Transient Radio Emission from Low-redshift Galaxies at $z < 0.3$ Revealed by the VLASS and FIRST Surveys

Fabao Zhang1, Xinwen Shu1, Luming Sun1, Lei Yang1, Ning Jiang2, Liming Dou3, Jianguo Wang4, and Tinggui Wang5

1 Department of Physics, Anhui Normal University, Wuhu, Anhui 241002, People’s Republic of China; xwselu@ahnu.edu.cn, sunluming@ahnu.edu.cn
2 Department of Astronomy, University of Science and Technology of China, Hefei, Anhui 230026, People’s Republic of China
3 Department of Astronomy, Guangzhou University, Guangzhou 510006, People’s Republic of China
4 Yunnnan Observatories, Chinese Academy of Sciences, Kunming 650011, People’s Republic of China

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Abstract

We present the discovery of a sample of 18 low-redshift ($z < 0.3$) galaxies with transient nuclear radio emission. These galaxies are not detected or are weakly detected in the Faint Images of the Radio Sky at Twenty cm survey, performed from 1993–2009, but have brightened significantly in radio flux (by a factor of $\gtrsim 5$) in the epoch I (2017–2019) observations of the Very Large Array Sky Survey (VLASS). All 18 galaxies have been detected in VLASS epoch II observations, from 2020–2021, from which the radio flux has been found to evolve slowly (with variability amplitudes of $\gtrsim 40\%$) over a period of about 3 yr. 15 galaxies have been observed in the Rapid ASKAP Continuum Survey, and a flat or inverted spectral slope between 888 MHz and 3 GHz is found. Based on the Sloan Digital Sky Survey spectra taken before the radio brightening, 14 of the 18 galaxies can be classified as LINERs or normal galaxies with weak or no nuclear activity. Most galaxies are red and massive, with more than half having central black hole masses above $10^6 M_\odot$. We find that only one galaxy in our sample displays an optical flare lasting for at least two months, with a long decay in the infrared light curve that can be explained as the dust-heated echo emission of a central optical flare, such as a stellar tidal disruption event. We discuss several possibilities for the transient radio emission and conclude that it is likely associated with a newborn radio jet triggered by short sporadic fueling of a supermassive black hole. Such a scenario can be tested with further multifrequency radio observations of these sources, via measuring their radio flux variability and spectral evolution.

Unified Astronomy Thesaurus concepts: Radio jets (1347); Radio transient sources (2008); Surveys (1671)

1. Introduction

Relativistic jets have been observed from stellar-mass black holes ($M_{\text{BH}} \sim 10 M_\odot$), in Galactic X-ray binaries (XRBs), and from supermassive black holes (SMBHs; $M_{\text{BH}} \sim 10^6$–$10^9 M_\odot$), in the centers of most galaxies (Blandford et al. 2019). It has been established that the form of the jet in an XRB is determined by the accretion state. During the low/hard state, a steady, compact radio jet is produced, which is significantly quenched in the high/soft state, however, where disk thermal emission is dominant (Fender et al. 2004). As sources transition from a low to a high accretion state, isolated radio flares associated with the launch of relativistic ejecta have also been observed (Hjellming & Rupen 1995; Bright et al. 2020). However, such a ubiquitous feature of jet production and quenching, regulated by accretion states, has rarely been seen in active galactic nuclei (AGNs). This is because several criteria must be met by the source at once, and such AGNs are not common. First, the X-ray variability should be large enough in order to identify the accretion model transition (e.g., Liu et al. 2020; Ricci et al. 2021). Second, there must be a well-measured radio emission in different accretion states, so that its evolution can be used to constrain the jet formation and quenching. Although “changing-look” AGNs are ideal targets for such studies, owing to the large changes in their accretion rates, no jet-related transient radio emission has been convincingly detected so far (Gezari et al. 2017; Yang et al. 2021). Furthermore, it remains mysterious as to why only a small fraction of AGNs ($\sim 10\%$) that are radio-loud are associated with relativistic jets (e.g., Kellermann et al. 2016; Blandford et al. 2019). While Moravec et al. (2022) have recently shown that different radio AGN populations may follow an evolutionary track on the X-ray hardness–luminosity diagram similar to XRBs, it is difficult to directly correlate them with specific accretion state transitions, as their X-ray spectra are still dominated by coronal emission.

Over the past two decades, time domain surveys have led to the discovery of a population of energetic nuclear transients in otherwise quiescent galaxies. They are mostly due to the stellar tidal disruption events (TDEs) of SMBHs. As the stellar debris is effectively accreted, a fraction of the accretion power could be converted into outflow, and under certain conditions produce a relativistic jet, which can be detected at radio wavelengths (e.g., van Velzen et al. 2011; Zauderer et al. 2011). Sw J1644+57 is the first—prototype—TDE displaying a relativistic jet (Burrows et al. 2011), from which a luminous and variable radio emission has been readily detected after the stellar disruption (Berger et al. 2012), presenting a natural SMBH analogy for the state changes of XRBs. However, despite extensive searches, radio observations of other TDEs have not yet produced conclusive detections of as powerful a jet as that in Sw J1644+57 (Bower et al. 2013; van Velzen et al. 2013, 2016; Alexander et al. 2020; Dai et al. 2020). It has been suggested that nonrelativistic outflows may be more ubiquitous than jets in TDEs (Alexander et al. 2016, 2017; Anderson et al. 2020; Mohan et al. 2022), but due to the
insufficient sensitivity of radio observations, most of them cannot be detected (van Velzen et al. 2016). The current lack of detections can also be explained by the delayed onset of the radio emission (Horesh et al. 2021a, 2021b).

Recent radio surveys, such as the Caltech-NRAO Stripe 82 Survey (CNSS; Mooley et al. 2016) and the Very Large Array Sky Survey (VLASS; Lacy et al. 2020), have opened a new window for selecting TDE candidates, as well as other types of nuclear radio transients. Using the CNSS data, Anderson et al. (2020) presented the discovery of the TDE candidate CNSS J0019+00, through the detection of its transient radio emission, possibly originating from the interaction of the nonrelativistic outflow with the surrounding medium. Ravi et al. (2022) reported the discovery of the fading radio transient FIRST J1533+2727, which can be described as the long-lasting radio afterglow of a TDE. On the other hand, brightened radio emission has been found in a sample of galaxies and quasars, by crossmatching the data taken from the Faint Images of the Radio Sky at Twenty cm survey (FIRST; Becker et al. 1995; Helfand et al. 2015) with that from either CNSS (Kunert-Bajraszewska et al. 2020; Wołoszka et al. 2021) or VLASS (Nyland et al. 2020). Since the hosts of most of these radio transients show powerful AGN activities in preflare optical spectra, their transient radio emission has been explained as the transition from a radio-quiet to a radio-loud state, possibly associated with a newborn jet. Follow-up multifrequency VLA observations have suggested that the radio emission is compact, with typical size of less than 0.1 kpc, and characterized by a curved radio spectral energy distribution (SED) peaking at ~5–10 GHz (Nyland et al. 2020; Wołoszka et al. 2021), making these sources consistent with the population of young radio AGNs (O’Dea & Saikia 2021, and references therein).

In this paper, we report the identification of a sample of nearby galaxies (z < 0.3) with nuclear radio transients using VLASS data. Section 2 describes the observations and the data, and Section 3 presents the selection of radio transients. The host galaxies and variability properties at the optical and mid-infrared (MIR) bands are analyzed in Section 4. In Section 5, we present a discussion of the possible origins of the transient radio emission. Section 6 provides a summary of our findings.

2. Observations and Data

The FIRST survey was conducted at a frequency of 1.4 GHz, with an angular resolution of 5″ and imaging rms down to 130 μJy beam⁻¹ at the deepest footprint. It covers 10,575 deg², approximately 25% of the total sky area. The first epoch of the FIRST survey was carried out in the period from 1993 to 2004, and then extended to cover a larger sky region, with the observations performed between 2009 and 2011. Given the coordinates of sources of interest, image cutouts can be extracted from the FIRST data archive.⁵

VLASS is an S-band (2–4 GHz) multi-epoch legacy survey aiming to detect various types of extragalactic radio transients (Lacy et al. 2020), such as TDEs, accretion state-changing AGNs, and afterglows of off-axis gamma-ray bursts (GRBs) and core-collapse supernovae (SNe). The angular resolution of VLASS is about 2.5″, and it is currently surveying the entire northern sky with Dec > −40° (33,885 deg²). VLASS observations are designed to map the same survey area three times, each separated by a period of approximately 32 months. Each VLASS epoch achieves a 1σ sensitivity of ~120 μJy/beam, which is comparable to the depth of FIRST. The combinations of the images taken from the three-epoch VLASS observations will achieve a 1σ sensitivity of ~70 μJy/beam, making it the deepest wide-field survey at ~3 GHz, after the final implementation of the survey plan. The VLASS program started in 2017, and it recently completed its first-epoch observations in 2019 (epoch I). The preliminary “QuickLook” images have been publicly released on the NRAO website, in order to help the scientific community to access the VLASS data in a timely manner. Gordon et al. (2021) have produced the source catalog from the VLASS epoch I “QuickLook” images, using the Python Blob Detector and Source Finder (PyBDSF; Mohan & Rafferty 2015), consisting of 1.7 x 10⁶ individual radio sources with a peak flux of ≥1 mJy beam⁻¹. The catalog and an associated User Guide are available at the CIRADA website.⁷

3. Selection of Radio Transients

The main goal of the present study is to select galaxies that have recently brightened in radio, i.e., bright radio transient sources (RTSs), in VLASS, but that do not have counterparts in the previous FIRST catalog (S₁.4GHz < 1mJy). We first crossmatched the FIRST catalog and the VLASS epoch I catalog (Gordon et al. 2021) to search for VLASS sources that are not detected in FIRST, within a matching radius of r = 2″.5. We restricted the sample to include only sources that have a GHz flux of ≥5 mJy in the VLASS catalog. This ensured that the variability amplitude was at least a factor of 5 in comparison with the FIRST upper limits, and also helped to eliminate spurious sources. Gordon et al. (2021) suggested that the detected radio components with a peak flux above 5 mJy beam⁻¹ tend to be more reliable in the VLASS “QuickLook” images (Quality_flag = 0 in the catalog). We then crossmatched the sample with the Sloan Digital Sky Survey (SDSS) spectroscopic catalog, and required all objects to be nearby, at z < 0.3, in order to provide efficient classifications of sources using the Baldwin, Phillips, and Terlevich (BPT) diagram, if emission lines were detected. The VLASS sources were inspected visually to ensure that they were not artifacts such as extended emission from brighter foreground galaxies, image artifacts, and side lobes due to imperfect complex gain solutions. This left a total of 20 VLASS sources.

Since the present work aims to investigate the transient radio emission that is likely associated with SMBH accretion, we need to exclude known SN explosions. We cross correlated with the open SNe catalog compiled by Guillochon et al. (2017), which includes 36,000 + SNe and related candidates. The crossmatching resulted in two known SNe, J122447.59 +053624.3 (SN 2012ab; Bilinski et al. 2018) and J131341.47 +471756.7 (PTF11qcj; Paliya et al. 2019). Note that the VLASS epoch I data for the latter SN, J131341.47+471756.7, is reported in Stroh et al. (2021). After removing the two known SNe, our final sample consists of a total of 18 galaxies with transient radio emission, for which a detailed analysis will be presented in this paper.

Footnotes:

⁵ http://sandog.stsci.edu/

⁶ https://archive-new.nrao.edu/vlass/quicklook/

⁷ https://cirada.ca/catalogs

⁸ The catalog is constructed using the data presented in the SN literature as well as other web-based catalogs; it is available on the website https://sne.space and updated to include all SNe (and candidates) reported up to 2022 January.
Figure 1. The percentage change in radio flux over the period of the two-epoch VLASS observations, which is defined as $(F_{\text{epoch II}} - F_{\text{epoch I}})/F_{\text{epoch I}}$. The flux errors include the 5% uncertainties in the flux densities measured from CASA, to account for the flux calibration uncertainties of the VLASS data (Lacy et al. 2020).

We used the IMFIT task in the CASA software (version 5.3.0; McMullin et al. 2007) to measure the integrated and peak flux for each galaxy. The ratio of the integrated flux to the peak flux is in the range 0.93–1.25, with a median value of 1.02, suggesting that most, if not all, of the radio emission is unresolved and compact at the resolution of 2′′5. We checked that the positional offsets of the radio sources relative to the optical centers obtained from the SDSS photometry are in the range 0″08–0″41, with a median offset of 0″2. Note that the positional offsets are comparable to the astrometric accuracy of VLASS (<0″4; Lacy et al. 2020) and that of SDSS (<0″15; York et al. 2000), implying that the radio emission originates from a region close to the galactic center. Although the 18 sources are not listed in the FIRST catalog, in order to ensure their radio faintness during the FIRST observations, we used the CASA software to measure the flux of each source in the FIRST images. Given the positions of the radio components detected by VLASS, we found that seven sources were detectable at $\sim 3\sigma$–$7\sigma$, with a flux in the range 0.46–0.97 mJy, while only upper limits could be obtained for the remaining 11 sources, i.e., the detection significance was $<3\sigma$. This confirms that the selected VLASS sources were indeed faint (<1 mJy) during the FIRST observations. All the 18 sources have also been detected in the VLASS epoch II observations. Considering the flux errors (including the 5% uncertainty in the flux calibration; Lacy et al. 2020), the flux densities between the two sets of VLASS observations are consistent with each other for 10 sources (Figure 1). The radio flux has been found to increase moderately (within a factor of 1.5) in four galaxies, while it declines in four galaxies with variability amplitude in the range 20%–50%. The source name, radio coordinates, redshift, VLASS observation date(s) and radio flux measurements, and FIRST observation date and flux measurements are reported in Table 1. The FIRST, VLASS epoch I, and VLASS epoch II images are shown in Appendix A. Note that the amount of the radio flux variation between the two VLASS observations is consistent with other samples of RTSs (Nyang et al. 2020; Wolowska et al. 2021), as shown in Appendix B.

We also searched for archival data at 888 MHz from the Rapid ASKAP Continuum Survey (RACS; McConnell et al. 2020). The first epoch of RACS observations were performed between 2019 April 21 and 2020 June 21. We found that 15 of the 18 sources were observed at 888 MHz, whose ASKAP images are shown in Appendix C. We then measured the integrated and peak flux, following the same procedures described above, and found that 13 of the 15 sources were detected. For two nondetections, we report the 3σ upper limit on the flux, based on the map rms at the off-source position, which is in the range 190–430 μJy/beam. Considering that the 3 GHz fluxes between the two-epoch VLASS observations did not vary dramatically, the radio SED was likely evolving slowly. Therefore, the RACS data at 888 MHz can be considered quasi-simultaneously with the VLASS data, which can be used to quantify the radio spectral slopes below 3 GHz. We used the VLASS data that are close to the RACS observing date for each source to determine the rest-frame radio slope between 888 MHz and 3 GHz. The results are shown in Figure 2. We found that the radio spectral index $\nu\alpha$ is in the range 0.11–2.43, with a median of 0.87. With the radio spectral index, we extrapolated the 3 GHz flux to that at 1.4 GHz for 15 galaxies, and found that it is a factor of $\geq$3–15 higher than the FIRST flux, confirming the transient nature of radio emission. Details of the RACS flux measurements and the derived radio spectral index $\nu\alpha$ can be found in Table 2.

4. Results

4.1. Host Galaxy Properties

In order to understand the nature of the VLA S RTSs, it is useful to assess the nuclear activity of these galaxies prior to the radio brightening detected byVLASS. Along with the SDSS data release, there are several works that provide value-added catalogs of the intrinsic properties of galaxies. We used the MPA-JHU SDSS spectroscopic catalog for the following analysis. After crossmatching with the catalog, we found that 15 out of 18 galaxies have emission-line flux measurements (or upper limits). The remaining three are not listed in the MPA-JHU catalog, likely because the emission lines are too weak to be detected. We carried out detailed spectral fittings to measure any emission lines, if present, and the results are shown in Appendix D. Two sources, J1217+2750 and J1337+3857, have no detectable emission lines, while only upper limits can be obtained for J0040+0823 and J1409+5420. The line ratios of N [III]/Hα and O [III]/Hβ are listed in Table 3. Note that one object, J0950+5128, clearly shows the spectral features of a quasar (Figure A1 in Appendix A), and is listed in the sample of quasars that have transitioned from radio-quiet to radio-loud (Nyland et al. 2020). Since the optical spectrum of J0950+5128 is dominated by quasar emission, making it a challenge to study the host galaxy and its stellar population, we do not consider it in the following analysis in relation to the host properties (Figures 4, 7, and 9). Using the emission-line flux ratios, we performed a diagnosis of the nuclear activity by classifying the sample into different subclasses, according to their location on the BPT diagram (Kewley et al. 2001), as shown in Figure 3 (lower panel). Among the 15 galaxies with emission-line measurements, three are classified as Seyfert 2 galaxies, two as star-forming galaxies, eight as low-ionization nuclear emission regions (LINERs), and two as composites.

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Note that CLEAN bias correction (White et al. 1997) was not considered in calculating the source detection significance.

See https://www.sdss.org/dr12/spectro/galaxy_portsmouth and https://www.sdss.org/dr12/spectro/galaxy_mpajhu.
LINER-like spectra often appear in off-nucleus regions of evolved stars or radiative shocks, rather than by AGNs, as emission lines to be passive galaxies. It should be noted that a We consider the remaining two objects with nondetections of the 17 galaxies in our sample of the rest-frame u-band and g-band luminosity, for which the dust extinction and k correction have been taken into account from the best-fitting SED for each galaxy. For the three galaxies that are not presented in the catalog of Chang et al. (2015), we derived the host stellar masses by fitting the SDSS and WISE photometry (Chang et al. 2015), covering a broader wavelength range of $\lambda = 0.4-22\mu m$. We calculated the $u-r$ colors based on the rest-frame $u$-band and $g$-band luminosity, for which the dust extinction and $k$ correction have been taken into account from the best-fitting SED for each galaxy. For the three galaxies that are not presented in the catalog of Chang et al. (2015), we derived the host stellar masses by fitting the SDSS and WISE photometry with the CIGALE code (Appendix D). It is well known that galaxies show a bimodal distribution on the color–magnitude diagram, and are mainly divided into a red sequence and a blue cloud, according to the colors, with a green valley in between (e.g., Strateva et al. 2001; Bell et al. 2004). Figure 4 (left panel) shows the extinction-corrected rest-frame $u-r$ color versus the total stellar mass for our galaxies (red circles). The SDSS spectroscopic sample from Chang et al. (2015) is overlaid in contours for comparison. It can be seen that the RTS host galaxies are dominated by red and massive galaxies, with the majority (14 of 17) falling into the locus of the red sequence.

Since the colors of galaxies are affected by both the current star formation rate (SFR) and the star formation history, it has been proposed that the H$\alpha$ equivalent width (EW) and the Lick H$\delta_A$ index are useful for quantifying the host properties according to star formation history (French et al. 2016). The

| Name            | R.A.  | Decl.  | z     | Obs. Date (VLASS) | Peak Flux (mJy/beam) | Int. Flux (mJy) | log($\nu/L_{\nu}(3.6\mu m)$) (erg s$^{-1}$) | Obs. Date (FIRST) | Int. Flux (mJy) |
|-----------------|-------|--------|-------|-------------------|----------------------|---------------|----------------------------------|-------------------|---------------|
| J0040+0823      | 10.1845 | 8.3978 | 0.214 | 2017-11-27        | 5.30 ± 0.07          | 5.20 ± 0.13  | 40.33                           | 2009-04           | 0.80 ± 0.12  |
| J0154-0111      | 28.5486 | −1.1971 | 0.046 | 2017-09-27        | 5.70 ± 0.13          | 5.88 ± 0.23  | 38.95                           | 1995-11           | 0.58 ± 0.14  |
| J0800+2928      | 120.0671 | 29.4714 | 0.045 | 2019-04-13        | 9.99 ± 0.07          | 10.09 ± 0.11 | 39.17                           | 1993-05           | <0.44        |
| J0950+5128      | 147.6532 | 51.4772 | 0.211 | 2019-04-18        | 8.94 ± 0.08          | 8.24 ± 0.13  | 40.51                           | 1997-04           | <0.41        |
| J0951+3703      | 147.9234 | 37.0596 | 0.236 | 2019-04-26        | 9.26 ± 0.11          | 9.46 ± 0.20  | 40.69                           | 2000-02           | <0.44        |
| J1029+0436      | 157.4603 | 4.6161 | 0.085 | 2017-11-26        | 5.82 ± 0.07          | 5.66 ± 0.12  | 39.49                           | 2004-08           | 0.46 ± 0.14  |
| J1129+3900      | 172.4168 | 39.0129 | 0.287 | 2019-05-04        | 11.39 ± 0.14         | 11.38 ± 0.24 | 40.94                           | 2019-08           | 0.46 ± 0.14  |
| J1217+2750      | 184.3733 | 27.8413 | 0.184 | 2017-11-24        | 10.71 ± 0.11         | 10.75 ± 0.19 | 40.92                           | 1995-11           | 0.31 ± 0.14  |
| J1301+2127      | 195.3815 | 21.4636 | 0.087 | 2017-09-25        | 7.68 ± 0.21          | 8.09 ± 0.39  | 39.67                           | 2019-08           | <0.43        |
| J1337+3857      | 204.4213 | 38.9587 | 0.243 | 2017-10-14        | 7.29 ± 0.09          | 7.28 ± 0.16  | 39.62                           | 2019-08           | 0.68         |
| J1407+1247      | 211.9427 | 12.7889 | 0.126 | 2019-04-17        | 6.89 ± 0.13          | 6.39 ± 0.21  | 39.91                           | 2019-12           | 0.97 ± 0.14  |
| J1409+5420      | 212.4675 | 54.3485 | 0.174 | 2017-12-01        | 5.58 ± 0.08          | 5.74 ± 0.14  | 40.17                           | 2019-05           | <0.42        |
| J1437+0033      | 219.3984 | −0.5567 | 0.180 | 2019-05-01        | 6.16 ± 0.12          | 6.38 ± 0.21  | 40.25                           | 2019-08           | <0.43        |
| J1558+1412      | 239.6987 | 14.2037 | 0.034 | 2019-04-11        | 28.67 ± 0.64         | 29.20 ± 1.10 | 39.38                           | 2000-01           | <0.40        |
| J1610+0606      | 242.5899 | 6.1162  | 0.156 | 2019-03-18        | 5.67 ± 0.15          | 5.53 ± 0.25  | 40.05                           | 2000-02           | <0.45        |
| J1642+3346      | 250.6908 | 33.7777 | 0.136 | 2017-10-17        | 4.57 ± 0.10          | 4.47 ± 0.18  | 39.96                           | 1994-06           | 0.79 ± 0.14  |
| J1646+4227      | 251.5293 | 42.4604 | 0.050 | 2019-05-04        | 4.74 ± 0.11          | 4.43 ± 0.18  | 39.83                           | 2019-10           | <0.40        |
| J2301+0544      | 345.4323 | 5.7387  | 0.140 | 2017-10-23        | 7.09 ± 0.15          | 7.53 ± 0.28  | 40.08                           | 2019-10           | 0.47 ± 0.12  |
Figure 2. Radio SEDs between 888 MHz and 3 GHz. For sources that are not detected in FIRST or RACS, the 3σ upper limits on the flux are shown. The error bars for the radio spectral index ($\alpha_{0.89-3\text{GHz}}$) are estimated using Monte Carlo simulations (the green shaded regions), assuming that the error on each flux follows a Gaussian distribution. The filled red circle in each panel represents the extrapolated 1.4 GHz flux density, based on the best-fit radio slope.
Hα EW can be used as a tracer for the current star formation history on timescales of ~10 Myr, while the HδA index can probe star formation on much longer timescales of ~1 Gyr. Figure 4 (right panel) shows the Hα EW versus Lick HδA index for SDSS galaxies from the MPA-JHU catalog, and the RTSs in our sample. Apparently, the majority of the sources in our sample (13 of 17) fall into the region with little to no Hα emission and low HδA. To encompass the 13 sources, we defined a selection cut HδA < 0 and Hα EW < 7Å. This cut includes 242, 249 SDSS galaxies, or a fraction of ~32%. This indicates that the host galaxies for the majority of the RTSs are characterized by a low recent specific SFR with a relatively old stellar population, consistent with normal massive galaxies in the red sequence. In comparison, the host galaxies of optically selected TDEs (the blue triangles in Figure 4) appear to show different stellar properties, and we will discuss the implications in detail in Section 5.2.

In Figure 5 we show cutouts of the SDSS color gri images for the 18 RTS galaxy hosts. We include the quasar J0950+5128 in the morphology analysis, as it is resolved in the SDSS imaging. Galaxies can be classified as elliptical-like or disk-like, based on the concentration index C = R50/R25, where R50 and R25 are the radii containing 50% and 50% of the Petrosian flux for a given band, respectively, and the likelihood ratio of the de Vaucouleurs model fit to that of the exponential model. Elliptical-like early-type galaxies can be selected with C > 2.5 in the i band and a likelihood ratio > 1.03 (Bernardi et al. 2003). Using the measurements derived with the SDSS pipeline, we found that 16 of 18 galaxies (~88%) meet the criterion C > 2.5 for early-type galaxies, which can also be better fitted by a de Vaucouleurs profile. On the other hand, we crossmatched against the Galaxy Zoo DR1 catalog (Lintott et al. 2011) and found 14 matched galaxies. Among the 14 galaxies, 10 are more likely to be elliptical (with a debiased probability P > 0.7), based on visual classifications, two are spiral galaxies, and two are ambiguous. Thus, we conclude that more than 70% of the sample are early-type galaxies, consistent with the results of the stellar population analysis.

### 4.2. Variability Properties in the Optical and MIR Bands

We now check whether optical flares are associated with these radio transients. We collected optical light-curve (LC) data from the Catalina Real-time Transient Survey (CRTS; Drake et al. 2009) and the Zwicky Transient Facility (ZTF; Bellm et al. 2019). Among the 18 objects in our sample, 16 were observed by both CRTS and ZTF, and one (J1029+0436) was only observed by CRTS. The remaining one (J1646+4227) was not observed by either CRTS or ZTF. For the CRTS data, the V-band LCs observed from 2005 to 2013 are public,11 and for ZTF, the LCs in the g, r, and i bands from 2018 are also public.12 As can be seen in Figure 6(a), the quasar J0950+5128 shows stochastic variability with an amplitude of ~0.2 magnitude, which is consistent with typical variability amplitude found in AGNs (Caplar et al. 2017). By visually inspecting the optical LCs, we found that for most of the nonquasar galaxies, the LCs are roughly consistent with flat lines with noise, and do not show flares with an amplitude of more than 0.2 magnitude. In Figure 6(a), we show the LC of the source J0040+0823 as an example. The only nonquasar galaxy that shows obvious variability is J1301+2127, whose LC is also displayed in Figure 6(a). J1301+2127 shows a flare between 2008 April and July. The peak of the flare was recorded in 2008 May, when the galaxy had brightened by 0.5 magnitude compared to the preflare level. In order to check the

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11 The data can be obtained from the CRTS data release 2 (http://nessi.cacr.caltech.edu/DataRelease/).

12 The data can be obtained from the NASA/IPAC Infrared Science Archive (https://irsa.ipac.caltech.edu/applications/Gator/).
For the ZTF data, the amplitude of variability is calculated as that are caused by photometric errors have not been removed. As shown in Figure 6, the typical error level is estimated using the rms value of the apparent amplitude of variability means that any variations -band LCs. For the CRTS data, it is similarly calculated for the period of 2 yr with the greatest amplitude.

Table 3
Jet Power and Host Galaxy Properties

| Name         | log$M_\star$ (M$_\odot$) | log$M_{BH}$ (M$_\odot$) | $u-r$ | Lick H$_\alpha$ [Å] | EW(H$_\alpha$) [Å] | log(N [III]/H$_\alpha$) | log(O [III]/H$_\alpha$) | log $\delta$_edd | log ($P_\gamma$/L$_\gamma$) | Type       |
|--------------|--------------------------|-------------------------|------|--------------------|------------------|------------------------|------------------------|----------------|----------------------------|------------|
| J0040-0823   | 11.85                    | 9.09                   | 2.865| 2.649              | 1.233           | 0.121                  | >-0.272                | >-3.71          | <-0.61                     | LINER      |
| J0154-0111   | 10.83                    | 8.761                  | 2.687| -1.858             | 3.376           | 0.117                  | -0.157                 | -3.97           | -1.10                      | LINER      |
| J0800-0928   | 10.05                    | 5.62                   | 1.940| 4.678              | 1.717           | 0.102                  | 0.922                  | -0.51           | -1.24                      | Seyfert    |
| J0951+3703   | 11.50                    | 8.500                  | 3.790| -1.919             | 5.349           | -0.345                 | -0.068                 | -2.34           | <1.17                      | Composite  |
| J1029-0436   | 10.95                    | 8.035                  | 2.809| -2.970             | 2.879           | -0.025                 | 0.047                  | -3.05           | -0.63                      | LINER      |
| J1129-3900   | 11.72                    | 8.277                  | 3.524| -0.873             | 2.478           | 0.166                  | 0.428                  | -1.25           | -2.21                      | LINER      |
| J1217-2750   | 11.16                    | 8.026                  | 2.791| -1.466             | 2.136           | ...                    | ...                    | ...             | ...                        | Passive    |
| J1301-2127   | 10.16                    | 6.098                  | 1.519| 2.522              | 20.505          | -0.406                 | -0.252                 | <-0.89          | <-1.14                     | Star-forming|
| J1337+3857   | 11.71                    | 8.233                  | 2.443| 0.075              | 0.919           | ...                    | ...                    | ...             | ...                        | Passsive   |
| J1407+1247   | 11.37                    | 7.671                  | 2.727| -2.290             | 1.223           | 0.160                  | 0.396                  | -1.76           | -1.57                      | LINER      |
| J1409+5420   | 11.11                    | 7.893                  | 2.906| -1.855             | 2.624           | 0.023                  | >0.208                 | >-2.69          | <-0.70*                    | LINER      |
| J1437-0033   | 11.79                    | 8.418                  | 3.156| -0.868             | 0.752           | 0.031                  | 0.161                  | -4.20           | 0.43                       | LINER      |
| J1558+1412   | 11.03                    | 7.842                  | 2.405| -0.517             | 2.381           | -0.038                 | 0.252                  | -2.62           | -1.55                      | LINER      |
| J1610+0606   | 11.12                    | 7.724                  | 3.195| -0.425             | 1.693           | 0.081                  | 0.554                  | -1.29           | >-2.06                     | Seyfert    |
| J1642+3346   | 11.52                    | 7.618                  | 2.680| -0.303             | 5.463           | -0.196                 | -0.036                 | -1.59           | -1.63                      | Composite  |
| J1646+4227   | 9.95                     | 6.415                  | 2.043| 1.846              | 11.077          | -0.393                 | -0.351                 | <-1.38          | >-1.25*                    | Star-forming|
| J2301-0544   | 11.55                    | 8.433                  | 2.839| 0.072              | 4.526           | 0.284                  | 0.773                  | -0.77           | -3.16                      | Seyfert    |

Note. These two sources are not covered by ASKAP observations, so we used the median value of $\alpha_{0.89-3}$ GHz = 0.87 to derive the rest-frame 1.4 GHz flux and hence the jet power (e.g., Equation (4) of Wołowska et al. (2021); see also Section 5.4).

reliability of the variations, we calculated the “apparent” amplitude of variability for our sample, and compared it with the typical error level of optical photometry. Here the “apparent” amplitude of variability means that any variations that are caused by photometric errors have not been removed. For the ZTF data, the amplitude of variability is calculated as the standard deviation of the magnitudes from the monthly binned g-band LCs. For the CRTS data, it is similarly calculated for the period of 2 yr with the greatest amplitude. The typical error level is estimated using the rms value of the photometric errors. As shown in Figure 6(b), for most nonquasar galaxies, the amplitudes of variability are comparable to or less than the typical errors, except for J1301+2127. The analysis supports the results from visual inspection. J1301+2127 is classified as a star-forming galaxy in the preflare optical spectrum. The optical flare in J1301+2127 lasts for several months, similar to those of many TDEs (van Velzen et al. 2021). In summary, of the 18 galaxies with transient radio emission, only one shows unambiguous evidence of an optical flare.

It is possible that optical flares (if present) could be missed occasionally, due to the low cadence of the optical photometric observations. We estimate the probability that a hypothetical TDE causing a radio flare is captured by the optical photometric
observations. The observational cadence of CRTS is as follows: during the 9 yr period from 2005 to 2013 (8 yr for a few sources), the monitoring lasted for four to nine months of each year (the average value is 5.8 months for our sample); in each month, there are one to three observing nights; and in each night, there are four exposures. By combining the data taken from the four exposures, the photometric error is 0.03–0.06 mag for our sample. As a TDE typically causes a brightening of 0.2–1 mag near the peak time (van Velzen et al. 2021), we estimate that a TDE would be detected as long as there were CRTS observations in the month when the TDE peaks. There are 15 nonquasar galaxies in our sample that were observed by CRTS. For each galaxy, 51 months, on average, are covered by the CRTS observations. If we assume that the TDE peak time is

![Figure 5. Composite SDSS griz color images of the RTS host galaxies. Each panel has a size of 30″ × 30″.](image)

![Figure 6. Optical and MIR time domain data of our sample and analysis. (a) CRTS V-band and ZTF g-band LCs of three typical galaxies: J0040+0823 (black) represents a galaxy without optical variability, while J0950+5128 (blue) and J1301+2127 (red) are two variable galaxies. For clarity, we display the monthly binned ZTF LCs by adding constants. (b) The apparent variability amplitude vs. the rms of the photometric errors for the CRTS V-band and ZTF g-band observations. (c) WISE W2-band LCs of the three galaxies. (d) Similar to (b), but using WISE/W2 data.](image)
uniformly distributed between the FIRST and the VLASS epoch I observations, which have a time interval of 249 months on average, the probability of a TDE being captured by CRTS is 20.5%. The expected number of optical flares to be detected by CRTS in these 15 galaxies can be estimated as 3.1. For the ZTF survey, the observation cadence is as follows: starting from 2018 March, the monitoring lasted for nine to 10 months in each year; in each month, there were 10–30 observational nights; and in each night, there was one exposure in each band. The photometric error of each observation is 0.02–0.12 mag for our sample. Thus, the cadence of single observation or observations over several consecutive nights is sufficient to detect a TDE peak lasting for one month. We then calculated the probability that a TDE peak would be captured by the ZTF survey, as we did for the CRTS observations. There are seven nonquasar galaxies in our sample that were observed during the period between the ZTF and the VLASS epoch I observations. The summed duration of the ZTF observations is 11 months, on average. Thus, the probability of a TDE being detected is 4.4% (11/249), and the expected number of detections in these seven galaxies is 0.3. By adding the detection probabilities for the CRTS and ZTF LCs, the expected number of optical flares to be recorded by the two surveys is 3.4. Note that this number is likely to be underestimated. This is because the optical flare of a TDE typically lasts for several months, and there is a possibility that its rising or falling phase could be recorded, even if its peak time was missed. In addition, if the radio emission lasts for less than 10 yr, as is expected for many optical TDEs (e.g., Alexander et al. 2020), the TDE occurrence time can be better constrained after 2004 for $z < 0.3$, the period with more overlap with the optical photometric observations. This will also increase the probability of the TDE flares in our sample being detected by optical surveys. However, only one optical flare (J1301+2127) is actually detected. Therefore, the low detection rate of the optical flares cannot simply be explained by the low cadences of the CRTS or ZTF observations.

An optical flare may also be missed due to dust obscuration. Fortunately, dust heated by a central UV is actually detected. Therefore, the low detection rate of the survey, the observation cadence is as follows: starting from 2018 March, the monitoring lasted for nine to 10 months in each year; in each month, there were 10–30 observational nights; and in each night, there was one exposure in each band. The expected number of optical flares to be detected by CRTS in these 15 galaxies can be estimated as 3.1. For the ZTF survey, the observation cadence is as follows: starting from 2018 March, the monitoring lasted for nine to 10 months in each year; in each month, there were 10–30 observational nights; and in each night, there was one exposure in each band. The photometric error of each observation is 0.02–0.12 mag for our sample. Thus, the cadence of single observation or observations over several consecutive nights is sufficient to detect a TDE peak lasting for one month. We then calculated the probability that a TDE peak would be captured by the ZTF survey, as we did for the CRTS observations. There are seven nonquasar galaxies in our sample that were observed during the period between the ZTF and the VLASS epoch I observations. The summed duration of the ZTF observations is 11 months, on average. Thus, the probability of a TDE being detected is 4.4% (11/249), and the expected number of detections in these seven galaxies is 0.3. By adding the detection probabilities for the CRTS and ZTF LCs, the expected number of optical flares to be recorded by the two surveys is 3.4. Note that this number is likely to be underestimated. This is because the optical flare of a TDE typically lasts for several months, and there is a possibility that its rising or falling phase could be recorded, even if its peak time was missed. In addition, if the radio emission lasts for less than 10 yr, as is expected for many optical TDEs (e.g., Alexander et al. 2020), the TDE occurrence time can be better constrained after 2004 for $z < 0.3$, the period with more overlap with the optical photometric observations. This will also increase the probability of the TDE flares in our sample being detected by optical surveys. However, only one optical flare (J1301+2127) is actually detected. Therefore, the low detection rate of the optical flares cannot simply be explained by the low cadences of the CRTS or ZTF observations.

An optical flare may also be missed due to dust obscuration. Fortunately, dust heated by a central UV/optical flare can reradiate in the infrared (IR), causing an IR flare as well as echo emission (e.g., Mattila et al. 2018; Jiang et al. 2021a). The IR flares caused by TDEs usually last for 1–10 yr with amplitudes of 0.2–2 mag (e.g., Dou et al. 2016; Jiang et al. 2016; Dou et al. 2017; Jiang et al. 2017, 2019, 2021b). We searched for IR flares using the IR data in the WISE $W_2$ band (at 4.6 μm). Similar to what we did for the optical data, we calculated the variability amplitudes, as well as the typical errors, as shown in Figures 6(c) and (d). For most of the nonquasar objects, the amplitudes of variability are comparable or less than the errors, and the only galaxy with an apparent IR variability amplitude larger than 0.2 mag is J1301+2127. The long-decaying IR emission in J1301+2127 is similar to those of TDE candidates with extreme coronal emission lines (Dou et al. 2016). For those galaxies without an optical flare, there is also no significant IR variation, as the amplitudes of variability are less than 0.1 mag. Note that the cadence of the WISE observations is once every six months, and the photometric errors are 0.02–0.08 mag, which are sufficient to detect IR echoes, if present. Therefore, we do not find evidence of dust-heated IR echoes from central optical flares for most our galaxies.

5. Discussion

We have identified 18 galaxies at $z < 0.3$ that display transient radio emission, by comparing between the radio flux observed with VLASS and the upper limit obtained with FIRST. It should be noted that the sample, as a consequence of its selection, is only sensitive to long-term radio variability properties on timescales of years to decades, and that the cadence of the observations is very sparse. We have carefully inspected the radio components detected in the VLASS epoch I observations, and found that they are not spurious sources. This result is supported by the detections in the VLASS epoch II observations for all of the sources in the sample. The long-term radio variabilities could originate from different physical processes, such as SN explosions, the intrinsic variability of a radio-quiet AGN, sporadic accretion onto an SMBH due to instability in an accretion disk or the tidal disruption of a star, or a recently launched young jet. We will discuss these scenarios in detail.

5.1. Stellar Explosions

Radio emission has been detected in about 30% of the nearby SN sample ($D < 100$ Mpc), from a few days to several years since the explosion (Bietenholz et al. 2021). A recent study of the luminous late-time radio emission from the SNe detected by VLASS has been presented in Stroh et al. (2021). As described in Section 3, we have cross correlated with the open SN catalog compiled by Guillotson et al. (2017) and found two matches in our initial sample of 20 galaxies. After excluding the two known SNe, the radio luminosities of our sources are high, with $L_{3GHz} \gtrsim 10^{35}$ erg s$^{-1}$, comparable to the most luminous type IIn SNe (Stroh et al. 2021), for which the host galaxies are blue with active ongoing star formation. This is not compatible with the fact that most of our galaxies have red colors and low current SFRs. The high radio luminosities rule out the possibility of the transient radio emission originating from SNe. A contribution to the observed radio variability from GRBs also seems unlikely, as the typical variability timescale of radio emission for GRBs is around one to two weeks (Pietka et al. 2015). Long GRBs can have a radio luminosity as high as $10^{40} - 10^{41}$ erg s$^{-1}$ (Stroh et al. 2021), but decay by more than an order of magnitude within several years of the explosion, which is inconsistent with the lack of significant flux variability of our sources in the two-epoch VLASS observations ($\lesssim$50%; Figure 1). Furthermore, the effect of interstellar scintillation causing the radio variability can also be ruled out, as the flux variability due to interstellar scintillation is at a level of ~30%–40% (Nyland et al. 2020), which is much lower than the radio brightening, by a factor of >3, between FIRST and VLASS observations (Section 3).

5.2. TDEs

Recent time domain surveys have discovered dozens of TDEs in the centers of otherwise quiescent galaxies (Gezari 2021), but only ~10% are accompanied by radio flares (Bower et al. 2013; van Velzen et al. 2013; Alexander et al. 2020), the nature of which are still poorly understood (Horesh et al. 2021a, 2021b). So far, there are two TDE candidates that have been identified only at radio wavelengths (Anderson et al. 2020; Ravi et al. 2022). It is possible that some of the RTSS in our sample are associated with TDEs. However, as shown in Figure 4, we find red colors and large host stellar
masses for the host galaxies of RTSs. Based on the TDE sample selected from the ZTF survey, and the known UV/optical-selected TDEs in the literature, van Velzen et al. (2021) show that the TDE host galaxies prefer to be located within the green valley region, where the galaxies are expected to transition from star-forming to quiescent. A Kolmogorov-Smirnov (K–S) test for the stellar-mass distribution between RTSs and optical TDEs results in a $p$ value of $3.3 \times 10^{-8}$, suggesting that they are not drawn from the same population. \(^{13}\)

A similar result can be obtained from the K–S test on the distribution in the rest-frame $u - r$ colors, with a $p$ value of $3 \times 10^{-8}$. It has been found that UV/optical-selected TDEs are overrepresented by poststarburst galaxies. \(^{14}\) Figure 4 (right) shows that only two RTSs lie in the branch for the TDE hosts (quiescent Balmer-strong galaxies). There are two sources with a Lick Hα index consistent with TDE hosts, but enhanced Hα emission, possibly dominated by the current star-forming activity and/or AGN. The above analyses suggest that the host properties of the RTSs presented in this work may be different from those of TDEs, at least for those discovered in the optical surveys.

The red colors and large stellar masses suggest that RTSs may possess larger SMBHs than the known TDEs or TDE candidates. By using the velocity dispersion measurements provided in the MPA-JHU catalog, and by adopting the $M_{\text{BH}} - \sigma_*$ relation used in Gültekin et al. (2009), we estimate their BH masses to be in the range $4.2 \times 10^5 - 1.2 \times 10^9 M_\odot$, with a median of $1.1 \times 10^8 M_\odot$. Figure 7 shows the distribution of the BH masses, and its comparison with a sample of 12 UV/optical-selected TDEs with BH masses measured by Wevers et al. (2017). It can be seen that our sample is much more spread out, with objects having either large or small masses, indicating the heterogeneity of the sample. A K–S test on the mass distribution between our sample and the optical TDEs results in a $p$-value of $2.9 \times 10^{-5}$, suggesting that they are not drawn from the same population. While 10 of the 12 optical TDEs have masses between $3 \times 10^5$ and $10^9 M_\odot$, only three of the 17 sources in our sample fall into this range. Among the three sources, two can be classified as star-forming galaxies, namely J1301+2127 and J1646+4227. As shown in Section 4.2 (and Figure 6), the clear optical flare and long-lasting IR echo suggest that J1301+2127 might be a TDE. J1646+4227 has no IR flux variations detected in the WISE LCs. The optical variability properties are not yet clear, as it is the only source in our sample without CRTS or ZTF observations. We note that very few optically discovered TDEs are found in star-forming galaxies, and this could be a selection effect (Jiang et al. 2021a, 2021b). If J1301+2127 and J1646+4227 were to be explained as TDEs, that would suggest that radio observations are important for offering a complete view of the TDE phenomenon. On the other hand, more than half the sources in our sample (9/17 = 53%) have BH masses larger than $10^8 M_\odot$, which is the upper limit for the tidal disruption of a main-sequence star around a Schwarzschild BH. In the TDE scenario, this suggests either the disruption of a post-main-sequence star (Kochanek 2016) or that the BH is spinning (Leloudas et al. 2016). However, such events are expected to be rare, based on the current observations of TDE candidates. In addition, this is difficult to reconcile with the nondetections of optical and MIR flares in the historical CRTS, ZTF, and WISE data sets. The analysis of long-term optical and MIR LCs, host properties, and BH mass distributions suggest that most of the RTSs in our sample are likely not TDEs.

5.3. Intrinsic Variability of Radio-quiet AGNs

As shown in Section 4.1, four of the 18 galaxies in our sample can be classified as AGNs (Seyfert or quasar), based on optical spectroscopy characteristics. However, the four AGNs are expected to be radio-quiet during the period of the FIRST observations. In fact, all of our sources have a low radio luminosity ($L_{1.4 \text{ GHz}} \lesssim 10^{21} - 10^{23} \text{ W Hz}^{-1}$), based on the weak detections or nondetections in the FIRST survey. This is at least an order of magnitude lower than the luminosity thresholds of $10^{24} - 10^{25} \text{ W Hz}^{-1}$ for radio-loud AGNs (Miller et al. 1990; Goldschmidt et al. 1999). While radio variability has been observed in radio-quiet AGNs on timescales from months to years, the variability amplitude is typically a few tens of percent (Pannessa et al. 2019). This contrasts with the large flux increases, by a factor of $\gtrsim 3$–15, between the FIRST and VLASS observations. Considering that the majority of our sources (14/18) can be classified as LINERs or normal galaxies, intrinsic AGN variability seems unable to explain the radio properties of our sources.

5.4. Recently Launched Young Radio Jets

We next consider the possibility that the central BH is at a long quiescent level, and fed episodically over a relatively short timescale, probably caused by instability within an accretion disk. The low-level accretion activity in the quiescent state may also explain the very common LINER optical spectra for most of our sources (Section 4.1). It has been hypothesized that radio activity is an intermittent phenomenon lasting $10^5$–$10^6$ yr, and that an AGN may undergo many such short-term phases during its lifetime (e.g., Reynolds & Begelman 1997; Czerny et al. 2009; An & Baan 2012; Wołoszka et al. 2017). Using

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\(^{13}\) The estimate of the true $p$ value might be affected by the small sample sizes used.

\(^{14}\) The central concentration of A stars in poststarburst galaxies could serve to enhance the TDE rate (Yang et al. 2008; Stone & van Velzen 2016).
Figure 8. Histogram of the radio spectral index between 888 MHz and 3 GHz for the RTs in our sample and those in Nyland et al. (2020). For comparison, we also show the optically thick spectral indices (α_{thick}) for the latter sample, which were derived by fitting a power-law model to the quasi-simultaneous flux densities at 1.4 GHz and 3 GHz. The error bars represent 1σ Poisson uncertainties.

CNSS and VLASS data, recent works have identified a population of quasars with switched-on radio activities (Mooley et al. 2016; Kunert-Bajraszewska et al. 2020; Nyland et al. 2020; Wołowska et al. 2021). The transition from the radio-quiet to the radio-loud phase in these sources can be explained by the appearance of newborn and young radio jets.

Young radio jets are characterized by curved radio SEDs peaking at $\sim 5$–10 GHz (Nyland et al. 2020). The spectral turnover at frequencies below the peak is likely due to synchrotron self-absorption and/or free–free absorption (O’Dea & Saikia 2021). Figure 8 shows the distribution of the radio spectral index between 888 MHz and 3 GHz for our sources. Interestingly, all have a flat or inverted spectrum, with $\alpha_{0.89–3 \text{ GHz}}$ in the range 0.1–2.4. For comparison, we also show the optically thick spectral index values (α_{thick}) below the turnover frequency for the sample presented in Nyland et al. (2020), which appear to be higher than ours. A K–S test for the two samples results in a p value of 0.01. Such a difference could be due to the poor spatial resolution of the ASKAP observations ($\sim 15''$), which may include the radio emission at a larger scale than the VLASS ones. In addition, α_{thick} for the latter sample was derived between 1.4 GHz and 3 GHz, which has a different frequency coverage. Therefore, we retrieved the ASKAP data at 888 MHz and measured $\alpha_{0.89–3 \text{ GHz}}$ for the sample of Nyland et al. (2020), whose distribution is also shown in Figure 8. In this case, a K–S test (p = 0.65) suggests that it could be drawn from the same population as ours. Although precise measurements of radio SEDs cannot be done with the current data for our sample, the flat or inverted spectral slopes between 888 MHz and 3 GHz imply that our sample might be similar in nature to that of Nyland et al. (2020), i.e., dominated by young radio jets. On the other hand, Wołowska et al. (2021) have suggested that small changes of the accretion rate (by $\sim 30%$–$40\%$) may be sufficient to trigger low-power radio activity that evolves on the timescale of decades. This may explain why most of our sources have not shown large amplitude variability in the optical and IR LCs (Figure 6).

Figure 9 shows the distribution of our sources in the $P_J/L_{bol} - \lambda_{Edd}$ plane (red dots). Excluding six sources with either upper or lower limits, only one has a jet power in excess of the disk luminosity ($P_J/L_{bol} > 1$), and the remaining sources are distributed within a range from $\log(P_J/L_{bol}) = -3.16$ to $-0.63$. Furthermore, the accretion rate in the sample spans a relatively wide range, between $\log(\lambda_{Edd}) = -4.2$ and $-0.5$, with $\sim 50\%$ falling below $10^{-2}$. While the jet production efficiency and accretion rate are similar to the sample of Wołowska et al. (2021; green dots), the distribution of the objects in the sample of Nyland et al. (2020) appears to be different (cyan dots). The latter sample occupies the locus of larger jet power and larger accretion rates, overlapping that of Fanaroff-Riley (FR) type II broadline radio galaxies and radio quasars from the sample of Rusinok et al. (2017). This is possibly due to selection effects, as the sample of Nyland et al. (2020) includes only powerful quasars with relatively high $\lambda_{Edd}$. In comparison to compact radio sources and GHz-peaked spectrum sources that are believed to be young radio galaxies, our sample tends to have a much lower jet production efficiency, by at least an order of magnitude. For example, the median $P_J/L_{bol}$ is $\sim 0.1$ for our sample, while it is 4.3 for the young radio galaxies. On the other hand, there appears to be no dependence of the jet production efficiency on the accretion rate.

There are several caveats to the above comparison of jet power between different populations, so the results should be

$$\eta_{jet} = \frac{P_j}{M_{\text{acc}} c^2} = \frac{\eta_{acc} P_j}{L_{bol}},$$

where $M_{\text{acc}}$ is the mass accretion rate and $\eta_{acc}$ is the radiative efficiency of the accretion disk. We have assumed a typical value of $\eta_{acc} = 10\%$ in this paper, when applicable. On the other hand, we have parameterized the accretion rate using the Eddington ratio, $\lambda_{Edd} = \frac{L_{bol}}{L_{Edd}}$, where $L_{Edd}$ is the Eddington luminosity. It has been suggested that an AGN could be transitioning between a radiatively efficient state and a radiatively inefficient state, if its accretion rate changes across $L_{bol}/L_{Edd} \sim 10^{-2}$ (Noda & Done 2018; Ruan et al. 2019).
treated with caution. First, the bolometric correction to O[III] luminosity is uncertain, with a variance of 0.38 dex (Heckman et al. 2004), and the intrinsic scatter in the $M_{\text{BH}} - \sigma_*$ relation is 0.44 dex (Gültekin et al. 2009). These make it difficult to robustly estimate the $L_{\text{bol}}$ and $L_{\text{Edd}}$ in individual sources. As a result, we could only show the typical error bars of $L_{\text{Edd}}$ and $P_J$ in the left corner of Figure 9. Second, the jet powers were calculated using the 1.4 GHz monochromatic radio luminosity. However, the scaling relation was originally derived using the radio luminosity at 151 MHz in FR type II radio galaxies (e.g., Willott et al. 1999). It is not clear how the calculation of the jet power is affected by changes of the radio spectral shape, as a radio spectral index of $\alpha = 0.8$ between 151 MHz and 1.4 GHz ($F_{\nu} \propto \nu^{-\alpha}$) was assumed (Rusinek et al. 2017). In fact, the jet power depends critically on the radio spectral index, as well as the upper and lower cutoff frequencies of the synchrotron spectrum (Equation (1) of Willott et al. 1999). Third, since the O[III] emission comes from much extended regions (∼kpc), it may not correspond to the same accretion power relevant to the brightened radio emission. Quasi-simultaneous X-ray observations, such as those obtained with the Swift X-ray Telescope (Burrows et al. 2005), might be useful for better constraining the accretion power related to the radio brightening, but such data are not yet available. Finally, although the RACS data at 888 MHz have been used to constrain the radio spectral shapes for our sources, they are still less accurate and insufficient for localizing the peak frequencies. Quasi-simultaneous multifrequency radio observations are highly encouraged to confirm the peaked radio spectra, one of the critical characteristics of young radio jets, which will help us to further understand the nature of the radio transients revealed in VLASS.

6. Conclusion

By analyzing the galaxies observed by FIRST and VLASS, we have identified a sample of 18 slow-evolving radio transients at $z < 0.3$, characterized by radio variability (brightening in the VLASS epoch I observations) on decadal timescales. The locations of the radio emission are consistent with the optical centers of the galaxies from SDSS photometry, with positional offsets of less than 0.5′, indicating an origin from the nucleus, perhaps associated with the accreting SMBHs. All these galaxies are detected in the VLASS epoch II observations, and the 3 GHz radio emission does not show significant variations over ∼30–36 months (∼50%). By checking the archival RACS data, we find that 15 of the 18 sources are observed, and an inverted radio spectrum between 888 MHz and 3 GHz can be inferred, suggesting an origin from optically thick regions. Based on the SDSS spectroscopy data, the 18 galaxies can be classified as LINERs (8), star-forming galaxies (2), passive galaxies (2), composites (2), and AGNs (4). Most of the host galaxies are intrinsically red and massive, consistent with them being early-type galaxies from morphological analysis. Except for one source, we do not detect any optical or MIR flares in the CRTS, ZTF, and WISE LCs spanning ∼8–12 yr before the start of the VLASS survey. The combination of radio luminosities, variability amplitudes and timescales, spectral shapes, and host galaxy properties rule out origins from stellar explosions, such as SNe and GRBs, as well as the intrinsic variability of radio-quiet AGNs. The nondetections of optical and MIR flares, as well as their relatively large BH masses ($M_{\text{BH}} \gtrsim 10^8 M_\odot$), suggest that most of the sources in our sample are not TDEs. Young radio jets remain a likely scenario, which can be tested with further multifrequency as well as high–spatial resolution radio observations of galaxies in the sample.
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Software: CASA (v5.3.0; McMullin et al. 2007), CIGALE (Boquien et al. 2019).

Appendix A
Optical Spectrum and Image Cutouts for Individual Sources

In Figure A1, we present the SDSS optical spectrum of each galaxy in our sample, the SDSS $r$-band optical image, the FIRST image, the VLASS epoch I image, and the VLASS epoch II image.
Figure A1. From left to right, SDSS optical spectrum of the host galaxy, SDSS r-band image, FIRST image, VLASS epoch I image, and VLASS epoch II image. The red circle has a radius of $r = 2.5''$, comparable to the beam size of the VLASS images. The red cross represents the center of the radio emission from the VLASS epoch I observations. Each image cutout has a size of $30'' \times 30''$. 

The Astrophysical Journal, 938:43 (19pp), 2022 October 10 Zhang et al.
Figure A1. (Continued.)
Appendix B
Comparison of Radio Flux Variations between Different Samples

Following the approaches presented in Section 3 (Figure 1), we retrieved the VLASS epoch I and II observations and measured the 3 GHz fluxes to compute the variability amplitudes for the samples of Nyland et al. (2020) and Wołowska et al. (2021). The former sample includes only quasars that may have transitioned from radio-quiet to radio-loud in VLASS, while the latter sample contains the galaxies with transient radio emission selected from the CNSS data. The constant or small flux variations at 3 GHz in our sample over timescales of 30–35 months are consistent with those presented in Nyland et al. (2020) and Wołowska et al. (2021), as shown in Figure B1. It should be noted that the two works either did not use the VLASS data or used only epoch I data. Our uniform analysis of the data from the VLASS epoch I and II observations makes the above comparison fair.

Figure B1. Left: the variability amplitude of the radio flux between the VLASS epoch I and epoch II observations for our sample (upper panel) and the sample presented by Nyland et al. (2020; lower panel). Right: the same as the left, but comparing with the sample presented by Wołowska et al. (2021).
Appendix C

RACS Images at 888 MHz

Figure C1 shows the radio images at 888 MHz for 15 of the 18 sources observed in RACS (McConnell et al. 2020). The remaining three sources (J0950, J1409, and J1646) are not covered by the RACS survey, due to their too-high decl. (DEC>+40).

Figure C1. The radio images at 888 MHz for 15 sources observed in RACS. The red circle in each panel has a radius of 25″. The image has a size of 4′ × 4′.
Appendix D
Optical Spectral Fittings and SED Fittings to SDSS and WISE Photometry

Three objects in our sample, including J0040+0823, J1337+3857, and J2301+0544, are not listed in either the MPA-JHU catalog or the combined SDSS and WISE photometric catalog (Chang et al. 2015), because their SDSS spectra were observed later than 2010. Thus, we measured the properties of their host galaxies by modeling their SDSS spectra and SEDs, as shown in Figure D1. We modeled the SDSS spectra following Dong et al. (2012). In brief, we modeled the continuum by fitting the spectra in regions unaffected by emission lines with a linear combination of simple stellar population templates from Bruzual & Charlot (2003). The templates were broadened with a Gaussian function, for which the \( \sigma \) value was used as the measurement of the stellar velocity dispersion. The results are shown in the left column of Figure D1. After subtracting the continuum model, we then fitted the H\( \beta \), [O\( \text{III} \)] \( \lambda \lambda 4959, 5007 \), H\( \alpha \), and [N\( \text{II} \)] \( \lambda \lambda 6548, 6583 \) emission lines with the following assumptions: (1) all the emission lines can be represented with single Gaussians, with redshifts and width (in velocity) tied together; and (2) the flux ratios of the O\( \text{III} \) and N\( \text{II} \) doublets are fixed at 3. The results are shown in the middle two columns of Figure D1. To obtain the stellar mass, we constructed the SEDs of the galaxies using photometric data from the SDSS and WISE surveys, and fitted the SEDs using the CIGALE code (Boquien et al. 2019). In the fittings, we also assumed that the star formation history was an exponential function, and the Salpeter initial mass function was adopted. The results are shown in the right column of Figure D1.

Figure D1. Illustration of the continuum and emission-line fittings of the SDSS spectrum (left panel). In the middle two panels, we show a zoomed-in view of the emission-line profile fittings for the H\( \beta + \)O\( \text{III} \) region and the H\( \alpha + \)N\( \text{II} \) region, respectively. The SED fitting results from CIGALE are shown in the right panel.
