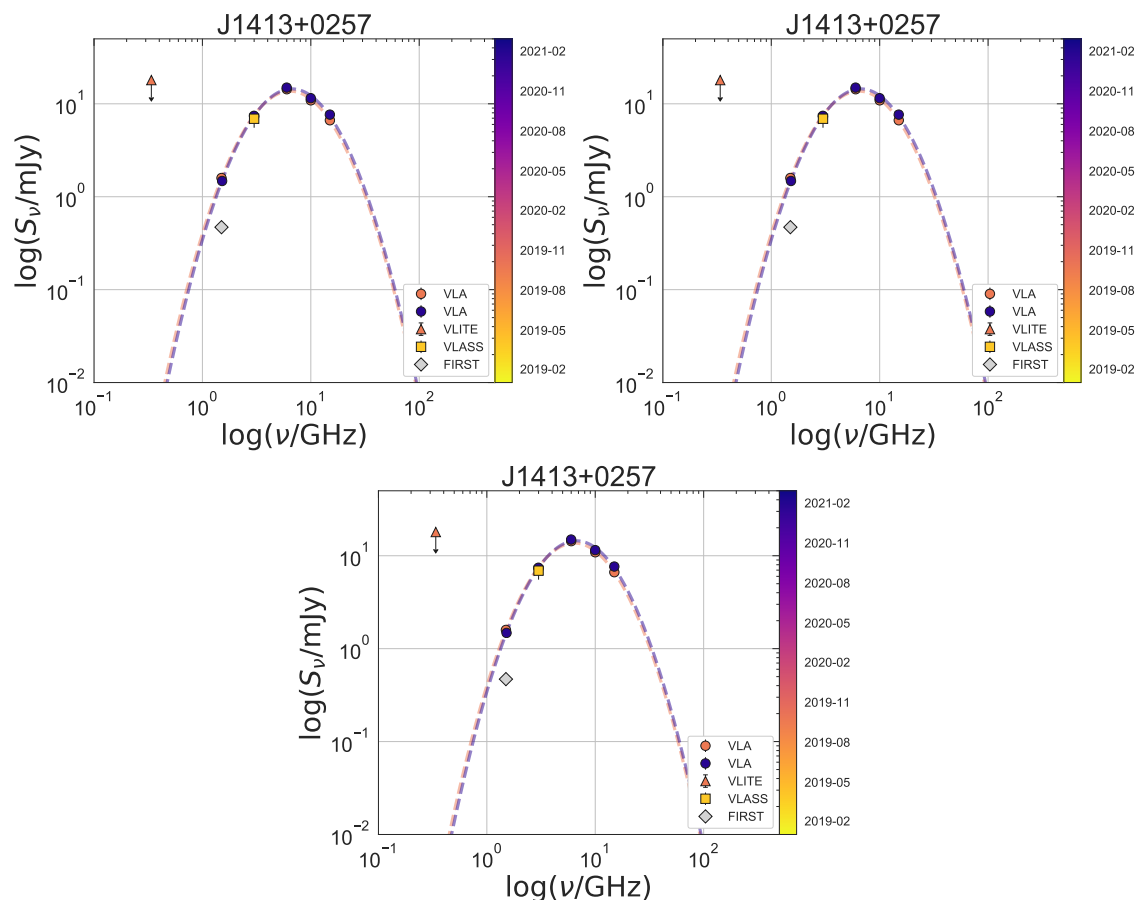


Fig. 5—Multi-epoch, multi-band radio spectra of three candidate young jets fit with curved power-law models (see [1] for details). On timescales of a couple of years, the radio spectra of candidate newborn jets may exhibit a) no signs of variability, b) steadily increasing optically-thick flux consistent with expectations for an adiabatically expanding young source, or c) extreme changes in shape indicative of relativistic beaming effects (Nyland et al. in prep.).

2.2 Re-started Jets

In order to investigate the incidence of restarted jets in the Nyland et al. [1] sample, we searched for low-frequency source counterparts in the 2nd data release of the LOFAR Two-metre Sky Survey (LOTSS; [3]). LOTSS DR2 provides deep ($\sigma \sim 83 \mu\text{Jy beam}^{-1}$) images over 27% of the sky at 144 MHz with $6''$ resolution. A total of 10/26 sources from [1] fall within the LOTSS DR2 footprint, and all but one of these sources (J1208+4741) is detected. As shown in Figure 6, most of the sources detected in LOTSS DR2 have compact morphologies, but 3 sources (J0742+2704, J1347+4505, and J1609+4306) have extended lobes.

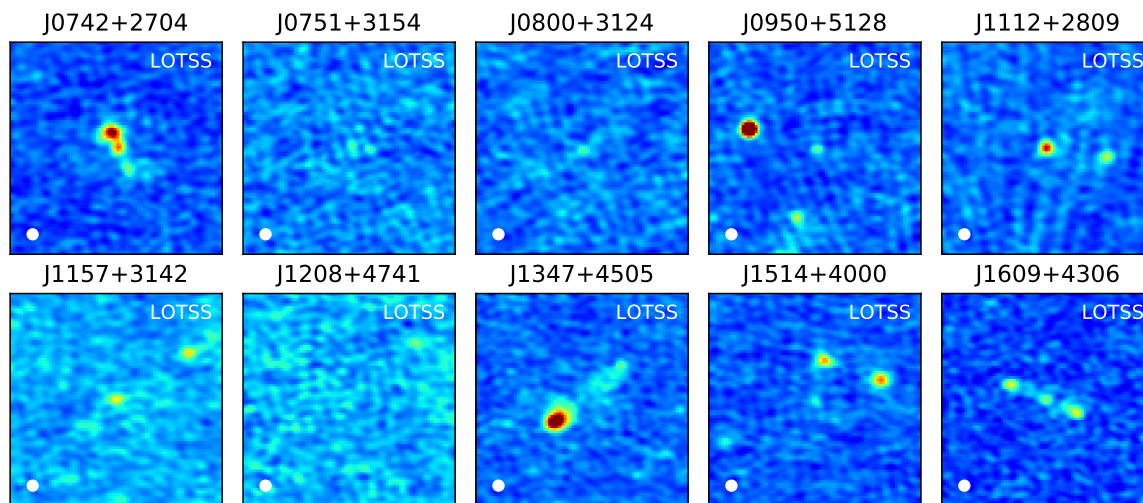


Fig. 6—Image cutouts for sources with 150 MHz data available from LOTSS DR2 [3]. Each cutout has a width of $2'$. The restoring beam has dimensions of $6'' \times 6''$, and is illustrated by the white circle in the lower-left corner of each image.

2.3 Quasar Host Galaxy Properties

Although quasar jets play an important role in galaxy evolution, we do not fully understand how they are triggered. Both external (mergers, tidal interactions) and secular (star formation, bar-driven fueling) processes may affect the accretion rate/mode of the SMBH and potentially trigger the formation of radio jets. Resolved imaging of the hosts of young quasar jets is needed to distinguish between these processes, and improve our understanding of how jets form, grow, and influence galaxies. The *Hubble* Space Telescope (*HST*) is the only telescope that can achieve the required sub-arcsecond resolution at optical/IR wavelengths.

Early *HST* studies established the generally accepted view argued that both radio-quiet/radio-loud quasars typically reside in massive, passively evolving ellipticals lacking major merger signatures (e.g. McLure et al. 21, Kukula et al. 22, Dunlop et al. 23). However, more recent studies have challenged this finding, suggesting that our understanding of the link between quasars, host galaxies, and radio jets remains incomplete. A high fraction of disturbed host galaxy morphologies, including both major and minor mergers, has been reported for quasars with outflows [24], dust obscuration [25], variability (e.g. changing-look AGN; Charlton et al. 26), and large-scale (i.e. FR II) radio jets/lobes [27]. Sample biases (redshift, luminosity, SMBH mass, etc.), timescale mismatches (e.g. delayed SMBH fueling following a merger), and observing limitations (sensitivity, resolution) likely contribute to disagreements in the literature. Additional exploratory and statistical studies of quasar hosts are therefore needed.

I led the first successful pilot *HST* program to study to explore the hosts of quasars with newborn jets that were recently caught switching on. Each target with a WFC3/IR wide filter covering the rest-frame optical emission of the host galaxy. The *HST* images are shown in Figure 7. I performed preliminary quasar/host decomposition for all 4 targets. A more rigorous analysis using the “Lenstronomy” [28] package is in progress. However, my initial work has already provided interesting insights into the properties of the host galaxies in the sample. Extended host galaxy emission is readily detected in the vicinity of one target. In another case, a faint tidal tail indicative of recent merger activity has been identified. After robust PSF modeling and decomposition of the quasar and host galaxy emission is performed, I will model the surface brightness profile of the host galaxy to determine its basic properties, including morphology and luminosity. This study will ultimately provide the first exploration of the hosts of quasars caught transitioning from radio-quiet to radio-loud on human timescales of decades.

3. SERVICE

During my year as a Karles fellow, I supported NRL and the broader scientific community through multiple service activities. These activities included leading the organizing team of a scientific conference, co-organizing the “Astronomy & Astrophysics talk series” at NRL, serving as a mentor to multiple students, and representing NRL at STEM outreach events.

3.1 VLASS Conference

I led the organizing team of an international hybrid conference, “The VLA Sky Survey in the Multiwavelength Spotlight.” This conference was sponsored by the National Radio Astronomy Observatory (NRAO). The goal of the conference was to share a diverse range of (unclassified) 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. The conference was held in-person in Socorro, New Mexico and virtually from September 7-9, 2022. My role as the science organizing committee chair of the conference required technical expertise in astrophysics, strong communication, and leadership skills. My duties included recruiting the organizing team, leading weekly planning meetings (from June 2021 to September 2022), defining the goals and scope of the conference, identifying and inviting keynote speakers, chairing the abstract review process, and summarizing the conference at its conclusion.

Over 200 astronomers from around the world participated in the conference, and the program included over 60 posters and 53 oral presentations. The scientific research presented at the conference covered a broad range of astrophysical topics of interest to NRL including low-frequency commensal instrumentation, radio-frequency observations of transient and variable sources, and supermassive black holes. These scientific topics are relevant to Navy interests in the ionosphere, radio-frequency communication, and the celestial reference frame.

3.2 Astronomy and Astrophysics Talk Series

I have been co-hosting NRL’s hybrid “Astronomy and Astrophysics talk series,” which is organized jointly by the Remote Sensing and Space Sciences divisions. In April 2022, I organized the first in-person visit and science talk in my division since the start of the pandemic. The science featured in this talk series is well-aligned with NRL interests, and the talk series has helped facilitate new collaborations with NRL staff. The talk series continues to provide a forum for cross-divisional communication and collaboration on the topic of astrophysics, and the Flank Speed Team that I created to support it is freely open to everyone at NRL.

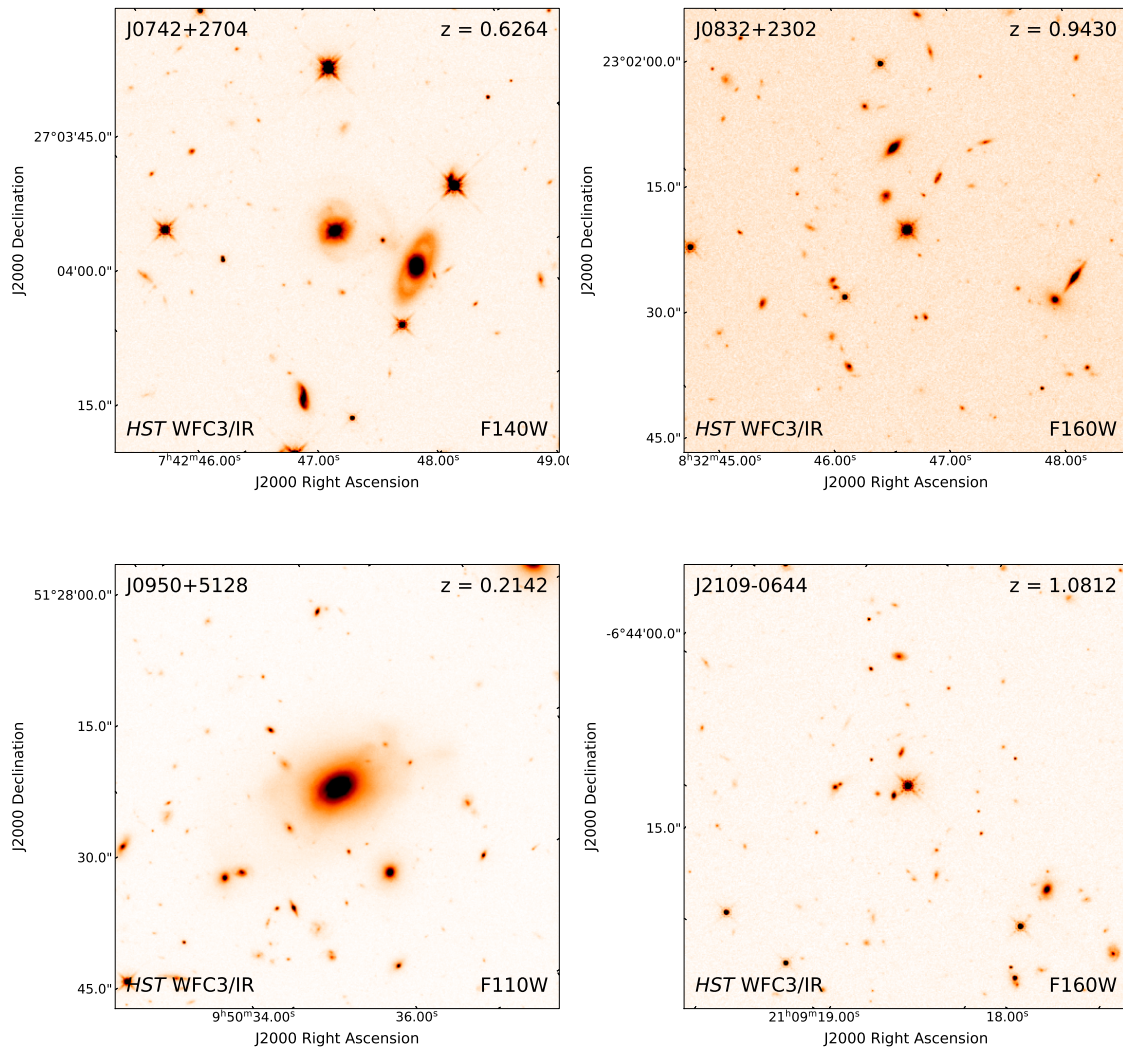


Fig. 7—Examples of the rest-frame optical morphologies from my recent Cycle 22 *HST* WFC3/IR pilot imaging program. Quasar-host decomposition has not yet been applied. The 2 lower-redshift sources in the left and center panels show clearly extended morphologies well suited to the observing capabilities of *HST*. In the center panel, J0742+2704 has a faint tidal tail indicative of recent merger activity.

3.3 Student Mentoring

I mentored a total of 4 students during my year as a Karles fellow, including 3 students affiliated with official NRL programs. A list of the students that I mentored, and my responsibilities for each one, is provided below:

- **Azia Robinson** (undergraduate student, Princeton University) – primary mentor. From October 2021 to May 2022, I supervised Azia Robinson in collaboration with Professor Jenny Greene (Princeton University) on an extragalactic HI imaging study with the VLA. The goal of this project was to study the formation history dwarf galaxies. My mentoring duties included teaching radio interferometry theory, VLA data processing, and scientific analysis. Azia was accepted into the graduate physics program at New Mexico Tech in the fall of 2022.
- **Emma Schwartzman** (graduate student, George Mason University) – co-mentor. I assisted other members of my section in mentoring Emma. Specific examples include providing VLA and VLBA technical expertise, assisting with Python programming skill development, providing scientific guidance on abstracts, presentations, and proposals.
- **Amaris McCarver** (undergraduate student, Texas Tech) – co-mentor. Amaris McCarver was an NREIP student in 2022. I assisted Amaris’s primary mentor (Tracy Clarke) with support on multiple VLITE projects, including assisting with proposal preparation for our group to follow-up a new millisecond pulsar discovered by the student.
- **Esonica Charles** (undergraduate student, University of the Virgin Islands) – supplemental mentor. Esonica Charles was an HBCU summer student at NRL in 2022. Her primary mentor was Jason Kooi. I provided supplemental mentoring for Esonica, as well as other students participating in NRL summer research programs in my section, by serving as the back-up on-site mentor (required for students to work in-person), assisting with technical questions, and facilitating student participation in in-person activities.

3.4 STEM Outreach

3.4.1 National Junior Science and Humanities Symposium

I represented NRL at the National Junior Science and Humanities Symposium (JSHS) The 60th NJSHS was held April 20-23, 2022, as an in-person competition in Albuquerque, NM. JSHS is a Tri-Service - Departments of the U.S. Army, Navy, and Air Force - program that encourages high school students to conduct original research in the fields of science, technology, engineering, and mathematics (STEM). JSHS aims to prepare and support students to pursue careers in science and engineering and to go on to conduct STEM research on behalf of, or directly for, the DoD. Over 8,000 talented youth annually compete in 49 JSHS regional symposia covering the U.S., Puerto Rico, and DoD Dependent Schools in Europe and the Pacific to receive recognition, incentives, and scholarships for their research achievements. The National JSHS brings together 245 high school students who qualify by submitting and presenting original scientific research papers in regional symposia held at universities nationwide. Approximately 130 high school teachers, mentors, university faculty, military personnel, and others also attend and join in encouraging the future generation of scientists and engineers and celebrating student achievement in the sciences.

My involvement at the JSJS as a Karles fellow included serving as a National Poster and Oral Presentation Judge in the Physical Sciences/Chemistry category, leading a student roundtable discussion during the researcher Meet and Greet event, and presenting my own research to students and other members of the DoD community during the Career and Reverse Science Fair. I was truly inspired by the level of young talent that I saw and the quality of the projects that I judged. The May 11, 2022 issue of *The Dish* featured an article on the National JSJS and highlighted my involvement in the event.

I also made new DoD and Navy contacts at this event. A networking highlight was meeting a professor at the U.S. Naval Academy who put in contact with the faculty members doing astrophysics. This led to an invitation to give a talk at the U.S. Naval Academy in October 2022 and my upcoming involvement in the 2023 NRL-USNA summer internship program for midshipmen.

3.4.2 Astronomy Festival on the National Mall

I helped organize and staff NRL's booth at the Astronomy Festival on the National Mall (AFNM). The AFNM is an annual public outreach event organized by Hofstra University and endorsed by the White House Office of Science and Technology that takes place on the National Mall in Washington, DC. The event features booths with activities and demonstrations staffed by educators from science organizations, universities, observatories, and laboratories. Thousands of visitors attend the event annually. I volunteered to help organize NRL's participation in the AFNM on June 25, 2022. This was the first AFNM event to take place following a two-year hiatus due to the pandemic. My duties at this event included performing public science demonstrations (such as star gazing), giving short presentations on my research on supermassive black holes, and providing general information on science and career opportunities at NRL. I was awarded a commander's coin by the CO, CAPT Petrovic, in recognition of my outstanding volunteer work at this event.

4. FUTURE WORK

4.1 Radio-frequency Monitoring

Continued monitoring of the evolution in the fluxes and spectra of quasars with young jets is necessary to test the hypothesis that they are young. Measurements of the spectral variability over timescales of a few years will further test whether beaming, multiple superimposed components (e.g. a re-started jet + fading "lobes"), or transient phenomena (e.g. extreme scattering events) contribute to the variable radio properties.

4.2 Very Long Baseline Interferometry

An analysis of VLBA follow-up observations is currently in progress to further investigate the source sizes and morphologies (Nyland et al., in prep). Source compactness down to parsec scales would support the newborn jet scenario and highlight exciting opportunities for long-baseline science with the next-generation Very Large Array (ngVLA¹; [29]).

5. SUMMARY

The Karles fellowship program at NRL allowed me to pursue new scientific research, leadership, and service opportunities. During my year as a Karles fellow, I led or co-authored a total of 12 peer-reviewed

¹The ngVLA is a new radio telescope currently under development by the National Radio Astronomy Observatory that will operate in the American Southwest.

papers, gave 6 scientific presentations (including 4 invited talks), and directly supervised or co-mentored 4 students on their research projects. The research I have been leading is providing new insights into the fundamental physics of quasars, including CRF sources that play an important role in positioning, navigation, and timing for the Navy. Specifically, my work has demonstrated that quasars may exhibit dramatic changes in radio fluxes on timescales of years to decades, effectively transitioning from “radio quiet” (undetected in systematic all-sky surveys and not suitable for reference frame use) to detected and potentially bright/compact enough for future CRF applications. The continued study of CRF quasars is important for understanding the connection between quasar and galaxy evolution and guiding future CRF realizations with the ngVLA.

ACKNOWLEDGMENTS

I am grateful for the generous funding support provided through the Jerome and Isabella Karle Fellowship program at NRL. 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. The authors have made use of `ASTROPY`, a community-developed core `PYTHON` package for Astronomy [30]. We also used `MONTAGE`, which is funded by the National Science Foundation under Grant Number ACI-1440620, and was previously funded by the National Aeronautics and Space Administration’s Earth Science Technology Office, Computation Technologies Project, under Cooperative Agreement Number NCC5-626 between NASA and the California Institute of Technology.

REFERENCES

1. K. Nyland, D. Z. Dong, P. Patil, M. Lacy, S. van Velzen, A. E. Kimball, S. K. Sarbadhicary, G. Hallinan, V. Baldassare, T. E. Clarke, A. D. Goulding, J. Greene, A. Hughes, N. Kassim, M. Kunert-Bajraszewska, T. J. Maccarone, K. Mooley, D. Mukherjee, W. Peters, L. Petrov, E. Polisensky, W. Rujopakarn, M. Whittle, and M. Vaccari, “Quasars That Have Transitioned from Radio-quiet to Radio-loud on Decadal Timescales Revealed by VLASS and FIRST,” *ApJ* **905**(1), 74 (Dec. 2020), doi:10.3847/1538-4357/abc341.
2. K. Nyland, D. Z. Dong, P. Patil, M. Lacy, S. van Velzen, A. E. Kimball, S. K. Sarbadhicary, G. Hallinan, V. Baldassare, T. E. Clarke, A. D. Goulding, J. Greene, A. Hughes, N. Kassim, M. Kunert-Bajraszewska, T. J. Maccarone, K. Mooley, D. Mukherjee, W. Peters, L. Petrov, E. Polisensky, W. Rujopakarn, M. Whittle, and M. Vaccari, “Powerful quasars with young jets in multi-epoch radio surveys,” *Astronomische Nachrichten* **342**(1146), 1146–1150 (Nov. 2021), doi:10.1002/asna.20210058.
3. T. W. Shimwell, M. J. Hardcastle, C. Tasse, P. N. Best, H. J. A. Röttgering, W. L. Williams, A. Botteon, A. Drabant, A. Mechev, A. Shulevski, R. J. van Weeren, L. Bester, M. Brügger, G. Brunetti, J. R. Callingham, K. T. Chyży, J. E. Conway, T. J. Dijkema, K. Duncan, F. de Gasperin, C. L. Hale, M. Haverkorn, B. Hugo, N. Jackson, M. Mevius, G. K. Miley, L. K. Morabito, R. Morganti, A. Offringa, J. B. R. Oonk, D. Rafferty, J. Sabater, D. J. B. Smith, D. J. Schwarz, O. Smirnov, S. P. O’Sullivan, H. Vedantham, G. J. White, J. G. Albert, L. Alegre, B. Asabere, D. J. Bacon, A. Bonafede, E. Bonnassieux, M. Brienza, M. Bilicki, M. Bonato, G. Calistro Rivera, R. Cassano, R. Cochrane, J. H. Croston, V. Cuciti, D. Dallacasa, A. Danezi, R. J. Dettmar, G. Di Gennaro, H. W. Edler, T. A. Enßlin, K. L. Emig, T. M. O. Franzen, C. García-Vergara, Y. G. Grange, G. Gürkan, M. Hajduk, G. Heald, V. Heesen, D. N. Hoang, M. Hoeft, C. Horellou, M. Iacobelli, M. Jamrozy, V. Jelić, R. Kondapally, P. Kukreti, M. Kunert-Bajraszewska,

- M. Magliocchetti, V. Mahatma, K. Malek, S. Mandal, F. Massaro, Z. Meyer-Zhao, B. Mingo, R. I. J. Mostert, D. G. Nair, S. J. Nakoneczny, B. Nikiel-Wroczyński, E. Orrú, U. Pajdosz-Śmierciak, T. Pasini, I. Prandoni, H. E. van Piggelen, K. Rajpurohit, E. Retana-Montenegro, C. J. Riseley, A. Rowlinson, A. Saxena, C. Schrijvers, F. Sweijen, T. M. Siewert, R. Timmerman, M. Vaccari, J. Vink, J. L. West, A. Wołowska, X. Zhang, and J. Zheng, “The LOFAR Two-metre Sky Survey. V. Second data release,” *A&A* **659**, A1 (Mar. 2022), doi:10.1051/0004-6361/202142484.
4. K. I. Kellermann, J. J. Condon, A. E. Kimball, R. A. Perley, and Ž. Ivezić, “Radio-loud and Radio-quiet QSOs,” *ApJ* **831**(2), 168 (Nov. 2016), doi:10.3847/0004-637X/831/2/168.
 5. A. C. Fabian, “Observational Evidence of Active Galactic Nuclei Feedback,” *ARA&A* **50**, 455–489 (Sept. 2012), doi:10.1146/annurev-astro-081811-125521.
 6. B. Czerny, A. Siemiginowska, A. Janiuk, B. Nikiel-Wroczyński, and L. Stawarz, “Accretion Disk Model of Short-Timescale Intermittent Activity in Young Radio Sources,” *ApJ* **698**(1), 840–851 (June 2009), doi:10.1088/0004-637X/698/1/840.
 7. M. E. Jarvis, C. M. Harrison, A. P. Thomson, C. Circosta, V. Mainieri, D. M. Alexander, A. C. Edge, G. B. Lansbury, S. J. Molyneux, and J. R. Mullaney, “Prevalence of radio jets associated with galactic outflows and feedback from quasars,” *MNRAS* **485**(2), 2710–2730 (May 2019), doi:10.1093/mnras/stz556.
 8. P. Patil, K. Nyland, M. Whittle, C. Lonsdale, M. Lacy, C. Lonsdale, D. Mukherjee, A. C. Trapp, A. E. Kimball, L. Lanz, B. J. Wilkes, A. Blain, J. J. Harwood, A. Efstathiou, and C. Vlahakis, “High-resolution VLA Imaging of Obscured Quasars: Young Radio Jets Caught in a Dense ISM,” *ApJ* **896**(1), 18 (June 2020), doi:10.3847/1538-4357/ab9011.
 9. D. Mukherjee, G. V. Bicknell, R. Sutherland, and A. Wagner, “Relativistic jet feedback in high-redshift galaxies - I. Dynamics,” *MNRAS* **461**(1), 967–983 (Sept. 2016), doi:10.1093/mnras/stw1368.
 10. G. V. Bicknell, M. A. Dopita, and C. P. O. O’Dea, “Unification of the Radio and Optical Properties of Gigahertz Peak Spectrum and Compact Steep-Spectrum Radio Sources,” *ApJ* **485**(1), 112–124 (Aug. 1997), doi:10.1086/304400.
 11. P. Patil, M. Whittle, K. Nyland, C. Lonsdale, M. Lacy, A. E. Kimball, C. Lonsdale, W. Peters, T. E. Clarke, A. Efstathiou, S. Giacintucci, M. Kim, L. Lanz, D. Mukherjee, and E. Polisensky, “Radio Spectra of Luminous, Heavily Obscured WISE-NVSS Selected Quasars,” *ApJ* **934**(1), 26 (July 2022), doi:10.3847/1538-4357/ac71b0.
 12. R. Barvainis, J. Lehár, M. Birkinshaw, H. Falcke, and K. M. Blundell, “Radio Variability of Radio-quiet and Radio-loud Quasars,” *ApJ* **618**(1), 108–122 (Jan. 2005), doi:10.1086/425859.
 13. M. E. Bell, M. T. Huynh, P. Hancock, T. Murphy, B. M. Gaensler, D. Burlon, C. Trott, and K. Bannister, “A search for variable and transient radio sources in the extended Chandra Deep Field South at 5.5 GHz,” *MNRAS* **450**(4), 4221–4232 (July 2015), doi:10.1093/mnras/stv882.
 14. K. P. Mooley, G. Hallinan, S. Bourke, A. Horesh, S. T. Myers, D. A. Frail, S. R. Kulkarni, D. B. Levitan, M. M. Kasliwal, S. B. Cenko, Y. Cao, E. Bellm, and R. R. Laher, “The Caltech-NRAO Stripe 82 Survey (CNSS). I. The Pilot Radio Transient Survey In 50 deg²,” *ApJ* **818**, 105 (Feb. 2016), doi:10.3847/0004-637X/818/2/105.

15. M. Lacy, S. A. Baum, C. J. Chandler, S. Chatterjee, T. E. Clarke, S. Deustua, J. English, J. Farnes, B. M. Gaensler, N. Gugliucci, G. Hallinan, B. R. Kent, A. Kimball, C. J. Law, T. J. W. Lazio, J. Marvil, S. A. Mao, D. Medlin, K. Mooley, E. J. Murphy, S. Myers, R. Osten, G. T. Richards, E. Rosolowsky, L. Rudnick, F. Schinzel, G. R. Sivakoff, L. O. Sjouwerman, R. Taylor, R. L. White, J. Wrobel, H. Andernach, A. J. Beasley, E. Berger, S. Bhatnager, M. Birkinshaw, G. C. Bower, W. N. Brandt, S. Brown, S. Burke-Spolaor, B. J. Butler, J. Comerford, P. B. Demorest, H. Fu, S. Giacintucci, K. Golap, T. Güth, C. A. Hales, R. Hiriart, J. Hodge, A. Horesh, Ž. Ivezić, M. J. Jarvis, A. Kamble, N. Kassim, X. Liu, L. Loinard, D. K. Lyons, J. Masters, M. Mezcua, G. A. Moellenbrock, T. Mroczkowski, K. Nyland, C. P. O’Dea, S. P. O’Sullivan, W. M. Peters, K. Radford, U. Rao, J. Robnett, J. Salcido, Y. Shen, A. Sobotka, S. Witz, M. Vaccari, R. J. van Weeren, A. Vargas, P. K. G. Williams, and I. Yoon, “The Karl G. Jansky Very Large Array Sky Survey (VLASS). Science Case and Survey Design,” *PASP* **132**(1009), 035001 (Mar. 2020), doi:10.1088/1538-3873/ab63eb.
16. R. H. Becker, R. L. White, and D. J. Helfand, “The FIRST Survey: Faint Images of the Radio Sky at Twenty Centimeters,” *ApJ* **450**, 559 (Sept. 1995), doi:10.1086/176166.
17. I. Pâris, P. Petitjean, É. Aubourg, A. D. Myers, A. Streblyanska, B. W. Lyke, S. F. Anderson, É. Armengaud, J. Bautista, M. R. Blanton, M. Blomqvist, J. Brinkmann, J. R. Brownstein, W. N. Brandt, É. Burtin, K. Dawson, S. de la Torre, A. Georgakakis, H. Gil-Marín, P. J. Green, P. B. Hall, J. P. Kneib, S. M. LaMassa, J. M. Le Goff, C. MacLeod, V. Mariappan, I. D. McGreer, A. Merloni, P. Noterdaeme, N. Palanque-Delabrouille, W. J. Percival, A. J. Ross, G. Rossi, D. P. Schneider, H. J. Seo, R. Tojeiro, B. A. Weaver, A. M. Weijmans, C. Yèche, P. Zarrouk, and G. B. Zhao, “The Sloan Digital Sky Survey Quasar Catalog: Fourteenth data release,” *A&A* **613**, A51 (May 2018), doi:10.1051/0004-6361/201732445.
18. Y. Shen, G. T. Richards, M. A. Strauss, P. B. Hall, D. P. Schneider, S. Snedden, D. Bizyaev, H. Brewington, V. Malanushenko, E. Malanushenko, D. Oravetz, K. Pan, and A. Simmons, “A Catalog of Quasar Properties from Sloan Digital Sky Survey Data Release 7,” *ApJS* **194**(2), 45 (June 2011), doi:10.1088/0067-0049/194/2/45.
19. C. P. O’Dea, “The Compact Steep-Spectrum and Gigahertz Peaked-Spectrum Radio Sources,” *PASP* **110**(747), 493–532 (May 1998), doi:10.1086/316162.
20. N. E. Gugliucci, G. B. Taylor, A. B. Peck, and M. Giroletti, “Dating COINS: Kinematic Ages for Compact Symmetric Objects,” *ApJ* **622**(1), 136–148 (Mar. 2005), doi:10.1086/427934.
21. R. J. McLure, M. J. Kukula, J. S. Dunlop, S. A. Baum, C. P. O’Dea, and D. H. Hughes, “A comparative HST imaging study of the host galaxies of radio-quiet quasars, radio-loud quasars and radio galaxies - I,” *MNRAS* **308**(2), 377–404 (Sept. 1999), doi:10.1046/j.1365-8711.1999.02676.x.
22. M. J. Kukula, J. S. Dunlop, R. J. McLure, L. Miller, W. J. Percival, S. A. Baum, and C. P. O’Dea, “A NICMOS imaging study of high-*z* quasar host galaxies,” *MNRAS* **326**(4), 1533–1546 (Oct. 2001), doi:10.1111/j.1365-2966.2001.04692.x.
23. J. S. Dunlop, R. J. McLure, M. J. Kukula, S. A. Baum, C. P. O’Dea, and D. H. Hughes, “Quasars, their host galaxies and their central black holes,” *MNRAS* **340**(4), 1095–1135 (Apr. 2003), doi:10.1046/j.1365-8711.2003.06333.x.
24. D. Wylezalek, N. L. Zakamska, G. Liu, and G. Obied, “Towards a comprehensive picture of powerful quasars, their host galaxies and quasar winds at $z \sim 0.5$,” *MNRAS* **457**(1), 745–763 (Mar. 2016), doi:10.1093/mnras/stv3022.

25. T. Urrutia, M. Lacy, and R. H. Becker, “Evidence for Quasar Activity Triggered by Galaxy Mergers in HST Observations of Dust-reddened Quasars,” *ApJ* **674**(1), 80–96 (Feb. 2008), doi:10.1086/523959.
26. P. J. L. Charlton, J. J. Ruan, D. Haggard, S. F. Anderson, M. Eracleous, C. L. MacLeod, and J. C. Runnoe, “Gemini Imaging of the Host Galaxies of Changing-look Quasars,” *ApJ* **876**(1), 75 (May 2019), doi:10.3847/1538-4357/ab0ec1.
27. M. Chiaberge, R. Gilli, J. M. Lotz, and C. Norman, “Radio Loud AGNs are Mergers,” *ApJ* **806**(2), 147 (June 2015), doi:10.1088/0004-637X/806/2/147.
28. S. Birrer and A. Amara, “lenstronomy: Multi-purpose gravitational lens modelling software package,” *Physics of the Dark Universe* **22**, 189–201 (Dec. 2018), doi:10.1016/j.dark.2018.11.002.
29. E. J. Murphy, A. Bolatto, S. Chatterjee, C. M. Casey, L. Chomiuk, D. Dale, I. de Pater, M. Dickinson, J. D. Francesco, G. Hallinan, A. Isella, K. Kohno, S. R. Kulkarni, C. Lang, T. J. W. Lazio, A. K. Leroy, L. Loinard, T. J. Maccarone, B. C. Matthews, R. A. Osten, M. J. Reid, D. Riechers, N. Sakai, F. Walter, and D. Wilner, “The ngVLA Science Case and Associated Science Requirements,” in E. Murphy, ed., *Science with a Next Generation Very Large Array*, volume 517 of *Astronomical Society of the Pacific Conference Series*, Dec. 2018, p. 3.
30. Astropy Collaboration, T. P. Robitaille, E. J. Tollerud, P. Greenfield, M. Droettboom, E. Bray, T. Aldcroft, M. Davis, A. Ginsburg, A. M. Price-Whelan, W. E. Kerzendorf, A. Conley, N. Crighton, K. Barbary, D. Muna, H. Ferguson, F. Grollier, M. M. Parikh, P. H. Nair, H. M. Unther, C. Deil, J. Woillez, S. Conseil, R. Kramer, J. E. H. Turner, L. Singer, R. Fox, B. A. Weaver, V. Zabalza, Z. I. Edwards, K. Azalee Bostroem, D. J. Burke, A. R. Casey, S. M. Crawford, N. Dencheva, J. Ely, T. Jenness, K. Labrie, P. L. Lim, F. Pierfederici, A. Pontzen, A. Ptak, B. Refsdal, M. Servillat, and O. Streicher, “Astropy: A community Python package for astronomy,” *A&A* **558**, A33 (Oct. 2013), doi:10.1051/0004-6361/201322068.