MAGNETIC FLUX PARADIGM FOR RADIO LOUDNESS OF ACTIVE GALACTIC NUCLEI

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ABSTRACT

We argue that the magnetic flux threading the black hole (BH), rather than BH spin or Eddington ratio, is the dominant factor in launching powerful jets and thus determining the radio loudness of active galactic nuclei (AGNs). Most AGNs are radio quiet because the thin accretion disks that feed them are inefficient in depositing magnetic flux close to the BH. Flux accumulation is more likely to occur during a hot accretion (or thick disk) phase, and we argue that radio-loud quasars and strong emission-line radio galaxies occur only when a massive, cold accretion event follows an episode of hot accretion. Such an event might be triggered by the merger of a giant elliptical galaxy with a disk galaxy. This picture supports the idea that flux accumulation can lead to the formation of a so-called magnetically choked accretion flow. The large observed range in radio loudness reflects not only the magnitude of the flux pressed against the BH, but also the decrease in UV flux from the disk, due to its disruption by the “magnetosphere” associated with the accumulated flux. While the strongest jets result from the secular accumulation of flux, moderate jet activity can also be triggered by fluctuations in the magnetic flux deposited by turbulent, hot inner regions of otherwise thin accretion disks, or by the dissipation of turbulent fields in accretion disk coronae. These processes could be responsible for jet production in Seyferts and low-luminosity AGNs, as well as jets associated with X-ray binaries.

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

1. INTRODUCTION

Half a century after the discovery of quasars, we are still struggling to understand the enormous diversity of their jet activities. In most quasars the jet power, $P_j$, is a factor $\sim 10^4$ times smaller than the accretion power, $P_{\text{acc}}$, while others have jet powers covering the range extending up to $P_j \sim P_{\text{acc}} = \epsilon M c^2$ (Rawlings & Saunders 1991; Ghisellini et al. 2010; Fernandes et al. 2011; Punsly 2011), where $M$ is the accretion rate and $\epsilon$ is the accretion efficiency. Such a broad range of jet production efficiencies, $P_j/P_{\text{acc}}$, can be explained via the Blandford–Znajek mechanism for powering jets (Blandford & Znajek 1977) if there is a sufficiently large spread of black hole (BH) spins and/or magnetic fluxes that thread the holes.

The broad range of jet production efficiencies is seen not only in quasars, but also in AGNs with luminosities much smaller than the Eddington limit (Sikora et al. 2007, and references therein). Radio-selected AGNs have been found to produce jets with efficiency typically three orders of magnitude larger than radio-detected, optically selected AGNs. To explain such a difference solely in terms of BH spin (i.e., according to the “spin paradigm”) requires dimensionless spin parameters spread over the range $a \sim 0.03–1$. But according to numerical simulations of the cosmological evolution of BH spins, such a range is rather difficult to reproduce (Volonteri et al. 2007, 2012). A phenomenological “spin-accretion” paradigm, adopting the Eddington ratio as a second parameter, also fails to explain the observed range of radio loudness (Sikora et al. 2007). This suggests that the main parameter driving the diversity of jet production efficiencies is the magnetic flux (Sikora et al. 2013).

In the case of the most powerful jets, with $P_j \sim P_{\text{acc}}$, the required magnetic flux is too large to be confined by the “static” pressure of the accretion disk, even for maximal BH spins (Moderski & Sikora 1996; Ghosh & Abramowicz 1997). However, this limitation can be overcome if very large magnetic fluxes can be forced onto the BH by the ram pressure of the magnetically affected accretion flow. Such a scenario is predicted by models that involve the central accumulation of large magnetic fluxes and the formation of magnetically arrested/choked accretion flows (MCAFs; Narayan et al. 2003; Reynolds et al. 2006; McKinney et al. 2012). The idea that a large net magnetic flux can be accumulated around a BH was already in place in the 1970s (Bisnovatyi-Kogan & Ruzmaikin 1976). However as Lubow et al. (1994) pointed out, large-scale poloidal magnetic fields cannot be dragged to the center by standard, geometrically thin accretion disks, because of the outward diffusion of magnetic field in the turbulence triggered by the magnetorotational instability. Noting that no such limitation applies in the case of geometrically thick accretion flows (Lubow et al. 1994; Livio et al. 1999; Cao 2011; Guilet & Ogilvie 2012), Sikora et al. (2013) suggested that in radio-loud AGNs the large magnetic fluxes were accumulated during a hot, low-accretion-rate phase prior to the current, cold accretion event. We explore this idea below and try to verify whether magnetic flux can be the main parameter responsible for the observed spread in radio loudness.

Our paper is organized as follows. In Section 2, we derive the conditions that must be satisfied by the hot and cold accretion rates and by the initial inner radius of the cold accretion disk (within which the flux is trapped), in order to initiate a magnetically choked accretion flow (MCAF). We next (Section 3) estimate the resulting efficiency of BH rotational energy extraction via the Blandford–Znajek mechanism, and investigate whether the Blandford–Znajek mechanism can explain...
the observed broad range and distribution of radio loudness of AGNs (Section 4). In Section 5, we speculate about why the flux accumulation in most AGNs is inefficient, discuss possible cosmological scenarios for BH evolution that may lead to the observed radio-demographics of AGNs, and suggest additional observational consequences.

2. MAGNETIC FLUX ACCUMULATION

Suppose a “hot” (geometrically thick) accretion flow, with mass flux \( M_h \), drags a net poloidal magnetic flux \( \Phi_{h,\text{tot}} \) into the central region of an AGN. Provided that this flux is larger than the maximum that can be confined on the BH by the ram pressure of the accreting plasma,

\[
\Phi_{h,\text{tot}} > \Phi_{\text{BH},\text{max}}(M_h) = \Phi(M_h, c r_g^2)^{1/2},
\]

such an accumulation will result in the formation of a “magnetosphere” extending out to a radius

\[
r_m(M_h) \simeq \left( \frac{\Phi_{h,\text{tot}}}{\Phi_{\text{BH},\text{max}}(M_h)} \right)^{4/3} r_g
\]

(Narayan et al. 2003), where \( r_g = GM_{BH}/c^2 \) is the gravitational radius and \( \Phi \) is a dimensionless factor which, according to numerical simulations by McKinney et al. (2012), is typically of order 50. The amount of magnetic flux enclosed within a radius \( r < r_m(M_h) \) is

\[
\Phi_h(r) \simeq \Phi_{\text{BH},\text{max}}(M_h) \left( \frac{r}{r_g} \right)^{3/4}.
\]

If the hot accretion phase is followed by a cold accretion event initiated by the formation of a cold disk at \( r_d < r_m(M_h) \), that disk will trap the flux

\[
\Phi_d = \Phi_h(r = r_d)
\]

and squeeze it to a radius

\[
r_m(M_d) \simeq \left( \frac{\Phi_d}{\Phi_{\text{BH},\text{max}}(M_d)} \right)^{4/3} r_g \simeq \left( \frac{M_h}{M_d} \right)^{2/3} r_d,
\]

or entirely enclose it on the black hole depending on whether \( \Phi_d \) is larger or smaller than \( \Phi_{\text{BH},\text{max}}(M_d) \sim \Phi(M_d, c r_g^2)^{1/2} \). Thus, a magnetosphere with \( r_m(M_d) > r_g \) is formed and the MCAF scenario proceeds if cold accretion at a rate \( M_d \) was preceded by hot accretion (satisfying condition (1)) at a rate

\[
M_h > (r_d/r_g)^{-3/2} M_d.
\]

3. JET PRODUCTION EFFICIENCY

If the condition given by Equation (6) is satisfied, then \( \Phi_d > \Phi_{\text{BH},\text{max}}(M_d) \) and the rate of energy extraction from the rotating BH via the Blandford–Znajek mechanism is

\[
P_{\text{BZ}}^{(\text{MCAF})} \simeq 4 \times 10^{-3} \Phi_{\text{BH},\text{max}}^2(M_d) \frac{\Omega_{\text{BH}}^2}{c} f_a(\Omega_{\text{BH}})
\]

\[
= 10(\phi/50)x_a^2 f_a(x_a) M_d c^2,
\]

where \( \Omega_{\text{BH}} \) is the angular velocity of the BH,

\[
x_a = r_g \Omega_{\text{BH}}/c = \left[2(1 + \sqrt{1 - a^2})\right]^{-1} a,
\]

\( f_a(x_a) \simeq 1 + 1.4x_a^2 - 9.2x_a^4 \), and \( a \) is the dimensionless angular momentum parameter (Tchekhovskoy et al. 2010). Although energy is also extracted from the magnetospheric region outside the event horizon, the latter can dominate the jet power only for very slowly rotating holes (\( a < 0.1 \); McKinney et al. 2012). Assuming \( a > 0.1 \), we find that the efficiency of jet production in the MCAF scenario is

\[
\eta_j \equiv \frac{P_j}{M_d c^2} \simeq 10(\phi/50)x_a^2 f_a(x_a).
\]

This gives \( \eta_j \simeq 1.9(\phi/50) \) for \( a = 1 \) and \( \eta_j \simeq 0.0063 \) for \( a = 0.1 \), and therefore the jet efficiency varies by a factor \( \approx 300 \) over the spin range \( 0.1 < a < 1.0 \). For the spin range \( 0.4 < a < 0.9 \), however, where most BHs are expected to lie, the efficiency varies by less than a factor of 10.

4. RADIO LOUDNESS

According to the analysis by Willott et al. (1999), the radio luminosity of a typical extended radio source is approximately proportional to the jet power. Adopting the modifications and approximations discussed by Sikora et al. (2013), we use

\[
P_j \sim 10^2 v_{1.4} L_{\nu_{1.4}} (f/3)^{3/2},
\]

where \( v_{1.4} = 1.4 \) GHz and \( f \) is a factor that is predicted to be in the range \( 1 < f < 20 \) (Willott et al. 1999). Then, using the standard definition of the radio loudness, \( R = L_{\nu_v}/L_{\nu_a} \), where \( \nu_v = 5 \) GHz and \( \nu_a = 6.8 \times 10^{14} \) Hz (Kellermann et al. 1989), we obtain that the radio loudness predicted by the MCAF model is

\[
R \equiv \frac{v_B}{v_\nu} \frac{vBL_{\nu_B}}{v_\nu L_{\nu_a}} \simeq \frac{P_j}{(f/3)^{3/2} P_d} \simeq 10^4 \frac{\eta_j}{\epsilon_d(f/3)^{3/2}},
\]

where \( \epsilon_d \equiv P_d/M_d c^2 \) is the radiative efficiency of the accretion disk, \( P_d \sim 10^8 v_B L_{\nu_a} \), and \( v_B \) is related to \( L_{\nu_{1.4}} \) assuming a radio spectral index \( \alpha_r = 0.8 \).

In the MCAF scenario the outer, radiative viscous disk is truncated at \( r_m(M_d) \). At smaller radii, the angular momentum of the accreting material is transferred to the magnetic field via interchange instabilities, allowing accretion to occur without substantial heating and radiative losses. We therefore estimate the radiative efficiency to be

\[
\epsilon_d \sim \frac{r_g}{r_m(M_d)} \simeq \left( \frac{\Phi_{\text{BH},\text{max}}(M_d)}{\Phi_d} \right)^{4/3} \simeq \frac{r_g}{r_d} \left( \frac{M_d}{M_h} \right)^{2/3},
\]

and then

\[
R \simeq 10^4 \frac{\eta_j}{(f/3)^{3/2}} \frac{r_g}{r_d} \left( \frac{M_h}{M_d} \right)^{2/3}.
\]

Replacing \( M_d \) by the Eddington-ratio parameter, \( \lambda \equiv P_d/L_{\text{Edd}} \), in Equations (11) and (12) gives

\[
\epsilon_d \approx \left( \frac{r_g}{r_d} \right)^{3/5} \left( \frac{\lambda}{\lambda_{\text{Edd}}} \right)^{2/5} \sim \left( \frac{\lambda}{\lambda_{\text{max}}} \right)^{2/5},
\]

and

\[
R \simeq 10^{8.5} \frac{\eta_j}{(f/3)^{3/2}} \left( \frac{\lambda}{\lambda_{\text{max}}} \right)^{-2/5}.
\]
where \( m_h \equiv M_{h} c^2 / L_{\text{Edd}} \) and

\[
\lambda_{\text{max}}^{\text{MCAF}} = \left( \frac{r_{d}}{r_{g}} \right)^{3/2} m_h
\]

is the maximal Eddington-ratio achievable in the MCAF for given values of \( m_h \) and \( r_g \) (see Equation (6)).

4.1. Quasars

Studies of nearby quasars indicate that their radio-loudness distribution is bimodal, with the majority of quasars narrowly clustered around \( R \sim 1 \) and others forming a tail extending up to \( R \sim 10^4 \) (Kimball et al. 2011; Baloković et al. 2012; Singal et al. 2013). While radio emission of quasars with \( R < 10 \) is likely to be associated with stellar processes in star formation regions, radio emission of quasars with \( R > 10 \) must involve the dissipation of jet energy. Values of \( R > 100 \) are achievable for jets produced via the Blandford–Znajek mechanism in the MCAF scenario. The radio loudness of such “MCAF” quasars is expected to cover a range from \( R \sim \text{tens} \) up to \( R \sim 10^4 \), with a spread determined by the range of BH spins and of the Eddington-ratio parameter \( \lambda \) (see Equations (9) and (14)).

Observations show a bottom-heavy distribution of quasar radio loudness, with only a few percent of quasars having \( R > 100 \) (de Vries et al. 2006; Lu et al. 2007; Baloković et al. 2012). According to the magnetic flux paradigm, this may indicate a bottom-heavy distribution of the hot accretion rate \( M_h \) (or the absence of a hot accretion phase altogether), leading to a small fraction of quasars that satisfy the MCAF condition (6). Alternatively, some systems could fail to meet the flux threshold condition (1), perhaps because the hot accretion phase is too brief or the external field too disordered, implying that the accumulated magnetic flux is too weak to support the magnetosphere and is entirely crushed into the hole by the disk flow. These “MCAF-failed” quasars produce less powerful jets. Such jets are likely to be efficiently decelerated within the galactic optical cores and most of them become subsonic with Fanaroff–Riley type I or other centrally dominated morphologies (Komissarov 1994; Bicknell 1995; Heywood et al. 2007). This can explain why radio emission in quasars with \( R < 100 \) is dominated by compact sources (Lu et al. 2007).

Radio emission at a level corresponding to \( R \lesssim 100 \) could also be contributed by jets associated with fluctuating magnetic fields. In the case of quasars, such fields would probably arise in a corona above the thin accretion disk, and the jet could be propelled thermally by efficient heating of the coronal plasma due to magnetic reconnection (Heinz & Begelman 2000). In sources where the inner region of the accretion flow becomes hot or geometrically thick for any reason, large magnetic field fluctuations could develop with coherence length \( \sim a \) and strength of the order of the ram pressure. These flows could deposit transient flux onto the BH, leading to intermittent jet production. We tentatively associate these stochastic jets with the radio activity detected in radio-intermediate quasars, low-luminosity AGNs, and X-ray binaries.

4.2. Strong-line Radio Galaxies (SLRGs)

Strong, broad-line and narrow-line radio galaxies (BLRGs and NLRGs, respectively) form together with radio-selected quasars an Eddington-ratio sequence that extends down to \( \lambda \sim 10^{-4} \) (Sikora et al. 2007, 2013). Sikora et al. (2013) showed that their radio loudness anticorrelates with the Eddington ratio, in accordance with the MCAF model prediction (see Equation (14)).

4.3. Seyferts

Seyferts dominate the population of radio-quiet AGNs. Though covering a similar Eddington-ratio range as SLRGs, they are two to four orders less radio-loud, with \( R \sim 1 \) like radio-quiet quasars (Sikora et al. 2007). According to the magnetic flux paradigm, this implies very inefficient flux accumulation prior to the start of the Seyfert activity phase. This inefficiency can be attributed to the lack of a hot accretion pre-phase. In the case of objects hosted by disk galaxies, this conjecture is supported by studies of the nuclei of disk galaxies at epochs of very low accretion rates. Broadband spectra of such low-luminosity AGN (LLAGN) indicate that at least the outer portions of their accretion disks are cold and geometrically thin (Nemmen et al. 2011; Yu et al. 2011).

Nevertheless, LLAGNs are found to be moderately radio loud (Ho 2002). Their radio activity, like that in low/hard states of XRBs, is presumably associated with a presence of a hot, radiatively inefficient accretion zone extending out to some distance from the BH. As discussed in Section 4.1, geometrically thick flows enable a significant poloidal magnetic field to impinge on the BH and thus generate jets or winds (Livio et al. 1999).

4.4. X-Ray Binaries (XRBs)

The MCAF scenario was suggested by Igumenshchev (2009) to explain jet activity and state transitions in XRBs. However, noting that the outer portions of the accretion disks in such objects are geometrically thin, it is not clear how magnetic flux can be advected efficiently to the vicinity of the BH. An alternative scenario may involve fluctuating magnetic fields, as mentioned earlier (Section 4.1). In low/hard states this could involve a central hot, geometrically thick accreting region with large-scale fluctuating poloidal magnetic fields, while in high/hard states the dominant mechanism could be thermal propulsion following dissipation of tangled magnetic fields in the disk corona.

5. EVOLUTIONARY AND OBSERVATIONAL CONSIDERATIONS

The proposed flux paradigm explains the relative rarity of radio-loud AGNs because it requires a special sequence of events to occur in order to trigger powerful jet activity. This contrasts with the spin paradigm, which appeals to a bottom-heavy distribution of BH spins that seems implausible in the light of recent evolutionary modeling.

The flux paradigm fits well with the observationally supported idea that the most luminous AGNs are triggered by mergers (Hirschmann et al. 2012; Treister et al. 2012; Ramos Almeida et al. 2012). To produce a radio-loud quasar or SLRG, a disk galaxy would presumably merge with a giant elliptical where hot accretion from the interstellar medium has been going on for some time. The precondition of hot accretion is actually a dual requirement because the hot accreting gas must also be carrying sufficient magnetic flux. Thus, we conjecture that the hot interstellar medium in at least some ellipticals contains a relatively coherent magnetic field that can be dragged inward. While the origin of large-scale magnetic fields in galaxies is still under debate, it is plausible that these fields
are seeded by stellar processes, through winds and supernova explosions, which suggests that the occurrence of powerful jets in AGNs should be correlated with the cosmic history of star formation, separately from any generic correlation that links the growth of supermassive BHs to star formation. In the central galaxies of cool-core clusters and groups, jet production is ubiquitous, suggesting that the gas in these relatively dense hot environments generally carries net magnetic flux (Burns 1990; Hardcastle et al. 2007; Tasse et al. 2008; Dunn et al. 2010).

The same cold accretion flow responsible for amplifying radio loudness could also serve as the circumbinary disk needed to drive the BHs in merging galaxies through the “final parsec” toward merger (Begelman et al. 1980; Cuadra et al. 2009; Dotti et al. 2012, and references therein). In this case, we could relate the radius within which the cold disk gathers up the trapped flux, $r_d$, to the circumbinary radius, which could be $\sim 10^8-10^9 r_g$, or larger.

To explain powerful jets, the MCAF scenario requires not only a large magnetic flux but also a substantial BH spin. Because accreting matter gives up its angular momentum to the dynamically dominant magnetic field as it falls through the magnetosphere, it reaches the BH with almost no angular momentum. As a result, angular momentum extracted from the BH during the MCAF phase is not replenished by the accreted matter, and the BH spin decreases. Thus, an additional requirement for a high level of radio loudness is that the BH should have a large spin prior to the start of the MCAF phase.

Considering the above requirements for producing radio-loud quasars, one might envisage two evolutionary tracks leading to radio-quiet quasars. One track would involve the merger of two disk galaxies, where magnetic flux has never been collected through an extended period of hot accretion. Another track would represent the last phases of MCAF activity where the BH has been spun-down to extremely small values of $a$. Noting, however, that significant reduction of a BH’s spin by zero-angular-momentum inflow requires its mass to be approximately doubled, and that such a doubling is not achievable during the typical lifetime of a classical double radio source, $t_{\text{BH}} \sim 3 \times 10^7$ years (O’Dea et al. 2009), we regard the latter option as rather unrealistic unless $M_d > M_{\text{edd}}$. Furthermore, an evolutionary connection between radio-loud and radio-quiet AGNs seems to be excluded by observations showing that the hosts of radio-loud AGNs are on average located in denser environments than those of radio-quiet AGNs (Shen et al. 2009; Donoso et al. 2010; Sabater et al. 2013).

We have focused mainly on the possible role of MCAFs in explaining the most luminous, radio-loud AGNs, but emphasize that other processes may trigger jets as well, albeit giving a lower level of radio loudness. We suggest that any hot or geometrically thick inner region of an accretion flow can develop magnetic field fluctuations of large enough spatial coherence and strength to produce an intermittent jet. The magnetic fields in these jets would undergo frequent reversals of polarity, possibly leading to enhanced dissipation through reconnection across the current sheets (Sikora et al. 2003) and resulting radiative signatures that could be used to distinguish them observationally from the jets produced by coherent magnetic flux in MCAFs. We tentatively associate these stochastic jets with the radio activity detected in radio-intermediate quasars, low-luminosity AGNs, and X-ray binaries in low/hard states. In quasars, Seyferts and XRBs in high/hard states, where thin disk flows probably extend all the way to the BH, radio-emitting jets or winds could be produced through the dissipation of fluctuating coronal magnetic fields.

As for testing the MCAF picture directly, we note that a cold accretion flow, disrupted by magnetic stresses inside the magnetospheric radius $r_m$, may have a unique structure that would allow it to be distinguished from a hot inner accretion flow or a thin disk enveloped by a hot corona. We expect the MCAF to consist of cold blobs or filaments dropping through the magnetosphere via interchange instabilities. These blobs might reprocess the surrounding disk emission more effectively than a thick disk or corona, and also provide more optical depth across the inner region surrounding the BH. Furthermore, the power-density spectrum of X-ray variations should have a high-frequency break at lower frequency in MCAFs than in viscous accretion flows. The best objects to look for signatures of MCAFs would be those with the most extended magnetospheres, primarily radio galaxies, both strong-line and weak-line.

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