The Astrophysical Journal Letters, 876:L20 (3pp), 2019 May 10 https://doi.org/10.3847/2041-8213/ab1be3

Resolving the Radio-loud/Radio-quiet Dichotomy without Thick Disks

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Received 2019 April 6; revised 2019 April 23; accepted 2019 April 24; published 2019 May 6

Abstract

Observations of radio-loud active galaxies in the *XMM-Newton* archive by Mehdipour and Costantini show a strong anti-correlation between the column density of the ionized wind and the radio-loudness parameter, providing evidence that jets may thrive in thin disks. This is in contrast with decades of analytic and numerical work suggesting that jet formation is contingent on the presence of an inner, geometrically thick disk structure, which serves to both collimate and accelerate the jet. Thick disks emerge in radiatively inefficient disks that are associated with sub-Eddington as well as super-Eddington accretion regimes, yet we show that the inverse correlation between winds and jets survives where it should not; namely, in a luminosity regime normally attributed to radio-quiet active galaxies that are modeled with thin disks. This, along with other lines of evidence, argues against thick disks as the foundation behind the radio-loud/radio-quiet dichotomy, opening up the possibility that jetted versus non-jetted black holes may be understood within the context of radiatively efficient thin disk accretion.

Key words: quasars: supermassive black holes

1. Introduction

Sikora et al. (2007) explored the inverse correlation between radio-loudness and Eddington accretion rate for a large sample of active galaxies including Seyfert galaxies and low-ionization nuclear emission-line regions (LINERs), optically selected quasars, Fanaroff and Riley Class I (FRI) radio galaxies, Fanaroff and Riley Class II (FRII) quasars, and broad-line radio galaxies. Despite a clear dichotomy in radio-loudness between objects referred to as radio-loud and those as radio-quiet, the data was insufficiently detailed to shed light on the jet-disk connection near the Eddington limit where we traditionally model the radio-quiet subset of the active galaxy family. This meant that radio-loud quasars might be considered to be different than radio-quiet quasars/active galaxies in the details of the inner accretion disk where radiative efficiency might drop, creating the conditions for thick disk structure that in turn might serve to collimate and accelerate a jet. These ideas have received support from general relativistic simulations over the last decade and a half (Koide et al. 1998, 2000; De Villiers & Hawley 2003, De Villiers et al. 2003, Gammie et al. 2003; De Villiers et al. 2005; McKinney 2006; Tchekhovskoy et al. 2010; McKinney et al. 2012). Despite incompatibility with the Soltan argument (Elvis et al. 2002), tension with the observed redshift distribution of radio galaxies and quasars (Garofalo 2013), and with the black-hole spin/Meier paradox (Meier 2002; Garofalo et al. 2016), hope that such a picture for powerful jet formation would eventually turn out correct has dominated the collective consciousness, in no small part due to the lack of viable alternatives.

Recent observational work on a small group of jetted active galaxies has confirmed a similar inverse trend as the radio-loudness/Eddington ratio of Sikora et al. (2007) that instead involves winds and jets (Mehdipour & Costantini 2019). The inverse correlation appears for a number of radio-loud active galaxies in a narrower range of Eddington ratios compared to Sikora et al. (2007). In this Letter we select the near-Eddington subset of these radio active galaxies, where the thin disk assumption most likely applies, to show that the inverse connection between winds and jets still holds. This, we argue, is unexpected and ultimately leads us to conclude that thin versus thick disks cannot constitute the bedrock upon which we understand the radio-loud/radio-quiet dichotomy. Instead, an additional parameter aside from accretion rate and black-hole spin is needed, which we provide.

2. Discussion

Mehdipour & Costantini (2019) report values of wind column density, radio-loudness, and Eddington ratios for 16 X-ray bright radio active galaxies from *XMM-Newton* whose Eddington ratios $\lambda = L_{\rm bol}/L_{\rm Edd}$ satisfy $0.46 \geqslant \lambda \geqslant 0.1$ with $L_{\rm bol}$ the bolometric luminosity and $L_{\rm Edd}$ the Eddington luminosity. They show a significant inverse correlation between the column density and the radio-loudness parameter. We extract the subset of these 16 jetted active galaxies whose Eddington ratios are equal to or greater than 10% and no greater than 46% of the Eddington limit and list them in Table 1, along with the values for the column density and radio-loudness. In Figure 1 we plot these objects in the N_H–R plane, which shows an inverse correlation spanning three decades in both parameters with a linear correlation coefficient of −0.525, which is actually stronger than the −0.395 for the entire data set.

A schematic for understanding our current picture for powerful jet formation in accreting black holes is provided in Figure 2 from Meier (2002). The theoretical boundary between an advection-dominated accretion flow (ADAF) and a radiatively efficient accretion flow is 10^{-2} of the Eddington accretion, so objects that are sufficiently above that boundary but below 1 are thought of both as thin disks and referred to as near-Eddington accretors. For accretion disks that accrete at sub-Eddington rates, an ADAF forms in the inner regions near the black-hole horizon (left column). When the black-hole spin is near zero, no energy is available for extraction from the black hole, which leads to a jetless or weak radio source. This models a LINER (Figure 2, upper left). If the black-hole spin is high, powerful jets are generated and a strong radio source or radio

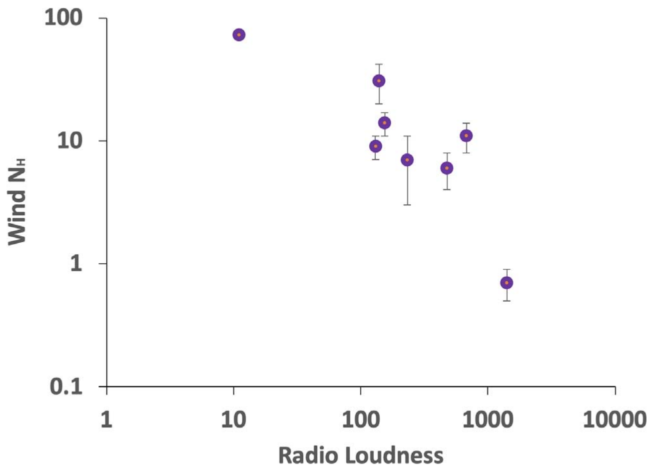

Figure 1. Wind column density (in units of 10^{20} cm^{-2}) vs. radio-loudness for the near-Eddington sources of Mehdipour & Costantini (2019).

Table 1
Near-Eddington Sources from Mehdipour & Costantini (2019)

Source	Wind	R	λ
1H 0323+342	9	130	0.46
3C 120	14	154	0.27
3C 273	0.7	1407	0.12
4C + 31.63	11	676	0.11
4C + 34.47	31	139	0.41
III Zw 2	7	233	0.21
Mrk 896	73	11	0.1
PKS 0405-12	6	477	0.3

Note. Column 1: source name; Column 2: wind column density x 10^{20}; Column 3: radio-loudness parameter; Column 4: Eddington ratio λ. The sources have Eddington ratios between 10% and 46%. In terms of the log of the Eddington ratio, this places these objects in between −1 and −0.33 which is quite close to the log of the Eddington limit in Figure 3 (which is at 0).

galaxy results (Figure 2, lower left). If, on the other hand, the disk is thin and radiatively efficient and the black-hole spin is near zero, these conditions produce radio-quiet active galaxies (Figure 2, upper right). These low black-hole-spin, radiatively efficient disks have been used to model the radio-quiet Palomar-Green (PG) quasars and radio-quiet Seyfert galaxies as shown in Figure 3 (from Sikora et al. 2007). Putting aside some ad hoc assumptions about tilted disks, the existence of radio quasars and broad-line radio galaxies in the context of these ideas requires both high-black-hole spin and super-Eddington accretion in the inner regions in order to motivate thick inner disks (Figure 2, lower right). Over the decade since the proposal of these ideas, and despite a small population, the distribution of black-hole spin in radio-quiet active galaxies appears to be top heavy (Brenneman 2013). The validity of these spin measurements, combined with the models described in Figure 2, implies that radio quasars should have a significant presence in Seyfert galaxies, contrary to observations (Sikora et al. 2007). As a result of the possibility of high-spinning black holes in many spiral galaxies, a conundrum arises that seems to be overcome by appealing to near-Eddington accretion rates for radio-quiet quasars/active galaxies, but super-Eddington accretion rates in radio-loud quasars/active galaxies. The difference between these two subgroups of active galaxies would amount to a thick disk geometry in super-Eddington systems that serves to collimate and accelerate jets in the same way as low-Eddington accretion systems. Perhaps, it was thought, broad-line radio galaxies and FRII quasars are characterized by super-Eddington accretion in their inner regions, reducing their Eddington luminosities but explaining the presence of powerful jets compared to the PG quasars, which instead seem to occupy near-Eddington luminosities (Figure 3). In summary, then, jets are associated with geometrically thick inner disks that are not present in radio-quiet quasars/active galaxies. We now show how this idea fails.

The above ideas suggest that radio galaxies and radio quasars do not experience near-Eddington luminosity regions, which instead are the domain of radio-quiet quasars and radio-quiet active galaxies. Because jets should disappear for active galaxies that live near the Eddington limit, it would not make sense to see both strong jets and the anti-correlation between jets and winds for systems that are best modeled as thin disks. We show, however, that the data in Mehdipour & Costantini (2019) not only provides evidence for powerful jets in active galaxies that reach their Eddington luminosities, but also that the inverse relation with the wind is just as strong a trend as it is at sub-Eddington values.

From the data in Mehdipour and Costantini we pick radio active galaxies whose Eddington ratios are greater than about 10% (Table 1) and explore whether or not the jet and wind remain correlated. As shown in Figure 1, the radio-loudness and the wind column density continue to experience the same trend observed below the Eddington luminosity. Despite the small numbers, the data supports the notion that the jet-disk anti-correlation is unrelated to inner disk thickness. Another strong argument against thick disk-based jet engines is that we now have evidence for collimation taking place over vastly larger scales than those of the disk scale height (Nakamura & Asada 2013; Blandford et al. 2018). The data in Sikora et al. (2007) shows the radio-loud active galaxies to be more restrained as they approach the near-Eddington limit (i.e., there are no objects with a positive log of Eddington ratios, unlike the radio-quiet ones). The data in this Letter argues that the cause of this must be understood in the context of thin disks. In short, the radio-loud/radio-quiet dichotomy must be understood as the result of a difference in some additional parameter for thin disks around high-spinning black holes. This has been done in Garofalo et al. (2010) with co-rotation of the disk compared to the black-hole rotation for radio-quiet active galaxies (the PG quasars of Sikora et al) and counterrotation of the disk for radio-loud quasars (the radio quasars and broad-line radio galaxies of Sikora et al). According to this picture, black-hole spin cannot be negligible in order for a powerful jet to exist, but a high-spinning black hole in co-rotation with its accretion disk is subject to strong winds and jet suppression (Neilsen & Lee 2009; Ponti et al. 2012). The strong wind is associated with the large radiative efficiency of the thin disk, which in turn is due to the small value of the innermost stable circular orbit (ISCO). Instead, in the counterrotating case the ISCO for a high-spinning black hole is almost an order of magnitude larger, which leads to weaker radiative efficiency (compatible with Figure 3 of Sikora et al. 2007) compared to high-spin black holes in co-rotation with the disk. As a result of the lower radiative efficiency, the disk wind produces relatively weaker jet suppression, which allows the jet to co-exist in a thin disk.

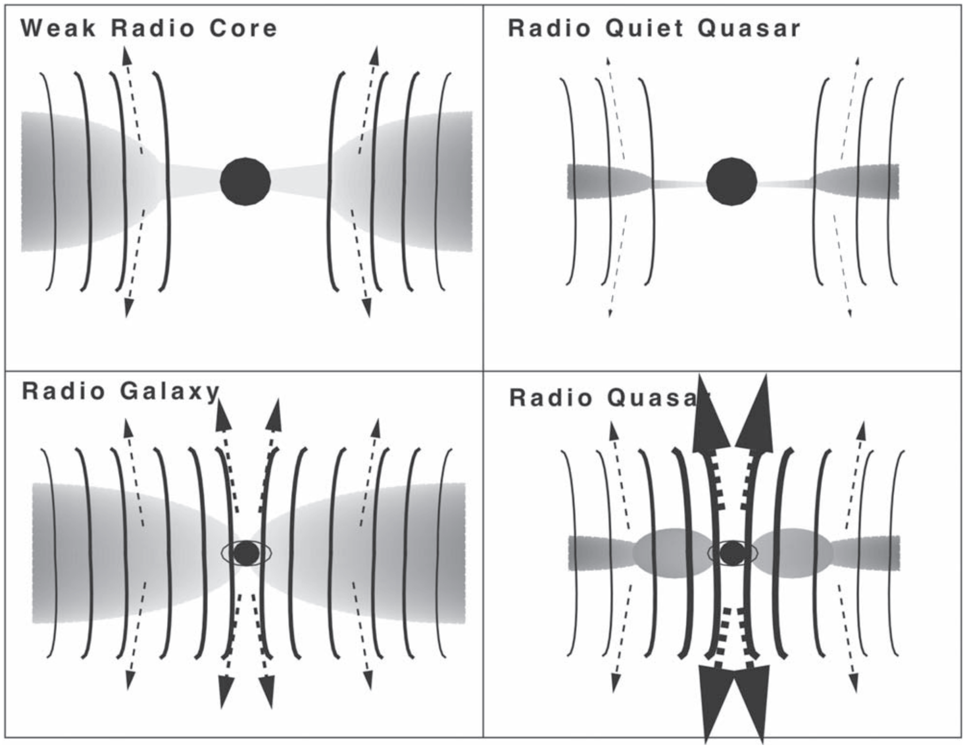

Figure 2. Schematic representation of four possible combinations of accretion state and black-hole spin. The top panels depict zero-spin black holes, while the bottom panels depict high-prograde-spin black holes. The left panels show low-accretion-rate (ADAF) tori, while the right panels represent higher accretion rates and thin disk models except for the inner region of the radio quasar (from Meier 2002).

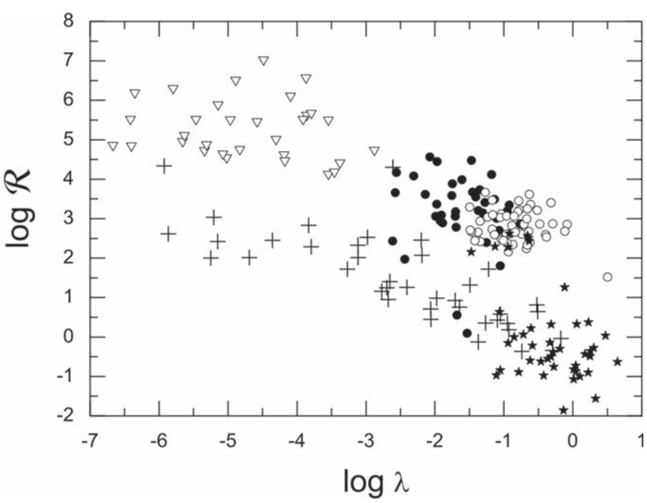

Figure 3. Logarithm of radio-loudness vs. logarithm of Eddington ratio. Broad-line radio galaxies are filled circles, radio-loud quasars are open circles, Seyfert galaxies and LINERs are crosses, FRI radio galaxies are open triangles, and PG quasars are filled stars (from Sikora et al. 2007, their Figure 3).

3. Conclusions

The development of ideas concerning the jet-disk connection for accreting black holes over the last two decades has produced a framework in which sub-Eddington bolometric luminosities are associated with powerful jets as a result of low and high accretion rates producing advection-dominated accretion and thick disks. We have shown that observations of powerful jets exist for near-Eddington accretion systems, and that the mechanism behind the jet-disk connection appears to be fully operative in standard thin accretion disks. Because these observations suggest that standard disks inform our models for the radio-loud as well as the radio-quiet population, and plenty of radio-quiet active galaxies have high measured spin values, there must be an additional parameter that breaks the degeneracy associated with high-black-hole-spin thin disks. In short, we need a reason for high-spinning black holes accreting in radiatively efficient disks to produce both radio-quiet as well as radio-loud active galaxies. This additional parameter turns out to be disk orientation with counterrotation associated with powerful jets and weaker winds, and weaker jets and more powerful winds for corotating disks.

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