On The Efficiency of Jet Production in Radio Galaxies

Rodrigo S. Nemmen,1,2,3,4⋆ Alexander Tchekhovskoy5,6,7

1 Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, São Paulo, SP 05508-090, Brazil
2 NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
3 Center for Research and Exploration in Space Science & Technology (CRESST)
4 Department of Physics, University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA
5 Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA
6 Department of Astronomy and Theoretical Astrophysics Center, University of California, Berkeley, CA 94720-3411, USA
7 NASA Einstein Fellow

Accepted 2014 Month 00. Received 2014 June 17; in original form 2014 March 31

ABSTRACT
The mechanisms that produce and power relativistic jets are fundamental open questions in black hole (BH) astrophysics. In order to constrain these mechanisms, we analyze the energy efficiency of jet production η based on archival Chandra observations of a sample of 27 nearby, low-luminosity active galactic nuclei. We obtain η as the ratio of the jet power $P_{\text{jet}}$, inferred from the energetics of jet powered X-ray emitting cavities, to the BH mass accretion rate $\dot{M}_{\text{BH}}$. The standard assumption in estimating $\dot{M}_{\text{BH}}$ is that all the gas from the Bondi radius $r_B$ makes it down to the BH. It is now clear, however, that in reality only a small fraction of the gas reaches the hole. To account for this effect, we first compute $\dot{M}_{\text{BH}}$ from the gas temperature and density profiles estimated around a few tens of $r_B$. Then, we account for the gas lost on the way to the BH via the standard disk mass-loss scaling, $\dot{M}(r) \propto (r/r_B)^{s} \dot{M}_{\text{BH}}$. This leads to much lower values of $\dot{M}_{\text{BH}}$ and higher values of η than in previous studies. If hot accretion flows are characterized by $0.5 \leq s \leq 0.6$ – on the lower end of recent theoretical and observational studies – then dynamically-important magnetic fields near rapidly spinning BHs are necessary to account for the high η ≈ 100−300 per cent in the sample. Moreover, values of $s > 0.6$ are essentially ruled out, or there would be insufficient energy to power the jets. We discuss the impact of a significant extra cold gas supply besides X-ray bright gas at $\sim r_B$ on our estimates and the implications of our results for the distribution of black hole spins.

Key words: accretion, accretion discs – black hole physics – galaxies: active – galaxies: jets – X-rays: galaxies.

1 INTRODUCTION
Collimated jets are often observed emanating from astrophysical compact objects accreting magnetized plasma, spanning a huge range of masses and diverse environments: black hole binaries, active galactic nuclei (AGNs), gamma-ray bursts, neutron stars and young stellar objects (Belloni et al. 2010). Out of these classes of objects, the most relativistic outflows are produced by the black hole engines in microquasars, radio galaxies and gamma-ray bursts. Despite a wealth of data and abundance of theoretical models, the exact details behind the production of these relativistic jets remain elusive.

⋆ E-mail: rodrigo.nemmen@iag.usp.br

One of the most popular ideas for the powering of relativistic jets is the Blandford-Znajek (BZ) mechanism: the idea that the free energy associated with black hole spin can be tapped by large scale magnetic field lines threading the horizon and carried away from the black hole in an electromagnetic jet (Blandford & Znajek 1977; Meier 2012). The basic tenets of this model have been confirmed in numerical simulations (e.g., Semenov, Dyadechkin & Punsly 2004; Tchekhovskoy, McKinney & Narayan 2012). There is circumstantial evidence supporting the BZ model in observations of stellar mass black holes, through a correlation between the 5 GHz radio luminosity of the transient ballistic jet launched in the near-Eddington accretion state (Fender & Belloni 2012) – which is a proxy of the jet power – and the spin parameter estimated via continuum fitting (Narayan & McClintock 2012; Steiner, McClintock & Narayan 2013) but...
Observational clues for the nature of jet production in active galactic nuclei (AGN) are less clear. Even though spin has been invoked to explain the radio-loudness distribution of AGNs (e.g., Sikora, Stawarz & Lasota 2007; Tchekhovskoy, Narayan & McKinney 2010) as well as various other observations (e.g., Gardner & Done 2014), the actual estimates of supermassive black hole (SMBH) spins in radio-loud AGN – crucial for probing BZ mechanisms – are currently affected by considerable uncertainties and/or are strongly model-dependent (e.g., Nemmen et al. 2007; Martinez-Sansigre & Rawlings 2011; King et al. 2013a; Daly & Sprinkle 2014). Given the small internal scatter in the correlation between the optical luminosity from the accretion disk and the lobe radio luminosity of FR II radio galaxies, van Velzen &Falcke (2013) concluded that either these quasars have very similar (high) spins or, alternatively, jet spin powering is not relevant at all. In the context of recent evidence for near-maximum spin of many jet-less SMBHs (Reynolds 2013), this result might actually suggest the opposite: that jet-producing SMBHs are also powered by near-maximally spinning BHs.

One promising approach for probing the physical conditions behind jet launching in AGNs is to evaluate the energy efficiency of jet production which we define as $\eta_{\text{jet}} \equiv P_{\text{jet}}/(M_\text{BH}c^2)$, given appropriate measurements of the jet power $P_{\text{jet}}$ and the mass accretion rate onto the black hole $M_\text{BH}$. Estimating the efficiency of jet production gives us an indirect diagnostic of the jet formation process and the source of jet power. For instance, high efficiencies would suggest spin powering and possibly dynamically important magnetic fields near the horizon (e.g., Tchekhovskoy, Narayan & McKinney 2011; Zamaninasab et al. 2014) as opposed to an outflow from an accretion disk (Blandford & Payne 1982; Ghosh & Abramowicz 1997; Livio, Ogilvie & Pringle 1999). $\eta_{\text{jet}}$ is also relevant for our understanding of the “radio mode” of AGN feedback in massive early-type galaxies (e.g., Allen et al. 2006; McNamara & Nulsen 2007; Fabian 2012) and it impacts the cosmological evolution and growth of massive black holes (e.g., Fanidakis et al. 2011; Volonteri 2012).

One of the most straightforward methods of estimating the jet power for radio-loud AGNs is by using the cavities observed in Chandra images of the environment of the galaxy as calorimeters of the jet; the jet power is then the energy required to create the cavity divided by the time required to inflate it (e.g., Dunn & Fabian 2004; Birzan et al. 2004; Dunn, Fabian & Taylor 2005; Allen et al. 2006; McNamara & Nulsen 2012). In the case of SMBHs, a reliable and clean way of estimating $M_\text{BH}$ is by using Chandra observations that probe the temperatures and densities of the plasma at the sphere of influence of the black hole (i.e. the Bondi radius $r_B$). Then, using the simple Bondi model (Bondi 1952) – which ignores angular momentum, viscosity, etc. – the inflow rate at the Bondi radius $\dot{M}_B$ can be estimated (e.g., Di Matteo et al. 2005).

Various works estimated $P_{\text{jet}}/(M_\text{BH}c^2)$ using the methods outlined above. For instance, Allen et al. (2006) observed that $P_{\text{jet}} \sim 0.1 \text{ few per cent } M_\text{BH}c^2$ (cf. also Merloni & Heinz 2007; Balmaverde, Baldi & Capetti 2008; Vattakunnel et al. 2010; Russell et al. 2013; McNamara, Rohanizadeh & Nulsen 2011) found that $P_{\text{jet}} > M_\text{BH}c^2$ for the most powerful radio galaxies, i.e. Bondi accretion is generally unable to provide enough power to the jets in these systems (cf. also Raferty et al. 2006). It should be noted that most of the systems analyzed by McNamara et al. are quite distant, such that large extrapolations are required in order to derive the Bondi rates leading in many cases to several orders of magnitude uncertainty in the Bondi rates.

Therefore, while the Bondi rate is simple and straightforward, it is a crude estimator of the mass accretion rate onto the black hole. The simple Bondi model neglects important phenomena in the accretion flow, most importantly rotation and viscosity/turbulence in the plasma. Important advances in our understanding of accretion theory have been made in the last decade. For instance, it was realized that not all gas fed at the Bondi radius may necessarily accrete onto black holes fed at low rates (Narayan & Yi 1994; Blandford & Begelman 1999). In fact, recent numerical simulations (e.g., Yuan, Wu & Bu 2012; Yuan, Bu & Wu 2012; Li, Ostriker & Sunyaev 2013), analytical models (e.g., Begelman 2012) and X-ray observations of the two low-luminosity AGNs for which we can currently resolve the Bondi radius with Chandra – A 3 C 78 and NGC 3115 (Wong et al. 2013; Wang et al. 2013) – indicate that in actuality the majority of the gas is lost in-between the Bondi radius and the event horizon in radiatively inefficient accretion flows (RIAFs; cf. Yuan & Narayan 2014 for a review), presumably in the form of winds. Nevertheless, previous attempts at estimating the efficiency of jet production using “X-ray cavity calorimetry” and Bondi rates have neglected these important advances in accretion theory. In this work, we set to estimate the efficiency of jet production from SMBHs using current constraints on jet power and inflow rate at the Bondi radius, as estimated from X-ray observations. We collate all available information on these observations and construct a sample of SMBHs accreting at sub-Eddington levels in radio galaxies. We then make use of the observationally-motivated advances in the understanding of RIAFs – taking into account particularly the issue of mass-loss – in order to relate the outer boundary conditions at $r_B$ to the inner boundary conditions near the event horizon and re-evaluate jet kinetic efficiencies. Our improved estimates place important constraints on the conditions of jet formation in SMBHs.

Our paper is organized as follows. In Section 2 we describe the sample of 27 radio galaxies that we used and the data. Section 3 evaluates the updated constraints on the relation between jet power and Bondi inflow rate implied by our sample. In Section 4 we describe the new estimates of the efficiency of jet production, taking into account RIAF models. We discuss the implications of our results as well as the caveats involved in it. We conclude by presenting a summary of our results in Section 5.

2 OBSERVATIONS

We searched the literature for Chandra-observed radio galaxies that show evidence for jet-inflated X-ray cavities in their central regions. These cavities can be used as calorimeters to estimate the jet power. We concentrate on those galaxies that in addition have measurements of gas tem-
temperature and density profiles and use them to estimate the Bondi inflow rate due to hot diffuse gas. We find about 53 X-ray luminous radio galaxies for which both estimates of jet power and Bondi rates are available Allen et al. 2006, Rafferty et al. 2006, Balmaverde, Baldi & Capetti 2008, Rafferty et al. 2013).

We estimated the jet powers as $P_{\text{jet}} = E_{\text{acc}} / \tau_{\text{acc}}$, where $E_{\text{acc}}$ is the energy required to create the observed cavities and $\tau_{\text{acc}}$ is the age of the cavity (e.g., Churazov et al. 2002, Birzan et al. 2004, Dunn & Fabian 2004, Dunn, Fabian & Taylor 2005, Allen et al. 2006, McNamara & Nulsen 2012).

The usual assumption in deriving $E_{\text{acc}}$ is that the cavities are inflated slowly such that $E_{\text{acc}} = 4 PV$ where $P$ is the thermal pressure of the surrounding X-ray emitting gas, $V$ is the volume of the cavity and the cavity is assumed to be filled up with relativistic plasma. The age of the cavity is usually assumed to be the sound-crossing timescale $\tau_{\text{acc}} = t_{\text{c}} / c_{s}$ where $D$ is the distance of the bubble centre from the black hole and $c_{s}$ is the adiabatic sound speed.

We estimated the rate of gas inflowing towards the black hole at large distances in the framework of the Bondi model which is the most simple configuration describing the accretion of gas onto a central black hole Bondi 1952: the model assumes a spherically symmetric flow with negligible angular momentum. The resulting mass inflow rate – often referred to as the Bondi accretion rate – can be written as $M_{\text{B}} = \pi \rho \nu_{\lambda} r_{B}^{2}$, where $r_{B} = 2GM/c_{s}^{2}$ is the accretion radius (or Bondi radius), $G$ is the gravitational constant, $M$ is the black hole mass, $c_{s}$ is the sound speed of the gas at $r_{B}$, $\rho$ is the density of gas at $r_{B}$ and $\lambda$ is a numerical coefficient that depends on the adiabatic index of the gas. This estimate is frequently used in studies of the central X-ray emitting gas in galaxies (e.g., Wang et al. 2013, Wong et al. 2014).

The values of $M_{\text{B}}$ for the systems were calculated from the gas temperature and density profiles measured with Chandra. The Bondi radius is not resolved in our sample and the appropriate density and temperature are determined by extrapolating the observed data, typically by a factor of 3 or greater, in radius (e.g., Russell et al. 2013).

Many of the systems we found in the literature are located at considerable distances with the Chandra spatial resolution $r_{\text{min}}$ considerably exceeding the accretion radius; and such these distant galaxies require a considerable extrapolation into the Bondi sphere making their Bondi accretion rates highly uncertain. In order to select only the sources with the most accurate estimates of $M_{\text{B}}$, we adopt the selection criterion in which we only keep galaxies with $r_{\text{min}}/r_{B} < 30$. As a result of applying our selection criterion, most of the sample of Rafferty et al. 2006 is excluded from our analysis because it consists mostly of distant sources.

Our final sample contains 27 radio galaxies hosting low-luminosity AGNs spanning 3 orders of magnitude in accretion and jet power. Table 1 displays the galaxies, jet powers and Bondi rates, parametrized as Bondi powers ($P_{\text{B}} \equiv 0.1 M_{\text{B}} c^{2}$) as traditionally defined in the literature. There is a some overlap between the samples studied by Rafferty et al. 2006, Allen et al. 2006, Merloni & Heinz 2007 and Russell et al. 2013. Whenever there is overlap, we choose the observations of Russell et al. 2013 since they correspond to an improved analysis of the nine sources previously studied by Allen et al. 2006 with new, deeper Chandra exposures.

We note that Vattakunnel et al. 2010 provide estimates of jet power and $M_{\text{B}}$ for two additional radio-loud AGNs which do not display extended radio jets or X-ray cavities. For this reason, their jet power estimates are based on an indirect method that relies on using a correlation between core radio luminosity and jet power. In our sample, we only keep sources for which $P_{\text{jet}}$ was estimated directly from X-ray cavities used as jet calorimeters and hence we exclude the two AGNs studied by Vattakunnel et al. 2010.

In the analysis that follows, we accept the estimates of the previously estimated Bondi accretion rates and jet powers at face value. In section 5.3 we discuss the uncertainties involved in such estimates.

| Galaxy | log $P_{\text{B}}$ (erg s$^{-1}$) | log $P_{\text{jet}}$ (erg s$^{-1}$) | Ref. |
|--------|---------------------------------|---------------------------------|-----|
| 3C066B | $4.59 \pm 0.16$                 | $4.25 \pm 0.40$                 | b   |
| 3C083.1| $4.11 \pm 0.10$                 | $4.69 \pm 0.40$                 | b   |
| 3C270  | $4.41 \pm 0.16$                 | $4.77 \pm 0.40$                 | b   |
| 3C296  | $4.36 \pm 0.14$                 | $4.05 \pm 0.40$                 | b   |
| 3C449  | $4.48 \pm 0.12$                 | $4.66 \pm 0.40$                 | b   |
| 3C465  | $4.15 \pm 0.12$                 | $4.58 \pm 0.40$                 | b   |
| UGC6297| $4.68 \pm 0.31$                 | $4.83 \pm 0.40$                 | b   |
| UGC7386| $4.95 \pm 0.24$                 | $4.38 \pm 0.40$                 | b   |
| UGC7808| $4.81 \pm 0.32$                 | $4.53 \pm 0.40$                 | b   |
| UGC8745| $4.62 \pm 0.26$                 | $4.28 \pm 0.40$                 | b   |
| NGC1399| $4.45 \pm 0.14$                 | $4.34 \pm 0.40$                 | b   |
| NGC3557| $4.02 \pm 0.15$                 | $4.87 \pm 0.40$                 | b   |
| IC1459 | $4.48 \pm 0.09$                 | $4.89 \pm 0.40$                 | b   |
| IC4296 | $4.23 \pm 0.10$                 | $4.94 \pm 0.40$                 | b   |
| A2199  | $4.60 \pm 0.18$                 | $4.17 \pm 0.40$                 | r   |
| Cen    | $4.71 \pm 0.05$                 | $4.78 \pm 0.40$                 | r   |
| HCG62  | $4.70 \pm 0.22$                 | $4.78 \pm 0.40$                 | r   |
| M84    | $4.11 \pm 0.03$                 | $4.04 \pm 0.25$                 | r   |
| M87    | $4.30 \pm 0.10$                 | $4.29 \pm 0.20$                 | r   |
| M89    | $4.70 \pm 0.29$                 | $4.18 \pm 0.27$                 | r   |
| NGC507 | $4.30 \pm 0.35$                 | $4.28 \pm 0.24$                 | r   |
| NGC1316| $4.70 \pm 0.70$                 | $4.15 \pm 0.26$                 | r   |
| NGC4472| $4.95 \pm 0.12$                 | $4.85 \pm 0.24$                 | r   |
| NGC4636| $4.70 \pm 0.08$                 | $4.43 \pm 0.19$                 | r   |
| NGC5044| $4.30 \pm 0.18$                 | $4.21 \pm 0.16$                 | r   |
| NGC5813| $4.00 \pm 0.15$                 | $4.85 \pm 0.27$                 | r   |
| NGC5846| $4.11 \pm 0.25$                 | $4.20 \pm 0.24$                 | r   |

References: b: Balmaverde, Baldi & Capetti 2008; r: Russell et al. 2013.

Table 1. Sample of galaxies, Bondi accretion rates ($P_{B} \equiv 0.1 M_{B} c^{2}$) and jet powers.

---

1 In the notation of Rafferty et al. 2006, $r_{\text{min}}$ corresponds approximately to their semi-major axis of the central region used for extraction.
4 Nemmen

3 AN UPDATE ON THE RELATION BETWEEN BONDI RATES AND JET POWERS

Figure 1 displays the relation between the Bondi and jet powers for our sample, which can be compared with previous analysis based on smaller samples (e.g., Allen et al. 2006). We perform a power-law fit to the $P_{\text{jet}} - P_{\text{B}}$ data parametrized as a linear fit. We adopt the BCES $Y/X$ regression method (bivariate correlated errors and intrinsic scatter) (Akritas & Bershady 1996) which takes into account measurement errors in both the “$X$” and “$Y$” coordinates and the intrinsic scatter in the data. This method has been widely used in fitting datasets in the astronomical community (e.g., Allen et al. 2006; Nemmen et al. 2012; Sifón et al. 2013).

We obtain a best-fit model log $P_{\text{jet}} = A \log P_{\text{B}} + B$ where $A = 1.05 \pm 0.19$ and $B = -3.51 \pm 8.49$. Hence the correlation is consistent with a linear correlation within 1σ. The total scatter about the best-fit relation is $\approx 0.7$ dex. Figure 1 compares our best-fit model with the previous result of Allen et al. (2006) and illustrates that the Allen et al. relation is substantially different from the present one: for a given value of $M_{\text{BH}}$, the mean jet powers predicted by the Allen et al. relation are larger than the ones predicted by our fit by $\approx 0.5$ dex on average. We find a significantly larger scatter in the $P_{\text{B}} - P_{\text{jet}}$ correlation compared to the 0.1 dex scatter inferred by Allen et al. Therefore, the new relation between accretion rates and jet powers is considerably less tight than previously claimed, a result that was already noticed by Russell et al. (2013) within the scope of their analysis of 13 radio galaxies.

On average, $P_{\text{jet}}/(M_{\text{BH}}c^2) \sim 1\%$; in other words, 1% of the rest mass energy associated with the Bondi inflow rate is converted to jet power, in agreement with previous estimates (Allen et al. 2006; Merloni & Heinz 2007; Balmaverde, Baldi & Capetti 2008). In the next sections, we will improve on the estimate of the kinetic efficiency, taking into account improvements beyond the Bondi model in our understanding of the fate of gas accreting at a low-rate onto SMBHs.

4 EFFICIENCY OF JET PRODUCTION

Our underlying assumption is that given the boundary conditions provided by the Chandra observations of hot inflowing ISM, we can estimate the accretion rate onto the SMBH as some function $M_{\text{BH}} = M_{\text{BH}}(M_{\text{B}})$. As such, our estimates of the kinetic efficiencies translate to

$$\eta_{\text{jet}} = \frac{P_{\text{jet}}}{M_{\text{BH}}(M_{\text{B}})}c^2$$

where the superscript “obs” explicitly denotes the observationally derived quantities. We reiterate that $\eta_{\text{jet}}$ is defined in this way – in terms of the of the innermost accretion rate – because it gives the best diagnostic on scenarios for jet production such as the BZ jet powering.

The magnetized gas reaching galactic nuclei will unavoidably have angular momentum which will modify the character of accretion with respect to the simple Bondi model. The theory of accretion flows has advanced considerably in the last two decades and has established that turbulent viscosity – driven by magnetic fields – as well as outflows, radiative cooling and possibly convection, will certainly modify the character of accretion (e.g., Narayan & McClintock 2008; McKinney, Tchekhovskoy & Blandford 2012; Li, Ostrikov & Sunyaev 2013; Yuan & Narayan 2014 and references therein). Therefore, in order to obtain a more physically realistic estimate of the mass accretion rate onto SMBHs in our sample, our task now is to seek improvements over the simple Bondi mode which capture the more complex accretion physics in-between $r_B$ and the Schwarzschild radius $r_S \equiv 2GM/c^2$.

Given that the radio galaxies in our sample are all known to host highly sub-Eddington, low-luminosity AGNs (LLAGNs; Merloni & Heinz 2007; Balmaverde, Baldi & Capetti 2008; Russell et al. 2013), we adopt the RIAF framework. The RIAF model is widely regarded as the model that best accounts for the properties of low-luminosity AGNs including our Galactic Center (e.g., Yuan, Quataert & Narayan 2003; Wu, Yuan & Cao 2007; Wang et al. 2013; Nemmen, Storchi-Bergmann & Eracleous 2014; Yuan & Narayan 2014). We first estimate a likely upper limit on $M_{\text{BH}}$ based on the theory of “classical” RIAFs, according to which all gas supplied at $r_B$ is accreted onto the black hole and hence provides a lower limit on $\eta_{\text{jet}}$. Then, we incorporate in our estimates the current understanding of RIAFs and the likely mass-loss involved in-between $r_B$ and $r_S$. 
4.1 Kinetic efficiencies based on the ADAF model

Assuming that all gas supplied at the outer radius of the RIAF ends up being accreted onto the black hole, the RIAF solution simplifies to the particular case of advection-dominated accretion flows (ADAF; Narayan & Yi 1994) which corresponds to the viscous rotating analog of spherical Bondi accretion. The density profile in ADAFs is given by \( \rho \propto r^{-3/2} \) and the corresponding mass accretion rate onto the black hole is related to the Bondi rate as \( \dot{M}_{\text{ADAF}} \approx \alpha \dot{M}_B \) in the self-similar approximation where \( \alpha < 1 \) is the standard \( \alpha \) prescription for the viscosity (Shakura & Sunyaev 1973; Narayan & Yi 1994; Narayan 2002). The more detailed calculations of Narayan & Fabian (2011) result in \( \dot{M}_{\text{ADAF}} \approx 0.3 \dot{M}_B \) for \( \alpha = 0.1 \). Given the evidence presented by King, Pringle & Livio (2007), it is likely that \( \alpha \sim 0.1 - 0.4 \) (cf. also the numerical work of Penna et al. 2013). We adopt \( \alpha = 0.1 \) in our calculations, as widely used in the literature (e.g., Yuan & Narayan 2014).

Figure 2 shows the distribution of kinetic efficiency estimates for our sample where we assume the existence of a giant ADAF extending from \( r_p \) down to the black hole horizon with \( \alpha = 0.1 \) such that \( \dot{M}_B \approx 0.3 \dot{M}_B \). For reference, we also plot in this figure the resulting efficiencies for \( \alpha = 1 \), i.e. \( \dot{M}_{\text{ADAF}} \approx \dot{M}_B \) (Narayan & Fabian 2011) and the efficiency is simply given as \( \eta_{\text{jet}} = \dot{M}_{\text{ADAF}} / \dot{M}_{B} \). The typical uncertainty on \( \eta_{\text{jet}} \) was estimated by carrying out a Monte Carlo error propagation based on the uncertainties in \( \dot{M}_{\text{jet}} \) and \( \dot{M}_B \). The typical uncertainty on \( \eta_{\text{jet}} \) is \( \approx 0.4 \) dex (median 1 s.d. uncertainty).

For \( \alpha = 0.1 \), the median efficiency is \( \approx 2.8^{+0.6}_{-0.2} \% \) (\( \approx 1 \% \) for \( \alpha = 1 \)). The lowest and highest efficiencies in the sample are achieved by M87 (\( \approx 0.1 \% \)) and the Centaurus cluster (\( \approx 90 \% \)), respectively. The sample standard deviation corresponds to 0.6 dex. The accretion rates estimated with the ADAF model can be thought of as upper limits to the accretion rate onto the black hole, since it ignores mass-loss as we will discuss in the next section. Therefore, the kinetic efficiencies estimated in the framework of the ADAF model should be regarded as lower limits on the efficiency of jet production.

4.2 Kinetic efficiencies based on the ADIOS model

In the early analytical studies of RIAFs, Narayan & Yi (1994, 1995) noted that the positivity of the Bernoulli parameters throughout the flow may lead to the natural production of outflows, therefore introducing potential “gas leakage” in ADAFs (Blandford & Begelman 1999) proposed a simple scaling of accretion rate with radius taking into account mass-loss such that

\[
\dot{M}(r) = \dot{M}_0 \left( \frac{r}{r_0} \right)^{s-2},
\]

where \( \dot{M}_0 = \dot{M}_{\text{ADIOS}} \approx \alpha \dot{M}_B \) is the accretion flow and \( s \) is a “mass-loss” index in the range \( 0 \leq s < 1 \). The corresponding density profile is given by

\[
\rho(r) \propto r^{-3/2}, \quad \beta \equiv 3/2 - s
\]

for \( r_S \leq r \leq r_p \); \( s = 0 \) corresponds to a classical ADAF. Models with \( s > 0 \) have been called ADIOS (adiabatic inflow-outflow solution); recently Begelman (2012) favored \( s = 1 \) (or \( \beta = 0.5 \)).

The general scaling of equations 2 and 3 has been widely supported by the results of several magnetohydrodynamic numerical simulations of RIAFs (e.g., Stone, Pringle & Begelman 1999; Hawley & Krolik 2001; Igumenshchev, Narayan & Abramowicz 2003; Proga & Begelman 2003; McKinney, Tchekhovskoy & Blandford 2012; Yuan, Wu & Bu 2012; Sadowski et al. 2013). For instance, Yuan, Wu & Bu (2012) find 0.54 \( \lesssim \beta < 0.65 \) and 0.65 \( \lesssim \beta \lesssim 0.85 \) for \( r > 10r_S \), McKinney, Tchekhovskoy & Blandford (2012); Sadowski et al. (2013) find similar results, although they estimate \( s \) in the limited radial range \( 6r_S \leq r \leq 15r_S \) (McKenny, Tchekhovskoy & Blandford 2012) and 10r_S \( \lesssim r \lesssim 100r_S \) (Sadowski et al. 2013). Narayan et al. (2012) on the other hand find no strong mass-loss for \( r \lesssim 100r_S \), noting that they are not able to confidently estimate the amount of mass-loss for \( r \gtrsim 100r_S \) (cf. discussion in Yuan, Wu & Bu 2012).

On the observational side, \( s \) has been estimated with a variety of methods as ranging between \( 0.5 \) and \( 1 \) (e.g., Baganoff et al. 2003; Marrone et al. 2007; Wang et al. 2013; Wong et al. 2011, 2014; Kuo et al. 2014). Particularly, a lower limit on \( s \) has been estimated for Sgr A* as \( \approx 0.6 \) from an upper limit on \( \dot{M}_{\text{BH}} \) based on sub-millimeter Faraday rotation measurements (Marrone et al. 2007) and a previous Chandra X-ray spectrum observation (Baganoff et al. 2003). \( s \approx 1 \) has been estimated from fitting a more recent 3 Ms
median observation of the quiescent X-ray spectrum (Wang et al. 2013). For NGC 3115, fitting the density profile within 5" (i.e. within $r_B$) measured with Chandra results in $s = 0.88^{+0.20}_{-0.20}$ or $\beta = 0.62^{+0.20}_{-0.20}$, when fitting a wider range of radii (within 5") [Wong et al. 2014] find that $s \approx 0.5$ or $\beta \approx 1$ is roughly consistent with their results. Such high values of the mass-loss parameter suggest that the inflow is essentially balanced by outflowing gas with only a small fraction of inflow rate actually being accreted onto the hole.

Motivated by these theoretical and observational results, we adopt the ADIOS self-similar model in order to estimate $M_BH$ and $\eta_{jet}$. We adopt $M_BH \approx M(10r_B)$ which we keep $s$ free in order to explore its effect on the efficiencies. We adopt $\alpha = 0.3$ as discussed previously and $r_B = 10^3r_s$ which corresponds to the typical Bondi radius in elliptical galaxies (Di Matteo et al. 2003).

The median kinetic efficiency computed in section [1] with the ADIOS model as a function of $s$ is given by

$$\eta_{jet} = 2.8 \times 10^{0.1s} \% \tag{4}$$

where the $10^{0.1s}$ factor corresponds to the $[r_B/(10r_s)]^s$ ratio. In other words, the median $\eta_{jet}$ depends strongly on $s$. This can be easily understood: the stronger the mass-loss, the less mass ends up being accreted by the black hole. Therefore, for fixed $M_B$ and $P_{jet}$, the central engine must have a higher jet production efficiency in order to account for a fixed jet power as $M_BH$ decreases.

Figure 3 shows the efficiencies as a function of $s$ up to 500%. We can see that for $s = 0$ we recover the efficiencies estimated with the ADAF model. In order to appreciate a few notable results in this plot, let us denote the value of $s$ above which $\eta_{jet}$ exceeds a certain per cent efficiency $\epsilon$ as $s_\epsilon = s(\eta_{jet} > \epsilon)$. We will explore the three critical values $s_{100}$, $s_{100}$, and $s_{400}$ at which the median $\eta_{jet}$ exceeds three relevant efficiencies of energy extraction from accreting black holes. The maximal radiative efficiency of a thin accretion disk around a black hole with a spin $a = 0.998$ is $\approx 30\%$ (Thorne 1974); our sample efficiencies exceed 30% at the relatively low value $s_{30} = 0.26 \pm 0.04$. The jet power exceeds the rest mass energy associated with the accreting gas $M_BHc^2$ (i.e. $P_{jet} > M_BHc^2$) at $s_{100} = 0.39 \pm 0.16$. Lastly, for a mass-loss index of $s_{400} = 0.51 \pm 0.16$, the kinetic efficiency of the sample exceeds $300\%$. This is the highest kinetic efficiency achieved so far in current general relativistic magnetohydrodynamical simulations (GRMHD) of jet production from spinning black holes accreting through magnetically arrested flows (Tchekhovskoy, Narayan & McKinney 2011; McKinney, Tchekhovskoy & Blandford 2012). It is worth noting that for $s = 1$ which is the value recently favored for Sgr A* from fitting the quiescent Chandra X-ray spectrum (Wang et al. 2013) as well as in recent ADIOS models (Begelman 2012), the resulting efficiencies considerably exceed $1000\%$; there is just not enough accreting rest mass energy or even black hole spin energy via BZ processes to power the jets. We will return to this point in section [5].

We show in Figure 3 the kinetic efficiencies estimated for the individual radio galaxies computed with the ADIOS model adopting $s = 0.5$ or $\beta = 1$. This value of $\beta$ is broadly consistent with the density profile within 5" around the Bondi radius for NGC 3115 (Wong et al. 2014) and is on the lower end of the estimates for Sgr A* (Baganoff et al. 2003, Marrone et al. 2007; Wang et al. 2013) and from recent numerical simulations (Yuan, Wu & Bu 2012; McKinney, Tchekhovskoy & Blandford 2012; Sadowski et al. 2013). For this value of the mass-loss index – which corresponds to $M_BH \sim 10^{-3}M_B$ – there are only four galaxies which have $\eta_{jet} < 100\%$ within 1σ: NGC 4472, M84, NGC 1399 and M87. All the other objects have jet powers which can exceed $M_BHc^2$ given the 1σ uncertainties; in particular, 11 of them have median efficiencies exceeding 300%.

5 DISCUSSION

The driving question that we set to attack in this work is to estimate the efficiency of jet production in radio galaxies in terms of the accretion rates at the BH, combining the most up to date observational constraints on the feeding of SMBHs and total jet powers with current constraints on RIAF density profiles. To this end, we compiled from the literature updated data on radio galaxies with both Bondi inflow rates – which can be used to estimate the hot gas inflow at the radius where the accretion flow begins – and jet powers estimated from X-ray cavities. Our sample was selected such that the Chandra spatial resolution $r_{min}$ is reasonably close to $r_B$ ($r_{min} < 30r_B$), in order to minimize possible extrapolations in radius which are required to derive the gas density and temperature at $r_B$, needed for computing $M_B$. Therefore, our sample consists of relatively nearby, low power, radio galaxies.

Our $M_Bc^2 - P_{jet}$ relation results in jet powers which are a factor of $\approx 3$ lower for a given Bondi rate when compared

© 2014 RAS, MNRAS 000.
We now discuss the possible implications of these results in the context of current scenarios for jet production around Kerr black holes. Then we critically assess our basic assumptions and explore the caveats and alternative interpretations.

5.1 The high efficiencies of jet production

As previously pointed out, the density profiles of RIAFs can be characterized by $\rho(r) \propto r^{-\alpha}$ with $0.5 \leq \beta \leq 1$ or equivalently $M(r) \propto r^{\beta}$ with $0.5 \leq s \leq 1$. Taking these constraints on $s$ and $\beta$ at face value for LLAGNs in radio galaxies, we find that the median jet production efficiency of our sample exceeds 300% for $s \geq 0.5$; even though a few sources at $s = 0.5$ would have $\eta_{\text{jet}} < 100\%$, 11 sources (41% of the sample) have efficiencies above 300%.

Is it possible at all to obtain such high efficiencies of energy extraction from accreting black holes? There are two viable mechanisms to power jets in galactic nuclei: (i) by tapping a fraction of the accretion energy and (ii) by confining a strong magnetic field around a spinning black hole and extracting spin energy from the hole via the BZ mechanism. In the case of an accreting Schwarzschild black hole, the energy extraction efficiency is of course limited to the rest mass energy associated with accreting material; if the black hole is surrounded by a magnetically arrested disk (hereafter MAD; Bisnovatyi-Kogan & Ruzmaikin 1974; Narayan, Igumenshchev & Abramowicz 2003) the efficiency could be close to 50% but not much higher. On the other hand, Kerr black holes do not suffer from this limitation. Since about 30% of the gravitational mass of a maximally rotating black hole is available to be tapped, the central engine could in principle tap the spin energy of the hole with efficiencies $> 100\%$.

Over the last few years, GRMHD simulations have shown that rapidly rotating black holes are able to produce relativistic jets via the BZ mechanism (e.g. Komissarov 2001; Koide et al. 2002; De Villiers, Hawley & Krolik 2003; McKinney & Gammie 2004; McKinney 2005; Hawley & Krolik 2006; Tchekhovskoy, Narayan & McKinney 2010; Tchekhovskoy, McKinney & Narayan 2012; Fragile, Wilson & Rodrigues 2012 and references therein). For instance, the simulations of Tchekhovskoy, Narayan & McKinney (2010, 2012) have demonstrated that $\eta_{\text{jet}} > 100\%$ can be attained provided that the black hole has a high spin and enough magnetic flux is accumulated near the horizon; i.e. the jet production efficiency through the BZ process is maximized when the black hole is flooded with large-scale magnetic flux and is accreting in the MAD state (cf. also Semenov, Dyadechkin & Punsly 2004). In fact, efficiencies as high as $\sim 350\%$ have been reported (McKinney, Tchekhovskoy & Blandford 2012; Tchekhovskoy, McKinney, Narayan & Blandford 2012).

If we accept the estimated jet powers and Bondi rates at face value as well as the emerging evidence that RIAFs are subject to considerable mass-loss as in the ADIOS scenario, it follows naturally that most radio galaxies produce jets with powers exceeding the rest mass energy of the material accreted onto the black hole. A likely explanation for such high $\eta_{\text{jet}}$ inferred in our analysis is the efficient tapping of the spin energy of SMBHs accreting in the MAD state.
state via BZ processes. In other words, the high values of $\eta_{\text{jet}}$ would constitute evidence that powerful, relativistic jets are produced during episodes of accumulation of magnetic flux around rapidly rotating black holes (Silk & Begelman 2013).

The interpretation above is supported by the recent results of Zamaninasab et al. (2014) who reported a tight correlation between the jet magnetic flux and the accretion disk luminosity for a sample of 76 radio-loud AGNs, comprised mostly of flat-spectrum radio quasars. The tight correlation obtained by Zamaninasab et al. is best explained if jet-producing SMBHs are accreting via MADs.

An alternative interpretation of our results is possible if the density profiles in radio galaxies are such that most of $M_B$ makes its way down to the horizon (Narayan & Fabian 2011). In the framework of the ADIOS model, values of the mass-loss index $s \leq 0.4$ would result in the more comfortable efficiencies $<100\%$. For instance, Narayan et al. (2012) find no significant outflows or convection in their GRMHD simulations of RIAFs for $r < 100r_S$. If this is the case, $\eta_{\text{jet}}$ would be much lower and easily accommodated by BZ models with moderate levels of magnetic flux (Nemmen et al. 2007), without requiring MADs. However, the possibility of $s \sim 0$ for radio galaxies has been disfavored by the recent sub-millimeter observations of M87, which allow a constraint on the Faraday rotation measure and hence on the accretion rate: $M_{\text{BH}} \lesssim 7 \times 10^{-3} M_B$ (Kuo et al. 2014). In the framework of self-similar ADIOS models, the Kuo et al. constraint on $M_{\text{BH}}$ suggests that $s > 0.4-0.5$ for M87 (considering $\alpha = 0.3-1$).

One additional possibility is that $M_B$ may not be an appropriate indicator of the inflow rates at the outer radius of the accretion flow. For instance, it could be that $M_B$ considerably underestimates the true inflow rate due to significant amount of cold gas at $\sim r_{\text{in}}$ and/or the gas inflow at such distances in elliptical galaxies is predominantly cold and chaotic as envisioned by Gaspari, Ruszkowski & Oh (2013). If that is the case, then the amount of gas reaching the black hole could increase significantly, compensating the ADIOS mass-loss. We discuss this possibility in more details in the section below.

5.2 Constraint on black hole spins and upper limit on RIAF mass-loss index

One of the advantages of the MAD model is that the inner flow properties are independent of the initial value of magnetic flux fed to the black hole (Tchekhovskoy & McKinney 2012, Tchekhovskoy, McKinney & Narayan 2012). MAD simulations result in the approximate dependence of jet production efficiency

$$\eta_{\text{MAD}} \approx 130 \left( \frac{h}{0.3} \right) a^2 \text{ per cent} \quad (6)$$

where $h \equiv H/r$ (Tchekhovskoy, McKinney & Nemmen, in preparation).

On the assumption that the radio galaxies in our sample

$$M = 21r_S$$

for practical purposes is approximately the same as our definition of $M_{\text{BH}} \equiv M(r = 10r_S)$.

Figure 5. Black hole spins that account for the jet efficiencies of the sample as a function of the mass-loss index $s$. SMBHs are assumed to be accreting in the MAD state (i.e. jet production efficiency is maximized). The jet efficiencies are estimated as in Fig. 3. The thick lines represent the spins that reproduce the median efficiency of the sample for two different accretion flow thicknesses. The shaded region corresponds to the scatter around the $H/r = 0.3$ model (cf. footnote 4).

are accreting in the MAD state during jet production ($\eta_{\text{jet}} = \eta_{\text{MAD}}$) with a self-similar density profile described by the ADIOS model, we can obtain a rough estimate of the spin distribution required to explain our estimated efficiencies, as a function of the mass-loss index. Figure 5 shows the spins inferred by applying the above equation to fit the median efficiency of our sample. A broad range of spins is consistent with the data. In particular, for $s > 0.4$ and $H/r = 0.3$, we find a $1\sigma$ lower limit of 0.5 on the spin.

Besides being useful for setting constraints on black hole spins, the MAD model can also be used to place upper limits on the amount of mass-loss occurring in the RIAFs. More specifically, we can obtain upper limits on $s$ for each radio galaxy by assuming that (i) during the production of powerful jets the SMBHs are accreting in the MAD state and (ii) the central engines are operating at the maximum possible kinetic efficiencies $\eta_{\text{max}}$. We solve for the maximum value of $s_{\text{max}}$ consistent with $\eta_{\text{max}}$ for each source:

$$s_{\text{max}} = \log P_{\text{obs}}^{\text{jet}} - \log P_{\text{jet}}^{\text{obs}} - \log(\alpha) - 1,$$

where we adopt the maximum jet production efficiency $\eta_{\text{max}} \approx 300\%$ (Tchekhovskoy & McKinney 2012, McKinney, Tchekhovskoy & Brandt 2012) and $\alpha = 0.1$, $r_i = 10r_S$, $r_B = 10^5r_S$ as before. We show in Fig. 6 the $1\sigma$ upper limit on $s$ computed in this way for each radio galaxy.

The median upper limit on $s$ for the sample according to Fig. 6 corresponds to $\approx 0.6$ (cf. also Fig. 3). From the results presented in Figures 5 and 6 it follows that for $s > 0.6$, not even maximally rotating black holes accreting in the MAD state are able to account for the efficiencies of the bulk of the sample.

© 2014 RAS, MNRAS 000, 1–13
5.3 Validity of jet power and Bondi inflow rate estimates

At this point, it is worth stating our basic assumptions in estimating the kinetic efficiencies, namely that:

(i) The X-ray cavity powers are taken at face value as proxies of the jet kinetic power; more precisely, they should be regarded as the power averaged over the timescale during which the central engine is actively producing jets.

(ii) We can map the mass accretion rate onto the hole to the Bondi rate such that the total inflow rate supplied to the RIAF at $r_B$ compared to the simple estimate given by $M_B$ (Krumholz, McKee & Klein 2006; Gaspari, Ruszkowski & Oh 2013).

Motivated by the above observational results, we take into account the possibility of an extra contribution to the inflow rate – e.g., potential mass loss from evolved stars within $r_B$ – in addition to $M_B$ which we denote as $\dot{M}_s$. We then assess the impact of such additional gas supply on the various estimates of $\eta_{\text{jet}}$. We adopt for simplicity $\dot{M}_s \equiv c_s M_B$ such that the total inflow rate supplied to the RIAF at $r_B$ is given by

$$\dot{M}_s = f(\dot{M}_s + M_B),$$

where $c_s$ is a free parameter and $f$ is a function of $\alpha (f \approx 0.3$ for $\alpha = 0.1$; cf. right panel of figure 4 in Narayan & Fabian 2011). For example, $c_s = 0$ would correspond to the accretion of hot, diffuse gas from the ISM, only. We consider below three illustrative cases: (i) $c_s = 1$ (amount of extra inflowing gas = amount of diffuse X-ray emitting gas); and (ii) $c_s = 10$ for which the extra gas exceeds by 10x the hot inflow rate as suggested by Soria et al. (2006).

Figure 7 shows the median per cent jet efficiencies estimated using the ADIOS model for different values of $c_s$. Considering the case of $c_s = 10$, $\eta_{\text{jet}}$ exceeds 30%, 100% and 300% for $s_{\text{eff}} = 0.52 \pm 0.16$, $s_{\text{jet}} = 0.65 \pm 0.16$. Another possible issue with the jet power estimate is related to the estimated age of the cavity. The usual assumption of $t_{\text{cav}} = t_c$ results in the shortest timescale by a factor of a few when compared to other possible estimates of the cavity age such as the “terminal velocity” and refilling timescales (Birzan et al. 2004; Rafferty et al. 2006). Despite the above-mentioned concerns with the estimates of the total jet energy and the associated timescales, it seems likely that the resulting jet powers is reasonable: the impact of underestimating the total jet energy may nearly cancel out the effect of overestimating the timescales involved (cf. discussion in Nemmen et al. 2007).

Regarding the second assumption, in our estimates we adopted physical models which take into account a reduction in $M_{\text{BH}}$ with respect to $M_B$ in the framework of the ADIOS model, assuming that the dominant source of gas supply to the black hole is the hot, diffuse, X-ray emitting gas directly observed with Chandra. Nonetheless, there might be other important sources of fuel in addition to the Bondi inflow of hot gas. For instance, Ho (2009) estimates that the Bondi accretion of hot gas contributes roughly the same amount as stellar mass loss, $\dot{M}_s \sim M_B$; on the other hand, Soria et al. (2006) find that stellar mass-loss can provide an amount of gas which can be an order of magnitude higher than $M_B$ in their analysis of quiescent early-type galaxies. In principle, cold molecular gas could also play an important role in feeding the AGN (e.g., Salomé & Combes 2003), however, McNamara, Rohanizadeh & Nulsen (2011) found no correlation between the jet power and the total mass of cold molecular gas in a sample of brightest cluster galaxies hosting radio galaxies. In addition, turbulence and thermal instabilities may boost considerably the inflow rate at $r_B$ compared to the simple estimate given by $M_B$ (Krumholz, McKee & Klein 2006; Gaspari, Ruszkowski & Oh 2013).

On the Efficiency of Jet Production in AGNs
and $s_{\text{ISO}} = 0.77 \pm 0.1$\footnote{The uncertainty on $s$ maps the sample standard deviation in $P_{\text{jet}}/M_c$.}. We conclude that more comfortable efficiencies are obtained within the range of $s$ values favored by theory and observations if there is extra inflow of gas neglected in the simple Bondi inflow estimate. Given that even for $c_s = 0$, $\eta_{\text{jet}}$ would still exceed 100% for the bulk of the sample at $s = 1$, we may conclude that an ADIOS with $s = 1$ as proposed by Begelman (2012) is only tenable if there is a considerable extra amount of inflow (i.e. $c_s \sim 100$). Such high values of $c_s$ would imply that the the amount of inflowing gas due to Bondi accretion would correspond to just a perturbation compared to other sources of gas. If this was the case, we would presumably expect no $M_B - P_{\text{jet}}$ correlation, since the jet power would respond predominantly to variations in $M_c$, which would be, in principle, decoupled from $M_B$. The fact that we observe a correlation with a 4.2σ significance\footnote{As obtained with a simple Pearson correlation test.} argues against such high values of $c_s$.

5.4 The scatter in $\eta_{\text{jet}}$

There are a couple of possible explanations for the significant scatter in the $M_Bc^2 - P_{\text{jet}}$ relation. There is the possibility that the scatter is primarily due to the uncertainties in the determination of the cavity power and the densities at the Bondi radius, as discussed in Russell et al. (2013) (see their section 4.3). Nonetheless, it is also possible that the scatter has a physical origin and there are a couple of possible physical processes that could contribute to it:

Varying amounts of mass-loss in the sample – Instead of universal value of $s$ characterizing the radial accretion rate profile, there could be rather a range of $s$-values in the sample.

Alternatively, the value of $s$ could remain the same in the different systems but the magnitude of mass-loss could depend on the spin such that the larger the spins, the stronger the mass-loss, as hinted by the simulation results of Sadowski et al. (2013). In any case, varying amounts of mass-loss in the sample would introduce considerable scatter in the $M_B - P_{\text{jet}}$ relation, even if the jet production mechanism gives a tight $P_{\text{jet}} - M_{\text{BH}}$ correlation. We find that a spread of $\sigma \approx 0.16$ around a fixed value would be sufficient to account for the observed scatter in $P_{\text{jet}}/M_c$ (cf. Fig. 2). These possibilities remain to be better explored in future simulations of accretion flows. Interestingly enough, $\sigma$ is similar to the dispersion of $s$ values obtained in the hydrodynamic RIAF simulations of Yuan, Wu & Bu (2012), Bu et al. (2013) for a range of initial conditions.

Range of black hole spins and/or magnetic flux threading the horizon – If powerful jets are produced via the BZ mechanism then the two fundamental parameters that regulate the jet power are the black hole spin $a$ and the magnetic flux $\Phi_h$ threading the horizon, besides the mass (Blandford & Znajek 1977; Semenov, Dyadechkin & Punsly 2004).

$$P_{\text{jet}} \propto \left( \frac{\Phi_h}{M} \right)^2; \quad (9)$$

i.e., $a$ and $\Phi_h$ are degenerate to some extent (cf. Tchekhovskoy, Narayan & McKinney 2010 for refinements on the above equation). According to recent simulations, a spread in the spins at $s \sim 0$ is the naturally expected outcome of the evolution of massive black holes following their history of mergers and accretion according to models based on the hierarchical scenario of galaxy mergers (Pan-Pacific et al. 2011; Dotti et al. 2013; Volonteri et al. 2013). A wide range of magnetic fluxes is also expected given the varying amounts of magnetic flux available to be accreted in the different environments of SMBHs in radio galaxies (Sikora & Begelman 2013).

We can quantify the possible scatter in spins required to explain the scatter in the sample, by assuming that the magnetic flux around the horizon accumulated to such a point where it reached saturation (MAD state) and $H/r = 0.3$. Roughly, $\sigma a \approx s$ (Fig. 2) is consistent with the scatter in spin for the different values of $s$; for $s \gtrsim 0.5$, $\sigma a \gtrsim 0.7$ (1σ lower limit) is required.

Variation in the amount of inflowing cold gas – As we discussed in section 5.3, the gas input provided via mass-loss from evolved stars in a star cluster close (or inside) $r_B$ could be relevant in elliptical galaxies. In fact, a varying contribution of gas due to stellar populations which inject gas amounts comparable to $M_B$ in the sample could also be a source of scatter in the $M_B - P_{\text{jet}}$ relation.

6 SUMMARY

With the goal of observationally constraining the jet energy efficiency $\eta_{\text{jet}} = P_{\text{jet}}/(M_Bc^2)$ in radio galaxies and probing scenarios for jet production in AGNs, we compiled the most up-to-date dataset with constraints on the jet power and mass accretion rate onto supermassive black holes. Jet powers were estimated from the X-ray cavities whereas the

\[ \text{Figure 7. Per cent kinetic efficiencies of the sample as a function of the mass-loss index $s$ for which the inflow rate at $r_B$ is increased with respect to the Bondi rate as $M_c = f(M_B + M_d)$ with $M_d \equiv c_s M_B$. We adopt the ADIOS density profile with $\alpha = 0.1$ and $r_\infty = 10^5 r_s$. The lines represent the median efficiency of the sample computed for $c_s = 0$ (dashed), $1$ (dotted) and $10$ (solid). The rest of the notation follows Fig. 2.} \]
accretion rates were obtained by combining the Chandra X-ray constraints on the boundary conditions at the onset of the hot accretion flow (estimated within 30 r_g in order to minimize uncertainties involved with density extrapolations below the spatial resolution of the observatory) with current models for the density profiles of RIAFs – which is justified since the sample consists of low-luminosity AGNs. By studying our sample of 27 radio galaxies, we have found the following results.

(i) When correlating the jet powers with the Bondi inflow rate, we find the relation $\log P_{\text{jet}} = A \log (M_B c^2) + B$ where $A = 1.1 \pm 0.2$ and $B = -4.6 \pm 8.5$ with a scatter of 0.7 dex. Our $M_B c^2 - P_{\text{jet}}$ relation is considerably less tight than found in previous studies (e.g., [Allen et al. 2006]).

(ii) If radio galaxies accrete in the ADAF mode with a viscosity parameter $\alpha \geq 0.3$, then we find the median $\eta_{\text{jet}} \approx 1 - 3\%$ for the sample. If hot accretion flows in radio galaxies are subject to mass-loss, this efficiency estimate is likely a lower limit.

(iii) If radio galaxies accrete in the ADIOS mode such that $M(r) \propto r^\alpha$, we find that the median $\eta_{\text{jet}}$ of the sample exceeds 100% for $s \geq 0.4$. This amount of mass-loss is quite on the lower end of current theoretical and observational estimates that suggest $s \geq 0.5$.

(iv) The median $\eta_{\text{jet}}$ exceeds the highest outflow efficiencies achieved in GRMHD simulations of jet production ($\sim 300\%$) for $s > 0.6$. If RIAFs in low power radio galaxies are characterized by $s \sim 0.5 - 0.6$, then rapidly rotating black holes $a > 0.9$ and magnetically arrested disks are required in order to account for the high outflow efficiencies of the bulk of our sample.

(iv) If RIAFs are subject to significant mass-loss, with $s$ considerably exceeding 0.6, even maximally rotating black holes and MADs are unable to provide sufficient power to the observed jets via the Blandford-Znajek process (on the assumption that the inflow rate near the accretion radius is dominated by the Bondi inflow of hot gas).

(vii) The presence of significant amounts of gas $M_i$ inflowing at the Bondi radius in addition to the Bondi rate – e.g., released by nuclear stellar populations – would lower the values of $\eta_{\text{jet}}$. We find that for $M_i = 10 M_B$, the median outflow efficiencies would exceed 300% for $s \geq 0.8$.

This work highlights the fact that estimates of the outflow efficiencies of radio galaxies cannot be disentangled from the density profiles of the accretion flow. We will have to wait for the success of Chandra in order to obtain high spatial resolution, sub-arcsecond X-ray observations of nearby radio-loud AGNs, that resolve the sphere of influence of the massive black hole. Such observations will allow us to constrain the density profiles similarly to what has been done for Sgr A* and NGC 3115 [Wang et al. 2013]. On the theoretical side, further simulations of RIAFs with large dynamical ranges including GRMHD effects should shed light on the issue of mass-loss.

Equally important is constraining the amount of cold feeding of atomic and molecular gas versus spherical inflow of hot keV gas in powering the jets. ALMA observations of the molecular gas reservoir in radio galaxies will be instrumental in this respect. Very high efficiencies of jet production are quite plausible in low power radio galaxies in the context of our current understanding of RIAFs. Theoretically, efficiencies $> 100\%$ seem to be possible only when the BZ process extracts black hole spin energy most efficiently, such as when the black hole is flooded with magnetic flux (MAD state) and also rapidly rotating. The theory of MADs must therefore reach a point where clean radiative signatures of the presence of this state and spin energy extraction are developed and tested against observations of radio-loud AGNs.

ACKNOWLEDGMENTS

We acknowledge useful discussions with Mihoko Yukita, Jonathan C. McKinney, Jeremy Schnittman, Markos Georganopoulos, Ramesh Narayan, Jeff McClintock, Feng Yuan, Ka-Wah Wong, Aleksander Sadowski and Sylvain Guiriec. RSN was partially supported by the NASA Postdoctoral Program (NPP) at Goddard Space Flight Center, administered by Oak Ridge Associated Universities through a contract with NASA. AT was supported by NASA through Einstein Postdoctoral Fellowship grant number PF3-140115 awarded by the Chandra X-ray Center, which is operated by the Smithsonian Astrophysical Observatory for NASA under contract NASA-806060, and NASA support via High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center that provided access to the Pleiades supercomputer, as well as NSF support through an XSEDE computational time allocation TG-AST100040 on NICS Kraken, Nautilus, TACC Stampede, Maverick, and Ranch. This project made considerable use of IPython [Pérez & Granger 2007] and the Astropy and mcerp libraries.

REFERENCES

Akritas M. G., Bershady M. A., 1996, ApJ, 470, 706
Allen S. W., Dunn R. J. H., Fabian A. C., Taylor G. B., Reynolds C. S., 2006, MNRAS, 372, 21
Baganoff F. K. et al., 2003, ApJ, 591, 891
Balmaverde B., Baldi R. D., Capetti A., 2008, A&A, 486, 119
Begelman M. C., 2012, MNRAS, 420, 2912
Belloni T., et al., 2010, The Jet Paradigm: From Microquasars to Quasars, Vol. 794. Springer Verlag
Birzan L., Rafferty D. A., McNamara B. R., Wise M. W., Nulsen P. E. J., 2004, ApJ, 607, 800
Bisnovatyi-Kogan G. S., Ruzmaikin A. A., 1974, Astrophys. Space. Sci., 28, 45
Blandford R. D., Begelman M. C., 1999, MNRAS, 303, L1
Blandford R. D., Payne D. G., 1982, MNRAS, 199, 883
Blandford R. D., Znajek R. L., 1977, MNRAS, 179, 433
Bondi H., 1952, MNRAS, 112, 195
Bu D.-F., Yuan F., Wu M., Cuadra J., 2013, MNRAS, 434, 1692
Cavagnolo K. W., McNamara B. R., Nulsen P. E. J., Carilli C. L., Jones C., Birzan L., 2010, ApJ, 729, 1066
Churazov E., Sunyaev R., Forman W., Bohringer H., 2002, MNRAS, 332, 729
Daly R. A., Sprinkle T. B., 2014, MNRAS, 438, 3233
De Villiers J.-P., Hawley J. F., Krolik J. H., 2003, ApJ, 599, 1238
Wang Q. D. et al., 2013, Science, 341, 981
Wong K.-W., Irwin J. A., Shcherbakov R. V., Yukita M., Million E. T., Bregman J. N., 2014, ApJ, 780, 9
Wong K.-W., Irwin J. A., Yukita M., Million E. T., Mathews W. G., Bregman J. N., 2011, ApJ, 736, L23
Wu Q., Yuan F., Cao X., 2007, ApJ, 669, 96
Yuan F., Bu D., Wu M., 2012, ApJ, 761, 130
Yuan F., Narayan R., 2014, ARA&A
Yuan F., Quataert E., Narayan R., 2003, ApJ, 598, 301
Yuan F., Wu M., Bu D., 2012, ApJ, 761, 129
Zamaninasab M., Clausen-Brown E., Savolainen T., Tchekhovskoy A., 2014, Nature, 510, 126

This paper has been typeset from a TeX/\LaTeX\ file prepared by the author.