A path to radio–loudness through gas–poor galaxy mergers and the role of retrograde accretion

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Abstract. In this note, we explore a pathway to radio–loudness under the hypothesis that retrograde accretion onto giant (MBH ∼ 10⁹ M⊙) spinning (a ≳ 0.7) black holes (BHs) leads to the launch of powerful jets, as seen in radio–loud QSOs and recently in LAT/Fermi and BAT/Swift Blazars. Counter–rotation of the accretion disc relative to the BH spin is here associated to gas–poor galaxy mergers progenitors of giant (missing–light) ellipticals. The occurrence of retrograde accretion enters as unifying element that may account for the radio–loudness/galaxy morphology dichotomy observed in AGN.

1 Relativistic jets and the radio-loud morphology dichotomy

Thanks to a wealth of observational and theoretical studies of AGN from radio to gamma-ray frequencies, radio-loud AGN are presently thought to contain relativistic jets which propagate from the nucleus out to kpc and, in some cases, Mpc scales. The power of jets required to at least fuel their radio lobes is huge, up to 10⁴⁷ erg s⁻¹ corresponding to an energy release of ∼ 10⁶² erg over a time of 10⁸ yr. In radio-quiet AGN, the radio emission is instead weak and large scale radio jets are absent. Although the boundary between these two classes is blurred, strong jets (in terms of kinetic relative to accretion power) exist only in a minority of AGN.

Optical studies of nearby galaxy nuclei (Capetti & Balmaverde 2006) have shown that all radio-loud AGN invariably reside in giant core (or missing–light; Kormendy et al. 2009) ellipticals, i.e. in early-type galaxies whose nuclear surface brightness profile shows a deficit in star-light with respect to the outer profile. By contrast, normal, less massive coreless (or extra–light; Kormendy et al. 2009) ellipticals all host radio-quiet AGN (Capetti & Balmaverde 2006), suggesting that a morphology-related dichotomy exists among ellipticals, likely determined by galaxy evolution. The dichotomy seems also to emerge from a sample of radio-loud and radio-quiet QSOs at redshift z < 0.2, the former residing in giant ellipticals that show signs of interaction, and the latter residing in
merging gas-rich galaxies of intermediate mass (Wolf & Sheinis 2008). Evidence exists that the most powerful radio and gamma–loud AGN are associated to the heaviest supermassive BHs in the universe, with \( M_{\text{BH}} \gtrsim 10^9 M_\odot \) (Ghisellini et al. 2009a,b) indicating that the BH mass can be a key parameter for radio-loudness.

From a theoretical point of view, the launching of jets from accreting BHs have been extensively studied in the past three decades, following the seminal paper by Blandford and Znajek (BZ hereafter; 1978). The BZ process exploits energy extraction from a rapidly rotating black hole via a purely electromagnetic interaction of a large scale magnetic field which threads the rotating event horizon. In this framework, jets are produced at the expense of the rotational energy of the black hole \( E_{\text{rot}} = M_{\text{BH}} [1 - 2^{-1/2}(1 + \sqrt{1 - a^2})^{1/2}] c^2 \), where \( a \) is the dimensionless spin parameter related to the BH spin \( J_{\text{BH}} = \hat{l} (G M_{\text{BH}}^2 a / c) \) pointing along \( \hat{l} \) (for a maximally rotating \([a = 1]\) Kerr BH of \( 10^9 M_\odot \), \( E_{\text{rot}} = 6 \times 10^{62} \) erg). This may suffice to power a jet and to explain why AGN with comparable optical luminosities can be either radio-loud (large \( a \)) or radio-quiet (small \( a \), as \( E_{\text{rot}} \) decays \( \propto M_{\text{BH}} a^2 / 8 \) for \( a \rightarrow 0 \)) depending on \( a \) (Wilson & Colbert 1995; Sikora et al. 2007).

Advanced fully general-relativistic magneto-hydrodynamical simulations of spinning BHs (McKinney 2005, 2006) predict high collimation of the inner Poynting flow, bulk Lorentz factors of order 10, and jet powers \( P_{\text{jet}} \propto a^2 \), or \( \propto a^6 \), implying in this last case high jet luminosities only for close to maximally spinning BHs (Tchekhovskoy et al. 2009). Another essential ingredient determining the BZ power is the value of the magnetic field threading the horizon, which is tied to the accretion rate and disc structure (Ghisellini et al. 2009a).

In two recent works, Garofalo (2009a,b) stressed the importance of the plunging region between the innermost stable circular orbit (ISCO\(^1\)) of the accretion disc and the BH horizon. In this region the magnetic field can be substantially amplified from its value at ISCO, particularly if the BH has a retrograde spin vector with respect to the accretion disc angular momentum (we will use here the convention of negative spin, \( a < 0 \), for retrograde accretion). As a consequence, high jet powers can be extracted even/also from non-maximally rotating BHs (Garofalo 2009b).

Here, we explore the consequences of Garofalo’s conjecture in the aim at connecting the BH spin and accretion mode to the structure of the underlying host galaxy. Moderately high values of the spin parameter \( a \) (\( \gtrsim 0.7 \)) and retrograde accretion appear to enter as unifying ingredients to account for the radio-loud/host morphology dichotomy observed, at low redshifts, among ellipticals\(^2\). These considerations go in the direction of the very recent proposal that most radio-loud AGN harbor spinning BHs accreting in the retrograde mode (Garofalo et al. 2010).

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1. ISCO, expressed in units \( GM_{\text{BH}} / c^2 \), is at 6 for \( a = 0 \), and at 9 (1) for retrograde accretion with \( a = -1 \) (prograde accretion with \( a = 1 \)).

2. See Sikora et al. (2007) for the discussion on the most general late/early-type versus radio-quiet/loud dichotomy observed in AGN, and Fanidakis et al. (2009) for a different spin dependent cosmological model of jet formation in AGN.
2 A pathway to radio–loudness through dry galaxy mergers

Can retrograde accretion onto a spinning BH be established during galaxy evolution?

2.1 Isolated disc galaxies

To answer this question in a broader context, we first consider isolated disc galaxies, in which BHs are expected to grow only by accretion. In these galaxies BH fueling can occur either via multiple uncorrelated episodes of accretion (Moderski et al. 1998), or via secular bar-in-bar instabilities (Shlosman, Frank & Begelman 1989) that remove gradually the gas angular momentum. In the first mode, episodes of chaotic accretion result in low BH spins (King & Pringle 2006; Volonteri et al. 2007). Prograde and retrograde accretion change both the BH spin modulus $a$ and direction $\hat{l}$. Since retrograde orbits carry a larger angular momentum than prograde orbits, random episodes result in average values of $\langle a \rangle \lesssim 0.4$. In this scenario, retrograde accretion events are common, but the accreting BH is always slowly spinning, so no powerful, long–lived collimated jets are produced. In the second scenario, the BH grows through coherent accretion. Even if $a \sim 0$ initially, accretion can spin the BH up to $a \sim 1$ after doubling its mass (precisely, a factor $\sqrt{6}$, Bardeen 1970). In this scenario, the BH spin $\mathbf{J}_{\text{BH}}$ aligns with the angular momentum of the accretion disc. The BH remains in the radio-quiet mode if $a \lesssim 0.9$, as retrograde accretion is unlikely to establish, given the coherence of the flow. A strong jet in a disc galaxy could be triggered by prograde accretion only if $a > 0.9$ (Tchekhovskoy et al. 2009), but the jet power would be $\sim 30$ times dimmer than that produced by retrograde accretion onto a maximally spinning BH (Garofalo 2009b).

2.2 Galaxy Mergers

The situation is different in the case of major mergers, i.e. mergers between galaxies of comparable masses. Galaxy mergers are commonly divided in two classes, gas rich (or wet) mergers where the fraction of cold gas is large ($\gtrsim 10\%$ of the mass in stars), and gas poor (or dry) mergers where gas is a small fraction of the stellar mass and has no dynamical effect in the merger.

2.2.1 Wet mergers

During a wet merger, the tidal field between the two disc galaxies drives large amounts of gas (up to 50% of the total gas mass) toward the centres of the two interacting galaxies (Mayer et al. 2007). When the two nuclei later merge in a single structure, the gas settles into a dense, selfgravitating circumnuclear disc in which the BH relative orbit becomes circular and corotating until the BHs form a Keplerian binary (Dotti et al. 2009). In this phase, lasting $\lesssim 10^7$ yr, the BHs accrete in a coherent manner at a rate sufficient to align their spins, initially oriented at random, to the angular momentum of the nuclear disc (Liu 2004; Bogdanovic, Reynolds & Miller 2007; Dotti et al. 2010): in response to the Bardeen–Petterson warping of the small–scale accretion discs grown around each BH, total angular momentum conservation imposes fast ($\lesssim 1$ Myr) alignment of the BH spins with the angular momentum of their orbit and so of the large–scale circumnuclear disc (Dotti et al. 2010). Thereafter, accretion remains
prograde until coalescence, with no major changes in the BH spin orientation. Under these circumstances the BH remnant retains the spin direction of the parent BH spins, both oriented parallel to the angular momentum of their orbit: the post-coalescence BH may thus acquire a large spin $a \gtrsim 0.7$ (Berti & Volonteri 2008; Kesden, Sperhake & Berti 2010), sum of the internal and orbital spins. Because of fast alignment and spin coherence relative to the flow, prograde accretion continues even after BH coalescence and so no powerful long–lived jets are produced, according to our working hypothesis, unless the BH remnant is close to be maximally rotating.

We can also follow the evolution of a wet merger by looking at the properties of the galaxy remnant. Gas rich galaxy mergers are expected to form either spheroids with residual rotation or discs, depending on their initial gas content (Robertson et al. 2006), encounter geometry and the presence of cold gaseous streams flowing onto the evolving remnant (Governato et al. 2009). The stellar nucleus of the relic galaxy can in principle be perturbed by the massive BH binary. The binary hardens ejecting stars via three-body scatterings (Merritt & Milosavljevic 2004) creating a stellar core. The post-coalescence BH can further heat the stellar nucleus if it experiences a strong gravitational–wave induced recoil ($\lesssim 1000$ km s$^{-1}$; Lousto & Zlochower 2009 and references therein): in its oscillations back to the galactic centre the BH deposits its kinetic energy expanding further the core (Boylan–Kolchin et al. 2004; Gualandris & Merritt 2008). However, in a gas–rich merger, these effects are strongly suppressed: the stellar deficit by the BH binary is weak since the binary hardens mainly via gaseous torques (see Colpi & Dotti 2009 for a review) and extra–light is produced following the formation of new stars inside the circumnuclear disc (Hopkins et al. 2009a). Furthermore, spin-orbit alignment from coherent accretion implies small gravitational kicks for the relic BH, limiting the effect of dynamical heating of the nucleus. As a consequence, we predict that wet mergers result mostly in radio–quiet AGN hosted by coreless, extra–light elliptical or spiral galaxies. Figure 1 illustrates schematically the evolution of the two BHs and of the remnant galaxy in a gas–rich merger.

### 2.2.2 Dry mergers

Mergers of gas–poor galaxies (e.g. between two ellipticals) lack massive nuclear gas discs. The BHs thus complete their inspiral in a collisionless background of stars. The BH spins are expected to be uncorrelated with the geometry of the encounter, so that, as the binary forms, their spins are randomly oriented relative to the binary orbit. The BHs may capture gas and experience episodes of retrograde accretion until they merge. At coalescence the BH spin changes in modulus and orientation, and memory is lost of the initial spin directions. Berti & Volonteri (2008) predict, for isotropic dry mergers, a broad distribution of final spins centred around $\langle a \rangle \sim 0.7$ (close to the value resulting from the coalescence of two non–spinning BHs) and also large recoil speeds (e.g. Lousto et al. 2009).

The end–result of a dry merger is expected to be a giant, missing–light elliptical whose nuclear region has been shaped by the BH (Hopkins et al. 2009b; Kormendy & Bender 2009). Hardening through three–body scatterings with stars excavates a stellar core in the nuclear region, further expanded by BH
Radio loudness and gas-poor mergers

Figure 1. Gas–rich mergers between nearly equal mass disc galaxies. The left and right branches of the scheme refer to the evolution of the galaxies and the BHs, respectively. Left: We hypothesize that the merger ends with the formation of a normal coreless elliptical where the central extra–light results for a major star formation episode triggered inside the massive circumnuclear disc. Galaxy evolution models do not exclude the survival or re–growth of the disc (Governato et al. 2009) so that a disc galaxy may form at the end of the merger. Right: Observations of normal coreless ellipticals indicate that they host BHs with $M_{BH} < 10^8 M_\odot$ (Kormendy & Bender 2009). The BHs that initially inhabit the two galaxies are expected to pair and form a binary corotating with the disc (Dotti et al. 2009). During inspiral under the action of gas-dynamical torques, gas accretion aligns the BH spins to the orbit (Dotti et al. 2010) so that the post-coalescence BH has a high ($a \gtrsim 0.7$) spin and corotates with the disc. After this phase and according to our working hypothesis the BH is radio-quiet. We notice that a short-lived radio-loud phase could be present, prior to BH coalescence, before disc-orbit and spin-orbit alignment occur.
heating by the recoil. The final giant rapidly spinning BH later settles in the galaxy’s centre and starts accreting. In the absence of a rotationally supported nuclear gas structure, half of the accretion events will be retrograde, and the BH enters the radio-loud phase.

If the BH is very massive ($M_{\text{BH}} > 10^9 M_\odot$), as seen in giant ellipticals (Kormendy & Bender 2009), we argue that its spin direction remains stable through all accretion episodes: because of its large BH mass and the lack of a massive nuclear disc, the BH angular momentum likely exceeds the angular momentum carried by the accretion disc (King et al. 2005). Indeed, we note that for giant BHs, the warp radius $R_{\text{warp}}$ (delimiting the distance for gravito-magnetic interaction between the BH and the disc) exceeds the outer radius of the accretion disc determined by self-gravity, $R_{\text{out}}$. Following Perego et al. (2009), for a $10^9 M_\odot$ BH, the outer radius $R_{\text{out}} \sim 40 M_{\text{BH},9}^{-52/45} f_E^{-22/45} R_G$ (where $R_G$ is the Schwarzschild radius and $f_E$ the Eddington factor) is smaller than $R_{\text{warp}} \sim 10^3 a^{4/7} M_{\text{BH},9}^{4/35} f_E^{6/35} R_G$ implying that over the Bardeen-Petterson timescale ($\lesssim 100$ yrs) the entire disc aligns or antialigns (depending on the disc’s initial orientation) with the BH spin vector that keeps its orientation stable. Thus the BH can sustain a collimated jet over large scales until accretion ceases.

We thus expect radio–loud AGN to be hosted in missing–light, core ellipticals, remnants of dry mergers. This second scenario is summarized in Figure 2.

3 Discussion

In this note, we propose that retrograde accretion onto a massive ($M_{\text{BH}} \gtrsim 10^9 M_\odot$) post-coalescence spinning BH is conducive to the generation of a powerful large-scale jet, in the gas-poor environment of a giant elliptical with core. This is in agreement with the observation that radio–loud AGN are hosted in bright ellipticals that show a stellar core (whenever optical data are available), and with the recent finding on the dichotomy in radio jet orientations in elliptical galaxies (Browne & Battye 2010). In less-louder radio-loud AGN, Browne and Battye find a tendency for the axis of the radio emission to align with the minor axis of the starlight of the host, an oblate rotationally supported elliptical. By contrast they find no preferred radio-optical alignment among the radio-louder objects possibly hosted in triaxial non-rotating ellipticals. This study appears to support our evolutionary scheme: coreless (extra–light) rotationally supported ellipticals (Kormendy et al. 2009) that likely form in gas-rich mergers are expected to host a BH accreting in the prograde mode with a high spin aligned with the angular momentum of the large-scale disc, and so aligned with the minor axis of the starlight. By contrast, core (missing–light) triaxial ellipticals are expected to host a BH that has a random spin orientation regardless its accretion mode (i.e. whether prograde or retrograde).

The model rests on Garofalo’s conjecture that around a retrograde BH, magnetic fields threading the horizon reach maximum amplification, resulting in a dramatic enhancement of the jet power even for non–extreme values of $a$. The interval of spin values for operation of this process is still weakly constrained by theory. Furthermore prograde accretion can also result in large BZ luminosities
Figure 2. Gas–poor mergers between nearly equal mass galaxies (e.g. between two ellipticals). The left and right branches of the scheme refer to the evolution of the galaxies and the BHs, respectively. Left: We hypothesize that the merger ends with the formation of a giant missing–light elliptical where a stellar core has been excavated by the BH binary in its hardening by scattering off single stars, and/or by heating from gravitational recoil after BH coalescence. Observations of giant core ellipticals indicate that they host very massive BHs with $M_{BH} \geq 10^{9}\, M_\odot$ (Kormendy & Bender 2009). Right: The BHs that initially inhabit the two galaxies are expected to pair, form a binary and eventually coalesce under the action of stellar torques. Prior to coalescence the two BHs have arbitrary spin moduli and random orientation. In the gas–poor environment the spins of the giant BHs do not align with the orbit and the post-coalescence BH ends with a high spin $a \gtrsim 0.7$ and large recoil. Once settled at the centre of the galaxy host the BH may experience episodes of retrograde accretion (in 50% of the cases) and become, according to our hypothesis a radio–loud AGN. In the remaining 50% cases the BH may be active and become an AGN. Observations indeed indicate that giant ellipticals host radio–quiet AGN, and this is a natural outcome of our working model.
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Thus, there should exist a zone of avoidance delimited by a maximum–negative $a_{\text{jet}}^-$ and a minimum–positive $a_{\text{jet}}^+$, outside which the generation of jets is possible. The values of $a_{\text{jet}}^-$ and $a_{\text{jet}}^+$ may not be symmetric as non–symmetric is the underlying Kerr spacetime. If retrograde accretion is a necessary condition only for the most powerful jets hosted in ellipticals, the value of $a_{\text{jet}}^-$ that our model requires is $a_{\text{jet}}^- \gtrsim -0.7$, resulting from isotropic BH coalescences in dry mergers. If prograde accretion vehicles the production of jets as well, a value of $a_{\text{jet}}^+$ close to $+0.4$ (from chaotic accretion) would imply the presence of jets in any type of galaxy, from discs in isolation to spheroids in clusters and groups. The paucity of radio–loud disc hosts and the lack, at low redshift, of radio–loud coreless host–ellipticals suggest that such a low value of $a_{\text{jet}}^+$ is unrealistic. One would be tempted to require $a_{\text{jet}}^+ \sim +1$, according to the models by McKinney (2005).

The rotational energy stored in giant BH ($M_{\text{BH}} \gtrsim 10^9$) may suffice to power a radio–loud AGN at an average level of $\sim 10^{46}$ erg s$^{-1}$ for a lifetime $\tau_{\text{jet}} \sim 10^8$ yr. However retrograde accretion causes the BH to spin down on a time $\tau_{\text{down}} \sim \min(\tau_{\text{ac}}, \tau_{\text{jet}})$. Spin–down by accretion occurs on $\tau_{\text{ac}} \sim J_{\text{BH}}/(M_{\text{net}}\tilde{l}_{\text{ISCO}}) \sim M_{\text{BH}}/M_{\text{net}}$ (where $M_{\text{net}}$ is the net inflow rate onto the BH, and $\tilde{l}_{\text{ISCO}}$ the angular momentum per unit mass of a test particle at ISCO). $\tau_{\text{ac}}$ is close to the Salpeter time for $e$–folding of the BH mass. The BZ timescale $\tau_{\text{jet}}$ depends on the magnitude of the magnetic field that threads the horizon and on the thermal/geometrical structure of the accretion disc (Moderski et al. 1998). In Garofalo’s scenario, retrograde accretion is a transitory phase during the lifetime of a BH (Garofalo et al. 2010) whose duration and recurrence depend on the way the BH is fed whether through continuous or chaotic accretion.

Recent observations of extremely bright Blazars with BAT/\textit{Swift} at redshifts $z > 2$ (Ajello et al. 2009; Ghisellini et al. 2009a) and of Blazars and FRGs with LAT/\textit{Fermi} (Ghisellini et al. 2009b) indicate that luminous radio-loud AGN host giant BHs, and that a prominent accretion disc co-exists with a powerful jet suggesting that extraction of rotational energy occurs through accretion (Maraschi 2001). We are tempted to associate the extreme BH mass, inferred from the disc luminosity, to the stability of the BH spin orientation and the jet power to its spin modulus and to accretion in the retrograde mode. Further studies on the stability of retrograde accretion will help in disentangling the nature on the AGN radio–loud/quiet dichotomy.

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