THE JET POWER AND EMISSION-LINE CORRELATIONS OF RADIO-LOUD OPTICALLY SELECTED QUASARS

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ABSTRACT

In this Letter, the properties of the extended radio emission form Sloan Digital Sky Survey Data Release 7 quasars with 0.4 < z < 0.8 is studied. This low-redshift sample is useful since any corresponding FIRST radio observations are sensitive enough to detect extended flux in even the weakest Fanaroff–Riley II (FR II) radio sources. In the sample, 2.7% of the sources have detectable extended emission on larger than galactic scales (>20–30 kpc). The frequency of quasars with FR II level extended radio emission is ≈2.3% and >0.4% of quasars have FR I level extended radio emission. The lower limit simply reflects the flux density limit of the survey. The distribution of the long-term time-averaged jet powers of these quasars, $Q$, has a broad peak $\sim 3 \times 10^{44}$ erg s$^{-1}$ that turns over below $10^{44}$ erg s$^{-1}$ and sources above $10^{45}$ erg s$^{-1}$ are extremely rare. It is found that the correlation between the bolometric (total thermal) luminosity of the accretion flow, $L_{\text{bol}}$, and $Q$ is not strong. The correlation of $Q$ with narrow line luminosity is stronger than the correlation with broad line luminosity and the continuum luminosity. It is therefore concluded that previous interpretations of correlations of $Q$ with narrow line strengths in radio galaxies as a direct correlation of jet power and accretion power have been overstated. It is explained why this interpretation mistakenly overlooks the sizeable fraction of sources with weak accretion luminosity and powerful jets discovered by Ogle et al.

Key words: accretion, accretion disks – black hole physics – galaxies: active – galaxies: jets

Online-only material: color figures

1. INTRODUCTION

Three major questions regarding relativistic jets in radio-loud extragalactic radio sources that are of fundamental interest are “how powerful is the typical radio jet?,” “how frequently do quasars produce long-term jets?,” and “how is the jet power related to the accretion flow thermal luminosity?.” The signature of long-term powerful jets are the radio lobes of Fanaroff–Riley II (FR II) radio sources. Quasars with double radio lobes are conspicuous, but quite rare. Thus, radio-selected samples are typically used to address the questions above since sufficient sample size is required for statistical merit. Most radio-loud sources4 do not display radio lobes with the resolution and sample size required for statistical merit. Most radio-loud quasars4 do not display radio lobes with the resolution and sample size required for statistical merit. Most radio-loud sources do not display radio lobes with the resolution and dynamic range of FIRST5 (deVries et al. 2006). Thus, in order to find the frequency of the FR II phenomenon in quasars and the complete distribution of their kinetic luminosity, one must have the ability to detect lobe emission that is below the FR I/FR II divide. The FR I/FR II distinction is both a morphological and a luminosity classification. In terms of long-term average jet power, $Q$, this approximate boundary is at $Q \approx 5 \times 10^{43}$ erg s$^{-1}$ (Rawlings & Saunders 1991; Punsly 2008). This divide corresponds to a 1.4 GHz flux density <12.5 mJy at $z < 0.8$, well within the sensitivity of the FIRST radio survey, even if the emissivity is distributed over 10 beamwidths (see Equation (1), below). Thus, the extant databases are now at a point where the questions above can be addressed rigorously.

We intend to study $Q$ with a carefully selected, large sample of Sloan Digital Sky Survey (SDSS) Data Release 7 (DR7) quasars (0.4 < z < 0.8) that is cross-referenced to the FIRST database. Selecting the sources in this way reveals prominent narrow lines ([O iii] $\lambda$5007 and [O ii] $\lambda$3727) and two broad lines H$\beta$ $\lambda$4861 and Mg ii $\lambda$2798 in the SDSS spectral window for all objects. This allows us to compare the various derived properties in the context of a single sample of objects in a way that removes the uncertainties associated with sample selection biases if a different set of objects and lines are used for the analysis depending on redshift. The cross-correlations between the different estimators of the photoionizing continuum allow us to segregate out the effects of Doppler beaming and line emission created by jet-induced shocks, thereby reducing systematic uncertainties in the bolometric luminosity, $L_{\text{bol}}$, the broadband thermal luminosity from IR to X-ray, of the active galactic nucleus (AGN).

In the next section, the sample is described as well as the extended radio flux data reduction and the optical spectra data reduction. Section 3 summarizes the distribution of $Q$ that is found. Section 4 discusses the correlations of $Q$ with the optical/UV spectral parameters.

2. SAMPLE DESCRIPTION AND DATA EXTRACTION METHODS

In order to determine the dependence of line luminosity on the thermal continuum in a quasar, we constructed a sample of SDSS DR7 quasars with 0.4 < z < 0.8 and spectra with a median S/N > 7, this yielded 10,069 AGNs. This base sample has been analyzed previously for other purposes in Punsly & Zhang...
(2010, 2011). The SDSS DR7 data were cross-referenced to the FIRST database. Of these, there were 9270 sources found within these FIRST fields that comprise our sample. Most of the radio-loud sources did not have extended radio flux with the dynamic range and resolution of FIRST, indicating a sub-galactic compact structure or very weak, FR I level, extended emission. The optical spectra were reduced as in Punsly & Zhang (2011) yielding the following for every quasar: the optical/UV continuum luminosity from 5100 Å to 3000 Å, $L_{\text{cont}}$, the luminosity of the broad components of Hβ, $L_{\text{Hβ}}$, and Mg ii, $L_{\text{Mg ii}}$, and the luminosity of the narrow lines [O iii] $\lambda$5007, $L_{\text{O iii}}$, and [O ii] $\lambda$3727, $L_{\text{O ii}}$.

The spatial resolution associated with the interferometer beamwidth of the FIRST survey is $\approx 20$ kpc at $z = 0.4$ and $\approx 30$ kpc at $z = 0.8$. The optically thin extended flux density on scales of this size and larger can be used to estimate the long-term time-averaged kinetic energy flux in a jet, $\mathcal{Q}$ (Willott et al. 1999). FIRST observations are at a fairly low frequency, 1.4 GHz, so they are sensitive to steep spectrum, optically thin, emission. Resolved emission at 1.4 GHz is very likely to be optically thin (Antonucci & Ulvestad 1985; Murphy et al. 1993). Thusly motivated, we want to extract this extended flux from the FIRST radio database for the SDSS quasars.

The first step was to cross-reference all FIRST sources within 30" of the SDSS sources. Each one of these radio fields was inspected visually. Diffuse emission that is roughly concentric with either the optical quasar position, or an unresolved radio core located within 3" of the optical position, is considered extended emission of the quasar. This would be core-halo type emission. Components within 10" of the optical/radio core are considered extended emission. Distant components located 10"–70" from the quasar/radio core position are considered to be associated with the quasar if there is an extension or jet pointing toward the direction of the optical quasar/radio core position, or if there is a second distant component located on a line that passes close to this optical quasar/core position (i.e., a classical triple). We also considered partially resolved sources in the image plane, quantifying the extended emission as the integrated flux minus the peak flux. Other configurations were not considered extended flux associated with the quasar (either chance background sources or core flux).

The most accurate estimates of $Q$ should use an isotropic estimator such as the radio lobe flux. The sophisticated calculation of the jet kinetic luminosity in Willott et al. (1999) incorporates deviations from the overly simplified minimum energy estimates into a multiplicative factor $f$ that represents the small departures from minimum energy, geometric effects, filling factors, protonic contributions, and low-frequency cutoff. The quantity, $f$, is argued to be constrained between 1 and 20. In Blundell & Rawlings (2000), it was further determined that $f$ is most likely in the range of 10–20. Thus, choosing a value of $f = 15$, Punsly (2005) converted the analysis of Willott et al. (1999) to the formulae in Equations (1) and (2), even though it is just a time average. It is assumed throughout this Letter that $Q$ is just a time average. It is assumed throughout this Letter that $Q$ is an isotropic method that allows one to convert 151 MHz flux densities, $F_{151}$ (measured in mJy), into estimates of $\mathcal{Q}$ (measured in erg s$^{-1}$):

$$\mathcal{Q} \approx 1.1 \times 10^{45} [(1 + z)^{1.4}] Z^{0.31} - (3.65) ((1 + z) - 0.203(1 + z)^{3} + 0.749(1 + z)^{2} + 0.444(1 + z) + 0.205)^{-0.125},$$

$$Z \equiv 3.31 - (3.65) ((1 + z) - 0.203(1 + z)^{3} + 0.749(1 + z)^{2} + 0.444(1 + z) + 0.205)^{-0.125},$$

where $F_{151}$ is the total optically thin flux density from the lobes (i.e., no contribution from a Doppler-boosted jet or the radio core). The spectral index is defined by the convention, $f_e \sim \nu^{-\alpha}$. The appropriate application of this equation requires that one must extricate the diffuse lobe emission from the Doppler-boosted core and jet. Expression (1) requires 151 MHz flux densities, so we extrapolate the 1.4 GHz extended flux from the FIRST observation. Without further knowledge, for lobe emission $\alpha \approx 0.8$ is the most typical value found in Kellermann et al. (1969), and this value is used to extrapolate the 1.4 GHz flux density to 151 MHz. These extrapolations were also cross-referenced to any available low-frequency data in NASAD/IPAC Extragalactic Database for a consistency check. There is no evidence that a significant amount of flux was resolved out by the FIRST beam size. For a discussion of the errors implicit in Equations (1) and (2), see the discussions of Fernandes et al. (2011), Blundell & Rawlings (2000), and Willott et al. (1999). The independent derivation in Punsly (2005) indicates that most estimates in a large sample will be accurate to within a factor of two.

3. LONG-TERM TIME-AVERAGED JET POWER

Figure 1 is a histogram of $\mathcal{Q}$ for the 266 quasars with detected extended radio emission. Note that there is a partition associated with an approximate FR I/FR II dividing line at $\mathcal{Q} = 5 \times 10^{43}$ erg s$^{-1}$ (Rawlings & Saunders 1991; Punsly 2008). The histogram shows that the FIRST sensitivity in this redshift range is capable of detecting FR I level extended emission. There are 220 FR II sources above the FR I/FR II divide and 46 sources below the divide. This corresponds to 2.3% of the optically selected quasars having FR II level extended emission and $>0.4\%$ having FR I level extended emission. The fraction that are FR I sources would certainly increase with deeper radio observations. The fraction that are FR II would also likely increase with deeper radio imaging (change some FR I levels to FR II levels) as faint diffuse flux is likely swamped by the FIRST rms noise. The frequency of 2.3% for the FR II quasars is consistent with the value of 1.7% deduced by devVries et al. (2006) since their sample has a mean of $z \approx 1.3$, so many faint, diffuse FR II sources (that are prominent in Figure 1) would be difficult or impossible to detect with FIRST sensitivity at these high redshifts, hence their lower deduced rate of occurrence. The significant fraction of FR I extended flux densities is consistent with the discovery of quasars with FR I extended radio emission in Gower & Hutchings (1984) and Blundell & Rawlings (2001).

A major advantage of this study is that the peak of the quasars extended luminosity distribution is resolved in Figure 1 due to the FIRST sensitivity in this redshift range. It shows that the most frequent luminosity (for sources with extended emission) is definitely at the FR II level. The peak level of the histogram is $\gtrsim 10^{44}$ erg s$^{-1}$ with marginal evidence of a second peak at $\approx 5 \times 10^{44}$ erg s$^{-1}$. Only 33 sources have $\mathcal{Q} > 10^{44}$ erg s$^{-1}$, $\approx 0.3\%$. Although powerful FR II quasars ($\mathcal{Q} > 10^{45}$ erg s$^{-1}$) are prominent in low-frequency radio surveys such as the 7C survey (Willott et al. 1999), these sources are extremely rare, perhaps the rarest subclass of quasar—an order of magnitude rarer than low-ionization broad absorption line quasars (Zhang et al. 2010). Whatever physical phenomenon creates these large values of $\mathcal{Q}$ must be very difficult to achieve and maintain for long periods of time in a quasar environment.
4. CORRELATIONS BETWEEN ACCRETION LUMINOSITY AND JET POWER

The blue continuum luminosity is the most basic signature of the thermal emission from the quasar, so it is the most commonly used quantity for estimating $L_{\text{bol}}$. Perhaps the most popular bolometric correction is the simple one proposed by Kaspi et al. (2000), $L_{\text{bol}} \approx 9 \lambda L_\lambda (5100 \, \text{Å})$. Clearly, using a portion of the optical/UV continuum is more accurate than a single point and we have that at our disposal, $L_{\text{cont}}$. In Punsly & Zhang (2011), in another study of these 10,069 SDSS sources, the Kaspi et al. (2000) relation was converted to

$$L_{\text{bol}} \approx 15 L_{\text{cont}}. \quad (3)$$

$L_{\text{cont}}$ is the most direct way to estimate $L_{\text{bol}}$. One can also estimate $L_{\text{bol}}$ from the spectral luminosity at 3000 Å for the sources in this sample. The average spectral index of the optical/UV continuum for the radio-quiet sources in the sample of 10,069 quasars was found in Punsly & Zhang (2011) to be $\alpha \approx 0.55$, where $L_\nu \sim \nu^{-\alpha}$. Thus, the Kaspi et al. (2000) estimator can also be realized as

$$L_{\text{bol}} \approx 7.1 \lambda L_\lambda (3000 \, \text{Å}). \quad (4)$$

It is interesting to see if there is a strong relationship between $L_{\text{bol}}$ and $\overline{Q}$ as has been inferred for radio galaxies in Rawlings & Saunders (1991) and Willott et al. (1999). An uncertainty in Equation (3), in the context of radio sources, is the high-frequency tail of the synchrotron emitting jet and its potential to dilute the pure $L_{\text{cont}}$ from the accretion flow. We have other reliable surrogates for $L_{\text{bol}}$. The synchrotron tail dies off rapidly with frequency in the optical/UV and the big blue bump from the accretion disk becomes more prominent in the UV (Malkan & Moore 1986). The spectral index of $L_\nu$ of the optical/UV synchrotron tail in quasars is typically $\alpha \sim 2$, compared with the accretion spectral luminosity with $\alpha \approx 0.55$ for the 10,069 sources in the SDSS quasar sample (Smith et al. 1988; Punsly & Zhang 2011). Thus, the ratio of the synchrotron tail luminosity ($\lambda L_\lambda$) to the accretion luminosity is typically $\gtrsim 2$ times larger at 5100 Å than at 3000 Å. Consequently, if synchrotron dilution is significant, there should be a noticeable difference in the correlations of quasar parameters with $L_{\text{cont}}$ and those with $L(3000 \, \text{Å})$. Furthermore, it was shown in Punsly & Zhang (2011) that the broad components of Mg II and in particular H$\beta$ are excellent surrogates for the underlying accretion disk luminosity. These spectral parameters are available for all sources in our sample. Figure 2 shows that $L_{\text{H}\beta}$ is an excellent surrogate for $L_{\text{cont}}$ for our radio sources as well. The best-fit relationship displayed at the top of the plot is nearly linear. The tight correlation is evidence that Doppler beaming of the high-frequency tail of the synchrotron jet is not a major contaminant to the continuum luminosity measured by SDSS in a statistical sense.

We explore the correlations between the spectral features and $\overline{Q}$ in the correlation matrix (Table 1). The statistical metric of choice is the Spearman rank correlation coefficient in Table 1. As expected, $L_{\text{cont}}$ and $L(3000 \, \text{Å})$ are tightly correlated and their correlations with $L_{\text{H}\beta}$ are also tight (see Figure 2). The most intriguing aspect of Table 1 and Figure 3 is that the weakest correlation with $\overline{Q}$ is from the continuum itself and then $L_{\text{H}\beta}$. The correlations of $\overline{Q}$ with the narrow line strengths are more significant than with the broad lines or the continuum. A lack of a strong correlation between $\overline{Q}$ and $L_{\text{cont}}$ is consistent with the right-hand panel of Figure 4 of Fernandes et al. (2011) based on a sample of optically selected radio-loud quasars.

Many previous studies have shown a strong correlation between narrow line strengths and $\overline{Q}$ for radio galaxies (Rawlings & Saunders 1991; Willott et al. 1999; Buttiglione et al. 2010, 2011; Koziel-Wierzbowska & Stasinska 2011). However, the
The narrow line strength and based on the correlation strengths in Table 1. Thus, the narrow line gas might be roughly in host galaxies (Heckman et al. 2004). Thus, correlations with parameter (Simpson 1998) and contamination by star formation due to at least two effects: the dependence on the ionization for the O\textsc{iii} emitting gas in FR II radio sources. It has been shown that L\textsc{o iii} is superior to L\textsc{oi} as a measure of L\textsubscript{bol} due to at least two effects: the dependence on the ionization parameter (Simpson 1998) and contamination by star formation in host galaxies (Heckman et al. 2004). Thus, correlations with L\textsc{oi} have a more direct physical interpretation. For O\textsc{iii}, the source of excitation for the narrow line gas might be roughly an equal mix of photoionization energy and jet-induced energy based on the correlation strengths in Table 1. Thus, the narrow line strength and are dependent statistical quantities. So, if a narrow line strength is used as a surrogate for L\textsubscript{bol} in a correlation analysis or a scatter plot with then the probability of large outlier sources (i.e., large and small narrow line strength) is greatly diminished compared to a scatter plot in the L\textsubscript{bol} plane (i.e., large and small L\textsubscript{bol}) because is itself a strong source of narrow line emitting gas. This interpretation seems to rectify a discrepancy seen here and elsewhere in the literature. Consider the bimodal scatter in the IR luminosity/radio luminosity plane noted by Ogle et al. (2006) in their Figure 1. They concluded that significant can exist in sources where there is essentially very little accretion thermal luminosity as well as in sources with large (quasar-like) L\textsubscript{bol}. A similar conclusion was reached when the X-ray luminosity was included in the analysis in Hardcastle et al. (2009). Conversely, the correlation between narrow line strength and in Rawlings & Saunders (1991) and Willott et al. (1999) led to the conclusion that accretion power was very closely linked to jet power. Based on Table 1, this difference in interpretation arises because a strong radio source with a weak ionizing continuum is still likely to be a major source of narrow line emission, thereby keeping these sources correlated with narrow line strength—even though they are not correlated with L\textsubscript{bol}. An important point to bear in mind is that only a small range of optical luminosity is probed here, with most sources being within one order of magnitude. Given the very large scatter in some of these correlations, it is clear that over such a small range of luminosity, correlation statistics can
give low values. Observations over many orders of magnitude with the same scatter would give much higher correlation coefficients, e.g., the correlations of Rawlings & Saunders (1991) and Willott et al. (1999). However, the scatter in these relationships is still significant, 0.54 dex (Willott 2001).

5. CONCLUSION

This Letter used a large SDSS DR7 sample and FIRST radio observations to address three fundamental questions in the study of quasar radio jets. We repeat them here with answers indicated by the sample considered.

1. How powerful is the typical radio jet? From Figure 1, typically, the long-term time-averaged jet power, $Q$, is a factor of a few above the FR I/FR II divide, $Q \sim (1-5) \times 10^{44}$ erg s$^{-1}$.

2. How frequently do quasars produce long-term jets? For $0.4 < z < 0.8$, 2.3% of the optically selected quasars have FR II level extended emission and $>0.4$% have FR I level extended emission indicative of long-term jet production.
How is the jet power related to the accretion flow thermal luminosity? In the last section (see Figure 3), it was established that the long-term time-averaged jet power, $\overline{Q}$, is not strongly correlated with the accretion flow thermal luminosity. The extended lobe emission used to compute $\overline{Q}$ was emitted from the quasar central engine $\sim 10^5–10^7$ years earlier than the observed optical/UV continuum used to evaluate $L_{\text{bol}}$ (Blundell & Rawlings 2000). Thus, the two properties are not contemporaneously determined and there is no a priori reason to expect them to correlate strongly, except possibly by the overall scaling of the central black hole mass responsible for both. No information was found in the sample that can be used to reliably determine a connection between the instantaneous jet power and $L_{\text{bol}}$.

Another major finding of this work, that is closely related to point 3 above, is that powerful FR II quasars ($Q > 10^{45}$ erg s$^{-1}$) are extremely rare, $\sim 0.3\%$ of all quasars. Thus, any theoretical model of the central engine must explain why it is so difficult for a quasar environment to maintain a configuration conducive to strong jet formation over $\sim 10^5–10^7$ years.

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