PKS 0743–67: AN ULTRALUMINOUS ACCRETION DISK AND A HIGH KINETIC LUMINOSITY JET

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ABSTRACT

Deep radio observations of the quasar PKS 0743–67 are presented that reveal a central engine capable of driving jets with enormous kinetic luminosity, \( Q > 4.1 \times 10^{46} \) ergs s\(^{-1}\). This result is significant because archival optical spectral data indicate that the accretion disk has a thermal luminosity \( L_{\text{bol}} > 2 \times 10^{47} \) ergs s\(^{-1}\). Furthermore, estimates of the mass of the central black hole from line widths indicate that \( Q/L_{\text{bol}} \approx 1 \). This suggests that neither a large \( L_{\text{bol}} \) nor \( Q/L_{\text{bol}} \) suppresses jet power in quasars, despite claims that they do in the recent literature. Earlier studies have found \( L_{\text{bol}} \) and \( Q \) to be correlated in blazars. However, by removing the BL Lac objects and leaving only the quasars in the sample, we found that \( Q \) is very weakly correlated with \( L_{\text{bol}} \) in the subsample.

Subject headings: accretion, accretion disks — black hole physics — galaxies: active — galaxies: jets — quasars: general — quasars: individual (PKS 0743–67)

1. INTRODUCTION

The connection between accretion flow parameters and radio jet production is a mysterious one. It has been argued by Wang et al. (2004) that the jet kinetic luminosity, \( Q \), is correlated with the bolometric luminosity of the thermal emission, \( L_{\text{bol}} \), produced by the accretion flow in blazar-type active galactic nuclei. However, using virtually identical techniques to those of Wang et al. (2004), Celotti et al. (1997) came to the opposite conclusion. In order to shed some light on this issue, we explore this question from a different perspective for the particular case of quasars. The vast majority (~90%) of quasars are radio-quiet whether their \( L_{\text{bol}} \) lies just above the Seyfert 1–quasar dividing line or they are at the other extreme, \( L_{\text{bol}} > 10^{47} \) ergs s\(^{-1}\). This observation indicates that there are additional parameters, beyond \( L_{\text{bol}} \) and \( L_{\text{bol}}/L_{\text{Edd}} \), that control the power of the radio jet.

We note that the very high \( Q \), FR II radio source Cygnus A, \( Q \approx 1.6 \times 10^{46} \) ergs s\(^{-1}\) (according to eq. [1a] of this Letter), harbors a hidden quasar with \( L_{\text{bol}} \) just above the Seyfert 1–quasar dividing line and has a low Eddington rate, the ratio of \( L_{\text{bol}} \) to the Eddington accretion rate, \( L_{\text{bol}}/L_{\text{Edd}} \sim 0.01 \) (Young et al. 2002; Tadhunter et al. 2003). Cyg A is an extremely powerful FR II radio source even when compared with low-frequency–selected samples at high redshift (Willott et al. 1999). It has a \( Q \) that is 2 orders of magnitude higher than most FR II quasars (see Punsly 2001 and references therein). Thus, Cyg A provides a well-studied “standard” candle for an extremely powerful FR II source. This motivated us to explore the opposite extreme in the quasar family, the very powerful quasar PKS 0743–67, which is luminous in all frequency bands and seemed to be a likely candidate to have extremely high \( Q \) jets. In §§ 3 and 4, we show that it has a powerful accretion luminosity, \( L_{\text{bol}} > 2 \times 10^{47} \) ergs s\(^{-1}\), \( L_{\text{bol}}/L_{\text{Edd}} \approx 1 \), a strong unresolved VLBI radio core, and prominent radio lobes. Even though the quasar is at a redshift of \( z = 1.511 \) (Bechtold et al. 2002), both the radio core and the radio lobe 5 GHz flux densities are ~1 Jy. In § 5, it is demonstrated that the high \( Q \) for these two extreme ends of the quasar range, Cyg A and PKS 0743–67, are not out of line with the properties of the quasar population as a whole. By studying a sample of quasars from Wang et al. (2004), we find that \( Q \) is not correlated with \( L_{\text{bol}} \) for radio-loud quasars that possess blazar cores. Secondly, we demonstrate that the inverse correlation claimed between \( Q/L_{\text{bol}} \) and \( L_{\text{bol}}/L_{\text{Edd}} \) by Wang et al., although true, is a trivial consequence of the fact that \( Q \) is not correlated with \( L_{\text{bol}} \) in quasars. The primary conclusion of this study is that the intrinsic power of a quasar jet is not, to first order, controlled by the accretion rate.

We have performed deep radio observations with the Australia Telescope Compact Array (ATCA)\(^2\) in order to understand the radio structure of PKS 0743–67; the lobe emission alone would qualify it for the 3C catalog if the source were in the northern hemisphere, and our observations indicate that the jet kinetic luminosity \( Q \) is far more powerful than that in Cyg A.

2. THE RADIO OBSERVATIONS

Previously, Rayner et al. (2000) imaged the radio structure of PKS 0743–67 at 4.8 GHz with ATCA. We performed deep observations at 2.496, 4.800, and 8.640 GHz in order to image the source structure and obtain higher resolution, as well as spectral and polarization, data. It is essential to obtain both higher resolution and accurate spectral data to assess the energy content of the extended structure. Our 8.640 GHz map is shown in Figure 1.

The data from our ATCA observations are presented in Table 1. Quasars with a strong flat-spectrum core often have Doppler-enhanced kiloparsec-scale jets (Punsly 1995). Thus, an estimate of \( Q \) in PKS 0743–67 requires an analysis of the data in Table 1 in order to determine if the jet and lobe emission to the east of the nucleus is Doppler enhanced or not. The

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1.25 Jy beam$^{-1}$. The beam size is 0.79′ × 1′ at a position angle of −78.8′. Contour levels for the Stokes $I$ emission are −0.125, 0.125, 0.25, 0.5, 1, 2, 4, 8, 16, 32, and 64 times 0.0125 Jy beam$^{-1}$. The peak fractional polarization is 52.1%. The vector lengths represent the electric field with 25.4% fractional polarization per arcsecond. The beam ellipse is plotted at lower left.

components E1, E2, and E3 denote the eastern jet/lobe components in Figure 1, numbered consecutively from west to east.

In Figure 1, the magnetic field (perpendicular to the electric field vectors plotted) at the core is parallel to the jet direction along the length of the jet, even though the eastern jet goes through a large apparent bend. At the end of the eastern jet, the magnetic field switches to being perpendicular to the jet direction, typical of a radio galaxy hot spot.

3. ESTIMATING THE JET KINETIC LUMINOSITY

In order to avoid the ambiguities associated with Doppler enhancement, we estimate the jet kinetic luminosity from the isotropic extended emission, applying a method that allows one to convert 151 MHz flux densities, $F_{151}$, measured in janskys, into estimates of kinetic luminosity, $Q$, from Willott et al. (1999) and Blundell & Rawlings (2000) by means of the formula derived in Punsly (2005):

$$Q = 1.1 \times 10^{45} [(1+z)^{1+z}Z^2F_{151}^{1/7} \text{ergs s}^{-1}, \quad (1a)$$

$$Z = 3.31 - 3.65(1+z) + 0.203(1+z)^2 + 0.749(1+z)^3 + 0.444(1+z)^2 + 0.205]^{1/8}, \quad (1b)$$

where $F_{151}$ is the total optically thin flux density from the lobes (i.e., no contribution from Doppler-boosted jets or radio cores).

We assume a cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_h = 0.7$, and $\Omega_{\Lambda} = 0.3$. In order to implement this technique, one needs to determine which components are optically thin and which are Doppler enhanced.

There are two possible interpretations of the data that one can use to calculate $Q$. The most straightforward approach is to note that all of the emission is optically thin and that the large angular size of the source, ≈250 kpc, argues against significant Doppler enhancement of the large-scale structures.

However, we choose the most conservative approach: assume that all of the eastern emission is part of a jetted system and it is all Doppler enhanced, even the hot spot to some extent (this would explain why the eastern hot spot is more luminous than the western hot spot). If the source were symmetric and viewed in the sky plane, then an upper limit to the total flux would be twice the observed flux from the western hot spot, 340 mJy at 2.496 GHz. Extrapolating this to 151 MHz yields a lobe flux of 8.8 Jy. Inserting this value into equation (1a) yields $Q = 4.1 \times 10^{44} \text{ergs s}^{-1}$. This equates to 2.5 times the kinetic luminosity of Cyg A computed by the same method. If the eastern lobe is not Doppler enhanced, then the kinetic luminosity is even larger. We note that no 151 MHz observations of PKS 0743−67 have been made. However, Large et al. (1981) measured the total flux density at 408 MHz to be 8.6 Jy. This measurement will be dominated by the extended emission of the source, making an estimate of 8.8 Jy at 151 MHz for the unbeamed emission conservative. A 2.3 GHz VLBI measurement of PKS 0743−67 was made by Preston et al. (1989). A secondary unresolved radio structure, presumably a strong knot in a jet, is directed to the east of the core toward the base of the kiloparsec jet seen in Figure 1. The VLBI emission is dominated by an unresolved core on a 10 milliarcsecond scale with 1.2 Jy. Not only is the time-averaged $Q$ from PKS 0743−67 enormous, but the powerful parsec-scale core indicates that the source is likely to still be highly energetic at the current time.

4. ESTIMATING THE EDDINGTON RATIO

One can estimate $L_{\text{bol}}$ as in Laor (1998), $L_{\text{bol}} \approx 8.3\nu L_{\nu}(3000 \text{ Å})$, a method that has been applied to both radio-quiet and radio-loud quasars. We apply this formula to the flux density at 3000 Å from the spectrum of PKS 0743−67 provided by di Serego Alighieri et al. (1994), yielding $L_{\text{bol}} = 4.7 \times 10^{43} \text{ergs s}^{-1}$. When making an estimate of the accretion flow luminosity, the strong radio core might raise some concern about contamination of the optical emission by means of a high-frequency synchrotron spectrum associated with the base of the jet. Thus, alternatively,
one could obtain an estimate of $L_{\text{bol}}$ using the method of Wang et al. (2004) that depends on line luminosity. Following the discussion in § 3 of Wang et al. (2004), the $C_{\text{IV}}/L_{\alpha}$ line-strength ratio from the composite quasar spectrum of Francis et al. (1991) and equation (1) of Wang et al. (2004) imply that the total broad-line luminosity is $L_{\text{BLR}} \approx 8.83L_{\text{CIV}}$, where $L_{\text{CIV}}$ is the $C_{\text{IV}}$ line strength. Secondly, Wang et al. estimate $L_{\text{bol}} \approx 10L_{\text{BLR}}$, and thus $L_{\text{bol}} \approx 88.3L_{\text{CIV}}$. Using the $C_{\text{IV}}$ line strength from di Serego Alighieri et al. (1994), this implies $L_{\text{bol}} \approx 2.91 \times 10^{47}$ ergs s$^{-1}$, in close agreement with the estimate above from the spectrum directly. One can estimate $L_{\text{bol}}/L_{\text{Edd}}$ using the value of $L_{\text{bol}}$ above in conjunction with an estimate of the black hole mass, $M_{\text{bh}}$, from the same $C_{\text{IV}}$ emission line. The $M_{\text{bh}}$ estimator of Vestergaard (2002) requires the luminosity at 1350 Å, $\lambda L_{\alpha}(1350 \text{ Å})$. To be consistent with the philosophy of not using the continuum spectrum, one can instead estimate $\lambda L_{\alpha}(1350 \text{ Å})$ from the $L_{\text{bol}}$ derived above from the $C_{\text{IV}}$ line strength with the aid of the relation from Laor (1998), $L_{\text{bol}} \approx 8.3\lambda L_{\alpha}(3000 \text{ Å})$, and assuming a typical quasar optical spectral index of 0.7 as was done by Wang et al. (2004) (the spectrum of di Serego Alighieri et al. [1994] yields a similar value, 0.75). One finds a central black hole mass of $M_{\text{bh}} = 1.62 \times 10^{8} M_{\odot}$ and $L_{\text{bol}}/L_{\text{Edd}} = 0.99$. One can check this result independently by using the $H\alpha$ line of PKS 0743−67 as measured by Espey et al. (1989) and the estimators from Greene & Ho (2005), $M_{\text{bh}} = 1.41 \times 10^{8} M_{\odot}$ and $\lambda L_{\alpha}(5100 \text{ Å}) = 2.27 \times 10^{46}$ ergs s$^{-1}$.

Converting the line luminosity to $L_{\text{bol}}$ as for the $C_{\text{IV}}$ estimate above, one finds $L_{\text{bol}} = 2.21 \times 10^{47}$ ergs s$^{-1}$ and $L_{\text{bol}}/L_{\text{Edd}} = 0.87$.

5. COMPARISON WITH OTHER RESULTS

Ostensibly, the existence of a high-($L_{\text{bol}}/L_{\text{Edd}}$) and high-$Q$ source such as PKS 0743−67 appears at odds with the result of Wang et al. (2004) that $Q/L_{\text{bol}}$ is inversely correlated with $L_{\text{bol}}/L_{\text{Edd}}$. The large $Q$ of Cyg A appears at odds with the other conclusion of Wang et al., that $Q$ is positively correlated with $L_{\text{bol}}$. However, closer inspection of the raw data used by Wang et al. indicates that this is not actually the case. The virtue of the estimates of Wang et al. is that they use the parsec-scale jet emission to estimate $Q$ contemporaneously with the estimate of $L_{\text{bol}}$. However, we warn the reader that such estimates are very sensitive to the uncertain Doppler factor. The method that Wang et al. adopted from Celotti et al. (1997) assumes that the X-ray energy emission is from synchrotron self-Compton emission; however, Dermer & Schlickeiser (1993) showed that external Compton scattering (ECS) of quasar disk photons or broad-line region photons by energetic particles in the jet will usually dominate the high-energy quasar spectrum, since ECS emission is enhanced by the jet Lorentz factor to the 6th power.

This type of estimator can lead to enormous errors in the estimated values of $Q$. As an example, Wang et al. (2004) es-
timate for 4C 52.27 (1317+520) $Q > 250Q_{\text{Cyg A}}$, where $Q_{\text{Cyg A}}$ is the kinetic luminosity of Cygnus A. By contrast, using the radio maps from Hintzen et al. (1983) and the isotropic estimator in equation (1a), we find a more reasonable value of $Q \approx 0.35Q_{\text{Cyg A}}$. First of all, Wang et al. (2004) present data in a log-log plot in their Figure 1a indicating that $L_{\text{bol}}$ and $Q$ have a strong linear correlation (note that they assume all of the estimates are identical. The data of Wang et al. and the correlation coefficient for $L_{\text{bol}}$ and $Q$ is even worse, indicating that $L_{\text{bol}}$ and $Q$ are uncorrelated with $Q_{\text{bol}}$. However, if one removes the BL Lac objects from the sample and fits a line to just the quasars on a log-log plot that is otherwise identical, then the squared multiple regression correlation coefficient $R^2 = 0.12$. If one removes the extreme estimate associated with 4C 52.27 given above, the linear fit is log $L_{\text{bol}} = 0.9309 \log (L_{\text{bol}}/L_{\text{Edd}}) + 47.121$ (see Fig. 2b). The correlation coefficient is $r = 0.820$, and $P < 10^{-4}$. Since $Q$ is uncorrelated with $L_{\text{bol}}$, it follows that $Q/L_{\text{bol}} \sim L_{\text{bol}}^{-1}$ (where we have introduced the symbol $\sim$ to represent correlation) and $L_{\text{bol}}/L_{\text{Edd}} \sim L_{\text{bol}}$ from Figure 2b. Combining the two relations, it follows that $L_{\text{bol}}/L_{\text{Edd}} \sim L_{\text{bol}}/Q$, that is, $Q/L_{\text{bol}}$ and $L_{\text{bol}}/L_{\text{Edd}}$ are inversely correlated, as shown in Figure 2c. The best linear fit is log $(Q/L_{\text{bol}}) = -0.814 \log (L_{\text{bol}}/L_{\text{Edd}}) - 0.67$, and the correlation coefficient for $L_{\text{bol}}/L_{\text{Edd}}$ and $Q/L_{\text{bol}}$ is $r = -0.654$ for the subsample of quasars, with $P = 3 \times 10^{-4}$. The anticorrelation of $L_{\text{bol}}/L_{\text{Edd}}$ and $Q/L_{\text{bol}}$ is spurious: there is no direct causal link between these two variables, as expressed statistically by the small value of the partial correlation coefficient of $Q/L_{\text{bol}}$ versus $L_{\text{bol}}/L_{\text{Edd}}$ with $L_{\text{bol}}$ held fixed, $-0.030$. Finally, we note that this result does not imply that there is the potentially interesting correlation between $Q$ and $L_{\text{bol}}/L_{\text{Edd}}$ evidenced by Figure 2d. The correlation is very weak, $r = 0.1489$ and $P = 0.244$.

6. CONCLUSION

PKS 0743–67 is an example of a quasar that has an ultraluminous accretion flow, $L_{\text{bol}} > 2 \times 10^{47}$ ergs s$^{-1}$, a very high Eddington rate, $L_{\text{bol}}/L_{\text{Edd}} \approx 1$ with $Q > 2.5Q_{\text{Cyg A}}$, and is presently active, as evidenced by the powerful unresolved VLBI radio core. By contrast, the high-$Q$ source Cygnus A lies at the low end of the quasar range of $L_{\text{bol}}$ and is a small $L_{\text{bol}}/L_{\text{Edd}}$ and is presently active, as evidenced by the jet’s extending from the lobes to within a few light-years of the central black hole (see Fig. 1.10 of Punsly 2001). Using a large sample of quasars, in Figure 2 it was shown that $L_{\text{bol}}$ is uncorrelated with $Q$. Hence, the diverse values of $Q/L_{\text{bol}}$ in Cyg A and PKS 0743–67 should not be unexpected. It appears that to first order, the parameters $L_{\text{bol}}/L_{\text{Edd}}$ and $L_{\text{bol}}$ are unrelated to the intrinsic quasar jet power. This is consistent with the observation that 90% of quasars are radio-quiet, from the most luminous quasars down to the quasar–Seyfert 1 dividing line. Consider the wide range of $L_{\text{bol}}$ in quasars that are associated with very powerful jets. It is argued in Semenov et al. (2004) and Punsly (2001) that a significant large-scale magnetic flux near a rapidly spinning black hole is the missing ingredient and is the primary determinant of FR II quasar jet power, not the accretion flow.

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