HIGH JET EFFICIENCY AND SIMULATIONS OF BLACK HOLE MAGNETOSPHERES

BRIAN PUNSLY
4014 Emerald Street No. 116, Torrance, CA 90503, USA; brian.punsly@comdev-usa.com

AND

ICRANet, Piazza della Repubblica 10, Pescara 65100, Italy; brian.punsly@verizon.net

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ABSTRACT

This Letter reports on a growing body of observational evidence that many powerful lobe-dominated (FR II) radio sources likely have jets with high efficiency. This study extends the maximum efficiency line (jet power ∼25 times the thermal luminosity) defined in Fernandes et al. so as to span four decades of jet power. The fact that this line extends over the full span of FR II radio power is a strong indication that this is a fundamental property of jet production that is independent of accretion power. This is a valuable constraint for theorists. For example, the currently popular “no-net-flux” numerical models of black hole accretion produce jets that are two to three orders of magnitude too weak to be consistent with sources near maximum efficiency.

Key words: accretion, accretion disks – black hole physics – galaxies: active – galaxies: jets – magnetohydrodynamics (MHD)

1. INTRODUCTION

Relativistic jets emanating from active galactic nuclei (AGNs) exist in a variety of strengths. Most quasars are radio-quiet objects that have either no measurable jets or jets that are so weak that they often cannot propagate out of the host galaxy. About >10% of AGNs have highly luminous radio jets of which ∼20% are classic FR II radio sources defined by jets that propagate hundreds of kpc, terminating in lobes of plasma with similar linear extent (deVries et al. 2006). The energy flux in these jets, Q, can be enormous with many independent estimates finding long-term time averages, Q ≥ 10^{47} $\text{erg s}^{-1}$ (Willott et al. 1999; Punsly 2007). These jets are not perfectly steady, so there are episodes in which the instantaneous power, Q(t), must be even larger. In this Letter, an attempt is made to expand on and consolidate the evidence for large jet power that has been accumulating in the literature since 2006.

The second section quantifies Q relative to the dynamics of the accreting gas. From observations, one can estimate the ratio of Q to the thermal luminosity of the accretion flow, L_{bol}, defined as R ≡ Q/L_{bol} or with respect to the mass accretion rate Q ≡ η_{th} M c^2, where η is called the efficiency. Strong radio sources can be described in terms of a concept of maximum efficiency for which η is called the efficiency. The maximum jet efficiencies implied by the expressions of term of a concept of maximum jet efficiency that was introduced by Fernandes et al. (2011), i.e., a maximum value of R or η_{th} for radio jets. The maximum jet efficiencies implied by various theoretical models are compiled. The results are analyzed for consistency and are critically examined in terms of the assumptions and limitations of each method.

In the third section, we discuss the high-efficiency sources from Section 2 in the context of current numerical work, the three-dimensional (3D) numerical simulations of magnetohydrodynamic (MHD) accretion flows around black holes with no net magnetic flux. The nexus between these simulations and observation is that the simulated Q is always expressible in terms of M c^2 by all research groups. By making reasonable assumptions about η_{th}, the thermal efficiency (L_{bol} ≡ η_{th} M c^2), as derived by accretion disk theory and new turbulent MHD simulations, one can compare the observations with the simulations.

2. EVIDENCE FOR HIGH JET EFFICIENCY

Ever since the seminal work of Rawlings & Saunders (1991), astrophysicists have been trying to estimate the enormous energy flux that feeds the radio lobes in FR II radio sources and relate it to the thermal luminosity of the accretion flow. The three most viable options for estimating Q are either based on the low-frequency (151 MHz) flux from the radio lobes on 100 kpc scales (e.g., Willott et al. 1999), or the work done creating the cavities that are carved out of the intracluster medium by the expanding radio lobes (e.g., Birzan et al. 2004; McNamara et al. 2011), or models of the broadband Doppler boosted synchrotron and inverse Compton radiation spectra associated with the relativistic parsec scale jet (e.g., Ghisellini et al. 2010). Each method has its advantage. The 151 MHz method is the most widely applicable, all that is needed is a radio spectrum. A disadvantage is that it involves long-term time averages, Q, that do not necessarily reflect the current state of quasar activity. The second method is also not contemporaneous, yet more accurate in principle than the first, but is restricted to low-redshift sources with deep X-ray observations. The last method is contemporaneous, so one can define a directly interpretable ratio of jet to accretion thermal power, R(t) ≡ Q(t)/L_{bol}. However, one is forced to deal with estimating the large Doppler enhancement factor, δ, which is a potential source of large uncertainty (the jet luminosity scales like δ^4). In this section, using these three methods, we expand on the notion of a maximum jet efficiency defined in Fernandes et al. (2011) that is based on 151 MHz flux estimate.

In Figure 1, the black squares are a scatter plot, Q/L_{bol} versus L_{bol}, of the complete sample of FR II narrow-line radio galaxies (NLRGs) from Fernandes et al. (2011). The low-frequency-selected sample is limited to 0.9 < z < 1.1, as a compromise between having sufficient cosmic volume to find strong radio sources and being sufficiently close so that these sources can be detected in the IR. L_{bol} ≈ 8.5 ν L_ν(12 μm) is computed from the IR luminosity at 12 μm (Richards et al. 2006). They define a diagonal line at R ≡ Q/L_{bol} = 25 (the black solid line in Figure 1), the maximum efficiency line. The dashed blue vertical line represents the approximate dividing line between Seyfert 1...
galaxy and quasar luminosity ($M_V = -23$). The dashed vertical orange line represents the dividing line between solely Seyfert 1 galaxies and a mixture of low-luminosity AGNs (LLAGNs) and weaker Seyfert 1 galaxies (Ho 2005). In contrast to Seyfert 1 galaxies and quasars, the LLAGNs do not have a strong “blue bump” in their spectra, the signature of strong thermal emission from an accretion flow (Ho 2005; Sun & Malkan 1989). The LLAGNs are estimated to have inefficient modes of accretion, expressed in terms of the Eddington luminosity as $L_{bol}/L_{Edd} < 10^{-5}$ in contrast to quasars and Seyfert galaxies which typically have $10^{-2} < L_{bol}/L_{Edd} < 1$ (Ho 2005; Sun & Malkan 1989). Thus, Figure 1 indicates that the NLRGs in the Fernandes et al. (2011) sample are likely to have a central black hole in a high-efficiency accretion state typical of a quasar or Seyfert 1 galaxy, but the optical/UV core is hidden.

One can expand the Fernandes et al. (2011) treatment to a larger range of black hole accretion states and jet power, by considering the low-redshift sample of IR observations of FR II NLRGs of Ogle et al. (2006). The same IR bolometric correction and $Q$ estimators can be used as in Fernandes et al. (2011). They noticed a diagonal boundary in a scatter plot of IR luminosity versus 178 MHz flux which is similar to the maximum efficiency line. In Figure 1, the orange circles represent these “weak mid-IR sources” from Ogle et al. (2006). Note how well the orange circles respect the maximum efficiency line. The trend now extends below the upper limit of LLAGN luminosity. Since Seyfert 1 galaxies also exist at such luminosity, and the trend looks smooth, there does not seem to be any evidence of a change in accretion mode for FR II NLRGs at $L_{bol} < 6 \times 10^{43}$ erg s$^{-1}$.

A small sample of FR II NLRGs from McNamara et al. (2011) is also plotted as blue triangles in Figure 1. In this sample, $Q$ is estimated by an independent method, the work done to create large bubbles in the intracluster medium. The IR luminosity is estimated from the data in Shi et al. (2005) with the synchrotron component subtracted off and the IR bolometric correction is from Richards et al. (2006). These data also conform with the maximum efficiency line concept.

Another method of quantifying a jet as highly efficient is to choose sources with $Q_{Edd} = Q/L_{Edd} > 1$. This is an extreme condition since $L_{bol}/L_{Edd} > 1$ quasars are either extremely rare or as are often argued nonexistent (Marconi et al. 2009; Netzer 2009). Thus, the $Q_{Edd}$ sources would almost certainly have instantaneous episodes with $R(t) > 1$. A small sample of these sources were found in Punsly (2007c). These are the red diamonds in Figure 1 and overlap the high end of the Fernandes et al. (2011) scatter. They are lobe-dominated quasars for which UV continuum emission and broad-line strengths were used to estimate $L_{bol}$, and 151 MHz flux was used to estimate $Q$. Note that the Fernandes et al. (2011) and the Punsly (2007c) samples are consistent with a maximum value of $Q \geq 10^{37}$ erg s$^{-1}$ that seems to make the maximum efficiency line bend over toward the equipartition line defined by $R = 1$.

The fact that $Q$ seems to reach a maximum does not necessarily mean that there are not even larger instantaneous jet powers. By fitting broadband blazar spectra, from the radio band to gamma rays, Ghisellini et al. (2010) believe that they have a method to extract the jet power within a few light years of the central black hole in a blazar—almost contemporaneous on cosmic timescales. The model is one of a highly relativistic magnetized plasmoid propagating in the radiation environment of the quasar. The inverse Compton emission is necessarily modeled simultaneously with an accretion disk model of the “big blue bump” for each source. The method is a bit controversial because of the large Doppler enhancement in blazar jets and the uncertainty that it introduces in the intrinsic luminosity. The appeal of this method is that it is completely independent of the techniques used for the other data in Figure 1. In order not to clutter Figure 1, only the $R(t) > 2$ quasars are plotted. These $Q(t)$ estimates (that are plotted as dark blue circles) also respect the maximum efficiency line with only two outliers.

None of the methods used to create the data sets in Figure 1 is a rigorous justification of the maximum efficiency line in isolation. However, the agreement that is achieved by these independent experiments is strong scientific evidence in support of the notion of the maximum efficiency line found in Fernandes et al. (2011) that is now extended to over four decades in $Q$. The fact that this line extends over the full span of FR II radio power is an indication that this is a fundamental property of jet production that is independent of accretion power. Another important aspect of Figure 1 is that powerful FR II radio sources are plentiful in the range $1 < R < 25$. Furthermore, since jet power is not steady over the lifetime of the QSO, many of the sources below the $R = 1$ line likely have episodes in the

![Image](image-url)
Figure 2. Comparison of 3D numerically simulated data with the constraints on jet power in terms of accretion rate ($Q/Mc^2$) imposed by observations. The “region of high jet efficiency” corresponds to the region between $R = 1$ and $R = 25$ in Figure 1.

high-efficiency range $1 < R < 25$, i.e., this is not an aberrant or outlier state of jet activity.

3. THEORETICAL DISCUSSION

In the past, we were forced to compare a scatter plot like Figure 1 to theory by means of parametric models. However, these models have a large unknown, the strength of the magnetic field (Blandford & Znajek 1977; Meier 2001; Nemmen et al. 2007). The ability of a turbulent accretion disk to transport and sustain large-scale magnetic flux is controversial, rendering the flux distribution as a major unknown (Ghosh & Abramowicz 1997; Livio et al. 1999; Rothstein & Lovelace 2008; Reynolds et al. 2006). Long-term MHD simulations in a generally relativistic background can at least provide a self-consistent magnetic field distribution (be it not necessarily unique). Thus, the best tools that we have to investigate the central engine of radio-loud AGNs, without the overriding uncertainty of the field distribution, are the current battery of long-term 3D numerical simulations of black hole accretion systems (McKinney & Blandford 2009; Beckwith et al. 2008b; Hawley & Krolik 2006; Krolik et al. 2005; Fragile et al. 2007). The initial state is a thick torus of gas in equilibrium that is threaded by concentric loops of weak magnetic flux that foliate the surfaces of constant pressure. There is no net magnetic flux in these simulations. If the loops are configured in the same orientation and are poloidal and not toroidal then the leading edge that accretes will deposit a net poloidal flux on the black hole and a jet forms (Beckwith et al. 2007a), and Punsly et al. (2010) have a strong ergospheric disk jet (as indicated in the Figure 2) that suppresses the B-Z jet (Punsly 2007b). To find the power of a pure B-Z jet, the raw data from two simulations (that were used for ray tracing in Beckwith et al. 2008a) that were generously provided to this author by John Hawley, KDEb ($a/M = 0.99$) and KDJd ($a/M = 0.99$), were reduced. These simulations were different from KDE and KDJ because the code was modified to include artificial diffusion terms in the equations of continuity, energy conservation, and momentum conservation as described in De Villiers (2006). The resultant numerical diffusion suppressed the ergospheric disk jet, giving a more pristine estimate of the B-Z efficiency than can be obtained from KDE and KDJ. The simulation, KDH ($a/M = 0.95$), has a weak ergospheric disk jet so the estimates for the B-Z power are straightforward (Punsly 2007b). The mechanical energy flux is included in these estimates which can

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1 Using the larger simulated $\eta_{th}$ values at high spin rates will just elevate the equipartition and maximum jet efficiency lines in the plot slightly, even farther from the already nonconforming simulation data.
be non-negligible in some of the high spin simulations (Punsly 2007b). There are no accretion disk jets that form in any of these simulations.

Note that all of the no-net-flux simulations in Figure 2 fall below the region of high jet efficiency, $1 < R < 25$ from Figure 1, being two to three orders of magnitude less efficient than the most efficient jets. The only simulations that are close are the high spin ergospheric disk jets from KDE and KDJ. But they are still just below the region of high jet efficiency. Can the $a/M = 0.998$ case be optimized to reproduce the high jet efficiency? To answer this, we explore the curious situation that the ergospheric disk jet in KDE is not much stronger than KDJ contrary to the theory (Punsly 2008). A spin-dependent expression for the ergospheric disk jet Poynting flux (approximately $Q$ in this discussion), $S$, can be approximated as

$$S \approx N(B^2)[(SA)\Omega_H]^2,$$

where the vertical magnetic field in the ergospheric disk is $B$, the surface area of the ergospheric disk is $SA$ and the field line angular velocity scales with the horizon angular velocity, $\Omega_H$, and $N(B^2)$ is a normalization constant (Punsly 2008). The theory does not fix the distribution on $B$ in time and space and SA of the jet producing region that will occur in a given numerical simulation. In Equation (1), the empirical distribution of $B^2$ is absorbed in the normalization constant $N$. In principle, SA of the equatorial plane in the ergosphere changes very rapidly with spin for $a/M \lesssim 1$, hence the expectation of significantly larger jet power for KDE than for KDJ (Punsly 2008). Setting $N = 0.0028$ in Equation (1) creates the "doubly truncated ergospheric disk," a two-parameter ($SA$ and $\Omega_H$) fit to the simulated data in Figure 2. It is doubly truncated because the jet does not fill the entire ergospheric equatorial plane, but is restricted to the region $r_m < r < 1.50M$, where $r_m$ is the inner calculational boundary (located outside the event horizon, $r_m > R_H$). For some unknown reasons, the vertical flux that creates the jet dies off rapidly beyond $r = 1.50M$ in the simulations. Yet, in principle, an ergospheric disk can exist throughout the ergosphere $R_H < r < 2M$ (Punsly 2008). The simple two-parameter equation (1) (with $N$ fixed) is a reasonable fit to the numerical data (the three blue dashes in Figure 2) and explains the dependence of $S$ on $a$. Equation (1) implies that the reason KDE is not much stronger than KDJ is because $SA$ in the computational grids of the two simulations is virtually identical ($\approx 18M^2$ in geometrized units). If one were to move $r_m$ in KDE inward so that it is normalized to the KDJ scaling of $r_m$(KDJ) $= 1.203M = 1.054r_H$, one expects a larger SA and therefore a larger jet power (i.e., change the inner calculational boundary in the numerical grid of KDE from $r_m$(KDE) $= 1.175M$ to $r_m = 1.054r_H = 1.12M$). $SA$ is increased to $23.3M^2$ for $a/M = 0.998$ if $r_m = 1.12M < r < 1.5M$. The black dashed curve in Figure 2 is a plot of the predicted $S$ from Equation (1) with the empirically fit value of $N = 0.0028$ from the simulated data and normalized numerical grids defined by $r_m = 1.054r_H$. Even with the enhancement in power for $a/M = 0.998$, with a renormalized grid, the curve barely penetrates the region of high jet efficiency. Based on this analysis of this most efficiently known simulated jet, it is concluded that any attempt to optimize the no-net-flux scenario will still be too weak to explain the region of high jet efficiency in Figure 2.

4. CONCLUSION

This study shows that the maximum jet efficiency condition, $R \approx 25$, extends over the entire range of known FR II jet powers. It is demonstrated that the no-net-flux accretion numerical models cannot explain the large number of high-efficiency jets with $R > 1$. Furthermore, the initial no-net-flux state in the considered simulations is configured to yield the maximum jet power. The no-net-flux situation is even more nonconforming if the initial field is not composed of loops of the same vertical orientation, but randomly oriented. In this case, the jet power can be reduced by three orders of magnitude or more (Beckwith et al. 2008b). It is concluded that the no-net-flux models are not suitable numerical models for powerful radio-loud quasars. Clearly, some other dynamical element is needed in the setup of the simulations. Perhaps it is the accretion of a large reservoir of large-scale magnetic flux as in Igumenshchev (2008). This can have two relevant effects. First, the ergospheric disk power should be greatly increased (Punsly et al. 2010). Also, unlike the no-net-flux simulations, a magnetized accretion disk forms in Igumenshchev (2008).

Finally, note that Figure 2 does not indicate that large "a" acts like a switch that transforms a radio-quiet black hole accretion system into one with high jet efficiency. The only thing that looks remotely like a switch in Figure 2 is the ergospheric disk. This conclusion is in accord with the B-Z switch model of Tchekhovskoy et al. (2010) that requires radio-quiet (loud) quasars to have spins $a \approx 0.15$ ($a \approx 1$). This scenario seems unlikely, radio-quiet quasars are typically selected by optical/UV luminosity and therefore should have elevated (mass and angular momentum) accretion rates and large $a$ (Bardeen 1970). The magnetospheres in Tchekhovskoy et al. (2010) are shaped by a boundary condition. There is no accretion in the simulation, therefore there is no calibrated measure of the jet strength with respect to $Mc^2$.

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