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Nyland, K.; Dong, D.Z.; Patil, P.; Lacy, M.; Velzen, S. van; Kimball, A.E.; ... ; Vaccari, M.

Received: 20 October 2021 | Accepted: 21 October 2021 | Published on: 25 November 2021

DOI: 10.1002/asna.20210058

Astronomische Nachrichten

PROCEEDING

Powerful quasars with young jets in multi-epoch radio surveys

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Abstract

Energetic feedback driven by the large-scale (100's of kpc) lobes of classical radio galaxies is known to play an important role in shaping galaxy evolution. However, the prevalence of young and compact jets – and their impact on the interstellar medium – remains an open question. Multi-epoch radio surveys with cadences of years to decades offer a promising means of identifying even faint (mJy-level) jets that are compact and potentially young on the basis of variability. Recently, a comparison of images from the Very Large Array Sky Survey (VLASS) and the Faint Images of the Radio Sky at Twenty Centimeters (FIRST) survey has revealed a population of distant ($0.2 < z < 3.2$) quasars that have brightened dramatically in the past 1–2 decades. These quasars appear to have transitioned from "radio-quiet" nondetections in FIRST to "radio-loud" detections in VLASS. Extensive multiband follow-up observations with the VLA from 1 to 18 GHz have revealed compact (sub-kpc) radio sources that are consistent with young jets that were recently triggered. Here, we summarize the status of our on-going study of quasars with newborn jets identified in the radio time domain.

KEYWORD

galaxies: active – galaxies: evolution – galaxies: jets – radio continuum: galaxies – quasars: general

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Funding information
6.1 Base

1 | INTRODUCTION

Active galactic nuclei (AGN) and quasars regulate the growth of galaxies and their supermassive black holes (SMBHs) through energetic feedback driven by powerful winds or radio-emitting jets. In the radio mode, it is well established that large-scale (100's of kpc) radio jets and lobes influence galaxy evolution by preventing hot halos of gas around galaxies from cooling and forming new stars (Fabian 2012). However, the impact and importance of radio jet-driven feedback on sub-galactic scales remains poorly constrained.

Simulations suggest that sub-galactic jets may influence the ambient ISM conditions, and perhaps even the star formation rates/efficiencies, of their host galaxies (Mukherjee et al. 2016). To test this possibility, a systematic search for young/compact radio jets and a detailed analysis of their properties are needed. Identifying young/-compact jets by directly resolving their morphologies remains unfeasible, particularly in the faint (mJy-level) and high-redshift ($z > 1$) domains, due to the limitations of historical all-sky radio surveys. An alternative approach is to compare multiple epochs of data from modern radio surveys with higher sensitivity and resolution.

2 | THE VLA SKY SURVEY

A game-changing advancement in the ability to search for young jets has recently been made possible by the Very Large Array (VLA) Sky Survey (VLASS; Lacy et al. 2020). VLASS is an on-going multi-epoch (3 epochs over 7 years) survey at 2–4 GHz of the entire northern sky visible to the VLA ($\delta > -40°$). The combination of high resolution, observing frequency, and multi-epoch design of VLASS are well-tuned for identifying young jets on the basis of their radio morphologies, spectral shapes, and variability (e.g., due to adiabatic expansion) over years to decades (Barvainis et al. 2005; Bell et al. 2015; Mooley et al. 2016; Nyland et al. 2020, Figure 1). VLASS is still in progress, but newborn quasar jets with characteristic peaked radio spectral shapes have already begun to be identified by comparing data from VLASS Epoch 1 taken from 2017 to 2019 and the Faint Images of the Radio Sky at Twenty Centimeters ((FIRST; Becker et al. 1995) taken from 1993 to 2011.

3 | SAMPLE

Nyland et al. (2020) identified a sample of known quasars based on optical/infrared diagnostics with radio fluxes that have brightened dramatically in the past 1–2 decades based on a comparison between FIRST and VLASS Epoch 1. The selection criteria are illustrated in Figure 2, and full details are provided id in Nyland et al. (2020). The final sample contains 26 radio-variable quasars with redshifts in the range of $0.2 < z < 3.2$ that were discovered in a search of VLASS Epoch 1 Quick Look images over ∼3,440 deg^2. Based on the typical 3 GHz VLASS radio luminosities of $\log\left(L_{3\mathrm{GHz}}/\mathrm{erg\ \ s}^{-1}\right) \approx 40 - 42$, these quasars would have previously been classified as radio-quiet on the basis of their formal nondetections in prior surveys at similar frequency, resolution, and sensitivity, such as FIRST. However, the VLASS data reveal radio luminosities that are now consistent with the radio-loud[1] quasar population. Simultaneous 1–18 GHz VLA/A-configuration observations of 14 candidate quasars with young jets were taken in 2019. The follow-up VLA data revealed large variability amplitudes (100% to >2,500%) at 1.4 GHz compared to FIRST and variability timescales > a few months at 3 GHz compared to VLASS. All of the sources with multiband VLA follow-data have peaked radio spectra with turnovers around ∼5–10 GHz and compact morphologies that constrain the source sizes to $< 0.1''$ ($\lesssim 1$ kpc) at 15 GHz (Figure 3).

The radio properties are consistent with young radio source classes, such as gigahertz peaked spectrum (GPS) or Compact Step Spectrum (CSS) sources (O'Dea & Saikia 2021; Orienti 2016; Patil et al. 2020). The long-term radio variability is thus likely associated with young and compact jets that were launched within the past few

[1]Based on the definition of radio-loudness given in Kellermann et al. (2016).

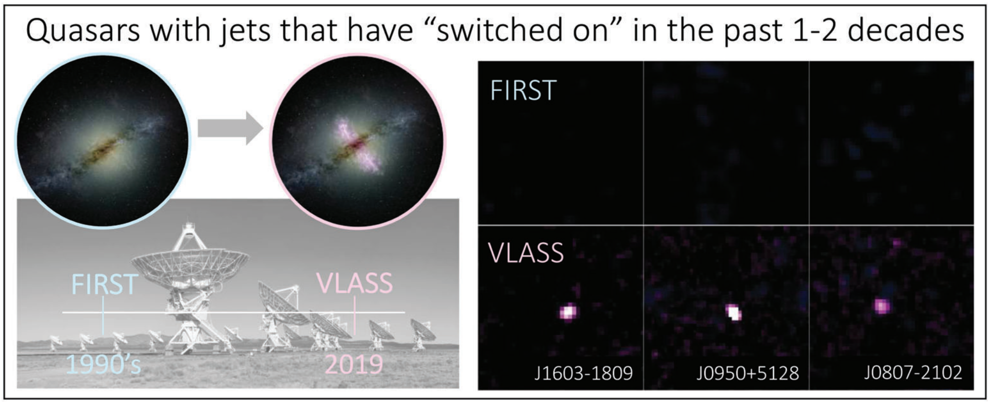

FIGURE 1 Multi-epoch radio surveys identify quasars that have switched from radio-quiet to radio-loud over timescales of years to decades, possibly signifying the birth of a young jet. Credits: Sophia Dagnello, NRAO/AUI/NSF, and Kristina Nyland

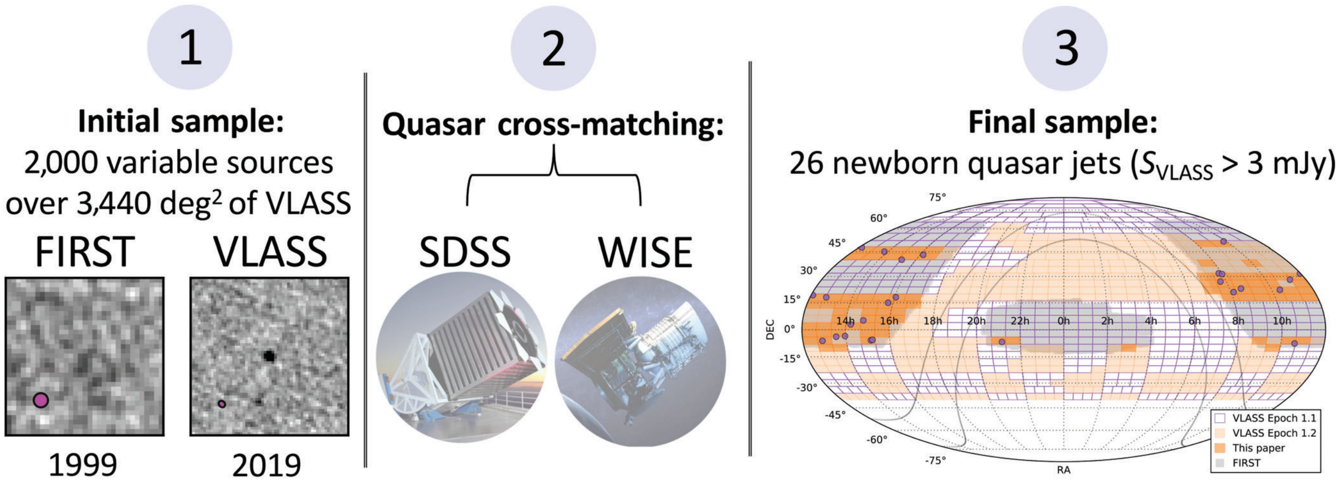

FIGURE 2 Illustration of the selection criteria for the sample presented in Nyland et al. (2020). The final 3 mJy beam^{-1} cut in flux serves to rule-out optically-thick sources that were steady between FIRST and VLASS

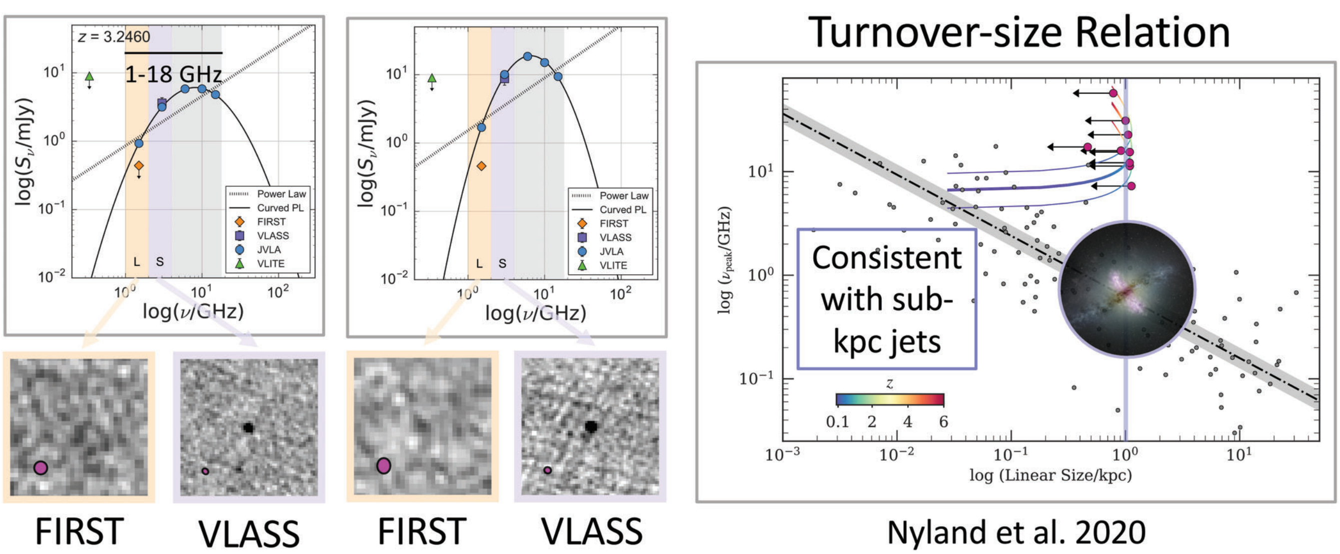

FIGURE 3 *Left*: Examples of the peaked radio spectra of the newborn quasar jets identified through a comparison between FIRST and VLASS. *Right*: The turnover-size relation (spectral peak vs. linear size) with the 14 candidate newborn quasar jets from Nyland et al. (2020) shown as magenta circles. *Credits*: Sophia Dagnello, NRAO/AUI/NSF, and Kristina Nyland

decades, possibly associated with a state transition of the SMBH (Kunert-Bajraszewska et al. 2020; Wołowska et al. 2021), making them among the youngest radio jets known (Gugliucci et al. 2005).

4 | DISCUSSION

The cumulative effects of recurring episodes of quasar jet activity remain an open area of research (Jurlin et al. 2020; Shabala et al. 2020). Here, we searched an area of $\sim$3,440 deg^2 and found a sky density of candidate newborn quasar jets of 4×10^{-3} deg^{-2}. Assuming jets that were triggered $\sim$20 years ago, we estimate a period of occurrence of 100,000 years. As discussed in Nyland et al. (2020), this is consistent with intermittent episodes in a quasar's life in which jets are (re-)triggered. 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 radio follow-up observations monitoring of the spectral variability (Tingay et al. 2015), as well as milliarcsecond-scale radio imaging with the Very Long Baseline Array (Keim et al. 2019), will be necessary to constrain the underlying absorption physics (synchrotron self absorption vs. free-free absorption) and the potential influence of effects like variable doppler boosting (e.g., due to jet bending/deflection) or superposition of components (e.g., a re-started jet + fading "lobes"). Multiwavelength follow-up studies (including *Chandra*, *HST*, and ALMA data), which will further constrain the quasar/host properties and their connection to the triggering of the jets, are in progress.

5 | CONCLUSIONS

The emergence of young jets on human timescales of decades challenges the idea that "radio-loudness" is a property of the quasar/AGN population that remains constant, thus inviting renewed exploration of the link between young/compact jets and galaxy evolution. The completion of VLASS will provide an exciting opportunity for extending the analysis described in this article. Upcoming multi-epoch radio surveys with Square Kilometre Array pathfinders (e.g., VAST;?) will further support the identification of young jets. Looking further ahead, the unique combination of dramatically improved sensitivity, resolution, and frequency coverage of the next-generation Very Large Array will facilitate a leap forward in our understanding of young jets and their impact on their host galaxies (Nyland et al. 2018).

ACKNOWLEDGMENTS

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.

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How to cite this article: Nyland, K., Dong, D. Z., Patil, P., et al. 2021, *Astron. Nachr.*, *342*, 1146. https://doi.org/10.1002/asna.20210058