Probing the Wind Component of Radio Emission in Luminous High-redshift Quasars

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Abstract

We discuss a probe of the contribution of wind-related shocks to the radio emission in otherwise radio-quiet quasars. Given (1) the nonlinear correlation between UV and X-ray luminosity in quasars, (2) that such a correlation leads to higher likelihood of radiation-line-driven winds in more luminous quasars, and (3) that luminous quasars are more abundant at high redshift, deep radio observations of high-redshift quasars are needed to probe potential contributions from accretion disk winds. We target a sample of 50 $z \approx 1.65$ color-selected quasars that span the range of expected accretion disk wind properties as traced by broad C IV emission. 3 GHz observations with the Very Large Array to an rms of $\approx 10$ μJy beam$^{-1}$ probe to star formation rates of $\sim 400 M_\odot$ yr$^{-1}$, leading to 22 detections. Supplementing these pointed observations are survey data of 388 sources from the LOFAR Two-meter Sky Survey Data Release 1 that reach comparable depth (for a typical radio spectral index), where 123 sources are detected. These combined observations reveal a radio detection fraction that is a nonlinear function of C IV emission-line properties and suggest that the data may require multiple origins of radio emission in radio-quiet quasars. We find evidence for radio emission from weak jets or coronae in radio-quiet quasars with low Eddington ratios, with either (or both) star formation and accretion disk winds playing an important role in optically luminous quasars and correlated with increasing Eddington ratio. Additional pointed radio observations are needed to fully establish the nature of radio emission in radio-quiet quasars.

Unified Astronomy Thesaurus concepts: Radio quiet quasars (1354); Galaxy accretion disks (562); Radio loud quasars (1349); Galactic winds (572); Radio continuum emission (1340); Optical observation (1169); Emission line galaxies (459)

Supporting material: machine-readable table

1. Introduction

Despite the fact that the first quasars to be discovered were strong radio sources (Schmidt 1963; Condon et al. 2013), the origin of radio emission from quasars (particularly radio-quiet (RQ) quasars) remains an unsolved question. Part of the problem is that there are likely multiple origins of radio emission, including jets, star formation (SF), accretion disk coronae, and shocks from winds (e.g., Simpson 2017; Kimball 2018; Panessa et al. 2019), yet investigations tend to make the implicit assumption that strong radio emission is due to jets, while weaker radio emission is dominated by SF. Another part of the problem is that the fraction of luminous quasars detected in the radio is quite small. Kellermann et al. (1989) examined 114 quasars from the Palomar Bright Quasar Survey (Schmidt & Green 1983)—the so-called Palomar–Green (PG) quasar sample—finding a radio-loud (RL) fraction of just 15%–20%. However, it is perhaps underappreciated that the ratio of RL to RQ quasars changes as a function of both redshift and luminosity (Jiang et al. 2007; Kratzer & Richards 2015). At low luminosity, Ho & Ulvestad (2001) and Ho & Peng (2001) argue that the majority of Seyfert (Seyfert 1943) galaxies are RL sources. At higher luminosity, the fraction of quasars from the Sloan Digital Sky Survey (SDSS; York 2000) that are even detected (let alone formally RL) at the $\sim 1$ mJy beam$^{-1}$ depth of the Faint Images of the Radio Sky (FIRST; Becker et al. 1995) survey is only 4% (Schneider et al. 2010). The fraction of those that are extended radio sources is only $\sim 10\%$ (i.e., $\sim 0.4\%$ of SDSS quasars; Ivezić et al. 2002).

For the luminous quasars that show radio lobes, it is clear that the dominant source of the radio emission is synchrotron emission from jets (Urry & Padovani 1995); thus, it is necessary to break quasars into dichotomous RL and RQ classes (or jetted and nonjetted; Padovani 2017). However, it is equally important to understand that RQ quasars are not a monolithic class of objects in terms of either optical/UV spectra (Richards et al. 2011) or radio emission (Panessa et al. 2019) and should, at a minimum, be divided into hard-spectrum and soft-spectrum RQ quasars (Kratzer & Richards 2015). When probing to fainter radio flux densities, the (generally unresolved) radio emission is expected to be dominated by SF processes that are largely unrelated to the central engine, either in the form of radio from free–free emission in H II regions produced by SF or from synchrotron emission produced by relativistic electrons accelerated by supernovae (Kimball et al. 2011b; Condon et al. 2013). Both active galactic nucleus (AGN) and SF sources of radio emission might be expected to depend on environment (e.g., Hickox et al. 2009; Retana-Montenegro & Röttinger 2017). Beyond SF, it is also important to determine whether some quasars really are radio silent, as well as whether there is evidence for weak “frustrated jets” (e.g., Barvainis et al. 1996; Blundell & Beasley 1998; Herrera Ruiz et al. 2016), coronal emission (Laor & Behar 2008; Raginski & Laor 2016; Laor et al. 2019), or shocks from winds interacting with gas in the host galaxy (e.g., Jiang et al. 2010; Zakamska & Greene 2014; Laor et al. 2019).
Thus, when investigating the radio demographics of AGNs, it is crucial to make clear what part of the AGN landscape is being probed (e.g., host-dominated AGNs vs. luminous quasars). Moreover, it must be established if the samples being investigated are capable of probing all radio origins. For example, given that optical luminosity is seen to correlate with the presence of accretion disk winds (via the well-known optical-to-X-ray correlation; Proga et al. 2000), low-redshift samples such as those investigated by Kimball et al. (2011b) are not as capable of testing for wind-based radio emission. Our approach is designed to particularly address radiation-line-driven winds capable of testing for wind-based radio emission. The empirical observation of an anticorrelation between the optical/UV and X-ray (e.g., Steffen et al. 2006) means that our investigation requires high-luminosity sources (in the optical/UV). The small volume available at low redshift translates into the need for high-redshift ($z \gtrsim 1$) sources. Over roughly $1.65 < z < 2.2$ the C IV emission line serves as a diagnostic indicating the presence of accretion disk winds (Richards et al. 2011).

At the inception of this investigation, there was a dearth of deep radio observations (e.g., as compared to those from the Faint Images of the Radio Sky (FIRST) survey; Becker et al. 1995), covering large enough area to include large numbers of high-redshift quasars. Thus, we proposed and were awarded pointed observations with the Karl G. Jansky Very Large Array (VLA; Perley et al. 2011); see Sections 3.1–3.4. Since that time, data from the LOw-Frequency ARray (LOFAR; van Haarlem et al. 2013) have become public and will be included as well (Section 3.5). A complementary investigation based entirely on the first data release of the LOFAR Two-meter Sky Survey (LoTSS; Shimwell et al. 2019) is presented by Rankine et al. (2021).

The targets were defined starting with the SDSS-DR7 quasar sample (Schneider et al. 2000). We imposed a limit on spectral signal-to-noise ratio ($S/N$) of $\gtrsim 10$ pixel$^{-1}$ over a window of 1600–3000 Å in the rest frame, giving a sample of 8653 quasars. To avoid biases inherent to the fact that some SDSS quasars were selected explicitly because of their radio emission (Richards et al. 2002), we included only 8403 SDSS quasars that were targeted by optical/UV quasar properties, RQ quasars vastly outnumber RL quasars; however, the differences between the optical spectral properties of RL and RQ quasars are subtle at best (Kimball et al. 2011a; Schulze et al. 2017), spanning nowhere near the full range of spectral properties that characterize quasar spectra (Boroson 2002; Richards et al. 2011). The primary goal of this investigation is to test for different possible origins of radio emission specifically in luminous, high-redshift RQ quasars—from jets to shocks to coronae to SF—using deep radio observations to levels of radio emission expected to be dominated by SF (at the redshift of the quasars). We focus on exploring the changes in radio luminosity and radio detection fraction as a function of C IV-based wind diagnostics in order to include shocks from winds as a potential source of radio emission (e.g., Jiang et al. 2010; Laor et al. 2019), specifically in RQ quasars.

This paper is organized as follows. In Section 2 we describe the targets, with Section 3 presenting the details of the radio observations. Section 4 outlines the empirical framework for the prediction of trends presented in Section 5. Section 6 discusses the relationships between the observed radio emission, emission-line properties, and SF. Finally, in Sections 7 and 8 we discuss these results in the context of different proposed origins of radio emission and present our conclusions and suggestions for future work. The cosmology assumed throughout the paper is $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$. The convention adopted for radio spectral index, $\alpha$, is $f_\nu \propto \nu^{-\alpha}$, and the ratio of radio to optical emission, $R$, was calculated as the ratio between the rest-frame 3 GHz and 2500 Å flux density.

2. Targets

We need a representative sample that is capable of probing multiple origins of radio emission in RQ quasars, specifically that can address the question of whether shocks from accretion disk winds can be contributors to radio emission in luminous quasars. Theoretical understanding of radiation-line-driven accretion disk winds (Murray et al. 1995; Proga et al. 2000) requires an abundance of UV photons (responsible for driving the wind) and a dearth of X-ray photons (that limit line driving) for strong radiation line driving. The empirical observation of an anticorrelation between the optical/UV and X-ray (e.g., Steffen et al. 2006) means that our investigation requires high-luminosity sources (in the optical/UV). We prefer to concentrate on the SDSS-DR7 sample, rather than the SDSS-DR16 (Lyke et al. 2020) sample that is currently available, as DR16 is based on less homogenous selection criteria. In practice, another important consideration is whether the quasars are part of the “uniform” selection criterion (which implies $i_{AB} < 19.1$); see Richards et al. (2002) and Richards et al. (2006). While we have chosen not to include that constraint in our investigation, it could be important for future work that attempts to explore radio emission from winds over a larger range in optical luminosity (where sources may be fainter than the magnitude limit of the “uniform” sample). The spectral reconstruction approach we have taken here (see Section 4) means that we have also not excluded quasars where broad absorption features (Weymann et al. 1991) corrupt the profile of the emission line when using more common analysis techniques.

3. Radio Data

3.1. VLA Experimental Design

For the sake of identifying a suitably sized pilot sample for deep observations with the VLA, we further limited the VLA targets to $1.645 \lesssim z \lesssim 1.6519$, which is the smallest range of
redshift at the lower end of the distribution that yielded the desired pilot sample of 50 quasars. The small redshift window has the added benefit of minimizing any redshift evolution in the sample. These targets span a range of bolometric luminosities\(^5\) of \(\log L_{\text{bol}}/[\text{erg s}^{-1}] = 46.13–46.81\), which is consistent with the requirement of probing sources capable of supporting radiation-line-driven winds (Veilleux et al. 2013; Zakamska & Greene 2014). Four of the 50 targets are known BAL quasars (as identified by Shen et al. 2011). The full VLA sample is presented in Table 1.

Two of the 50 potential VLA targets were bright enough \((f_i > 1 \text{ mJy beam}^{-1})\) to be detected in the FIRST survey (Helfand et al. 2015), while the other 48 required new, deeper radio observations, using the VLA. We observed these targets in the VLA C configuration and in the S band \((\sim 2–4 \text{ GHz})\) in order to optimize the angular resolution of our images, as well as to leverage archival data from past and ongoing/future radio sky surveys (e.g., FIRST and the VLA Sky Survey (VLASS); Lacy et al. 2020). Since our investigation entails testing the possible origins of radio emission, it was necessary to observe down to limits consistent with processes driving the radio emission in RQ quasars. Magliocchetti et al. (2016) evaluate the typical break luminosity between star-forming galaxies and AGNs in the 1.4 GHz radio luminosity function (RLF) for \(z > 1\) to be \(\log(L_{1.4\text{GHz}}[\text{W Hz}^{-1}\text{sr}^{-1}]) \approx 21.7 + z\). For the mean redshift of our sample, \(z \approx 1.65\) (and changing to units of \(W\) \(\text{Hz}^{-1}\)), that corresponds to \(\log(L_{1.4\text{GHz}}[\text{W Hz}^{-1}]) = 24.45\), which is roughly consistent with other estimates of the break luminosity at this redshift (Jarvis & Rawlings 2004; Simpson 2017). Using a typical radio spectral index for a star-forming galaxy \((\alpha = -0.7;\ Condon 1992)\) and aiming to probe at least a factor of five deeper than the observed break in the RLF with a \(3\sigma\) detection, the desired sensitivity limit was approximately \(7.5 \mu\text{Jy}\).\(^6\) With 25% loss of bandwidth due to radio frequency interference (RFI) in the S band, 28 minutes of on-source observing time per target were required to meet the depth criterion. Such a depth provided a good balance between the total observing time for a large sample and the ability to attribute nondetections to processes different from those that drive radio emission in RL quasars.

Similar-depth “pencil-beam” surveys are insufficient to conduct this investigation. For example, of the 449 sources detected to 7.5 \(\mu\text{Jy}\) at 1.4 GHz by Seymour et al. (2004), only 1 has a known redshift in the range of \(1.5 < z < 1.8\). Similarly, of the more than 10,000 sources detected in 2.6 deg\(^2\) of the COSMOS field at 3 GHz, only 2 have \(1.6 < z < 1.7\) (Smolčić et al. 2017). Thus, pointed observations such as those presented here have an effective area more than an order of magnitude larger than even moderately wide surveys to deep radio limits.

3.2. VLA Data Reduction

We processed the VLA data using the Common Astronomy Software Application (CASA, version 5.4.2; McMullin et al. 2007). Raw data from the VLA were first calibrated by the standard VLA calibration pipeline, and the calibration data were later fine-tuned by us. We first reviewed the calibrations of our data from the initial pipeline run to check whether any further flagging of our data must be done manually (e.g., for RFI excision or poorly behaved antennas). If significant flagging of one or more of the calibrators was necessary (as opposed to just flagging the target), we reran the pipeline on the flagged data set. Once we performed/reviewed preliminary calibrations on our target, we were able to begin the imaging process with the object’s fully calibrated measurement set.

To create all images, we utilized the tclean task in CASA with natural weighting (which is the weighting scheme that provides the best sensitivity to point sources). For images that contain other very bright contaminating sources within the field of view, or exhibit clear tropospheric phase errors, we applied up to three rounds of phase-only self-calibration.

While we designed our observations to reach a target sensitivity of \(7.5 \mu\text{Jy}\), the actual noise level of an interferometric image depends on weather during the observation, the amount of flagged data, the quality of calibration, and the proximity of bright sources within the field of view. For 21 of our targets (13/21 are nondetections), we successfully reached noise levels of \(\approx 7.5–10 \mu\text{Jy}\); a further 16 targets yielded sensitivity levels of \(< 15 \mu\text{Jy}\) (with 10/16 undetected). Of the 11 remaining VLA targets, 10 were constrained to noise levels \(< 20\mu\text{Jy}\), owing mostly to augmented interference in regions coinciding with the Clarke belt. Four of these 10 are nondetections; for these nondetections a \(20 \mu\text{Jy}\) rms gives a \(3\sigma_{\text{rms}}\) upper limit of \(\log(L_{1.4\text{GHz}}[\text{W Hz}^{-1}]) = 23.91\). Finally, the image of SDSS 1058+0152 is severely dynamic range limited, owing to a powerful 120 mJy source at 105829.56+013401.02 (offset \(\sim 18\prime\) from the central target), and making it difficult to obtain useful radio data for this target. We nevertheless retain its \(\approx 220 \mu\text{Jy}\) rms, which corresponds to a \(3\sigma_{\text{rms}}\) upper limit on its radio luminosity at \(\log(L_{1.4\text{GHz}}[\text{W Hz}^{-1}]) < 24.94\).

3.3. VLA Detections and Limits

Of our 50 targets, 22 are detected at peak flux densities \(f_i > 50 \mu\text{Jy beam}^{-1}\), while \(3\sigma_{\text{rms}}\) upper limits are obtained for the peak flux densities of the 28 nondetections. All radio data taken from our sample are reported in Table 1. Images of the 22 detections (including two from FIRST) are shown in Figure 1, while a histogram of total radio flux density is shown in the left panel of Figure 2. Measured 3 GHz radio luminosities are converted to 1.4 GHz assuming \(\alpha = -0.7\) and also to \(\log R\) in the middle panel assuming the median optical luminosity of the sample \(\log L_{2500\lambda}[\text{W Hz}^{-1}] = 23.81\).

Overall, 12 objects (24%) are detected at high significance \((S/N > 6)\), while the other 10 detections (20%) are more marginal at \(S/N = 3–6\). SDSS 2353–0859 (a FIRST source) is the only object to exhibit clear signs of extended morphology (what appears to be a core with two lobes, one brighter than the core, one fainter), with just one other object that may have weak extended emission (SDSS 0013–0024). It is possible that some sources with wide separation lobes, which are not easily associated with the core, exist. However, most of the potential candidate lobes either have optical counterparts or would be at separations of >500 kpc.

We also performed a median stacking analysis on the 28 undetected sources, finding a median peak flux density of \(22 \mu\text{Jy beam}^{-1}\) with rms noise in the stacked image of 2.9 \(\mu\text{Jy beam}^{-1}\). Thus, while the majority of our sources are formally undetected, we would have expected them to be detected at \(3\sigma\) on average had we been able to achieve our goal of \(7.5 \mu\text{Jy}\) rms uniformly across the full sample.

\(^5\) Using Equation (9) from Krawczyk et al. (2013).

\(^6\) In practice, 15 of the 28 nondetections had rms sensitivity >10 \(\mu\text{Jy}\), owing to issues such as crowded fields and the Clarke belt.
Our sample of 50 targets was drawn from a parent sample of 8403 known, color-selected, high-S/N SDSS quasars as discussed in Section 2. For the sake of comparison, we performed forced photometry for the parent sample using the radio images from the NRAO-VLA Sky Survey (NVSS; Condon et al. 1998), measuring the image peak flux density at the known position of each object. A Gaussian fit to the distribution, sigma-clipping the tail of bright sources, yields a median of 0.09 mJy beam$^{-1}$ with a standard deviation of $\sigma = 0.49$ mJy beam$^{-1}$. The error on the median peak is just $\sigma/\sqrt{N} = 0.005$ mJy beam$^{-1}$, which strongly indicates that

(https://www.cv.nrao.edu/nvss/NVSSPoint.shtml)
3.5. LOFAR Data

While focused on a very different part of the radio spectrum (144 MHz) than our VLA S-band observations, the median depth (71 µJy beam⁻¹ median) of the LoTSS data is similarly sensitive to quasars with radio spectral indices of ≈−0.7. Thus, LoTSS provides an additional source of data for our experiment. We specifically make use of the data from the first data release (DR1; Shimwell et al. 2019), covering over 400 deg², with optical identifications and morphological classifications provided by Williams et al. (2019).

Rankine et al. (2021) demonstrate that RL LOFAR detections (using a definition of RL that is adjusted for the differences in frequency coverage between VLA and LOFAR) are likely drawn from the same parent population as RL sources identified by FIRST. Thus, it is possible to combine the 3 GHz and 144 MHz data, despite the order-of-magnitude difference in frequency. Of the 8403 color-selected sources in our parent sample, there are 388 sources for which LoTSS DR1 should reach comparable depth (for a typical radio spectral index). Of those 388, 123 sources are detected. These detections are shown in the right panel of Figure 2. Sources with existing FIRST detections are shown in orange as for the VLA data.

While the LoTSS DR1 sample covers only a small area of sky, the detection fractions both for our VLA observations and in the LoTSS area make it clear that, for the immediate future (until the Square Kilometer Array precursors⁸ begin data releases), pointed observations will continue to be needed for investigations into the origin of radio emission in RQ quasars. Neither VLASS nor LoTSS reaches depths that enable detections of the majority of z ≈ 1.5–2 sources that can best probe a wind origin for radio emission and do so for large areas of sky.

4. Defining the C IV Parameter Space

What we seek to learn herein is to what extent the radio properties of quasars are uniform across a parameter space sensitive to the presence of accretion disk winds, or if the radio properties are systematically changing across that space. Ideally the parameter space would be defined by physical properties such as black hole mass, accretion rate, spin, and orientation. However, each of those properties is difficult to determine robustly for individual objects. Thus, we adopt the approach of Rivera et al. (2020) and Rankine et al. (2021) and explore the radio properties in an empirical parameter space characterized by the C IV λ1550 emission line.

At low redshift, the principle component analysis (PCA) of Boroson & Green (1992)—primarily involving the H/β, [O iii], and Fe II emission lines—concisely describes the diversity of the quasar population in a 2D space, and this type of analysis has been extended by many authors (e.g., Brotherton & Francis 1999; Marziani et al. 2018). At high redshift, the C IV emission line by itself defines a 2D space—EW and blueshift (a measure of line asymmetry)—that can be used to empirically distinguish quasars with very different physical properties, even without measuring those properties directly (Richards et al. 2011; Rivera et al. 2020). Thus, we ask how the radio properties are changing across as a function of C IV EW and blueshift, guided by expectations as to how the extrema in this parameter space translate to extrema in physical properties, a key assumption being that the anticorrelated behavior of the C IV EW and blueshift (Figure 3) is indicative of the strength of an accretion disk wind.

Core to our analysis is spectral reconstruction based on independent component analysis (ICA) as discussed in more detail by Allen et al. (2011), Rankine et al. (2020), and Rivera et al. (2020). ICA serves as a tool to provide a nearly noise-free reconstruction of the spectral features, enabling the most robust measurements of the C IV line parameters. We use the ICA components adopted in the analysis of Rankine et al. (2020)

⑧ https://www.skatelescope.org/precursors-pathfinders-design-studies/
and compare our results to a similar analysis of a sample of 133 diverse quasars from the SDSS “Reverberation Mapping” program (SDSS-RM; Shen et al. 2015), as investigated by Rivera et al. (2020).

Just as a spectrum can be reconstructed using PCA eigenvectors that are common to a sample with eigenvalues specific to each object (Francis et al. 1992; Yip et al. 2004), so too can a spectrum be reconstructed using ICA “components” and the component “weights” that are specific to that object. The ICA components derived by Rankine et al. (2020), analyzed in the same manner as Rivera et al. (2020), are employed, and the Appendix presents the spectral reconstructions for all 50 quasars in the VLA sample. We use these reconstructions to extract the EW and blueshift from the spectra (both the VLA and LoTSS quasars) in a manner that results in higher S/N than measurements made directly from the SDSS spectra themselves (as a result of the reconstructions incorporating information from the entire optical/UV spectrum, rather than just the C IV emission line itself).

Figure 3 shows the distribution of C IV EW and blueshift for three sources of data: our color-selected VLA targets (large blue/red points), color-selected LoTSS quasars (blue/red contours and small points), and the SDSS-RM sample from Rivera et al. (2020), as represented by the light-blue track. Throughout we will refer to the “C IV distance,” which we define using the best-fit curve from the SDSS-RM sample as a “control,” projecting each point in the VLA and LoTSS samples to the nearest orthogonal location on the curve. Quasars that project onto the start of the curve in the upper left corner are defined to have zero C IV distance, with increasing values of C IV distance toward the lower right. Thus, high-blueshift quasars have large C IV distance, with increasing blueshift being correlated with Eddington ratio (Rankine et al. 2020, Figure 14).

The top and side panels show the marginal distributions, while the bottom panel combines the EW and blueshift information to reveal that the radio detection fraction is a nonlinear function of C IV distance.

It is instructive to look at the data more closely to see whether the two subsamples find the same nonlinear trend. The overall radio detection fraction for our two color-selected samples is 33.1% ± 2.8%, and for VLA and LoTSS objects separately the fractions are 44.0% ± 9.4% and 31.7% ± 2.9%, respectively. At low blueshift and high EW (C IV distance less than 0.50) we find that the detection fraction is instead 44.4% ± 8.4% and is higher for both the VLA and LoTSS quasars separately (50% ± 22% and 43% ± 9%, respectively).

While those detection fractions are less than 2σ above the average, moving to moderate blueshift and EW (moderate C IV distance), we find a significantly lower radio detection fraction. Overall it drops to 25.9% ± 3.0% and is lower for both the VLA and LoTSS quasars (36% ± 11% and 25% ± 3%, respectively).

Then, moving to high blueshift and low EW (C IV distance larger than 0.75), the radio detection fraction again increases. The overall fraction is 51.3% ± 8.1% and is higher for both the VLA and LoTSS quasars (71% ± 32% and 49% ± 8%, respectively). These results are summarized in Table 2.

As the goal of this work is to probe the origin of radio emission in RQ quasars, it is important to also consider these fractions after excluding FIRST sources, which are likely to be dominated by jet emission at the redshifts probed herein. Doing so leaves the overall trend in radio detection fraction unchanged: 37.5% ± 8.2% at small C IV distance, 23.4% ± 2.9% at moderate C IV distance, and 47.1% ± 8.3% at large C IV distance. Again the trend is consistent for both the VLA and LoTSS data.

An obvious concern is that dust reddening could be playing a role in the radio detection fraction given known trends between...
radio emission and both intrinsic quasar colors in the optical and the presence of dust reddening (Richards et al. 2003; White et al. 2007; Kratzer & Richards 2015; Klindt et al. 2019; Fawcett et al. 2020; Rosario et al. 2020). The color-selected nature of our samples should mitigate against a bias toward more easily finding RL quasars in dust-reddened sources explicitly due to being targeted as radio sources. However, we find that the trends with C IV distance remain even if we exclude the most likely dust-reddened sources ($\Delta(g - i) > 0.3$; Richards et al. 2003): 40.1% ± 8.3% at small C IV distance, 24.5% ± 3.0% at moderate C IV distance, and 51.4% ± 8.3% at large C IV distance.

Rankine et al. (2021, Figure 3) see a similar distribution in radio detection fraction with blueshift for LoTSS quasars that are not restricted to being color selected—but without a well-defined rise at low values. This difference (fall then rise of the C IV detection fraction with C IV distance in our work vs. a consistent rise with C IV blueshift in Rankine et al. 2021) may point to the C IV distance being a better metric. For example, in addition to being correlated with blueshift at high blueshift, $L/L_{\text{Edd}}$ is also seen to be anticorrelated with C IV EW (Baskin & Laor 2004; Shemmer & Lieber 2015). Indeed, there is other evidence for the type of nonlinearity that the C IV distance captures. For example, Rankine et al. (2020) find a gradient of He II EW along what we define as the C IV distance, which distinguishes moderate- and high-EW sources at similar blueshift. We further note that White et al. (2007, Figure 13) found a similar nonlinear distribution in radio-loudness as a function of optical color. These trends will be discussed in more detail in Section 7.1.

5. Possible Origins of Radio Emission

An experiment that fully explores the diversity of quasars and thus the occurrence of the four potential sources of radio emission from quasars (e.g., Panessa et al. 2019) might be expected to reveal one (or more) of the following trends with respect to C IV distance.

If the radio emission in RQ quasars is dominated by winds, then we might expect the radio detection fraction to increase with C IV distance—due to objects with stronger winds (as indicated by larger C IV blueshifts) being more likely to have shock-related radio emission (e.g., Laor et al. 2019). The correlation need not be one-to-one, as said radio emission would require the presence of dense material for the wind to run into; therefore, not all sources with winds would be expected to exhibit radio emission.

If RQ quasars are instead dominated in the radio by coronal emission, the radio detection fraction would decrease (Raginski & Laor 2016; Giustini & Proga 2019; Laor et al. 2019) with C IV distance. X-rays provide the indicator of the expected direction of the trend assuming that changes in the X-ray are correlated with the overall size of the corona and that the coronal X-ray emission and radio emission are correlated. X-ray emission gets weaker with increasing $L/L_{\text{Edd}}$ both as found empirically (Sulentic et al. 2007; Kruczek et al. 2011; Timlin et al. 2020) and as predicted by accretion disk wind models (Giustini & Proga 2019). Thus, we expect radio emission of coronal origin to result in less radio emission with increasing C IV distance.

### Table 2

| C IV Distance | VLA | LoTSS | Combined |
|---------------|-----|-------|----------|
| Low           | 50% ± 22% | 43% ± 9% | 44.4% ± 8.4% |
| Moderate      | 36% ± 11% | 25% ± 3% | 25.9% ± 3.0% |
| High          | 71% ± 32% | 49% ± 8% | 51.3% ± 8.1% |

**Note.** Radio detection fractions for VLA (50 quasars) and LoTSS (388) samples. “Low” and “High” regions of C IV distance are illustrated by the dashed lines in Figure 3, marking points with C IV distance <0.50 and >0.75, respectively.

**Figure 3.** Top: distribution of sources in C IV parameter space. Larger points represent the 50 targets observed with the VLA, while smaller points and contours plot the 388 LoTSS objects as discussed in Section 3.5. The location of each point’s orthogonal projection onto the best-fit line (light blue; see Rivera et al. 2020) defines a “C IV distance” metric that we use in comparing each object’s location in C IV space (see text in Section 4). Dashed lines (perpendicular to the curve in a scaled data space) show an illustrative division into low, moderate, and high C IV distance regimes. Bottom: radio detection fraction as a function of C IV distance. Fractions are computed in seven bins with equal numbers of quasars, including both the VLA and LoTSS objects; 1σ Poisson errors are shown by the shaded region.
In terms of an SF origin, a naive prediction might be that there would be no trend in C IV distance. At the redshifts investigated herein the parent sample of SDSS quasars are all brighter than the “characteristic” luminosity, $L_\text{ch}$, that defines the break in the quasar luminosity function (Richards et al. 2006; Shen et al. 2020). That being the case, we might expect the SDSS-DR7 sample to lack the diversity of the full AGN population (i.e., objects both brighter and fainter than $L_\text{ch}$)—in terms of properties such as host galaxy morphology and environment—which is potentially related to star formation rate (SFR) and SFR-related radio emission (see Section 6). Moreover, all of our targets herein are drawn from a very narrow range of both redshift and optical luminosity. If, however, SF is influenced by “feedback” processes (e.g., Silk & Rees 1998), including accretion disk winds, then a trend with C IV distance might be expected—given the known correlation between accretion disk winds and C IV distance (Richards et al. 2011; Wang et al. 2011). Specifically, if winds generate positive feedback—in the sense of increasing SF—then a higher radio detection fraction would be expected with increasing C IV distance. For negative feedback, the opposite would be expected.

Of course, there is no a priori reason why SF and accretion processes would have to be contemporaneous, and we are implicitly assuming that the gas content and SF efficiencies of quasar hosts remained unchanged with C IV distance.

As for a possible jet origin, we do not make a prediction so much as point out that strong radio sources are anticorrelated with C IV distance,

\[ \approx 20 \times \] deeper than FIRST, we might not expect more than a single source with jetted emission: FIRST’s depth was chosen in order to probe the break in the RLF, below which SF starts to dominate over the jetted population. Therefore, we do not expect to find significant jet emission among sources that were not already detected by FIRST. However, we acknowledge that our observations (indeed most radio observations) lack the resolution to identify small-scale jets. In Section 7 we discuss some insights on whether the presence of such small-scale jets may increase or decrease with C IV distance.

In short, our experiment is about looking for trends in radio emission with C IV distance. Our VLA pilot study, even when combined with LoTSS DR1, is, no doubt, too small to definitively answer the question of the origin of radio emission in RQ quasars. However, in the absence of information about small-scale jets, an increase of the radio detection fraction with C IV distance might suggest that radio emission is produced by either winds or SF with positive feedback, while a decrease of the radio detection fraction with C IV distance would point to either a coronal origin or SF origin (with the AGN contributing negative feedback).

6. Star Formation Rates

As the predictions in Section 5 involve expectations not just for radio emission but also for SFRs, we turn to a discussion of how radio and SFRs are expected and observed to be related in these data. We estimate the level of detectable SF using the far-infrared (FIR) radio correlation (Helou et al. 1985; Yun et al. 2001; Calistro Rivera et al. 2017), which ties together SFRs, FIR emission, and radio emission. For our VLA observations, we find that a $3\sigma$ detection in an image with an rms of 10 $\mu$Jy should probe to SFRs of $\approx 400 M_\odot$ yr$^{-1}$. In estimating the SFR probed (blue points in Figure 4), we are naively applying the Yun et al. (2001) relationship to objects at a very different redshift from that where the correlation was derived. Furthermore, according to Yun et al. (2001), the relationship between SFR and 1.4 GHz radio applies for objects fainter than $\log(L_{\text{radio}})$, $[\text{W} \text{Hz}^{-1}]$, $\approx 24$. More accurately, the relation applies to objects below the break of the luminosity function (above which the AGN is thought to be contributing as much or more than SF to the radio emission). A break luminosity at $z \approx 1.65$ of $\log(L_{\text{radio}})$, $[\text{W} \text{Hz}^{-1}]$ $\approx 24.45$ translates to an SFR of $\approx 1650 M_\odot$ yr$^{-1}$. Thus, radio luminosities (or SFRs) in our sample that are higher should be taken as a strong sign that something other than SF is contributing to the radio emission, and we indicate this in Figure 2 as where AGN-related processes might be expected to dominate SF.\(^{10}\)

We can also make specific predictions for radio emission from SF by taking advantage of FIR observations, with the assumption that continuum emission at FIR wavelengths is dominated by SF rather than the AGN. Specifically, Harris et al. (2016) performed stacking analysis on a sample of 1000 SDSS quasars at $2 < z < 3$ that are largely undetected by Herschel. These data were used to determine the SFR as a function of various properties, under the assumption that the FIR emission ($\lambda_{\text{rest}} > 80$ $\mu$m) is dominated by SF and not the AGN itself; see also Rosario et al. (2013). Harris et al. (2016) present results as a function of the C IV EW and optical luminosity, which makes their investigation an excellent source

\(^{10}\) Note that an SFR in excess of $\approx 1650 M_\odot$ yr$^{-1}$ is high, but Rowan-Robinson et al. (2018) have argued for the existence of “extreme” starbursts with SFRs in excess of $5000 M_\odot$ yr$^{-1}$.
of comparison for our own work. They also investigated the SFR as a function of C IV FWHM and the C IV line asymmetry; we have not made use of either of these two results, as it is not clear that the FWHM of C IV has a clear relationship with black hole mass (Coatman et al. 2017) and the asymmetry parameter is different from the blueshifts investigated herein. However, Maddox et al. (2017) perform a similar analysis to that of Harris et al. (2016), measuring the C IV blueshifts (using the same definition adopted herein) of a sample of 1185 quasars at $1.6 < z < 4.8$ with $2\sigma$ detections at $\lambda_{\text{obs}} > 250$ $\mu$m (and a matched sample of undetected sources). Therefore, we can compare our work to independent indicators of SFR as a function of both EW (Harris et al. 2016) and blueshift (Maddox et al. 2017), i.e., as a function of C IV distance.

Over a range of more than three orders of magnitude in optical luminosity, Harris et al. (2016) find an increase in SFR from $\approx 100$ to $\approx 450 M_\odot$ yr$^{-1}$ with increasing optical luminosity; see also Stanley et al. (2017). For the narrow luminosity range of our sample, the expected systematic increase in SFR is from $\approx 490$ to $\approx 620 M_\odot$ yr$^{-1}$. The SFRs determined by Harris et al. (2016) from binning by C IV EW span a larger SFR range ($\approx 50$ to $\approx 500 M_\odot$ yr$^{-1}$) with decreasing EW (from $\approx 135$ to $\approx 25$ A). Our sample spans a larger range of EWs than the Harris et al. (2016) sample; the predicted SFRs range from $\approx 190 M_\odot$ yr$^{-1}$ for the largest EW sources ($\approx 65$ A) to one object with very low EW (SDSS J1200 +0005) having a predicted value of SFR $\approx 1690 M_\odot$ yr$^{-1}$. While Maddox et al. (2017) do not perform the same sort of stacking analysis, their comparison of FIR detections to nondetections indicates that quasars with larger C IV blueshifts are systematically brighter in the FIR. Thus, objects with large C IV distance might be expected to have higher SFRs.

Figure 4 shows the expected SFR based on the correlation between SFR and both EW (orange) and optical luminosity (green) found by Harris et al. (2016)—against the observed radio luminosity. With the caveat that these calculations intrinsically assume that all quasars are similar to the mean quasar, comparing the green and orange points (with SFRs predicted from nonradio data) to the blue points (with SFRs predicted from the radio luminosity using Yun et al. 2001) reveals that the most luminous radio sources may have contributions to the radio in excess of that expected from SF. However, we can use the results of Rankine et al. (2021) to understand what might be expected from analysis of a distribution of quasars instead of considering mean quasar properties via stacking analysis. Based on detections and nondetections from LoTSS, Rankine et al. (2021) performed a Monte Carlo simulation that suggests that the radio observations are consistent with a population of SFRs from tens to thousands of solar masses per year that could potentially produce radio emission to levels as high as $\log(L_{1.4\text{GHz}}[\text{W Hz}^{-1}]) \approx 26$, which is equivalent to $\log(L_{1.4\text{GHz}}[\text{W Hz}^{-1}]) \approx 25.3$ for $\alpha = -0.7$. It may be that Harris et al. (2016) do not find SFRs in the thousands as a result of the small area of sky sampled by Herschel in their study (i.e., a lack of sensitivity to rare quasars with high SFRs), and thus that their stacking approach causes us to underestimate the range of SFRs using their empirical correlations. Therefore, even given the apparent discrepancy with the Yun et al. (2001) SFR predictions starting at $\log(L_{1.4\text{GHz}}[\text{W Hz}^{-1}]) \approx 24$, it is quite possible that SF accounts for the radio emission up to $\log(L_{1.4\text{GHz}}[\text{W Hz}^{-1}]) \approx 24.5$–25.3.

Figure 5 (left) scales the points in the C IV space of Figure 3 by the expected SFR as predicted by Harris et al. (2016). Here we have averaged the SFRs predicted from both the EW and optical luminosity. It is apparent that the results of Harris et al. (2016) and Maddox et al. (2017) would predict a trend of increasing radio luminosity (from SF) with C IV distance.

Figure 5. Left: C IV plot with points scaled by SFR predicted from the average of the optical luminosity ($M(z = 2)$) and EW relations from Harris et al. (2016). Right: C IV plot with points scaled by the ratio of observed radio luminosity to that predicted by the Harris et al. (2016) and Yun et al. (2001) relationships. Point sizes larger than that of the nondetections indicate more radio emission than predicted from SF; the detected quasars are generally brighter in the radio than expected from SF. The color scheme of both panels follows that of Figure 3. Dashed lines (which are perpendicular to the best-fit curve in scaled space) divide the parameter space into regions of low (upper left), moderate (lower left), and high (lower right) C IV distance (see Section 4).
On the other hand, there is also reason to think that the SFRs estimated by the Harris et al. (2016) analysis are instead overestimates. As noted by Harris et al. (2016), their assumption of an SFR origin for the entirety of the FIR emission ignores the possible kiloparsec-scale dust distribution in AGNs. Nevertheless, they conclude that AGNs are likely to contribute significantly only to the shortest-wavelength Herschel bandpass. A possible reason that this modeling may be incomplete is the assumption of a single spectral energy distribution (SED) to describe all AGNs, whereas it is well known that AGNs can have significantly different SEDs as a function of luminosity, at 10–20 µm (Krawczyk et al. 2013) and even to ~80 µm (Lyu & Rieke 2017; Bernhard et al. 2021).

Wang et al. (2013) and Temple et al. (2021) find a significant correlation between C IV blueshift and hot dust, attributing that correlation to a greater ability to view the hot dust component in quasars with strong winds. If that hot dust component is correlated with a cooler dust component on larger scales, then the assumption inherent to the Harris et al. (2016) argument may not be true. In such a case, it is possible that the FIR emission is a stronger indicator of AGN-related processes than SFR-related processes; see Symeonidis (2017), but also Bernhard et al. (2021) for a counterargument.

While Symeonidis et al. (2016) find no significant difference between low- and high-luminosity AGNs in the FIR, we note that the objects used in that investigation, while luminous for their redshift, are much less luminous than the samples investigated in Harris et al. (2016) and herein. Thus, the Symeonidis et al. (2016) results do not necessarily contradict the finding of higher FIR emission in more luminous quasars.

The predicted trend of SFR with C IV distance is such that if the FIR is indeed due to SF, then quasar winds either are correlated with the same physics that regulates SF or are providing positive feedback since those objects with evidence of strong winds are correlated with higher rates of SF. If, on the other hand, the results of Temple et al. (2021) and Symeonidis (2017) lead to the conclusion that the FIR emission is AGN dominated, or, perhaps more accurately, that the AGN contribution to the FIR changes across the C IV space more than is probed by Herschel sources (Bernhard et al. 2021), then the predictions for radio emission from SF derived by Harris et al. (2016) must be considered upper limits (and the prediction of increasing SFR with C IV distance is then uncertain).

7. Discussion

Having made predictions for radio emission and SFRs as a function of C IV distance, what do we find? We explore this question in terms of the radio detection fraction, the radio luminosity, and the radio luminosity relative to that expected from SFR—as a function of C IV distance (Section 7.1). With our basic results in mind (no simple linear correlation between radio luminosity or detection fraction with C IV distance and radio detections in excess of that expected from SF at low C IV distance), we discuss recent work from the literature (Section 7.2) in an attempt to frame an explanation for our findings (Section 7.3).

7.1. Results

The nonlinear trend in radio detection fraction with C IV distance seen in Section 4 does not itself reveal the origin of radio emission in RQ quasars, but it does strongly suggest that there is more than one source of radio emission in RQ quasars, as the observations show a more complex relationship with C IV distance than predicted from SF. In terms of our predictions from Section 5, the initial decline in radio detection fraction could come from negative feedback on SF, the corona, or decreasing presence of weak jets. The subsequent rise in radio detection fraction could come from positive feedback on SF or shock-related emission due to winds. More work is needed to explore trends in the RL fraction (e.g., as explored by Jiang et al. 2007, White et al. 2007; Kratzer & Richards 2015; Rankine et al. 2021) with C IV distance to determine whether it also follows a nonlinear distribution.

Unlike the trend in radio detection fraction, we do not observe any clear trends with C IV distance in terms of radio luminosity. However, it is instructive to explore how the radio luminosity relative to that expected from SF (Figure 5, left) changes as a function of C IV distance. In the right panel of Figure 5 we instead plot sources according to the ratio of their measured radio emission (for detections) as compared to their predicted radio emission (from the left panel), where points larger than the nondetections (red) are indicative of radio emission in excess of SF. While the Harris et al. (2016) predictions only capture the median SFR, there is a systematic trend that may nevertheless be robust. Specifically, small C IV distance quasars have radio emission in excess of that predicted from SF, whereas quasars at large C IV distance (thought to have higher L R/L Edd) are more consistent with SFR predictions of radio emission.

If the origin of radio emission is primarily related to the AGN, then one might expect the radio luminosity to scale simply with the optical/UV luminosity. We test that prediction by comparing our data to those of Kimball et al. (2011b) and Condon et al. (2013) in Figure 6, finding that our sources are about 1.1 dex more luminous in the optical/UV and 1 dex more luminous in the radio. Of course, it is possible that the observed higher radio luminosity with higher optical luminosity could also be associated with higher SF (Stanley et al. 2017). The radio nondetections, despite having much higher optical/UV luminosity, have upper limits on their radio luminosities that are not inconsistent with those from the lower-redshift sample from Kimball et al. (2011b) and Condon et al. (2013).

7.2. Literature Review

Kimball et al. (2011b) analyzed a sample of 179 SDSS quasars with 0.2 < z < 0.3 and more luminous than M r = −23. They concluded that the RLF is consistent with two independent origins for radio emission in quasars, which they attributed to starburst-level SF processes at the faint end and AGN processes at the bright end. The transition region is roughly log L 6 GHz = 29.5–30.5 erg s −1, which corresponds to log L 24 GHz = 23.34–24.34 W Hz −1; assuming linear evolution of the break luminosity with redshift. Figure 6 demonstrates that the objects in our sample are much more luminous than the lower-redshift sample of Kimball et al. (2011b) in the optical/UV and also the radio.

Condon et al. (2013) extended the work of Kimball et al. (2011b) by building a larger low-redshift sample (1513 quasars at 0.2 < z < 0.45) and adding a high-redshift sample (2471 quasars at 1.8 < z < 2.5), which is more similar to the sample investigated herein. They found that, analogous to the low-redshift sample, there is a sign of multiple radio origins among NVSS sources: radio emission in the RL tail is dominated by
extend this sample to photometry of our parent sample of 8403 quasars (sample of 179 quasars from Kimball et al. at low AGNs, but the radio luminosity distribution must have a bump at low flux densities, which is consistent with an SF origin dominating the radio emission for the fainter sources. They argued that the level of radio emission in their high-AGNs, but the radio luminosity distribution must have a bump at low flux densities, which is consistent with an SF origin dominating the radio emission for the fainter sources. They argued that the level of radio emission in their high-$z$ sample suggests SFRs as high as $\approx 70 \text{ yr}^{-1}$. Mullaney et al. (2013), Zakamska & Greene (2014), and Hwang et al. (2016) analyzed a sample intermediate in redshift between the two Condon et al. (2013) samples, specifically 70 $z \approx 1$ Herschel AGNs. As with Harris et al. (2016), they used FIR emission as a tracer of SF—assuming that AGNs contribute little at the longest FIR wavelengths. Using two SFR correlations, they found that 92% of RQ quasars have radio emission that is accretion dominated and that 80% of the emission is due to accretion.

Mullaney et al. (2013), Zakamska & Greene (2014), and Hwang et al. (2016) confirmed that radio emission in RQ quasars is dominated by the AGN but argued that the emission is related to shocks from uncollimated, subrelativistic winds interacting with the interstellar medium. Papers addressing such an origin from the theoretical perspective include Ciotti et al. (2010), Jiang et al. (2010), and Nims et al. (2015). Nims et al. (2015) argued that it should be possible to distinguish between jets and winds by the spatial extent of emission and radio spectral index (where they suggest $\alpha \approx -1$ for winds). However, it is harder to then distinguish between AGN and SF—without looking to other wavelengths for help.

Zakamska & Greene (2014) found that the [O III] velocity width of outflows is correlated with radio luminosity in RQ quasars and that the width is additionally correlated with mid-IR luminosity, also suggesting an AGN-intrinsic origin (because the mid-IR is dominated by the AGN). Zakamska & Greene (2014), however, instead looked to shocks from quasar-driven winds as suggested by Stocke et al. (1992), similar to how supernovae produce radio emission. They concluded that it would be hard to distinguish jet emission from wind emission based on morphology of the ionized gas or the radio spectral index, but there must be a threshold for wind driving on the order of bolometric luminosity, $L_{\text{bol}} = 3 \times 10^{45} \text{ erg s}^{-1}$. The median $\log L_{\text{bol}}$ for our targets is 46.3 in those same units—consistent with the design of the observing program to target quasars likely to show evidence of accretion disk winds.

To further connect the Zakamska & Greene (2014) result with our own, we note that Coatman et al. (2019) showed that [O III] blueshift and EW are correlated and anticorrelated, respectively, with C IV blueshift. Thus, if winds contribute significantly to radio emission in RQ quasars, we might expect a bias toward more/higher radio emission at high blueshift (large C IV distance). While there are indications of winds in the form of BALQSOs across the full C IV parameter space (Rankine et al. 2020), if radio emission is coming from shocks due to winds, then we might expect quasars with the strongest troughs (largest balnity indices; Weymann et al. 1991) to produce more radio emission. We note, however, that the winds highlighted by Zakamska & Greene (2014) are associated with strong [O III], whereas the strongest BALQSOs tend to have weak [O III] (Turnshek et al. 1997). Thus, it may be that [O III] is no longer useful as a tracer of winds for the very objects where it might be most interesting (i.e., those with the strongest winds; compare Figure 8 in Coatman et al. 2019 and the right column of Figure 16 in Rankine et al. 2020). One explanation is that the narrow-line region (NLR) may be “running out of gas” at high luminosity (Netzer 1990; Hainline et al. 2014). Moreover, only with IR spectroscopy is [O III] available at $z \sim 2$ redshifts—spanning the peak of SF and AGN activity. Thus, investigation of winds using C IV allows for construction of larger samples. While the winds traced by [O III] and C IV presumably are at very different distances from the central engine, the NLR wind traced by [O III] in the results of Coatman et al. (2019) suggests that the NLR may be connected to winds driven by the central engine, which ultimately influences galaxy scales.

Zakamska et al. (2016) analyzed two $z < 1$ samples: type 2 objects from Reyes et al. (2008) and type 1 objects from Shi et al. (2007). While they agree with Kimball et al. (2011b) and Condon et al. (2013) that their results indicate that a second contribution beyond jets is needed, they concluded that the SF is insufficient to explain radio by an order of magnitude. As a result, Zakamska & Greene (2014) and Zakamska et al. (2016) make the case for radio emission resulting from shocks due to uncollimated, subrelativistic winds impacting the ISM of the host galaxy.

Hwang et al. (2018) found that a special population of quasars (extremely red quasars at $2 < z < 4$) have moderate-luminosity, compact radio sources with steep spectra. They argued that the excess emission is more likely to be due to uncollimated winds than SF or coronal emission. Such outflows can be from radiation-line-driven winds, radiation pressure on dust, or magnetic fields—all of which can produce synchrotron
7.3. Multiple Sources of Radio Emission in RQ Quasars?

Even at the depth probed by our observations, less than 50% of quasars are detected in the radio, making it difficult to identify clear trends with C IV distance that can be used to test the hypotheses that we have outlined (where the stochasticity of the detections may itself be an important clue to the origin of radio emission in RQ quasars). However, one of the reasons for the lack of a clear trend may be that RQ quasars have multiple sources of radio emission, and it may be that those origins have opposite trends in terms of C IV distance.

Taken at face value, the results of Harris et al. (2016) and Figure 5 suggest that quasars with small to moderate C IV distance have a significant source of radio emission in excess of that from SF, which becomes less significant for low-EW (higher-$L/L_{\text{Edd}}$) sources. Such a source could be the corona (see Section 5). For example, in the picture of Raginski & Loar (2016), radio emission from the X-ray corona could correlate with X-ray luminosity. The X-ray luminosity decreases with increasing C IV distance as a result of trends with overall luminosity (and the well-known $L_{\text{X-ray}} - \alpha_{\text{ox}}$ relationship) and cooling of the corona by the accretion disk. Such a trend could thus reproduce the decrease in radio detection fraction with C IV distance at small to moderate C IV distance.

This radio excess and the decreasing radio detection fraction with C IV distance are inconsistent with the predictions of Harris et al. (2016) and an SF origin of this radio emission in RQ quasars. These empirical results are also unlikely to be due to winds (given that the shape of the optical-to-X-ray SED changes across C IV space in a way that one would predict weaker winds at high C IV EW; e.g., Giustini & Proga 2019).

As the prevalence of RL sources decreases with C IV distance (Stocke et al. 1992; Richards et al. 2011; Kratz & Richards 2015; Rankine et al. 2021), we suggest that the presence of jets decreases with C IV distance; see also Timlin et al. (2021). If frustrated/weak/small-scale or newly active jets (e.g., Ulvestad et al. 2005; Nyland et al. 2020) will evolve into RL sources, such jets may follow the same trend as RL sources and could account for the excess of radio emission over that expected from SF at small C IV distances. That would also be consistent with radio detection fraction going down from the lowest to moderate C IV blueshifts.

Going from moderate to high C IV distance, we instead see a trend of increasing radio detection fraction, consistent with the results of Rankine et al. (2021). Given the anticorrelation with the RL fraction and with X-ray emission, it would seem that the source of this trend is unlikely to be weak jets or coronal emission (Laor et al. 2019). Instead, it is more consistent with SF or shocks from winds. Considering the well-known Baldwin effect (Baldwin 1977) and the anticorrelations between C IV EW and luminosity, the simplest conclusion may be that the trend of increasing radio detection fraction with C IV distance simply reflects more SF in higher-luminosity sources (e.g., Stanley et al. 2017, and indirectly illustrated in the left panel of Figure 5). The right panel of Figure 5 is indeed consistent with that hypothesis, as the point sizes indicate that the expected radio emission is broadly consistent with that expected from SF at large C IV distance.

However, we caution that that is not the only interpretation of the agreement between predicted and observed radio emission at large C IV distance. If the IR emission that is crucial to the construction of the SFR estimates in Harris et al. (2016) is contaminated by emission from an AGN (despite evidence to the contrary from PG (Lyu & Rieke 2017) and Herschel (Bernhard et al. 2021) sources, respectively), then the FIR predictions for radio emission break down. The apparent agreement between predicted and observed radio emission at large C IV distance could instead be indicative of radio emission dominated by shocks from winds. That is, consistency with predictions from SF does not necessarily confirm an SF origin for radio emission in RQ quasars at large C IV distance. Indeed, such a trend in C IV space is exactly the behavior we might have expected from a component of radio emission with a wind-shock origin. As such, it is not clear that trends in C IV alone could be used to distinguish between an SF origin and a wind origin of radio emission. More observational and theoretical work is needed to determine whether the predictions themselves at large C IV distance could be influenced by accretion disk winds. However, such an observation is most consistent with either a direct wind origin for radio emission, winds contributing positive feedback to SF, or the radio and SF being driven by the same underlying physical parameter/conditions. A wind-related origin could explain both the increasing radio detection fraction (but decreasing RL fraction) with C IV distance and the stochastic nature of radio detection in an otherwise-homogeneous sample. Thus, we conclude that a wind-related shock origin for radio emission in RQ quasars merits further investigation.

Laor et al. (2019) make the case that the origin of radio emission in RL and RQ quasars is different as a result of different trends in those two populations. Our work is consistent with that interpretation and further suggests that, even within the RQ quasar population, there may be multiple sources of radio emission and that the C IV distance is a useful diagnostic tool for exploring that hypothesis. Thus, we must consider the possibility that radio emission in quasars simply does have multiple origins: jets, SF, coronae, and winds (e.g., Kimball 2018), where it may be the case that those processes are anticorrelated in a way that hinders answering the question of the origin of radio emission in RQ quasars. This picture is consistent with the results of Timlin et al. (2021), who find that only RQ quasars that are flat-spectrum and have high radio luminosity exhibit excess X-ray emission from jets. That conclusion is equivalent to saying that only such RQ quasars

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11 As might be suggested by the correlation seen between blueshift and hot dust by Wang et al. (2013) and Temple et al. (2021)—which cannot be due to direct SF processes, but could be due to a wind-modulated connection between the hot dust at small distances from the black hole and cold dust at large distances.
have their radio emission dominated by jets. As they find that these sources have large He II EWs, they also have small C IV distance.

8. Conclusions

We targeted 50 color-selected individual SDSS quasars at $z \approx 1.65$ for VLA radio observations probing the origin of radio emission in otherwise-RQ quasars. We coupled these data with 388 quasars covered by LoTSS DR1 that were drawn from the same parent sample of color-selected quasars. Such luminous, high-redshift quasars provide an important complement to investigations of radio emission in RQ quasars based on evidence for winds from [O III] emission, as the C IV emission line provides a unique diagnostic of winds that are likely to have an origin in radiation line driving. To aid in this analysis, we define a C IV “distance” that maps both C IV EW and blueshift onto a single nonlinear parameter and explore the radio properties of RQ quasars as a function of that distance (large EW having small distance and large blueshift having large distance).

We find that only 22 of our targets are detected at radio luminosities in excess of $log L_{1.4GHz}/[W \, Hz^{-1}] = 23.71$, which corresponds to an SFR of $\approx 300 \, M_\odot \, yr^{-1}$ using the method of Yun et al. (2001). Similarly, only 123 of the 388 LoTSS sources are detected. For quasars with small C IV distance, the detected quasars have radio emission intermediate between that expected from predictions of median SF and that typically seen in sources with large-scale jets, possibly suggesting coronal emission or weak/small-scale jets. There is evidence for a higher radio detection fraction at either extremum of the C IV distance, possibly suggesting multiple origins of radio emission in RQ quasars. Until new surveys come on line, more pointed observations are needed on more quasars to deeper radio limits (and higher resolution) in order to resolve the question of the origin of radio emission in these sources and determine the level to which winds, coronae, or weak jets may compete with SF processes. That said, the nondetections in our sample have radio emission that is consistent with that predicted from SF, but only if SFR predictions based on FIR emission are not biased by AGN-heated dust on galactic scales, which could imply greater contribution from winds.

Future observational work suggested by this investigation would be to determine the C IV distances of weak/young jet sources such as those from Nyland et al. (2020). Similarly, additional deep, high-resolution observations are needed to test for compact jets. It would further be useful to explore not just the radio detection fraction of the parent sample but the RL fraction as well, since past work has shown those properties to be anticorrelated (Kratzer & Richards 2015; Rankine et al. 2021). However, the tiny fraction of quasars that are RL mean that this requires survey data. Finally, following Laor et al. (2019), an analysis of spectral indices (or more generally radio SEDs) of the sample (e.g., using VLASS data) would reveal whether there are any trends in terms of optically thick versus optically thin radio emission as a function of C IV distance that could be used to understand the origin of the radio emission in RQ quasars.

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Appendix

ICA Reconstructions

Figure 7 shows the ICA reconstruction of each of the 50 SDSS quasars in our sample that were observed by the VLA. The C IV EW and blueshifts are derived from these reconstructions rather than from the original spectra.
Figure 7. Spectra and the reconstructions from which C IV emission parameters are measured. The legend labels the abbreviated SDSSJ name of each spectrum’s corresponding target and further specifies which of our three ICA reconstructions were applied to each target: the 10-component “Standard” or “Low” EW fit, or the 7-component “High” EW; see Rankine et al. (2020). BALQSOs are indicated based on classifications in Shen et al. (2011).

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