Quasars That Have Transitioned from Radio-quiet to Radio-loud on Decadal Timescales Revealed by VLASS and FIRST

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ABSTRACT

We have performed a search over 3440 deg2 of Epoch 1 (2017–2019) of the Very Large Array Sky Survey to identify unobscured quasars in the optical (0.2 < z < 3.2) and obscured active galactic nuclei (AGN) in the infrared that have brightened dramatically in the radio over the past one to two decades. These sources would have been previously classified as “radio-quiet” quasars based on upper limits from the Faint Images of the Radio Sky at Twenty Centimeters survey (1993–2011), but they are now consistent with “radio-loud” quasars that have been previously classified as “radio-quiet” quasars based on upper limits from the Faint Images of the radio-loud quasars. A quasi-simultaneous, multiband (~ 1 – 18 GHz) follow-up study of 14 sources with the VLA has revealed compact sources (< 0.1″ or <1 kpc) with peaked radio spectral shapes. The high-amplitude variability over decadal timescales at 1.5 GHz (100% to >2500%), but roughly steady fluxes over a few months at 3 GHz, are inconsistent with extrinsic variability due to propagation effects, thus favoring an intrinsic origin. We conclude that our sources are powerful quasars hosting compact/young jets. This challenges the generally accepted idea that “radio-loudness” is a property of the quasar/AGN population that remains fixed on human timescales. Our study suggests that frequent episodes of short-lived AGN jets that do not necessarily grow to large scales may be common at high redshift. We speculate that intermittent but powerful jets on
subgalactic scales could interact with the interstellar medium, possibly driving feedback capable of influencing galaxy evolution.

Keywords: galaxies: active — galaxies: evolution — radio continuum: galaxies

1. INTRODUCTION

Until recently, synoptic surveys of the dynamic sky have been dominated by optical, X-ray, and gamma-ray observing campaigns, with systematic radio studies of transient and variable sources, in particular those at high redshift, often performed as follow-up in response to a shorter wavelength trigger. Thus, the slow transient (or slowly varying) extragalactic radio source population remains largely unexplored, particularly among sources invisible to synoptic surveys conducted at shorter wavelengths (e.g., due to obscuration by dense columns of gas and dust). Large-scale synoptic radio surveys are thus a key way forward for both current radio telescopes, such as the Karl G. Jansky Very Large Array (VLA), and prospective instruments under development over the next decade, such as the next-generation Very Large Array\(^1\) (ngVLA; Murphy et al. 2018; Selina et al. 2018) and Square Kilometre Array\(^2\) (SKA; Dewdney et al. 2009; Braun et al. 2015, 2019).

Active Galactic Nuclei (AGN) represent the most dominant source of variability and transient activity in the radio sky (e.g. Carilli et al. 2003; Thyagarajan et al. 2011; Bannister et al. 2011; Frail et al. 2012; Bell et al. 2015; Mooley et al. 2016). The majority of AGN exhibit variability (a well-known multiwavelength hallmark of an AGN Hovatta et al. 2007) in the radio regime at the few tens of percent level over a wide range of timescales, between a few days and a few decades (e.g. Barvainis et al. 2005; Thyagarajan et al. 2011; Gralla et al. 2020; Sarbadhicary et al. 2020). This variability is often attributed to extrinsic effects related to propagation (e.g. interstellar scattering) or intrinsic effects directly related to AGN itself (Bignall et al. 2015, and references therein) such as the propagation of shocks along the jet (e.g. Marscher & Gear 1985).

More extreme radio AGN variability (with a variability amplitude \(\gtrsim 100\%\)) occurring over longer timescales of years to decades has also been observed (e.g. Barvainis et al. 2005), and may be caused by jets that have reoriented themselves toward our line of sight or young, expanding jets that have been recently triggered. In the case of jet reorientation, precession due to perturbations from the presence of a binary SMBH or stochastic effects related to accretion (An et al. 2013) may alter the jet inclination angle and degree of Doppler boosting, thereby leading to high-amplitude, long-term variability. Bonafide candidates for new jet activity have also been identified (Mooley et al. 2016; Kunert-Bajraszewska et al. 2020), suggesting that short-lived, intermittent AGN jet activity recurring on timescales of \(\sim 10^4 - 10^5\) years could be common, consistent with predictions (e.g. Reynolds & Begelman 1997; Czerny et al. 2009).

Compact radio AGN with subgalactic extents residing in gas-rich host galaxies, especially those at redshifts of \(1 \lesssim z \lesssim 3\), are an important, yet still poorly studied class of objects for understanding the role of jet-ISM feedback in influencing galaxy growth and evolution (Mukherjee et al. 2016; Nyland et al. 2018; Jarvis et al. 2019). Specifically, the prevalence of radio AGN variability driven by different intrinsic effects, as well as the magnitude and impact feedback from subgalactic jets on SMBH-galaxy co-evolution, remain uncertain.

Here, we present follow-up, quasi-simultaneous, multiband VLA observations of a subset of AGN with high-amplitude (100% to \(>250\%\)) radio variability identified in a search for transients on decades-long timescales between the Faint Images of the Sky at Twenty centimeters (FIRST; Becker et al. 1995) and \(\sim 3,440\) deg\(^2\) of Epoch 1 of the Very Large Array Sky Survey (VLASS; Lacy et al. 2020). We describe our sample and selection criteria in Section 2. In Section 3, we describe the observing and data reduction heuristics for our new multiband VLA observations. An assessment of the radio continuum properties of our sources, variability, and multiband spectral energy distributions (SEDs) is provided in Section 4. We consider a variety of possibilities for the origin of the radio variability in our sources in Section 5, and discuss implications for the life cycles of radio AGN and their connection to galaxy evolution in Section 6. We summarize our results and assess prospects for further insights through future follow-up observations in Section 7. We adopt a standard \(\Lambda\)CDM cosmology with \(H_0 = 67.7\) km \(s^{-1}\) Mpc\(^{-1}\), \(\Omega_\Lambda = 0.691\) and \(\Omega_M = 0.307\) (Planck Collaboration et al. 2016) throughout our study. Errors shown are 1\(\sigma\) unless otherwise stated.

2. SAMPLE

As part of our ongoing compilation of radio transients observed at 3 GHz in Epoch 1 of VLASS, which will be presented in its entirety in Dong et al. (in prep.), we have selected a preliminary sample of radio AGN exhibiting extreme variability on timescales of \(\sim 1-2\) decades. In the remainder of this section, we provide details on the radio surveys used to

\(^1\) https://ngvla.nrao.edu
\(^2\) https://www.skatelescope.org
conduct our search for variable AGN and describe our sample selection criteria.

2.1. Radio Surveys

2.1.1. FIRST

FIRST is a 20 cm (1.4 GHz) survey conducted with the pre-upgrade VLA covering a total sky footprint of 10,575 deg$^2$ (Becker et al. 1995; Helfand et al. 2015). FIRST observed approximately 9,000 deg$^2$ of the north Galactic cap from 1993–2004, and a smaller $\sim 2.5^\circ$-wide strip of the south Galactic cap along the Celestial equator in 2009–2011. The VLA was undergoing the upgrade of its receivers during the latter time range, leading to slightly different image characteristics in the different regions of sky covered by FIRST, but the quality of the survey’s sky coverage in the northern and southern regions are functionally equivalent.\footnote{http://sundog.stsci.edu/} FIRST images have a resolution of approximately $5''$, rms sensitivity of approximately 0.15 mJy beam$^{-1}$, and astrometric uncertainty of $\lesssim 1''$. The published catalog of emission components from FIRST is 95% complete to 2 mJy and 80% complete to the catalog limit of 1 mJy. Peak flux densities and integrated flux densities in the published catalog were determined from two-dimensional Gaussian fits to each co-added FIRST image.

2.1.2. VLASS

VLASS is a wide-area (33,885 deg$^2$), high-resolution ($2.5^\circ$), full-polarization, broadband radio continuum survey currently being carried out by NRAO at $S$-band (2–4 GHz). The relative sky footprints of FIRST and VLASS are illustrated in Figure 1. In order to enable transient science, a key science goal of the survey, VLASS observations are being taken over a series of 3 epochs with a cadence of 32 months. Each VLASS epoch reaches a $1\sigma$ sensitivity of 0.12 mJy beam$^{-1}$, comparable to the depth of FIRST.

VLASS Epoch 1 observations have recently been completed (2017–2019), and preliminary “QuickLook” images have been made publicly available on the NRAO archive\footnote{https://archive-new.nrao.edu/vlass/quicklook/}. The VLASS QuickLook images have flux uncertainties up to ~20% and are not final survey data products (see Lacy et al. 2020 for details). Despite the limitations of the QuickLook images, they are valuable for identifying transient and variable sources that have experienced substantial changes in flux (larger than a factor of 2) in the time period between FIRST and VLASS.

2.2. Variable AGN Selection Criteria

Currently, no “official” source catalog for VLASS has been made publicly available. We therefore produced our own source catalog over a subset of VLASS Epoch 1.2 covering an area of $\sim 3,440$ deg$^2$. We used the source finding algorithm PyBDSF to compile a raw VLASS catalog based on the QuickLook images of sources brighter than 1 mJy. Although our goal is to identify sources that have recently brightened in the radio, we note that similar studies of reverse transients (i.e. sources that were previously detected in FIRST but discovered to have declined drastically in flux when re-observed in VLASS 1–2 decades later) are also currently in progress (e.g. Law et al. 2018; Cendes 2020).

We performed a positional cross-match (within a radius of 1") with the FIRST catalog. The high prevalence of artifacts (uncleaned sidelobes) in the VLASS QuickLook images poses a challenge for reliable source extraction. We manually vetted our preliminary catalog of VLASS-FIRST transients by eye to remove spurious VLASS sources associated with image artifacts or diffuse emission (radio lobes) with inherently ill-defined positions. Such spurious sources account for the vast majority (~90–90%) of our preliminary transient catalog. Our manually-vetted catalog covering the 3,440 deg$^2$ of VLASS Epoch 1 analyzed thus far contains ~2000 candidate transients that are compact and brighter than 1 mJy in VLASS but below the formal detection threshold (1 mJy) of FIRST. Additional details will be presented in Dong et al. (in prep.).

To select AGN with variable radio emission, we considered both optical and infrared AGN selection techniques to capture both the unobscured and obscured populations. In the optical, we used the compilation of spectroscopically verified quasars from the Sloan Digital Sky Survey (SDSS; York et al. 2000) DR14 (Pâris et al. 2018) and found 52 candidate radio-variable quasars within $< 1^\circ$ of the VLASS position. Obscured AGN that have recently brightened in the radio were identified on the basis of their infrared colors using data from the Widefield Infrared Survey Explorer (WISE; Wright et al. 2010). We used the "R90" diagnostic criteria from Assef et al. (2018), which were designed to identify AGN with 90% reliability. A total of 144 obscured AGN with variable radio emission were identified using the R90 catalog, of which 29 sources also met our optical selection criteria, making a total of 167 AGN associated with our manually-vetted FIRST/VLASS sample.

With the AGN associations confirmed, we selected a subset of sources with peak flux densities brighter than 3 mJy beam$^{-1}$ in VLASS. This selects a more reliable sample radio-variable AGN, since the implied spectral index between FIRST and VLASS would be steeper than $\nu^{2.0}$, thereby ruling out steady sources that are optically thick\footnote{We emphasize that steady, albeit optically-thick, radio sources associated with powerful optical/IR AGN are an extremely interesting source population in their own right. Such sources may represent young radio} due...
Figure 1. Relative sky footprints of the VLASS and FIRST surveys. VLASS tiles from Epochs 1.1 and 1.2 are shown in purple and light orange, respectively. The large gray shaded regions illustrate the coverage of the FIRST survey. The 86 tiles from VLASS Epoch 1.2 analyzed in this paper are indicated by the dark orange regions. The gray curves denote coordinates within 10 degrees of the Galactic plane. The positions of our 26 candidate radio-variable AGN identified via comparison with data from FIRST are shown by the purple circles.

This paper

Figure 1. Relative sky footprints of the VLASS and FIRST surveys. VLASS tiles from Epochs 1.1 and 1.2 are shown in purple and light orange, respectively. The large gray shaded regions illustrate the coverage of the FIRST survey. The 86 tiles from VLASS Epoch 1.2 analyzed in this paper are indicated by the dark orange regions. The gray curves denote coordinates within 10 degrees of the Galactic plane. The positions of our 26 candidate radio-variable AGN identified via comparison with data from FIRST are shown by the purple circles.

2.3. Source Properties

We summarize the basic properties of our sample in Tables 1 and 2. Of these 26 sources, 13 are selected from SDSS spectroscopy and the remaining 13 are obscured AGN selected based on the WISE criteria described in Section 2.2. The 13 optically-selected AGN are classified as broad-line quasars with redshifts in the range $0.2 < z < 3.2$. Shen et al. (2011) report bolometric luminosities of $\log(L_{\text{bol}}/\text{erg s}^{-1}) = 45.2 - 46.8$ from SDSS spectroscopy, virial SMBH masses in the range $\log(M/M_\odot) = 8 - 9.7$, and Eddington ratios of 6–20% (consistent with radiatively efficient SMBH accretion; e.g. Heckman & Best 2014). All of our sources would have previously been classified as radio-quiet based on their upper limits in FIRST. The observed increase in radio flux between FIRST and VLASS suggests they are no longer in a radio-quiet state. Given the high VLASS radio luminosities ($L_{\text{3 GHz}} = 10^{40-42}$ erg s$^{-1}$), our sources are now consistent with radio-loud quasars (Kellermann et al. 2016).

In Figure 3, we show image cut-outs from FIRST and VLASS. The 1$\sigma$ rms sensitivities of the FIRST and VLASS images are typically 0.15 mJy beam$^{-1}$ and 0.12 mJy beam$^{-1}$, respectively. The local rms noise level measured in each image is given in Table 2. The quality of the FIRST images is generally quite good. However, we note that one source in particular (J1157+3142) appears to have unusually poor image quality in the FIRST survey, making its classification as a variable AGN uncertain. We emphasize that while none of our sources met the formal detection threshold criteria ($F_{\text{peak}} > 1$ mJy) of the final release of the FIRST source catalog (Helfand et al. 2015), 12 sources have faint FIRST emission at the location of the VLASS source at the 3–3.6$\sigma$ level (J1204+1918). We list sources with peak FIRST flux densities $> 3\sigma$ as FIRST “detections” in Table 2.

The VLASS QuickLook image cut-outs shown in Figure 3 highlight the radio variability of our sources on timescales of $\sim 1 - 2$ decades as well as their compactness on $\sim$arcsecond scales. Some of the VLASS QuickLook images suffer from strong imaging artifacts, such as prominent sidelobes due to insufficient cleaning and/or the presence of residual phase errors. This is due to the rough nature of the QuickLook im-

AGN with radio spectral energy distributions peaking in the GHz regime (see O’Dea 1998 for a review).
Figure 2. Venn diagram illustrating the selection criteria for our sample of AGN that have recently brightened in the radio in the last 1–2 decades. Previously radio-quiet AGN are selected based on both optical and infrared AGN diagnostics in SDSS and WISE, respectively. Further details are provided in Section 2.2.

ages\(^6\), which we emphasize are not the final VLASS survey products. Despite the known limitations of the QuickLook images, we find the peak VLASS flux densities of our compact sources to typically be consistent with our independent VLA follow-up imaging at S-band (see Section 4.2 for a discussion of source variability at S band). Thus, our study supports the viability of the use of VLASS QuickLook images for science as long as users take the known limitations into account.

3. VLA FOLLOW-UP DATA

We performed high-resolution, multiband VLA observations for 14/26 candidate variable AGN through project 19A-422 (PI: Gregg Hallinan). These observations took place from July 23 – October 13, 2019, primarily during the VLA A configuration. For each source, the observations at \( L \) (1–2 GHz), \( S \) (2–4 GHz), \( C \) (4–8 GHz), and \( X \) (8–12 GHz) band were performed within a single scheduling block (SB) no longer than 2.75 hr, and we therefore refer to these observations as “quasi-simultaneous” in nature.

In addition to the 1–12 GHz observations, the majority of our sources also have quasi-simultaneous data at \( K_u \) (12–18 GHz) band. Because a preliminary analysis of our first three pilot sources (J0807+2102, J0832+2302, and J0950+5128) showed rising fluxes at high frequencies, we modified our observing strategy to add higher frequency \( K_u \)-band observations (12–18 GHz) for the remaining sample, and returned later to our three pilot sources on September 19, 2019 to repeat the \( X \)-band observations and add \( K_u \) band. We discuss the \( X \)-band variability on \( \sim \)weeks timescale for these three sources in Section 4.2. Finally, for the pilot source J0807+2102 with the most optically-thick spectrum, we added a \( K \)-band (18-26 GHz) observation. The dates and frequencies of all our VLA observations are given in Table 3.

3.1. Calibration and Imaging

We calibrated our data using the scripted VLA calibration pipeline\(^7\) for the Common Astronomy Software Applications (CASA) package (McMullin et al. 2007) version 5.3.0. In order to ensure the use of an optimal calibration solution interval for each band, the pipeline was run separately for each band of each SB.

Imaging and self-calibration were performed in CASA 5.6.0 following standard heuristics for widefield, broadband

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\(^6\) See Lacy et al. (2020) for a detailed description of VLASS and the limitations of the QuickLook image products.

\(^7\) https://science.nrao.edu/facilities/vla/data-processing/pipeline/scripted-pipeline
Table 1. Sample

| Source     | RA (J2000) | Dec (J2000) | z     | $L_{\text{Bol}}$ (erg s$^{-1}$) | $\log(M_{\text{SMBH}})$ (M$_\odot$) | $L_{\text{Bol}}/L_{\text{Edd}}$ | Type       |
|------------|------------|-------------|-------|-------------------------------|----------------------------------|-----------------------------|------------|
| J0742+2704 | 115.701796 | 27.070113   | 0.6264 | 45.57                         | 8.67                             | -1.20                       | SDSS, WISE |
| J0751+3154 | 117.877557 | 31.904037   | 1.8640 | 46.57                         | 9.47                             | -1.00                       | SDSS, WISE |
| J0800+3124 | 120.044683 | 31.415871   | 1.9368 | 46.93                         | 9.56                             | -0.73                       | SDSS, WISE |
| J0807+2102 | 121.767970 | 21.035786   | 1.5588 | 46.31                         | 9.34                             | -1.13                       | SDSS, WISE |
| J0832+2302 | 128.198513 | 23.042816   | 0.9430 | ...                           | ...                              | ...                         | SDSS, WISE |
| J0950+5128 | 147.653173 | 51.477212   | 0.2142 | ...                           | ...                              | ...                         | SDSS       |
| J1023+2219 | 155.842720 | 22.321296   | ...   | ...                           | ...                              | ...                         | WISE       |
| J1037+0736 | 159.491631 | -7.607362   | -7.607362 | ...                           | ...                              | ...                         | WISE       |
| J1112+2809 | 168.055854 | 28.165137   | ...   | ...                           | ...                              | ...                         | WISE       |
| J1157+3142 | 179.388528 | 31.707514   | 0.8910 | ...                           | ...                              | ...                         | SDSS, WISE |
| J1204+1918 | 181.218737 | 19.306199   | 2.3440 | ...                           | ...                              | ...                         | SDSS, WISE |
| J1208+4741 | 182.241352 | 47.698944   | 1.0915 | ...                           | ...                              | ...                         | SDSS, WISE |
| J1246+1805 | 191.518270 | 18.089036   | ...   | ...                           | ...                              | ...                         | WISE       |
| J1254-0606 | 193.521438 | -6.109209   | -6.109209 | ...                           | ...                              | ...                         | WISE       |
| J1333-0349 | 203.334269 | -3.832307   | ...   | ...                           | ...                              | ...                         | WISE       |
| J1347+4505 | 206.836689 | 45.098706   | ...   | ...                           | ...                              | ...                         | WISE       |
| J1357-0329 | 209.443830 | -3.484817   | ...   | ...                           | ...                              | ...                         | WISE       |
| J1413+0257 | 213.454848 | 2.953648    | ...   | ...                           | ...                              | ...                         | WISE       |
| J1447+0512 | 221.817580 | 5.207433    | 1.7475 | 46.36                         | 9.02                             | -0.76                       | SDSS, WISE |
| J1507-0549 | 226.962335 | -5.819718   | ...   | ...                           | ...                              | ...                         | WISE       |
| J1512-0533 | 228.096364 | -5.550100   | ...   | ...                           | ...                              | ...                         | WISE       |
| J1514+0400 | 228.520730 | 40.013724   | 2.1226 | 46.80                         | 9.74                             | -1.04                       | SDSS       |
| J1546+1500 | 236.641541 | 15.010193   | ...   | ...                           | ...                              | ...                         | WISE       |
| J1603+1809 | 240.828155 | 18.151432   | 3.2460 | ...                           | ...                              | ...                         | SDSS       |
| J1609+4306 | 242.441175 | 43.106462   | ...   | ...                           | ...                              | ...                         | WISE       |
| J2109-0644 | 317.320264 | -6.743461   | 1.0812 | 46.38                         | 9.05                             | -0.77                       | SDSS       |

Note—Column 1: Source name. Columns 2 and 3: Source right ascension and declination. Column 4: Spectroscopic redshift from SDSS DR14 from Pâris et al. (2018). Column 5: Bolometric quasar luminosity. Column 6: Virial supermassive black hole mass estimate from SDSS spectroscopy from Shen et al. (2011). Column 7: Eddington ratio. Column 8: AGN type. Sources are classified as AGN on the basis of optical spectroscopy from SDSS ((Pâris et al. 2018) and/or infrared colors based on data from WISE (Assef et al. 2018).
### Table 2. FIRST and VLASS Properties

| Source    | Date\(_{\text{FIRST}}\) | \(\sigma_{\text{FIRST}}\) (mJy beam\(^{-1}\)) | \(F_{\text{FIRST}}\) (mJy beam\(^{-1}\)) | Date\(_{\text{VLASS}}\) | \(\sigma_{\text{VLASS}}\) (mJy beam\(^{-1}\)) | \(F_{\text{VLASS}}\) (mJy beam\(^{-1}\)) | \(\log(L_{\text{VLASS}})\) (erg s\(^{-1}\)) |
|-----------|--------------------------|------------------------------------------|-----------------------------------|--------------------------|------------------------------------------|-----------------------------------|----------------------------------|
| J0742+2704| 1995 Nov 10              | 0.166                                    | 0.53                              | 2019 Apr 10              | 0.146                                    | 9.19                              | 41.68                           |
| J0751+3154| 1995 Oct 23              | 0.148                                    | < 0.44                            | 2019 Apr 13              | 0.148                                    | 3.00                              | 42.36                           |
| J0800+3124| 1994 Jun 04              | 0.123                                    | 0.38                              | 2019 Apr 13              | 0.125                                    | 4.54                              | 42.58                           |
| J0807+2102| 1998 Sep                 | 0.157                                    | < 0.47                            | 2019 Apr 14              | 0.137                                    | 3.69                              | 42.26                           |
| J0832+2302| 1995 Dec 28              | 0.157                                    | 0.48                              | 2019 Apr 13              | 0.130                                    | 3.08                              | 41.64                           |
| J0950+5128| 1997 Apr 29              | 0.148                                    | < 0.44                            | 2019 Apr 18              | 0.126                                    | 8.77                              | 40.57                           |
| J1023+2219| 1996 Jan                 | 0.205                                    | 0.65                              | 2019 Apr 18              | 0.145                                    | 3.50                              | ...                             |
| J1037-0736| 2002 Jun                 | 0.136                                    | < 0.41                            | 2019 Apr 16              | 0.151                                    | 12.95                             | ...                             |
| J1112+2809| 1995 Nov 04              | 0.156                                    | 0.49                              | 2019 Apr 13              | 0.120                                    | 3.19                              | ...                             |
| J1157+3142| 1994 Jun 06              | 0.601                                    | 2.02                              | 2019 Apr 14              | 0.135                                    | 8.58                              | 42.03                           |
| J1204+1918| 1999 Nov                 | 0.149                                    | 0.48                              | 2019 Mar 21              | 0.145                                    | 5.09                              | 42.84                           |
| J1208+4741| 1997 Apr 05              | 0.157                                    | < 0.47                            | 2019 Apr 15              | 0.117                                    | 3.20                              | 41.82                           |
| J1246+1805| 1999 Nov 24              | 0.147                                    | < 0.44                            | 2019 Apr 12              | 0.122                                    | 7.09                              | ...                             |
| J1254+0606| 2001 Apr                 | 0.144                                    | 0.46                              | 2019 Mar 07              | 0.247                                    | 8.76                              | ...                             |
| J1333+0349| 1998 Sep                 | 0.14                                     | < 0.42                            | 2019 Mar 24              | 0.175                                    | 3.09                              | ...                             |
| J1347+4505| 1997 Mar 03              | 0.151                                    | < 0.45                            | 2019 Mar 19              | 0.129                                    | 3.58                              | ...                             |
| J1357-0329| 1998 Sep                 | 0.156                                    | 0.49                              | 2019 Mar 24              | 0.170                                    | 3.11                              | ...                             |
| J1413+2057| 1998 Jul                 | 0.142                                    | 0.47                              | 2019 Apr 02              | 0.229                                    | 6.91                              | ...                             |
| J1447+0512| 2000 Feb                 | 0.16                                     | 0.49                              | 2019 Mar 12              | 0.152                                    | 4.30                              | 42.45                           |
| J1507+0549| 2001 Apr                 | 0.139                                    | < 0.42                            | 2019 Mar 07              | 0.159                                    | 4.73                              | ...                             |
| J1512+0533| 2001 Apr                 | 0.233                                    | < 0.70                            | 2019 Mar 07              | 0.200                                    | 3.25                              | ...                             |
| J1514+0400| 1994 Aug 21              | 0.141                                    | < 0.42                            | 2019 Mar 28              | 0.164                                    | 3.49                              | 42.57                           |
| J1546+1500| 1999 Dec                 | 0.144                                    | < 0.43                            | 2019 Apr 11              | 0.122                                    | 4.69                              | ...                             |
| J1603+1809| 1999 Nov                 | 0.148                                    | < 0.44                            | 2019 Apr 12              | 0.116                                    | 3.61                              | 43.03                           |
| J1609+4306| 1994 Jul 24              | 0.124                                    | 0.45                              | 2019 May 04              | 0.126                                    | 4.53                              | ...                             |
| J2109-0644| 1997 Feb 28              | 0.153                                    | < 0.46                            | 2019 Apr 05              | 0.170                                    | 18.30                             | 42.57                           |

**Note:** Column 1: Source name. Column 2: Date of FIRST observation. For some sources, only the year and month are provided in the header of the FIRST image. Column 3: Local 1σ rms noise in FIRST. Column 4: Peak flux density at 1.4 GHz from FIRST. Newly identified sources in VLASS that have faint FIRST counterparts with peak flux densities > 3\(\sigma_{\text{FIRST}}\) are reported as detections. All other sources are reported as FIRST upper limits. We note that none of the sources in this table meet the selection criteria of the FIRST catalog (Helfand et al. 2015). Column 5: Date of VLASS observation. Column 6: Local 1σ rms noise in VLASS. Column 7: Peak flux density at 3 GHz from VLASS. Column 9: Radio luminosity at 3 GHz from VLASS.

Transient Experiment (VLITE; Clarke et al. 2016; Polisen-sky et al. 2016), records data at 340 MHz simultaneously with regular VLA observing programs. During our VLA observations, commensal VLITE data with a maximum of 18 antennas were recorded.

VLITE data are automatically calibrated and imaged through an analysis pipeline based on the Obit (Cotton 2008) data reduction package. The VLITE pipeline images from our snapshot observations typically achieve a 1σ depth of 3 mJy beam\(^{-1}\) and a maximum angular resolution of \(\approx 5\)′. We visually inspected all VLITE imaging pipeline products and found that none of our sources was detected, as expected given their curved or flat radio SEDs. We discuss constraints on the radio SEDs and underlying emission mechanisms using the upper limits from VLITE in Section 4.3.
4. RESULTS

4.1. Radio flux densities and Morphologies

Source flux and shape measurements for the VLA data above 1 GHz were made using the CASA IMFIT task and are reported in Table 6. For the majority of sources, the flux errors include a standard 3% uncertainty in the absolute flux scale (Perley & Butler 2017), added in quadrature with the flux error reported by IMFIT. Due to scheduling limitations, one of our sources (J2109−0644) was observed using 3C48 as the flux calibrator. Because 3C48 is currently flaring, we conservatively report a flux uncertainty of 20% for
Table 3. Summary of New Multiband VLA Observations

| Source       | Observing Date | Configuration | VLA Bands | Flux calibrator |
|--------------|----------------|---------------|-----------|-----------------|
| J0742+2704  | 2019 Oct 03    | A             | L, S, C, X, Ku | 3C147          |
| J0807+2102  | 2019 July 23   | BnA → A       | L, S, C, X   | 3C286          |
|              | 2019 Sept 19   | A             | X, Ku, K     | 3C138          |
| J0832+2302  | 2019 July 23   | BnA → A       | L, S, C, X   | 3C286          |
|              | 2019 Sept 19   | A             | X, Ku        | 3C138          |
| J0950+5128  | 2019 July 23   | BnA → A       | L, S, C, X   | 3C286          |
|              | 2019 Sept 19   | A             | X, Ku        | 3C138          |
| J1037-0736  | 2019 Oct 13    | A             | L, S, C, X, Ku | 3C286        |
| J1204+1918  | 2019 Oct 11    | A             | L, S, C, X   | 3C286          |
| J1208+4741  | 2019 Oct 11    | A             | L, S, C, X   | 3C286          |
| J1246+1805  | 2019 Oct 11    | A             | L, S, C, X   | 3C286          |
| J1254+0606  | 2019 Nov 01    | A → D         | L, S, C, X, Ku | 3C286       |
| J1413+0257  | 2019 Sept 23   | A             | L, S, C, X   | 3C286          |
| J1447+0512  | 2019 Sept 23   | A             | L, S, C, X   | 3C286          |
| J1546+1500  | 2019 Sept 23   | A             | L, S, C, X   | 3C286          |
| J1603+1809  | 2019 Sept 23   | A             | L, S, C, X   | 3C286          |
| J2109-0644  | 2019 Sept 10   | A             | L, S, C, X   | 3C48           |

Note—Column 1: Source name. Column 2: Observing date(s). Column 3: VLA configuration. Column 4: VLA band, defined as follows: L: 1–2 GHz, S: 2–4 GHz, C: 4–8 GHz, X: 8–12 GHz, Ku: 12–18 GHz, K: 18–26 GHz. Column 5: Flux density calibrator. We note that the calibrator 3C48 is currently experiencing an ongoing flaring event. As a result, the absolute flux uncertainty of sources calibrated against this source will be increased. We therefore assume a conservative flux uncertainty of 20% for all sources using 3C48 as the primary flux calibrator. All other flux calibrators are expected to provide an absolute uncertainty of 3% Perley & Butler (2013).

Each measurement of J2109−0644 following current NRAO guidelines10.

Our sources are characterized by compact (≤0.1″) radio continuum emission over the full frequency range of our VLA study, which provides a maximum angular resolution of θ_{max} ≤ 0.1″ (for the Ku-band/A-configuration data). This corresponds to an upper limit on the intrinsic linear source sizes that is < 1 kpc.

4.2. Constraints on Variability

We illustrate the flux variations of our sample at L and S band over two epochs probing two different timescales in Figures 4 and 5. We also show the variability at X-band for the 3 sources (J0807+2102, J0832+2302, and J0950+5128) in our sample with a gap of several weeks between observations from 1–12 GHz (L, S, C, and X band) and 12–18 GHz (Ku band). Tables 2 and 3 provide additional details on the observing dates of the data from FIRST, VLASS, and our new multiband JVLA follow-up observations.

10 https://science.nrao.edu/facilities/vla/docs/manuals/oss/performance/fdscale

At L-band, the two epochs shown in the top panel of Figure 4 are from the FIRST survey (with observing dates ranging from 1995 to 2002 for our sample) and our 2019 JVLA follow-up study. The L-band source flux densities from our new JVLA observations range from ∼1–11 mJy. Thus, compared to the FIRST flux measurements made 17 to 24 years earlier, our sources have L-band flux densities that have increased dramatically by factors of ∼2–25. The left panel of Figure 5 shows the variability amplitude at L band between FIRST and our 2019 observations for each source. The weighted median value is ∼200%. However, we emphasize that since half of our sources remain undetected below the 3σ level in FIRST, this is likely to be a lower limit. Thus, the true L-band variability amplitude on timescales of ∼1–2 decades could be even higher.

At S-band, the two observing epochs shown in Figure 4 span a much narrower range of time (∼months) compared to the variability timescale constraints at L band (∼decades). The S-band flux densities between our JVLA follow-up observations and VLASS are approximately constant over timescales of 3–7 months. This is clearly illustrated in the right panel of Figure 5, which shows the S-band variability...
amplitude has a median value of $\sim 15\%$. Thus, our follow-up JVLA $S$-band data are typically in good agreement within the current $\sim 20\%$ flux uncertainties of VLASS. We note that the most substantial outlier in the right panel of Figure 5 is the source J2109-0644, which as discussed in Section 3 may have unusually large absolute flux errors due to the variability of the flux calibrator.

At $X$-band, the two observing epochs shown in Figure 4 for J0807+2102, J0832+2302, and J0950+5128 span an even narrower range of time ($\sim$weeks) compared to the variability timescale constraints at $L$ and $S$ band. The $X$-band flux densities are roughly constant, although all 3 sources exhibit a slight increase in flux of $\sim 10\%$ over a period of 58 days. Although an increase in flux density of this magnitude could be due to the evolution of a nascent jet (see Section 5), the presence of residual errors in the absolute flux scale of similar magnitude cannot be entirely ruled out. This is because the first epoch of $X$-band observations was taken during the move from the hybrid BnA configuration to the standard A array, which lead to poor PSF quality that ultimately posed challenges for self calibration and deconvolution (see Section 3). Nevertheless, we conclude that the $X$-band flux densities are in close enough agreement to justify the inclusion of the observations above 12 GHz in our radio SED analysis.

Although our time domain assessment is currently crude and would benefit from higher-cadence monitoring in the future, we conclude that our sources are characterized by large amplitude ($2$–$25X$) variability at $L$ band on timescales 1–2 decades, but maintain roughly constant flux densities over timescales of a few months at $S$ band. Thus, the typical variability timescale, $\tau_{\text{var}}$, likely falls in the range of 3–7 months $< \tau_{\text{var}} < 17$–24 years. We discuss implications of these constraints on the origin of the radio variability in Section 5.

### 4.3. Quasi-simultaneous Radio SEDs

In Figure 6, we show the radio SEDs of the 14 sources from our sample with quasi-simultaneous VLA observations from 1–18 GHz. The radio SEDs have peaked spectral shapes with varying degrees of curvature easily discernible by eye. This indicates the presence of an underlying absorption mechanism, such as synchrotron self absorption (SSA) or free-free
Figure 4. Radio flux variability at $L$, $S$, and $X$ band. Two observing epochs are shown for each band. At $L$ band, we show the flux measurements or upper limits from FIRST (1993–2011) and the flux densities from our 2019 JVLA follow-up observations. At $S$ band, we show the flux densities from VLASS Epoch 1.2, which were observed in early 2019, and the $S$-band flux densities from our follow-up observations taken a few months later. All of the VLASS $S$-band measurements are shown with a conservative 20% flux uncertainty (Lacy et al. 2020). The large uncertainty (20%) in the flux of a single object (J2109-0644) is apparent at both $L$ and $S$ band in our 2019 observations; we discuss limitations of the absolute flux scale calibration for this source in Section 3. At $X$ band, only 3 sources (J0807+2102, J0832+2302, and J0950+5128), which have two epochs of $X$-band observations, are shown (see Sections 3 and 4.2).
Figure 5. Variability amplitude as a function of time from the dual-epoch observations at \(L\) and \(S\) band shown in Figure 4. In the left panel, the variability amplitude is shown as the percent change in flux between FIRST and our 1.5 GHz follow-up observations, or \((F_{\text{FIRST}} - F_{1.5\text{GHz}})/F_{\text{FIRST}}\). In the right panel, the variability amplitude is the percent change in flux between VLASS and our 3 GHz follow-up observations, or \((F_{\text{VLASS}} - F_{3\text{GHz}})/F_{\text{VLASS}}\). The dashed lines indicate the median variability amplitude at each band and the gray shaded regions denote the weighted 1σ standard deviations. The large errors on the \(S\)-band variability amplitudes are dominated by the conservative 20% uncertainty in the flux densities measured from the VLASS Epoch 1 QuickLook images (Lacy et al. 2020).

absorption (FFA), as is commonly associated with compact radio sources (Callingham et al. 2017; Collier et al. 2018).

4.3.1. Radio SED Modeling

To quantify the location of the spectral peak and degree of curvature, we performed least squares fits to the quasi-simultaneous VLA data above 1 GHz using two basic synchrotron emission models:

1. A standard non-thermal power-law model defined by \(S_\nu = a\nu^\alpha\), where \(S_\nu\) is the flux at frequency \(\nu\), \(a\) represents the amplitude, and \(\alpha\) is the spectral index.

2. A curved power-law model defined by \(S_\nu = a\nu^\alpha e^{q(\ln\nu)^2}\), where \(q\) represents the degree of spectral curvature (the breadth of the peak of the radio SED). The \(q\) parameter is defined by \(\nu_{\text{peak}} = e^{-\alpha/2q}\), where \(\nu_{\text{peak}}\) is the turnover frequency. Significant spectral curvature is typically defined as \(|q| \geq 0.2\) (Duffy & Blundell 2012; Callingham et al. 2017).

We note that our use of the curved power-law model is phenomenological in nature. More physically motivated spectral curvature models, such as SSA or FFA (or models with contributions from multiple electron populations; Tingay et al. 2015), require more than 3 free parameters, and thus have only a few degrees of freedom given the number of bands (typically 5; see Table 3) available for each source.

We summarize our spectral modeling analysis in Table 4. Based on the reduced chi-square values provided in this table, a curved power-law model provides a better fit compared to a simple power-law model for all sources. The observed spectral turnover frequencies for our sources range from 2.5–22.7 GHz, with a median value of \(\nu_{\text{peak}} = 6.0\) GHz. For sources with measured redshifts, the corresponding rest-frame turnover frequencies lie in the range of \(\nu_{\text{peak, rest}} = 6.8 - 58.1\) GHz. Likewise, the values of \(q\) from the curved power-law fits span the range \(0.18 < |q| < 1.09\) confirming that essentially all are strongly curved. The exception is J2109-0644, which is only marginally below the formal limit of \(|q| > 0.2\), and the VLITE upper limit at 340 MHz supports a curved, not flat, radio SED.

In Table 4, we also provide the optically-thick and optically-thin spectral index values (\(\alpha_{\text{thick}}\) and \(\alpha_{\text{thin}}\)) below and above the turnover frequency, respectively. We estimated \(\alpha_{\text{thick}}\) by fitting a power-law model to the quasi-simultaneous flux densities at the two lowest frequency VLA bands (\(L\) and \(S\) band) below the turnover frequency. Estimates for \(\alpha_{\text{thick}}\) are only provided for sources with \(\nu_{\text{peak}} > 4\) GHz (spectral peaks above the VLA \(S\) band). For \(\alpha_{\text{thin}}\), we performed a power-law fit to the quasi-simultaneous flux densities at the
Figure 6. Broadband radio SEDs showing our quasi-simultaneous multiband JVLA imaging (blue circles), the VLASS detection (purple squares), FIRST upper limit or 3σ detection (orange diamonds), and VLITE upper limit (green triangles). For each source, two models based on the quasi-simultaneous JVLA data are shown: a standard non-thermal power-model (dotted line) and a curved power-law model (solid line).
two highest frequency VLA bands (either $X$ and $Ku$ band or $Ku$ and $K$ band\footnote{\textsuperscript{11} \textit{K}-band data were obtained for one source, J0807+2102, in order to constrain the radio SED shape on the optically-thin side of $v_{\text{peak}}$ (which is above $X$-band for this source).} above the turnover frequency. We required the quasi-simultaneous VLA data to include at least two independent bands above the turnover frequency to estimate $\alpha_{\text{thin}}$. The uncertainties in $\alpha_{\text{thick}}$ and $\alpha_{\text{thin}}$ provided in Table 4 were calculated using standard propagation of errors.

Based on the radio spectral modeling analysis described here, we conclude that the radio SEDs of our sources are best represented by curved power-law models (as opposed to flat power-law models lacking curvature), thus supporting the presence of significant spectral curvature. In a future study, we will incorporate new data from forthcoming VLA and Giant Metre-wave Radio Telescope (GMRT) observations spanning a broader frequency range (the full contiguous frequency range of the VLA from 1–50 GHz and deep measurements below 1 GHz using the VLA and GMRT). This will enable a more rigorous radio SED modeling analysis that will allow us to test whether SSA of FFA are responsible for the observed spectral curvature (Mhaskey et al. 2019a,b).

4.3.2. Radio Color-color Diagram

In Figure 7, we show our sources on a radio color-color diagram ($\alpha_{\text{thick}}$ vs. $\alpha_{\text{thin}}$). All of our sources reside in the second quadrant of this figure, which characterizes peaked radio spectral shapes indicative of an underlying absorption mechanism commonly associated with source compactness due to youth and/or confinement by an external medium (O’Dea 1998; O’Dea & Saikia 2020; Orienti 2016). Most of our sources also meet the more strict selection criteria for peaked-spectrum radio sources from Callingham et al. (2017) of $\alpha_{\text{thick}} > 0.1$ and $\alpha_{\text{thin}} < -0.5$.

Our sources have optically-thick spectral index constraints that are consistent with SSA, though improved spectral coverage at low frequencies ($<$ 1 GHz) will ultimately be needed (Callingham et al. 2015; Collier et al. 2018; Mhaskey et al. 2019a,b; Keim et al. 2019). The identification of FFA associated with any of the newly radio-loud AGN in our sample would be of particular interest in the context of galaxy evolution since simulations have shown that it may arise from jet-ISM interactions (Bicknell et al. 1997, 2018). Such jet-ISM interactions may subsequently influence the ambient star formation rate and/or efficiency, as argued by recent observational studies in low-redshift galaxies (Morganti et al. 2013; Nyland et al. 2013; Mukherjee et al. 2018; Husemann et al. 2019; Jarvis et al. 2019; Ruffa et al. 2019).

In Figure 8, we show the distribution of the 14 sources from our multiband VLA follow-up campaign in \textit{WISE} infrared color space ($W2 - W3$ vs. $W1 - W2$). A summary of the infrared properties of our sources is provided in Table 5. All but one these sources meet the infrared color selection criteria for obscured quasars defined by Mateos et al. (2012). The single exception is J1603+1809, which is identified as a Type 1 quasar in SDSS, but does not meet the \textit{WISE} AGN selection criteria of the Assef et al. (2018) R90 catalog. We also highlight the region occupied by extremely red and powerful AGN defined by $(W1 - W2) + 1.25(W2 - W3) > 7$ (Lonsdale et al. 2015) in Figure 8. Sources with such extreme mid-infrared colors are believed to be heavily obscured, ultra-luminous quasars. Of our 14 sources one source, J1413+0257, meets the Lonsdale et al. (2015) selection criteria. Although this source currently lacks redshift information, Patil et al. (2020) reported redshifts in the range $0.4 < z < 3.0$ (with a median value of $z \sim 1.5$) and luminosities of $\log(L_{bol}/L_\odot) \sim 11.7 - 14.2$ for a sample of quasars in the Lonsdale et al. (2015) color space also harboring compact radio sources.

Finally, we use Figure 8 to investigate possible relationships between the \textit{WISE} colors and two key parameters from our radio spectral modeling: the spectral curvature parameter, $q$, and the optically-thick spectral index, $\alpha_{\text{thick}}$. Qualita-
Figure 8. WISE infrared color-color diagrams (W1 = 3.4 µm, W2 = 4.6 µm, and W3 = 12 µm) in Vega magnitudes. The black wedge defines the color space for luminous AGN in WISE defined by Mateos et al. (2012). The shaded region bounded by the dashed diagonal line, defined as (W1 − W2) + 1.25(W2 − W3) > 7, identifies extremely red sources likely to be heavily obscured, luminous AGN (Lonsdale et al. 2015; Patil et al. 2020). The points in the left- and right-hand plots are colorized by the radio spectral curvature parameter (q) and the optically-thick radio spectral index (αthick), respectively.

Figure 8 suggests an association between both a higher degree of spectral curvature (a narrower spectral peak) and αthick values for redder sources.

Previous studies have reported evidence for a connection between quasar reddening and radio jet properties possibly arising from hierarchical SMBH-galaxy co-evolution (Georgakakis et al. 2012; Glikman et al. 2012; Klindt et al. 2019; Patil et al. 2020; Fawcett et al. 2020; Rosario et al. 2020). In such a scenario, a quasar may transition to a radio-loud phase following a gas-rich merger and subsequent change in SMBH accretion state and/or spin conducive to jet formation. In a future study, we will investigate this possibility in more detail by constraining the origin of the reddening in our sample through optical and infrared SED modeling. Ultimately, observations of a larger sample will be needed to more firmly establish the relationship between the infrared colors and radio SED properties in young radio quasars.

5. ORIGIN OF THE RADIO VARIABILITY

In this section, we consider different scenarios for the origin of the radio variability in our sample based on the current constraints on source luminosities, radio spectral shapes, and observed variability properties (amplitude and timescale). Regarding the variability properties, we emphasize that our cadence is currently very sparse, with only three observations (FIRST, VLASS, and our multiband follow-up) spaced by roughly six months and two decades. Although this is clearly insufficient to infer the full character of the variability, we assume that the simple flux ratios provide a provisional measure of the variability on each timescale (see Section 4.2). Future observations will yield a richer cadence that will further clarify the variability on different timescales.

5.1. Plasma Propagation Effects

Radio waves traveling through an inhomogeneous plasma may be modulated by scattering or lensing phenomena. This may lead to variations in the observed properties of compact sources, such as flat-spectrum radio AGN. Physical mechanisms responsible for such propagation effects include interplanetary scintillation (IPS; Morgan et al. 2018, and references therein), interstellar scintillation (ISS; Jauncey et al. 2016, and references therein), and extreme scattering events (ESEs; Fiedler et al. 1987).

IPS arises from turbulence in the solar wind plasma and leads to rapid flux variability on timescales of roughly seconds in low-frequency (∼100 MHz) radio observations. Although IPS has proven to be a powerful tool for identifying compact radio AGN, it is not compatible with the variability timescales and amplitudes observed in our sample above 1 GHz.

ISS is caused by the refraction or diffraction of radio waves emitted by a microarcsecond-scale source as they pass through fluctuations in the plasma density and/or magnetic
field of the ionized ISM in our Galaxy (Stanimirović & Zweibel 2018). This leads to variable radio emission on timescales of hours to days with a strong dependence on galactic latitude.

Observational manifestations of ISS (i.e. variability amplitude and timescale) depend on the Galactic free electron density along a particular line of sight as well as the observing frequency. The distribution of our sources in Galactic latitude is approximately flat (Figure 1), arguing against ISS as the main driver of the observed radio variability. As a more quantitative test of an ISS variability origin for each source, we computed the critical frequency,\(^\text{12}\) \(\nu_0\), below which the modulation due to scintillation is in the strong regime.\(^\text{13}\) At the positions of our sources we find \(\nu_0 = 7.1–11\) GHz. For observations at \(\nu = 1.5\) GHz, we are therefore well within the strong scattering regime and the equations from Section 3.2 of Walker (1998) apply. For point sources in this limit that are experiencing refractive scintillation, the equations from Walker (1998) apply.

\(^{12}\) The critical frequency was estimated using the online calculator available at https://www.nrl.navy.mil/rsd/RORF/ne2001/ based on the Cordes-Lazio model for the Galactic distribution of free electrons (Cordes & Lazio 2002, 2003).

\(^{13}\) For an in-depth review of optics and ISS theory, we refer readers to Narayan (1992).

### Table 5. Infrared Source Properties

| Source          | W1 (mag) | W2 (mag) | W3 (mag) | W4 (mag) | \(\log(L_{6\mu m, \text{rest}})\) (erg s\(^{-1}\)) |
|-----------------|----------|----------|----------|----------|------------------------------------------|
| J0742+2704      | 14.42±0.03 | 13.68±0.04 | 11.25±0.15 | ... | 45.05                                    |
| J0751+3154      | 15.98±0.06 | 14.86±0.07 | ... | ... | 46.24                                    |
| J0800+3124      | 15.91±0.05 | 14.70±0.07 | 12.26±0.41 | ... | 46.30                                    |
| J0807+2102      | 15.91±0.06 | 14.72±0.07 | 11.64±0.25 | ... | 46.14                                    |
| J0832+2302      | 13.84±0.03 | 12.46±0.03 | 9.45±0.04 | 7.21±0.11 | 46.07                                    |
| J0950+5128      | 13.43±0.02 | 12.80±0.03 | 10.40±0.08 | 8.22±0.25 | 44.13                                    |
| J1023+2219      | 15.85±0.05 | 14.77±0.07 | 11.32±0.20 | 8.47±0.34 | ...                                      |
| J1037-0736      | 14.82±0.03 | 13.83±0.04 | 11.22±0.16 | ... | ...                                      |
| J1112+2809      | 16.33±0.07 | 15.40±0.10 | ... | ... | ...                                      |
| J1157+3142      | 14.98±0.03 | 13.82±0.04 | 11.26±0.16 | 8.62±0.41 | 45.40                                    |
| J1204+1918      | 16.07±0.06 | 15.17±0.09 | 12.08±0.33 | 8.85±0.41 | 46.54                                    |
| J1208+4741      | 16.16±0.06 | 15.18±0.07 | 12.70±0.43 | ... | 45.26                                    |
| J1246+1805      | 16.53±0.07 | 15.43±0.10 | 12.72±0.47 | ... | ...                                      |
| J1254-0606      | 15.92±0.05 | 14.65±0.06 | 10.35±0.06 | 7.83±0.16 | ...                                      |
| J1333-0349      | 15.34±0.04 | 14.35±0.05 | 11.99±0.25 | ... | ...                                      |
| J1347+4505      | 15.22±0.04 | 13.87±0.03 | 10.82±0.09 | ... | ...                                      |
| J1357-0329      | 13.87±0.03 | 12.77±0.03 | 9.87±0.05 | 7.39±0.10 | ...                                      |
| J1413+0257      | 18.14±0.25 | 16.11±0.17 | 11.65±0.17 | 8.94±0.32 | ...                                      |
| J1447+0512      | 16.20±0.06 | 15.14±0.07 | ... | ... | 46.03                                    |
| J1507-0549      | 15.97±0.06 | 15.12±0.10 | 12.04±0.29 | ... | ...                                      |
| J1512-0533      | 16.66±0.08 | 15.19±0.10 | 12.43±0.39 | 9.10±0.47 | ...                                      |
| J1514+4000      | 16.22±0.05 | 15.54±0.08 | 12.13±0.19 | 9.53±0.52 | 46.21                                    |
| J1546+1500      | 15.97±0.05 | 14.90±0.07 | ... | ... | ...                                      |
| J1603+1809      | 16.10±0.05 | 15.47±0.09 | 12.59±0.48 | ... | 47.05                                    |
| J1609+4306      | 16.38±0.05 | 15.41±0.08 | 13.12±0.43 | 9.62±0.48 | ...                                      |
| J2109-0644      | 15.14±0.04 | 14.07±0.04 | 11.21±0.17 | 8.22±0.31 | 45.71                                    |

**Note**—Column 1: Source name. Columns 2-5: WISE W1 (3.4\(\mu\)m), W2 (4.6\(\mu\)m), W3 (12\(\mu\)m), and W4 (22\(\mu\)m) band magnitudes and errors from the AllWISE source catalog (Cutri & et al. 2013). Column 6: Estimated rest-frame 6\(\mu\)m luminosity extrapolated from a power-law fit to the AllWISE photometry.
pected flux modulation at 1.5 GHz is \( m = (\nu_0/\nu)^{17/30} \sim 30\text{–}40\% \). This modulation is expected to occur on a timescale of \( t_r \sim 2(\nu_0/\nu)^{11/5} \) hours \( \sim 2\text{–}7 \) days. This stands in sharp contrast to the observed modulations of \( \gtrsim 100\% \) to \( \gtrsim 2500\% \) occurring on observed timescales of months to decades for our sources, thus ruling out refractive ISS as the origin of the radio variability in our sample.

Diffractive ISS, which is associated with interference, leads to variability over an even narrower bandwidth and shorter timescale, making it considerably less plausible than refractive ISS. The fluctuations (of order unity) last for only \( \sim 0.1 \text{–} 0.3 \) hours. Furthermore, at 1.5 GHz, any diffractive ISS would be decorrelated over a bandwidth of \( \delta \nu \sim 1 \text{–} 5 \) MHz. This modulation would thus be washed out by averaging over a single VLA frequency channel.

Another plasma lensing phenomenon known to produce radio variability is that of ESEs (Fiedler et al. 1987). In this case, refractive defocusing by the transverse passage of a discrete, high-density plasma lens in front of a compact radio source leads to a reduction of flux with a characteristic U-shaped light curve (Clegg et al. 1998; Bannister et al. 2016). The variability amplitude (a reduction in emission of \( \lesssim 50\% \)) and timescale (weeks to months) for an ESE are typically larger in magnitude compared to ISS. At least one case of an ESE with a threefold modulation in flux in the centimeter-wave radio regime is known (Bannister et al. 2016). This overlaps with the lower range in variability amplitude of our sample. However, we note that the timescale for the high-amplitude radio variability reported in Bannister et al. (2016) is a few months. This stands in sharp contrast to our sources, which vary on decades-long timescales but are steady over periods of a few months.

While we cannot totally rule out contributions to the observed radio variability by serendipitous propagation effects, we find such scenarios to be unlikely given inconsistencies with the high variability amplitudes and long timescales observed in our sample.

5.2. Supernovae and Gamma-Ray Bursts

Variable radio emission may be associated with supernovae and gamma-ray bursts (GRBs), arising from collimated outflows of high-mass supernovae and compact object mergers (neutron stars and stellar-mass black holes) (Weiler et al. 2002; Woosley & Bloom 2006; Berger 2014). However, the high luminosities of our sources (Table 2) rule out the possibility of a radio supernova afterglow (Palliyaguru et al. 2019) as a progenitor scenario. Regarding the possibility of radio variability associated with a GRB origin, we note that our sources are on par with, or more luminous than, on-axis GRBs, which have peak luminosities of \( \sim 10^{31} \text{ erg s}^{-1} \text{ Hz}^{-1} \) (Chandra & Frail 2012). However, the typical variability timescale of radio emission associated with GRBs is around 1–2 weeks (Pietka et al. 2015). This is considerably shorter than the variability timescale constraints for our sources (> a few months), thus ruling-out the possibility of a GRB progenitor.

5.3. Tidal Disruption Events

Tidal disruption events (TDEs; e.g., Komossa 2015, and references therein) occur when a star passes within the tidal radius of a SMBH and is ripped apart and partially accreted onto the SMBH. This leads to a multi-wavelength flare, which in some cases includes the production of radio continuum emission associated with non-thermal jets or thermal outflows (van Velzen et al. 2011, 2016; Anderson et al. 2020). The most radio luminous known TDE, Swift J1644+57, peaked at \( \sim 10^{32} \) erg s\(^{-1}\) Hz\(^{-1}\) (Eftekhari et al. 2018), which is roughly in line with the radio luminosities of our sources. In addition, recent studies have suggested that TDEs may be responsible for triggering a significant fraction of the changing-look AGN population, particularly at \( z > 2 \) (Padmanabhan & Loeb 2020). Because more massive black holes have weaker tidal fields near their event horizons, TDEs for main sequence stars become increasingly rare above a critical mass of about \( 10^8 \) \( M_\odot \), Hills 1975). Main sequence stars that approach SMBHs above this limiting mass are “swallowed whole” (MacLeod et al. 2012), and thus do not lead to the production of an electromagnetic flare\(^{14} \). As shown in Table 1, the available SMBH mass estimates of our sources typically exceed \( 10^8 \) \( M_\odot \), suggesting that TDEs are unlikely progenitors for the majority of our sources.

On the other hand, evolved stars with large diffuse envelopes, such as red giants, are in principle susceptible to tidal disruption by a SMBH with \( M_{\text{SMBH}} > 10^8 \) \( M_\odot \). However, such events are expected to be rare due to the relatively short duration of the red giant phase compared to main sequence lifetimes. Recent studies have also argued that TDEs of giant stars by SMBHs with masses above \( 10^8 \) \( M_\odot \) may be less luminous than TDEs associated with lower-mass SMBHs (Bonnerot et al. 2016).

Although TDEs may provide a plausible mechanism for driving the extreme radio variability in some of our sources, the current literature consensus is that TDEs with powerful relativistic jets are rare (e.g., van Velzen et al. 2018), composing only a few percent of the known TDE population\(^{15} \) (Alexander et al. 2020, and references therein). Thus, based on the high radio luminosities and SMBH masses of our sam-

\(^{14}\) We note that rapidly rotating stars, including those on the main sequence, could conceivably be disrupted by SMBHs with \( M_{\text{SMBH}} \) up to \( \sim 7 \times 10^8 \) \( M_\odot \) (Kesden 2012).

\(^{15}\) For an alternative perspective on the radio detection rates of TDEs, we refer readers to Dai et al. (2020).
ple, as well as the low space density of radio-loud TDEs, we conclude that the radio variability in our sources is most likely not associated with TDEs.

5.4. Intrinsic AGN Variability

While the large-scale lobes of radio galaxies are believed to remain steady over Myr to Gyr timescales (Blandford et al. 2019), intrinsic radio variability on human timescales (days to years) is common among AGN with compact (< 1 kpc) jets such as blazars (Lister 2001), unbeamed radio quasars/galaxies with young jets (Torniainen et al. 2005; Orienti & Dallacasa 2020; Kunert-Bajraszewska et al. 2020), the cores of FRI/FRII (Fanaroff & Riley 1974) radio galaxies (Chatterjee et al. 2011; Maccagni et al. 2020), and low-luminosity AGN (Mundell et al. 2009; Brunthaler et al. 2005). Although the physics of the intrinsic variability of compact AGN jets remains an unsolved problem, plausible mechanisms include the propagation of shocks along the jet (Marscher & Gear 1985) and changes in the SMBH accretion properties such as accretion disk instabilities (Czerny et al. 2009; Janiuk & Czerny 2011) or accretion state changes (Koay et al. 2016; Wołowska et al. 2017). In addition to variability mechanisms directly related to accretion, radio variability may also arise from the jet itself owing to jet reorientation and the evolution of a young, expanding jet (e.g. Kunert-Bajraszewska et al. 2020; An et al. 2020). We focus on accretion-driven radio variability in this section and discuss jet reorientation and youth in Sections 5.5 and 5.6.

Each radio variability scenario described above is characterized by differences in variability amplitude level, as well as temporal and spectral evolution. Thus, distinguishing amongst them is best accomplished through multiepoch, broadband radio studies. For instance, low-amplitude (~tens of percent) radio flares occurring on timescales of days to months are popularly attributed to shock propagation. The low variability amplitudes and short timescales typically associated with this flaring mode contrast with the properties of our sources, which were selected to exhibit large (100% to >2500%) flux increases at ~GHz frequencies over decadal timescales and were later found to be steady over timescales of a few months.

Furthermore, the radio luminosities of our sources are typical of flares from AGN with bright, persistent counterparts (such as the ~2 Jy, $6 \times 10^{33}$ erg s$^{-1}$ Hz$^{-1}$ blazar J0851+202; Pietka et al. 2015). Blazar flares typically represent less than a twofold change in quiescent flux, which we emphasize is considerably lower than the typical variability amplitude observed in our sample (more than an order of magnitude in the most extreme cases).

5.5. Jet Reorientation

For jets aligned at small angles to our line of sight, special relativistic effects cause the source to be beamed, which in the time domain leads to an apparent increase in the variability amplitude and a decrease in the variability timescale (Lister 2001). A rapid reorientation of a compact jet toward our line of sight during the ~20 years between FIRST and VLASS Epoch 1 would lead to an apparent brightening of an intrinsically low-luminosity radio source due to an increase in the Doppler factor.

Potential underlying causes for jet reorientation that may lead to variability on human timescales include helical magnetic fields, flaring blazars, jet-ISM interactions, and SMBH orbital motion. Confirming or refuting the possibility of helical magnetic fields requires multiepoch observations with milliarcsecond-scale resolution to identify key signatures such as periodic changes in the position angle of the jet (Britzen et al. 2017). We discuss the remaining possibilities in this section.

5.5.1. Blazar Contamination

Blazars represent the brightest and most well-studied class of relativistically beamed objects and have characteristic flat radio spectral shapes and double-peaked multiwavelength SEDs from the radio to gamma-energy regimes (Fossati et al. 1998; Meyer et al. 2011; Böttcher 2019). Unlike blazars, the majority of our sources (with the exception of J2109-0644; see Section 4.3) have peaked radio spectra. However, we note that flaring blazars, including those hosted by quasars, are known to exhibit temporarily peaked radio spectra on timescales of weeks to months (Tinti et al. 2005; Torniainen et al. 2005; Orienti et al. 2010; Fromm et al. 2015). The high-energy (X-ray and gamma-ray) properties of our sources, and hence their multiwavelength SEDs, are not currently known.

Besides the radio SED shapes, another argument against blazar variability as the origin of the observed radio brightening in our sources is the lack of substantial variability on timescales of a few months (Section 4.2). We plan to constrain the Doppler factors of our sources by measuring their parsec-scale brightness temperatures and morphologies in an upcoming VLBA study.

Important evidence against the blazer hypothesis is also obtained from the NEOWISE data (Mainzer et al. 2011). These data comprise about 5 years of monitoring observations at 3.4 and 4.6 μm. With one exception (J1413+0257), all sources in our sample have sufficient detections in NEOWISE to allow the construction of a light curve. None of the sources in our sample display the erratic and large-amplitude variability that blazars (or flat-spectrum radio quasars) typically display at mid-IR wavelengths (Anjum et al. 2020).

We have also investigated the optical variability by comparing SDSS imaging observations (a single observation, obtained between 2000 and 2005) and the more recent multi-epoch Zwicky Transient Survey (ZTF; Graham et al. 2019) observations, obtained between 2018 and 2020 (DR3). Since
the ZTF catalog contains only PSF photometry, we restrict our sample to sources that are detected as point-like in SDSS imaging observations, leaving 14 quasars with detections in both SDSS and ZTF. The ZTF light curves of these sources are unremarkable. Furthermore, we find no evidence for a persistent flux increase or decrease between the SDSS and ZTF epoch. The mean magnitude difference between ZTF and SDSS observations is $-0.08$ mag with a standard deviation of 0.35 mag, which is common for the $\approx 15$ year time difference between SDSS and ZTF (MacLeod et al. 2012).

### 5.5.2. Interaction with a Dense ISM

Radio variability may also arise from jet deflection (An et al. 2020) or interaction with a dense ambient medium (Middelberg et al. 2007; Kunert-Bajraszewska et al. 2010; An et al. 2013; Mukherjee et al. 2016; Siemiginowska et al. 2016; Williams et al. 2020; Lister et al. 2020). In such scenarios, brightening in the radio may be caused by an increased Doppler factor and/or the production of shocks associated with the jet plowing into the ISM. Such interactions have been observed out to high redshift ($z > 5$; An et al. 2020). In addition to flux variability, evidence for jet-ISM interactions on parsec scales typically includes jet asymmetries, evidence for jet deceleration, and enhanced polarization at the edge of the jet.

While we emphasize that there is currently no evidence for the presence of jet-ISM interactions in our sample, at least one of our sources has extremely red \textit{WISE} colors in the hyperluminous quasar regime. Recent studies have argued that the combination of radio compactness and mid-infrared colors may be associated with subgalactic jets propagating through a dense ISM (Patil et al. 2020). Such jets have the potential to influence galaxy evolution, perhaps by altering star formation rates/efficiencies or through “self-regulation” of the SMBH accretion rate. Quantifying the amount of energy transferred by subgalactic jets to a dense ambient ISM in the form of feedback, particularly at $z \sim 1 - 3$, is a key goal of studies with next-generation telescopes (Nyland et al. 2018).

### 5.5.3. SMBH Binary Orbital Motion

Orbital motion associated with an SMBH binary system (Palenzuela et al. 2010; Kaplan et al. 2011; Schnittman 2013; Kulkarni & Loeb 2016) could conceivably lead to periodic radio variability. However, such systems should be quite rare: Holgado et al. (2018) predict that no more than 1/100 blazars host SMBH binaries with periods $< 1$ yr. Merging SMBHs with smaller separations would be even rarer than this, though such systems may produce radio variability by either the disruption of an existing jet or the formation of a new jet launched by the circumbinary accretion disk (e.g. Komossa et al. 2020).

Simulations of SMBH mergers predict boosts in radio jet luminosity that are expected to have maximum magnitudes and durations for near-equal-mass binaries of high-mass SMBHs ($10^9 - 10^{10} M_\odot$; Khan et al. 2018). An improved understanding of the physics of jet formation associated with SMBH binary mergers awaits future multimessenger studies incorporating constraints from both multitelescope radio surveys (Murphy et al. 2013) and pulsar timing arrays (Burke-Spolaor et al. 2019).

### 5.6. Young Radio Jets

Young radio AGN, such as gigahertz-peaked spectrum (GPS) sources, are characterized by compact morphologies and inverted radio SEDs below their turnover (peak) frequencies, which are typically in the GHz regime (O’Dea 1998), consistent with the morphologies and radio SEDs of the majority of our sources. After a jet is launched, models predict a rapid increase in luminosity ($P_{radio} \sim t^{2/5}$) as the dominant energy-loss mechanism transitions from adiabatic to synchrotron losses (An & Baan 2012), making the identification of young radio AGN in VLASS that have emerged in the time since the FIRST survey (17–24 yr for our sample) plausible. For a nascent radio jet that has been triggered within the past 20 yr, the model of An & Baan (2012) suggests an increase in radio luminosity of $> 300\%$. The identification of such young radio AGN is not unprecedented; the youngest known sources have kinematic ages as low as 20 yr (Gugliucci et al. 2005).

Based on the currently available radio continuum constraints, which include large variability amplitudes (with flux increases from 100% to $> 2500\%$) at 1.5 GHz compared to FIRST over timescales of decades, steady flux densities on timescales less than a few months at 3 GHz compared to VLASS, source size constraints $< 0.1''$ ($\lesssim 1$ kpc), and curved radio SEDs peaking at $\sim 5$–10 GHz, we find the radio properties of our sources to be consistent with young and compact radio AGN.

If the jet youth scenario for our sources is supported by higher-cadence, multiband follow-up data, there are exciting prospects for forthcoming radio surveys. Wide-area, broadband, synoptic radio surveys above a few GHz conducted over timescales of years to decades would be particularly well tuned for identifying large statistical samples of AGN with recently launched jets.

In Figure 9, we plot our sources on the turnover-size relation, along with a sample of young radio AGN from the literature. This relationship is believed to arise from the evolving radio spectral shapes of expanding young radio sources. As a young and compact radio source expands, the opacity due to SSA or FFA decreases, which causes the spectral peak (or turnover) to shift to lower frequencies (e.g. Bicknell et al. 1997; O’Dea 1998; Tingay & de Kool 2003). Since we only
Figure 9. Spectral turnover as a function of linear size. The small gray circles are drawn from literature measurements of young radio AGN compiled by Jeyakumar (2016). The black dot-dashed line shows the empirical fit to the turnover-size relation from O’Dea (1998), and the dark gray shaded region indicates the uncertainty in the relation. Upper limits on the sizes of sources with quasi-simultaneous, multiband VLA follow-up from our sample that have spectroscopic redshifts available are shown by the large purple circles. For sources lacking redshifts, the linear size upper limits are shown over a range of possible redshifts as indicated by the rainbow-colored arcs.

As an example, we consider J0807+2102 at $z = 1.5588$. The observed spectral turnover of this source is 21.9 GHz, which corresponds to a rest-frame turnover frequency of 56.2 GHz. Based on Figure 9, this implies a source size of 1–10 pc. Assuming a conservative value for the jet advance speed of $0.1c$, we obtain a rough estimate of the source age of $\sim 30$–300 yr. Thus, the young jet model passes this important consistency check.

Very long baseline interferometric (VLBI) studies with sub-milliarcsecond resolution will ultimately be needed to test whether our sources are indeed compact on parsec scales, as expected for young jets. Nevertheless, the radio SED shapes and source size limits from the VLA data presented in this study are consistent with radio variability arising from the evolving radio SEDs of jets that have recently been triggered.

6. DISCUSSION

Based on the radio properties of our sources, in particular their high luminosities, size constraints, variability amplitudes/timescales, and sky coordinates, we rule out extrinsic variability related to plasma propagation as a radio variability scenario. We also conclude that intrinsic variability associated with supernovae, GRBs, or TDEs is unlikely. We therefore favors an intrinsic AGN variability scenario in which the observed radio brightening is driven by a change in the SMBH accretion rate, jet reorientation, or the formation of newborn jets.

We emphasize that multiple mechanisms may contribute to the observed radio variability in a given source. A source could simultaneously be young, mildly Doppler boosted, and flaring owing to the propagation of shocks along the jet. Since our source flux densities are typically steady on
timescales of a few months but vary substantially (100% to >2500%) over timescales of two decades, we find jet youth and/or jet reorientation to be the most plausible radio variability scenarios.

6.1. Accretion State Change

The large observed changes in radio flux may be associated with AGN transitioning between a radio-quiet state to one in which synchrotron-emitting radio jets are present. Extreme radio variability is typical of Galactic radio sources such as X-ray binaries (e.g. Mirabel & Rodríguez 1999). In these sources, the short timescales associated with black holes with masses $\sim 1 - 10 M_\odot$ mean that the change in state from a radio-quiet mode associated with soft X-ray emission to a mode with a hard X-ray spectrum and radio jets can happen on timescales of minutes. Given the $\sim 10^7 - 10^9 M_\odot$ SMBH masses that are typical of AGN, similar transitions may occur (Maccarone et al. 2003; Falcke et al. 2004; Nipoti et al. 2005; Körding et al. 2006), but the corresponding timescales may be longer.

Previous attempts have been made to identify radio sources whose jets may have recently switched off (e.g. Marecki & Swoboda 2011), but such objects still have radio emission from their lobes (though such sources are interesting in their own right in the context of restarted jets). An alternative approach is to identify AGN with a new onset of radio activity potentially associated with jets that have recently switched on. By their very nature these objects are expected to be relatively rare, but by surveying the radio emission from a large number of AGN in two or more well-separated epochs, it may be possible to find objects that are candidates for AGN undergoing this transition.

6.2. Comparison to Previous Studies

Although rare, previous studies have identified quasars with high-amplitude radio variability over timescales of years to decades (de Vries et al. 2004; Barvains et al. 2005; Pandoni et al. 2010; Bell et al. 2015). In the Caltech NRAO Stripe 82 Survey (CNSS) pilot survey, Mooley et al. (2016) reported the detection of a single radio-loud type 2 quasar at $z = 1.65$ (VTC233002-002736) that lacked any detectable emission in the FIRST survey. Follow-up observations revealed a nearly ten-fold flux increase at 1.5 GHz over a 15 year period and a curved radio SED, very similar in nature to our sources. Another example of such behavior in the CNSS, found in the $z = 0.94$ quasar CNSS 013815+00, has been reported recently by Kunert-Bajraszewska et al. (2020). A newborn expanding radio jet is responsible for GPS-like characteristics of the radio spectrum of 013815+00. In addition, the transition from the radio-quiet to the radio-loud phase in 013815+00 coincides with changes in its accretion disk luminosity. Thus, the burst of radio activity in 013815+00 is interpreted as a result of an enhancement in the SMBH accretion rate. We note that only 013815+00 is identified in the Páris et al. (2018) SDSS quasar catalog, but both of the CNSS quasars are classified as AGN in the mid-infrared by Assef et al. (2018) and would therefore meet the AGN and radio selection criteria of our sample (see Section 2).

We note that only one source matching our selection criteria was identified in the 50 deg$^2$ pilot CNSS footprint. This is loosely consistent (within a factor of a few) with our observed detection rate so far over 3440 deg$^2$ of the VLASS-FIRST footprint of one confirmed optical or infrared AGN with newly radio-loud activity per $\sim 20 \pm 13$ deg$^2$. A more formal assessment of the areal density of AGN that have transitioned from radio-quiet to radio-loud on decades-long timescales that incorporates the entirety of VLASS Epoch 1 will be presented in a future study.

6.3. Implications for Galaxy Evolution

The large-scale radio jets and lobes launched by some active galactic nuclei (AGN) are believed to have long lifetimes and duty cycles on the order of millions of years. The properties of such “classical” radio AGN contrast sharply with those of radio jets featuring compact (subgalactic) extents, younger ages (decades to thousands of years), and shorter lifetimes that have previously been identified (Lähteenmäki et al. 2018; Kunert-Bajraszewska et al. 2020).

In the case of re-orienting jets, the change in jet direction may facilitate the transfer of energy over a large volume of the ISM of the host galaxy, thus potentially influencing ambient ISM conditions (Gabler et al. 2011; Mukherjee et al. 2016). However, the prevalence and basic physical properties of re-orienting jets, regardless of origin (see Section 5.5), have not been well constrained owing to inherent observational challenges (the combined requirements of high angular resolution imaging and high-cadence monitoring). If re-orienting compact jets are common, particularly at $z > 1$, they may contribute substantially to SMBH-galaxy co-evolution via the regulation of star formation from jetISM feedback or a disruption in SMBH growth in response to the launching of a jet.

Intermittent, albeit short-lived, episodes of radio-loud activity associated with powerful AGN may also be important in the context of galaxy evolution. Numerous studies over the past few decades have used a variety of arguments (such as the overrepresentation of compact jetted AGN in flux-limited surveys) in favor of the existence of a large population of short-lived and/or rapidly retrigged compact radio AGN.

\[16\] There are 3 additional variable radio sources identified as AGN in Table 2 of Mooley et al. (2016) that meet our VLASS and FIRST selection criteria ($S_{\text{VLASS}} > 3$ mJy and a non-detection in FIRST). However, none of these sources are identified in the optical or infrared AGN surveys (Páris et al. 2018 and/or Assef et al. 2018) as required for our sample.
as radio-loud. This translates to an areal density of \( \sim \). Ivezic et al. (2002) found 1154 SDSS quasars detected by FIRST over 774 deg\(^2\), corresponding to an areal density of radio-loud quasars of \( \sim 1 \) deg\(^{-2}\). If these quasars have a lifetime of \( \sim 10^9 \) yr, we would only expect a very small fraction, \( \sim 1 \) in \( 10^5 \), to be within their first decade of being identified as radio-loud. This translates to an areal density of \( \sim 10^{-5} \) deg\(^{-2}\) compared to our detection rate of 13 newly radio-loud type 1 quasars in 3,440 deg\(^2\), i.e., \( \sim 4 \times 10^{-3} \) deg\(^{-2}\), consistent with a typical period of occurrence of \( \sim 10^5 \) yr.

We speculate that frequent episodes of short-lived AGN jets that do not necessarily grow to large scales could be associated with higher-efficiency jet-driven feedback into the hosts of high-z galaxies. A similar conclusion was reached by van Velzen et al. (2015), who found that the fraction of powerful jets that grow beyond \( \sim 100 \) kpc scales decreases with redshift. Future studies investigating the ISM content and conditions of the hosts of newly radio-loud AGN will be important for placing quantitative constraints on the energetic impact of feedback from compact jets at cosmic noon.

7. SUMMARY

As part of an ongoing search for slow radio transients between FIRST and VLASS Epoch 1 covering 3,440 deg\(^2\) so far, we have identified a sample of 26 sources with radio variability on decadal timescales associated with known powerful quasars in SDSS and/or WISE. These sources were previously radio-quiet quasars in FIRST but are now consistent with the radio-loud quasar population following their detection in VLASS Epoch 1.

To investigate the origin of the radio variability in our sample of newly radio-loud quasars, we performed multiband, quasi-simultaneous VLA follow-up observations of 14 sources. All of our sources are characterized by high radio luminosities (\( L_{3 \text{GHz}} = 10^{40-42} \text{ erg s}^{-1} \)) in the quasar regime, compact (\( \lesssim 0.1'' \)) emission, and broadband radio SEDs from 1–18 GHz with significant spectral curvature.

A comparison between the VLASS images (all of which were observed in 2019 during Epoch 1.2) and our follow-up VLA \( S \)-band data a few months later revealed good agreement within the current \( \sim 20\% \) flux uncertainties of VLASS, suggesting a typical variability timescale longer than a few months. At \( L \)-band, the observed variability amplitudes range from 100\% to \( >2500\% \) in the 17–24 yr since FIRST.

Based on the radio properties of our sources, including their SED shapes, variability timescale and amplitude constraints, and high radio luminosities, we conclude that variability due to extrinsic propagation effects or transient phenomena (including GRBs, supernovae, and TDEs) is unlikely. We therefore favor an intrinsic AGN variability scenario for our sample.

We conclude that our sources are most consistent with powerful quasars hosting compact, possibly young jets, which poses a challenge to the generally accepted idea that “radio-loudness” is a property of the quasar/AGN population that remains fixed on human timescales. Our study suggests that frequent episodes of short-lived AGN jets that do not necessarily grow to large scales may be common at high redshift. We speculate that intermittent but powerful jets on subgalactic scales could interact with the interstellar medium leading to feedback that could influence the evolution of galaxies at cosmic noon.

Further multiband follow-up with the VLA, as well as parsec-scale imaging with the Very Long Baseline Array, will be essential for placing tighter constraints on the evolutionary stages of our sources. Additional follow-up efforts across the electromagnetic spectrum, including optical/infrared observations to determine the basic properties of the host galaxies, studies of the molecular gas content and conditions using millimeter/submillimeter telescopes, and explorations of the accretion physics and large-scale environments from high-energy (e.g., X-ray) data, will be required.

Ultimately, the completion of the remaining two VLASS epochs, as well as future surveys of the dynamic radio and millimeter sky with the Square Kilometre Array and its pathfinders (e.g., Bignall et al. 2015; Murphy et al. 2013), will provide new insights into the life cycles of radio jets. In addition to radio surveys, detailed studies of individual objects quantifying the impact of jets on their ambient environments with telescopes such as the Atacama Large Millimeter/Submillimeter Array and the next-generation Very Large Array (Nyland et al. 2018) will be essential for determining the overall importance of feedback on ISM scales driven by compact jets for galaxy evolution.

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**Facilities:** VLA
NEWLY RADIO-LOUD QUASARS

Software: Astropy (Astropy Collaboration et al. 2013), CASA (McMullin et al. 2007), Obit (Cotton 2008), and Montage (Jacob et al. 2010; Berriman & Good 2017).

REFERENCES

Alexander, K. D., van Velzen, S., Horesh, A., & Zauderer, B. A. 2020, SSRv, 216, 81
An, T., & Baan, W. A. 2012, ApJ, 760, 77
An, T., Baan, W. A., Wang, J.-Y., Wang, Y., & Hong, X.-Y. 2013, MNRAS, 434, 3487
An, T., Mohan, P., Zhang, Y., et al. 2020, Nature Communications, 11, 143
Anderson, M. M., Mooley, K. P., Hallinan, G., et al. 2020, ApJ, 903, 116
Anjum, A., Stalin, C. S., Rakshit, S., Gudennavar, S. B., & Durgapal, A. 2020, MNRAS, 494, 764
Assef, R. J., Stern, D., Noirot, G., et al. 2018, ApJS, 234, 23
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Bannister, K. W., Murphy, T., Gaensler, B. M., Hunstead, R. W., & Chatterjee, S. 2011, Monthly Notices of the Royal Astronomical Society, 412, 634. https://doi.org/10.1111/j.1365-2966.2010.17938.x
Bannister, K. W., Stevens, J., Tuntsov, A. V., et al. 2016, Science, 351, 354
Barvainis, R., Lehár, J., Birkinshaw, M., Falcke, H., & Blundell, K. M. 2005, ApJ, 618, 108
Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559
Bell, M. E., Huynh, M. T., Hancock, P., et al. 2015, MNRAS, 450, 4221
Berger, E. 2014, ARA&A, 52, 43
Berriman, G. B., & Good, J. C. 2017, PASP, 129, 058006
Bicknell, G. V., Dopita, M. A., & O'Dea, C. P. O. 1997, ApJ, 485, 112
Bicknell, G. V., Mukherjee, D., Wagner, A. e. Y., Sutherland, R. S., & Nesvadba, N. P. H. 2018, MNRAS, 475, 3493
Bignall, H. E., Croft, S., Hovatta, T., et al. 2015, Advancing Astrophysics with the Square Kilometre Array (AASKA14), 58
Blandford, R., Meier, D., & Readhead, A. 2019, ARA&A, 57, 467
Bonnerot, C., Rossi, E. M., & Lodato, G. 2016, MNRAS, 458, 3324
Böttcher, M. 2019, Galaxies, 7, 20
Braun, R., Bonaldi, A., Bourke, T., Keane, E., & Wagg, J. 2019, arXiv e-prints, arXiv:1912.12699
Braun, R., Bourke, T., Green, J. A., Keane, E., & Wagg, J. 2015, in Advancing Astrophysics with the Square Kilometre Array (AASKA14), 174
Briggs, D. S. 1995, in Bulletin of the American Astronomical Society, Vol. 27, American Astronomical Society Meeting Abstracts, 1444
Britzen, S., Qian, S. J., Steffen, W., et al. 2017, A&A, 602, A29
Brunthaler, A., Falcke, H., Bower, G. C., et al. 2005, A&A, 435, 497
Burke-Spolaor, S., Taylor, S. R., Charisi, M., et al. 2019, A&A Rv, 27, 5
Callingham, J. R., Gaensler, B. M., Ekers, R. D., et al. 2015, ApJ, 809, 168
Callingham, J. R., Ekers, R. D., Gaensler, B. M., et al. 2017, ApJ, 836, 174
Carilli, C. L., Ivison, R. J., & Frail, D. A. 2003, ApJ, 590, 192
Cendes, Y. 2020, PhD thesis, Leiden University
Chandra, P., & Frail, D. A. 2012, ApJ, 746, 156
Chatterjee, R., Marscher, A. P., Jorstad, S. G., et al. 2011, ApJ, 734, 43
Chhetri, R., Morgan, J., Ekers, R. D., et al. 2018, MNRAS, 474, 4937
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, 9906SB
Clegg, A. W., Fey, A. L., & Lazio, T. J. W. 1998, ApJ, 496, 253
Collier, J. D., Tingay, S. J., Callingham, J. R., et al. 2018, MNRAS, 477, 578
Cordes, J. M., & Lazio, T. J. W. 2002, arXiv e-prints, astro—. 2003, arXiv e-prints, astro
Cornwell, T. J., Golap, K., & Bhatnagar, S. 2005, in Astronomical Society of the Pacific Conference Series, Vol. 347, Astronomical Data Analysis Software and Systems XIV, ed. P. Shopbell, M. Britton, & R. Ebert, 86
Cotton, W. D. 2008, PASP, 120, 439
Cutri, R. M., & et al. 2013, VizieR Online Data Catalog, II/328
Czerny, B., Siemiginowska, A., Janiuk, A., Nikiel-Wroczyński, B., & Stawarz, Ł. 2009, ApJ, 698, 840
Dai, B. B., Shu, X. W., Jiang, N., et al. 2020, ApJL, 896, L27
de Vries, W. H., Becker, R. H., White, R. L., & Helfand, D. J. 2004, AJ, 127, 2565
Dewdney, P. E., Hall, P. J., Schilizzi, R. T., & Lazio, T. J. L. W. 2009, Proceedings of the IEEE, 97, 1482
Duffy, P., & Blundell, K. M. 2012, MNRAS, 421, 108
Effekhari, T., Berger, E., Zauderer, B. A., Margutti, R., & Alexander, K. D. 2018, ApJ, 854, 86
NEWLY RADIO-LOUD QUASARS

Mukherjee, D., Wagner, A. Y., Bicknell, G. V., et al. 2018, MNRAS, 476, 80
Mundell, C. G., Ferruit, P., Nagar, N., & Wilson, A. S. 2009, ApJ, 703, 802
Murphy, E. J., Bolatto, A., Chatterjee, S., et al. 2018, in Astronomical Society of the Pacific Conference Series, Vol. 517, Science with a Next Generation Very Large Array, ed. E. Murphy, 3
Murphy, T., Chatterjee, S., Kaplan, D. L., et al. 2013, PASA, 30, e006
Narayan, R. 1992, Philosophical Transactions of the Royal Society of London Series A, 341, 151
Nipoti, C., Blundell, K. M., & Binney, J. 2005, MNRAS, 361, 633
Nyland, K., Alatalo, K., Wrobel, J. M., et al. 2013, ApJ, 779, 173
Nyland, K., Harwood, J. J., Mukherjee, D., et al. 2018, ApJ, 859, 23
O’Dea, C. P. 1998, PASP, 110, 493
O’Dea, C. P., & Saikia, D. J. 2020, arXiv e-prints, arXiv:2009.02750
Orienti, M. 2016, Astronomische Nachrichten, 337, 9
Orienti, M., & Dallacasa, D. 2020, MNRAS, 499, 1340
Orienti, M., Dallacasa, D., & Stanghellini, C. 2010, MNRAS, 408, 1075
Padmanabhan, H., & Loeb, A. 2020, arXiv e-prints, arXiv:2003.07365
Palenzuela, C., Lehner, L., & Liebling, S. L. 2010, Science, 329, 927
Palliyaguru, N. T., Corsi, A., Frail, D. A., et al. 2019, ApJ, 872, 201
Paris, I., Petitjean, P., Aubourg, É., et al. 2018, A&A, 613, A51
Patil, P., Nyland, K., Whittle, M., et al. 2020, ApJ, 896, 18
Perley, R. A., & Butler, B. J. 2013, ApJS, 204, 19
—. 2017, ApJS, 230, 7
Pietka, M., Fender, R. P., & Keane, E. F. 2015, MNRAS, 446, 3687
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2016, A&A, 594, A13
Polisensky, E., Lane, W. M., Hyman, S. D., et al. 2016, ApJ, 832, 60
Prandoni, I., de Ruiter, H. R., Ricci, R., et al. 2010, A&A, 510, A42
Rau, U., & Cornwell, T. J. 2011, A&A, 532, A71
Reynolds, C. S., & Begelman, M. C. 1997, ApJL, 487, L135
Rosario, D. J., Fawcett, V. A., Klinkt, L., et al. 2020, MNRAS, 494, 3061
Ruffa, I., Prandoni, I., Laing, R. A., et al. 2019, MNRAS, 484, 4239
Sarbadhicary, S. K., Tremou, E., Stewart, A. J., et al. 2020, arXiv e-prints, arXiv:2009.05056
Schnittman, J. D. 2013, Classical and Quantum Gravity, 30, 244007
Selina, R. J., Murphy, E. J., McKinnon, M., et al. 2018, in Astronomical Society of the Pacific Conference Series, Vol. 517, Science with a Next Generation Very Large Array, ed. E. Murphy, 15
Shabala, S. S., Jurlin, N., Morganti, R., et al. 2020, MNRAS, 496, 1706
Shen, Y., Richards, G. T., Strauss, M. A., et al. 2011, ApJS, 194, 45
Siemiginowska, A., Sobolewska, M., Migliori, G., et al. 2016, ApJ, 823, 57
Stanimirović, S., & Zweibel, E. G. 2018, ARA&A, 56, 489
Thyagarajan, N., Helfand, D. J., White, R. L., & Becker, R. H. 2011, ApJ, 742, 49
Tingay, S. J., & de Kool, M. 2003, AJ, 126, 723
Tingay, S. J., Macquart, J. P., Collier, J. D., et al. 2015, AJ, 149, 74
Tinti, S., Dallacasa, D., de Zotti, G., Celotti, A., & Stanghellini, C. 2005, A&A, 432, 31
Torniainen, I., Tornikoski, M., Teräsranta, H., Aller, M. F., & Aller, H. D. 2005, A&A, 435, 839
van Velzen, S., Bower, G. C., & Metzger, B. D. 2018, in Astronomical Society of the Pacific Conference Series, Vol. 517, Science with a Next Generation Very Large Array, ed. E. Murphy, 737
van Velzen, S., Falcke, H., & Körding, E. 2015, MNRAS, 446, 2985
van Velzen, S., Körding, E., & Falcke, H. 2011, MNRAS, 417, L51
van Velzen, S., Anderson, G. E., Stone, N. C., et al. 2016, Science, 351, 62
Walker, M. A. 1998, MNRAS, 294, 307
Weiler, K. W., Panagia, N., Montes, M. J., & Sramek, R. A. 2002, ARA&A, 40, 387
Williams, D. R. A., Baldi, R. D., McHardy, I. M., et al. 2020, MNRAS, 495, 3079
Wołowska, A., Kunert-Bajraszewska, M., Mooley, K., & Hallinan, G. 2017, Frontiers in Astronomy and Space Sciences, 4, 38
Woosley, S. E., & Bloom, J. S. 2006, ARA&A, 44, 507
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868
York, D. G., Adelman, J., Anderson, Jr., J. E., et al. 2000, AJ, 120, 1579
APPENDIX
A. SOURCE PROPERTIES

The basic properties of our sources from our multiband VLA follow-up observations are presented in Table 6. We note that all sources are unresolved at the angular resolution provided in Column 6 of Table 6.

| Source          | Date       | Band | $\nu$ (GHz) | $\sigma_{\text{rms}}$ (\mu Jy beam$^{-1}$) | $\theta_{\text{maj}} \times \theta_{\text{min}}$ (arcsec$^2$) | $S_{\text{peak}}$ (mJy beam$^{-1}$) |
|-----------------|------------|------|-------------|------------------------------------------|------------------------------------------------|---------------------------------|
| J0742+2704      | 2019 Oct 03| L    | 1.5         | 47                                       | $2.00 \times 0.89$                              | $3.80 \pm 0.04$                 |
|                 |            | S    | 3.0         | 25                                       | $0.95 \times 0.49$                              | $10.97 \pm 0.02$                |
|                 |            | C    | 6.0         | 20                                       | $0.43 \times 0.25$                              | $25.20 \pm 0.04$                |
|                 |            | X    | 10.0        | 20                                       | $0.27 \times 0.18$                              | $25.23 \pm 0.03$                |
|                 |            | Ku   | 15.0        | 10                                       | $0.17 \times 0.12$                              | $19.70 \pm 0.01$                |
| J0807+2102      | 2019 July 23| L    | 1.5         | 187                                      | $4.44 \times 1.11$                              | $0.86 \pm 0.03$                 |
|                 |            | S    | 3.0         | 87                                       | $2.31 \times 0.57$                              | $3.15 \pm 0.07$                 |
|                 |            | C    | 6.0         | 45                                       | $1.15 \times 0.28$                              | $7.83 \pm 0.03$                 |
|                 | 2019 Sept 19| X    | 10.0        | 26                                       | $0.67 \times 0.20$                              | $15.10 \pm 0.02$                |
|                 |            | Ku   | 15.0        | 13                                       | $0.18 \times 0.13$                              | $17.42 \pm 0.01$                |
|                 |            | K    | 22.0        | 28                                       | $0.11 \times 0.09$                              | $13.03 \pm 0.03$                |
| J0832+2302      | 2019 July 23| L    | 1.5         | 70                                       | $4.63 \times 1.11$                              | $1.41 \pm 0.05$                 |
|                 |            | S    | 3.0         | 35                                       | $2.33 \times 0.65$                              | $3.25 \pm 0.03$                 |
|                 |            | C    | 6.0         | 20                                       | $1.14 \times 0.34$                              | $5.69 \pm 0.01$                 |
|                 | 2019 Sept 19| X    | 10.0        | 21                                       | $0.71 \times 0.21$                              | $5.28 \pm 0.02$                 |
|                 |            | Ku   | 15.0        | 13                                       | $0.26 \times 0.19$                              | $5.97 \pm 0.01$                 |
|                 |            | K    | 22.0        | 28                                       | $0.17 \times 0.12$                              | $6.57 \pm 0.02$                 |
| J0950+5128      | 2019 July 23| L    | 1.5         | 58                                       | $4.11 \times 1.48$                              | $3.93 \pm 0.05$                 |
|                 |            | S    | 3.0         | 41                                       | $2.23 \times 0.68$                              | $10.21 \pm 0.02$                |
|                 |            | C    | 6.0         | 19                                       | $1.10 \times 0.39$                              | $15.61 \pm 0.02$                |
|                 | 2019 Sept 19| X    | 10.0        | 23                                       | $0.65 \times 0.24$                              | $17.09 \pm 0.02$                |
|                 |            | Ku   | 15.0        | 12                                       | $0.28 \times 0.19$                              | $18.69 \pm 0.01$                |
|                 |            | K    | 15.0        | 33                                       | $0.16 \times 0.13$                              | $13.12 \pm 0.05$                |
| J1037-0736      | 2019 Oct 13| L    | 1.5         | 69                                       | $1.79 \times 1.10$                              | $6.68 \pm 0.07$                 |
|                 |            | S    | 3.0         | 68                                       | $0.72 \times 0.53$                              | $15.48 \pm 0.07$                |
|                 |            | C    | 6.0         | 22                                       | $0.34 \times 0.26$                              | $19.13 \pm 0.06$                |
|                 |            | X    | 10.0        | 16                                       | $0.24 \times 0.16$                              | $16.08 \pm 0.02$                |
|                 |            | Ku   | 15.0        | 14                                       | $0.17 \times 0.11$                              | $13.31 \pm 0.01$                |
| J1204+1918      | 2019 Oct 11| L    | 1.5         | 90                                       | $1.32 \times 1.14$                              | $2.00 \pm 0.01$                 |
|                 |            | S    | 3.0         | 26                                       | $0.70 \times 0.55$                              | $4.83 \pm 0.02$                 |

*Table 6 continued*
| Source          | Date         | Band | $\nu$ (GHz) | $\sigma_{\text{rms}}$ (\(\mu\text{Jy beam}^{-1}\)) | $\theta_{\text{maj}} \times \theta_{\text{min}}$ (\(\& \times \&\)) | $S_{\text{peak}}$ (mJy beam\(^{-1}\)) |
|-----------------|--------------|------|-------------|---------------------------------|--------------------------------|---------------------------------|
| J1546+1500      | 2019 Sept 23 | L    | 1.5         | 0.32 \times 0.31                | 5.10 \pm 0.01                  |                                 |
|                 |              | X    | 10.0        | 0.23 \times 0.18                | 3.20 \pm 0.01                  |                                 |
|                 |              | Ku   | 15.0        | 0.16 \times 0.12                | 2.00 \pm 0.01                  |                                 |
| J1208+4741      | 2019 Oct 11  | L    | 1.5         | 1.14 \times 0.98                | 1.06 \pm 0.01                  |                                 |
|                 |              | S    | 3.0         | 0.62 \times 0.49                | 2.46 \pm 0.01                  |                                 |
|                 |              | C    | 6.0         | 0.29 \times 0.25                | 2.95 \pm 0.01                  |                                 |
|                 |              | X    | 10.0        | 0.18 \times 0.15                | 2.29 \pm 0.01                  |                                 |
|                 |              | Ku   | 15.0        | 0.12 \times 0.10                | 1.74 \pm 0.01                  |                                 |
| J1246+1805      | 2019 Oct 11  | L    | 1.5         | 1.45 \times 1.17                | 3.39 \pm 0.01                  |                                 |
|                 |              | S    | 3.0         | 0.76 \times 0.56                | 8.25 \pm 0.02                  |                                 |
|                 |              | C    | 6.0         | 0.32 \times 0.27                | 11.58 \pm 0.02                 |                                 |
|                 |              | X    | 10.0        | 0.18 \times 0.18                | 12.20 \pm 0.01                 |                                 |
|                 |              | Ku   | 15.0        | 0.13 \times 0.11                | 11.75 \pm 0.03                 |                                 |
| J1254-0606      | 2019 Nov 01  | L    | 1.5         | 1.70 \times 0.89                | 1.69 \pm 0.08                  |                                 |
|                 |              | S    | 3.0         | 0.90 \times 0.55                | 10.06 \pm 0.03                 |                                 |
|                 |              | C    | 6.0         | 0.33 \times 0.23                | 18.51 \pm 0.05                 |                                 |
|                 |              | X    | 10.0        | 0.22 \times 0.15                | 15.03 \pm 0.05                 |                                 |
|                 |              | Ku   | 15.0        | 0.15 \times 0.10                | 9.39 \pm 0.04                  |                                 |
| J1413+0257      | 2019 Sept 23 | L    | 1.5         | 1.45 \times 1.04                | 1.38 \pm 0.06                  |                                 |
|                 |              | S    | 3.0         | 0.87 \times 0.60                | 7.30 \pm 0.02                  |                                 |
|                 |              | C    | 6.0         | 0.40 \times 0.25                | 14.58 \pm 0.02                 |                                 |
|                 |              | X    | 10.0        | 0.30 \times 0.19                | 10.92 \pm 0.01                 |                                 |
|                 |              | Ku   | 15.0        | 0.21 \times 0.12                | 6.68 \pm 0.01                  |                                 |
| J1447+0512      | 2019 Sept 23 | L    | 1.5         | 1.55 \times 1.09                | 2.71 \pm 0.05                  |                                 |
|                 |              | S    | 3.0         | 0.92 \times 0.58                | 4.02 \pm 0.02                  |                                 |
|                 |              | C    | 6.0         | 0.49 \times 0.30                | 2.38 \pm 0.01                  |                                 |
|                 |              | X    | 10.0        | 0.32 \times 0.19                | 1.55 \pm 0.01                  |                                 |
|                 |              | Ku   | 15.0        | 0.18 \times 0.13                | 1.30 \pm 0.01                  |                                 |
| J1546+1500      | 2019 Sept 23 | L    | 1.5         | 1.41 \times 1.15                | 3.30 \pm 0.04                  |                                 |
|                 |              | S    | 3.0         | 0.76 \times 0.58                | 5.61 \pm 0.02                  |                                 |
|                 |              | C    | 6.0         | 0.42 \times 0.30                | 5.28 \pm 0.01                  |                                 |
|                 |              | X    | 10.0        | 0.26 \times 0.19                | 4.03 \pm 0.01                  |                                 |
|                 |              | Ku   | 15.0        | 0.16 \times 0.10                | 3.50 \pm 0.02                  |                                 |
| J1603+1809      | 2019 Sept 23 | L    | 1.5         | 1.22 \times 1.01                | 0.88 \pm 0.04                  |                                 |
|                 |              | S    | 3.0         | 0.71 \times 0.58                | 3.16 \pm 0.01                  |                                 |
|                 |              | C    | 6.0         | 0.38 \times 0.30                | 5.85 \pm 0.01                  |                                 |
|                 |              | X    | 10.0        | 0.24 \times 0.19                | 5.81 \pm 0.01                  |                                 |
|                 |              | Ku   | 15.0        | 0.17 \times 0.12                | 4.80 \pm 0.01                  |                                 |
| J2109-0644      | 2019 Sept 10 | L    | 1.5         | 1.43 \times 1.06                | 11.17 \pm 0.05                 |                                 |

Table 6 continued
Table 6 (continued)

| Source | Date | Band | $\nu$ (GHz) | $\sigma_{\text{rms}}$ (\(\mu\)Jy beam\(^{-1}\)) | $\theta_{\text{maj}} \times \theta_{\text{min}}$ (\('' \times ''\)) | $S_{\text{peak}}$ (mJy beam\(^{-1}\)) |
|--------|------|------|------------|-----------------|-----------------|-----------------|
| S      | 3.0  | 22   | 0.80 × 0.57 | 12.51 ± 0.01    |                 |
| C      | 6.0  | 15   | 0.39 × 0.29  | 16.97 ± 0.01    |                 |
| X      | 10.0 | 10   | 0.25 × 0.18  | 15.79 ± 0.01    |                 |
| Ku     | 15.0 | 11   | 0.17 × 0.11  | 13.00 ± 0.02    |                 |

**Note** — Column 1: Source name. Column 2: Observing date(s). Column 3: VLA band, defined as follows: L: 1–2 GHz, S: 2–4 GHz, C: 4–8 GHz, X: 8–12 GHz, Ku: 12–18 GHz, K: 18–26 GHz. Column 4: Central image frequency. Column 5: 1\(\sigma\) rms noise. Column 6: Clean beam dimensions (major × minor axis). Column 7: Peak flux density.