On the role of black hole spin and accretion in powering relativistic jets in AGN

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Abstract. Motivated by the remarkable results on the general properties of blazars obtained from Fermi observations we discuss the role of spin and accretion in powering relativistic jets in AGNs. We consider studies of the Blandford–Znajek mechanism taking into account advection of magnetic flux from an accretion disk surrounding the Black Hole (BH) which indicate that the mechanism is inhibited for values of the BH spin $a \lesssim 0.5$. However large scale propagation of the jet with highly relativistic bulk acceleration likely requires even larger spin values. The Blandford–Znajek mechanism then predicts a tight connection between jet power and accretion power, accounting for the correlation between $\gamma$-ray luminosity and accretion disk luminosity found in the bright Fermi blazar sample. The suggested spin threshold would lead to a grand unification of AGN based on only two intrinsic parameters: the BH spin and the accretion rate in Eddington units.

1. Introduction

It is now commonly accepted that the non thermal emission from radio loud Active Galactic Nuclei (AGN) is powered by relativistic jets emanating from the nucleus. (Begelman, Blandford & Rees 1984, Blandford 1990).

However the physical mechanism producing relativistic jets is not yet completely understood (see e.g. Tchekhovskoy, Narayan & McKinney 2010 and references therein). Present investigations focus on the mechanism first studied by Blandford & Znajek (1977) (hereafter BZ mechanism) which still appears to be the most promising candidate. This process, purely electromagnetic, rests on the differential rotation between a spinning Black Hole (BH) and its magnetosphere. In the case of AGN advection of the necessary magnetic flux can be naturally associated with the accretion flow, leading to the generation of a collimated Poynting flux \textit{at the expense of the BH rotational energy}.

Particles in the jet can be accelerated up to bulk Lorentz factors $\Gamma$ of $10–100$ at $r \simeq 100–1000 \, R_S$ with collimation consistent with jet phenomenology (McKinney 2006 and references therein). Thus in general the mechanism appears successful in accounting for the properties of relativistic jets in AGN. However the efficiency of the process, in particular its dependency on the spin parameter $a = Jc/GM^2$ (where $J$ is the BH angular momentum and $M$ the BH mass), is still under discussion. Spin dependencies in the range $a^2–a^6$ have been obtained (Mc Kinney
2005, Tchekhovskoy et al. 2010), while a global efficiency of \(\simeq 10\%\) seems attainable for maximal BH spin (McKinney 2006).

On the observational side the results provided by the Fermi satellite, continuously surveying the whole sky in gamma-rays (100 MeV - 10 GeV) with the LAT instrument have opened a new era for the study of relativistic jets. AGN represent the dominant population in the gamma-ray sky, the vast majority being classified as “blazars”, radio loud AGN whose relativistic jets closely align with the terrestrial line of sight. Most of their radiative luminosity is emitted in the gamma-ray range. The results of the first three months of observations, the “bright AGN survey” performed by LAT (LBAS, Abdo et al. 2009) are still of particular importance since this sample is completely identified and complemented by multifrequency data allowing to study in a systematic way the general properties of the population (Abdo et al. 2010, Ghisellini et al. 2010; hereafter G10).

In the following we will argue that the correlation between gamma-ray luminosity and accretion disk luminosity found in the three month Fermi blazar sample (G10) supports the hypothesis that relativistic jets in AGN are generated only for high spin values. In §2 we summarize existing studies of the dependency of the strength of the BZ process on the BH spin. In §3 we discuss the correlation mentioned above with minimal assumptions on radiation models. We conclude in §4 outlining a scheme for a “grand” unification” of AGN.

2. Arguments for an effective spin threshold in the Blandford–Znajek mechanism

The analytic formula for the power generated via the BZ mechanism as derived by e.g. MacDonald and Thorne (1982) is given by:

\[
L_{\text{BZ}} \simeq k \frac{\Omega_F (\Omega_H - \Omega_F)}{\Omega_H^2} a^2 \times B_H^2 \gamma_H^2 c
\]

Eq. (1) shows that, in order to produce a positive power, \(\Omega_H\) must be larger than \(\Omega_F\), corresponding to the physical intuition that, in order to brake the spinning BH, the rotation of external field lines should be slower than the hole itself. In the opposite case the process would correspond to absorption rather than emission of power. BZ suggested that the field angular velocity will adjust to \(\Omega_F \simeq \Omega_H / 2\) as found in their approximate analytic solution. For this value of \(\Omega_F\) the extracted power is maximized. This result is confirmed by Komissarov (2001, 2004) via direct numerical simulations and with an improved description of the electrodynamics around a spinning black hole in the force-free approximation.

The above models however do not include a description of how the field is advected to the BH from an accretion flow, the only possible source of magnetic flux in the AGN case. In the latter case, one could assume, approximately, that the poloidal component of the field, frozen in the disk, rotates with the same angular velocity as the rotating gas at the innermost stable corotating orbit (ISCO), i.e., \(\Omega_F \sim \Omega_{\text{ISCO}}(a)\). For low values of the BH spin, \(\Omega_{\text{ISCO}}(a)\) exceeds \(\Omega_H(a)\): the crossing occurs at \(a_{\text{cr}} \approx 0.35\). For \(a < a_{\text{cr}}\) the analytic expression for the BZ power (Eq. 1) suggests that the process would not take place as long as \(\Omega_F > \Omega_H\). This is physically plausible: in fact the interaction of the slowly spinning BH with the faster rotating infalling magnetized plasma, should result in a torque of opposite sign with respect to that acting in the case of the BZ process, as previously noted and discussed by Li (2000a,b) and Li & Paczyński (2000).
Computing the analytic expression of the BZ power for $\Omega_F = \Omega_{\text{ISCO}}$ for different values of $a$ one can verify that the difference with respect to the BZ hypothesis is minor for intermediate values of $a$, but the power becomes becomes negative for values of $a \lesssim 0.4$. In other words, for $a \lesssim 0.4$ the conditions necessary for the BZ process to work may not be met.

This rather simplistic approach, finds some support in appropriate GRMHD simulations. In fact Mc Kinney and Gammie (2004) studied the self consistent evolution of a rotating BH surrounded by a weakly magnetized torus ($H/R = 0.1$), a situation close to that described above. We mention two aspects of the results discussed in their paper: one is the finding that $\Omega_F$ tends to $\Omega_{\text{ISCO}}$ at the equator and remains constant throughout the plunging region; the other one is that the ratio of “electromagnetic luminosity” to nominal “accretion luminosity”, i.e. the efficiency of the BZ process is very small below $a = 0.6$ and becomes negative for $a < 0.5$, i.e. the BZ effect is not operating. Thus an ”effective” spin threshold is found in the above paper at $a > 0.5$. This threshold does not seem to be present in the simulations of Tchekhovskoy et al. (2010). More general estimates of the power output from a rapidly rotating black hole with self–consistently determined geometry and magnitude of the magnetic field for a realistic accretion disk are summarized in Mc Kinney (2005). Due to the different structure of the magnetosphere which depends on the BH spin, a higher fraction of the power is emitted in the polar regions (jet) for high spin. In any case below $a = 0.5$ the jet efficiency is less than $10^{-4}$.

For a rapidly rotating BH a larger magnetic flux is generated close to the nearly force free poles. Due to the low density and high magnetic field these are the only regions that can give rise to highly relativistic jets, generating particle flows with bulk Lorentz factors reaching 10 - 100 on large scales (10–1000 $r_g$) and collimation properties consistent with what inferred from observations (Mc Kinney 2006). Note however that the latter results are valid only if the pressure of the surrounding medium is small compared to the magnetic pressure in the jet. If, for the same value of the accretion rate the BH has a relatively low spin, $0.5 \lesssim a \lesssim a_{\text{lim}}$, the magnetic pressure in the forming jet could be insufficient to satisfy the condition for large scale bulk acceleration. The production of highly relativistic jets may therefore require a higher “effective” spin threshold $a_{\text{lim}} > 0.5$.

The jet power efficiency in terms of accretion power for $a > 0.5$ is estimated as $\eta_{\text{jet}} = 6.8 \times 10^{-2} [\Omega_H / \Omega_H(a = 1)]^5$ (Mc Kinney 2005). Since $\Omega_H(a)$ decreases by a factor 2 between $a = 1$ and $a = 0.8$, with a predicted decrease of a factor 30 in jet power for the same accretion power. A further drop of a factor 30 in efficiency is predicted between $a = 0.8$ and $a = 0.5$. Given the large decrease in efficiency we provisionally adopt an ”effective” spin threshold for relativistic jet production at $a_{\text{lim}} \simeq 0.8$. The threshold value may also depend on the accretion rate. For larger accretion rates the ambient pressure may be higher and a higher field (spin) may be required to launch large scale relativistic jets.

3. The power of relativistic jets and accretion

The physical scale of the power produced in the form of collimated Poynting flux is given by the dimensional factor in the BZ formula, which corresponds to the magnetic energy flux at the horizon. Assuming that beyond $R_{\text{ISCO}}$, i.e. in the nearly free fall or “plunging” region, the flow is quasi–spherical and the magnetic and kinetic energy densities are in near equipartition, the value of the magnetic field at the horizon can be directly linked to the accretion rate (Krolik 1999, Maraschi 2001, Levinson 2010). The resulting equation shows that the physical scale of the process is proportional to the accretion power.

$$B_H^2 r_H^2 c^2 \sim 8\pi \rho c^2 r_H^2 c \simeq 2 \dot{M} c^2$$ (2)

Eq. (2) does not include the dependence of the jet power on BH spin. If relativistic jets are generated only for a limited range of spin ($a > 0.8$), a direct correlation between jet power and accretion power is predicted.
Relativistic jets in AGN emit most their radiative power in the γ-ray band as indicated already by the results obtained with the Gamma Ray Observatory (e.g., von Montigny et al. 1995). Early estimates of jet power and accretion power in few brightest quasars and BL Lac objects led to the suggestion that the two powers were comparable and a connection was present, though with large uncertainties (Maraschi 2001, Ghisellini & Celotti 2002, Maraschi and Tavecchio 2003, Celotti & Ghisellini 2008).

The ongoing all sky survey of the Fermi satellite with the LAT instrument has opened a new era in γ-ray astronomy providing rich and unbiased samples of γ-ray selected blazars. The ”Bright AGN sample” based on the 3 months survey by the LAT instrument on board Fermi (LBAS, Abdo et al. 2009), completely identified and complemented by a rich set of multifrequency data has been fully modelled by G10 who found a significant correlation between jet power and accretion power for the FSRQ subsample in agreement with the expectation from Eq. 2. The correlation was further extended by analogous modelling of a group of 28 FSRQ with high (z > 2) redshift (Ghisellini et al. 2011).

Here we consider observed quantities, i.e. the observed γ-ray luminosities vs. the accretion disk luminosities or upper limits (Fig. 1). This choice is intended to show that a correlation exists prior to modelling. Few points should be recalled:

(i) The accretion disk luminosity is derived from the measured luminosity of a blue bump which is present in the SED of FSRQs. If a blue bump is not apparent, as is typical for BL Lac objects, an upper limit is reported.

(ii) The observed γ-ray emission is beamed, therefore depends on the angle to the line of sight. However it can be shown (see Celotti & Ghisellini 2008) that the total power spent by the jet to produce the observed γ-ray emission is \( P_\gamma \sim L_\gamma / \Gamma^2 \), where \( \Gamma \) is the bulk Lorentz factor of the jet. Since \( L_\gamma \) often dominates the bolometric output, especially for FSRQs, it represents a good proxy for the radiative power of the jet \( P_{\text{rad}} \sim L_{\text{bol}} / \Gamma^2 \), which yields in turn a robust lower limit to the jet power \( P_{\text{jet}} \).

(iii) Excluding upper limits, \( L_\gamma \) and \( L_d \) correlate (see Fig. 1), with a random probability of \( P_{\text{random}} = 5.6 \times 10^{-3} \) after subtracting off the common redshift dependence (see Padovani 1992 for the partial correlation analysis used here). The analogous correlation derived in G10, where each source was modelled yielding individual values for the bulk Lorentz factor, has higher significance, however the existence of a correlation between observed quantities shows that it is robust, and confirms, a posteriori, the relatively narrow range of \( \Gamma \) derived earlier for these sources: 10 \( \leq \Gamma \leq \) 17 with an average of \( \langle \Gamma \rangle = 13 \). From Fig. 1 one derives \( L_\gamma \simeq 30 L_d \) and this implies \( P_\gamma \sim L_\gamma / \Gamma^2 \sim 0.18 L_d \).

The bottom line is that also from this simple, model independent analysis one derives that for FSRQs jet power and accretion power are correlated. This is expected if the jet is produced through the BZ mechanism because the magnetic field at the horizon which determines the jet power is naturally related to the accretion energy density as discussed above (eq. 2).

Moreover the relation \( P_{\gamma} \simeq 0.18 L_d \) allows to estimate the efficiency of the jet production mechanism. Assuming that the total power carried by the jet is \( P_{\text{jet}} = 10 P_\gamma \) one derives \( P_{\text{jet}} = 1.8 L_d = 1.8 \eta_{\text{acc}} M c^2 \). The efficiency of the accretion process \( \eta_{\text{acc}} \) is estimated to be 6% for a “standard” accretion disk around a non rotating BH therefore for the FSRQs in this sample we derive \( P_{\text{jet}} = 0.108 M c^2 \) i.e. a jet production efficiency \( \eta_{\text{jet}} \simeq 0.1 \).

Comparing with the results of GRMHD simulations we find that a 10% efficiency is at the top of the expected values. Moreover all the simulations predict that the efficiency is strongly dependent on the value of the BH spin (e.g. Martinez-Sansigre & Rawlings 2011 for a direct comparison of the results of different simulations). Hence the observed correlation implies that i) the jet production efficiency is high, i.e. \( \eta_{\text{jet}} \simeq 10^{-1} \), and ii) all these sources should have close to maximal spin.
Figure 1. The \( \gamma \)-ray luminosity \( L_\gamma \) as a function of the accretion disk luminosity \( L_d \) for the blazars discussed in G10. Triangles correspond to upper limits of \( L_d \). The grey stripe, which is only indicative, corresponds to \( L_d \propto M \) above a critical \( \dot{M}/\dot{M}_{\text{Edd}} \) value, and \( L_d \propto M^2 \) below, while \( L_\gamma \propto M \) for any value of \( M \).

Clearly these estimates suffer from uncertainties. If the average jet Lorentz factors in the emission regions were higher the jet powers could be lower. However we have assumed for the accretion disk the “standard” efficiency, while in the case of a spinning BH the accretion efficiency could be larger, implying even larger jet production efficiency.

A second important point concerns the comparison of the properties of FSRQ and BL Lac objects: FSRQs populate the luminosity range \( 10^{47} \text{--} 10^{45} \text{ erg/s} \) and disappear below this limit, while BL Lac objects populate the lower luminosity region. The luminosity separation was interpreted as due to a population of AGN with similar BH mass \( (10^{9} M_\odot) \) but decreasing accretion rates (see Ghisellini et al. 2009). This is consistent with physical models of AGN evolution (Cavaliere et al. 1985). Accretion disk models predict that for \( \dot{m} \equiv \dot{M}/\dot{M}_{\text{Edd}} \) below \( 10^{-2} \), due to the reduced opacity, the radiative efficiency of the disk diminishes (e.g. Narayan, Garcia & McClintock 1997) causing the disappearance of the optically thick emission (Blue Bump) and of the Broad Line Region, turning the jetted AGN into a BL Lac object. However, according to Eq. 2, the BZ power (i.e. the jet power) is still proportional to the accretion rate. The jet radiative efficiency should not change substantially since particle acceleration and radiation processes remain similar. As a result in this regime the jet power and \( L_\gamma \) still trace the accretion rate, while the accretion disk luminosity drops faster, causing a flattening of the expected \( L_\gamma - L_{\text{disk}} \) relation. The predicted behaviour is shown as a grey stripe in Fig. 1.

4. Conclusions: a grand unification scheme for AGN ?

Based on the results of some GRMHD simulations we argued for the adoption of an “effective” spin threshold to launch relativistic jets in an accreting SMBH. The threshold value should be above \( a = 0.5 \) and possibly as high as \( a \sim 0.8 \). The correlation between \( \gamma \)-ray luminosity and accretion disk luminosity found in the Fermi Lat Bright AGN Sample supports this hypothesis. The relation between the power produced in \( \gamma \)-rays and the luminosity of the accretion disk is found to be \( P_\gamma \sim 0.2L_d \) implying \( P_{\text{jet}} \sim 2L_d \) i.e. an efficiency of the jet production mechanism
Figure 2. Grand Unification Scheme for AGN: the four quadrants qualitatively depict the properties of AGN for different accretion rates and BH spin intervals. The vertical axis represents the value of $\dot{m}$: the pink circles indicate that the accretion flow occurs in the ADAF mode (low $\dot{m}$), the blue ellipses indicate a standard accretion disk (high $\dot{m}$). The horizontal axis represents the value of the BH spin $a$: for $a$ larger than 0.5-0.8 a relativistic jet is generated. The associated radio source is likely FRII for high values of $\dot{m}$ and FR I for low values of $\dot{m}$. If viewed at small angle the AGN will be classified as FSRQ or BL Lac respectively.

close to the radiative efficiency of the accretion disk. Given the efficiencies for jet production estimated by McKinney (2005) our result requires that all the sources in the sample have close to maximal spin. Deeper $\gamma$-ray samples, which will be obtained in few years from now, may probe this hypothesis in more depth but will require extensive work for identification of the optical counterparts and study of their properties.

The link between accretion power and jet power together with the limited range of spin for which the process can actually take place naturally suggests a Grand Unification Scheme for AGNs in terms of the main intrinsic astrophysical properties, i.e. mass, spin and accretion rate. We will not consider the mass explicitly but will use mass normalized quantities, i.e. the adimensional angular momentum $a$ and the accretion rate in Eddington units $\dot{m}$.

The hypothesis that the BH spin was the physical parameter underlying the radio-loud radio quiet dicotomy of AGN has been repeatedly discussed in the past without definitive answers (e.g Wilson and Colbert 1995, Blandford 1990, Meier 1999, 2002, Sikora et al. 2007). The existence of an effective spin threshold for the BZ process at $a_{\text{lim}} \approx 0.8$ introduces a definite separation between radio loud and radio-quiet AGN with the following properties:

- In luminous radio loud AGN ($a > a_{\text{lim}}$), accreting at $\dot{m} > 10^{-2}$ (where $\dot{m}$ is the accretion rate measured in Eddington units, $\dot{m} \equiv M/M_{\text{Edd}},$ $M_{\text{Edd}} \equiv L_{\text{Edd}}/(\eta c^2)$ and $\eta = 0.1$) highly relativistic jets are able to carry significant non thermal powers to large or intermediate distances from the nucleus; The luminosity of the accretion disk and the power carried by the jet are comparable. The radio source morphology should be FR II. Viewed along the jet axis these objects would be classified as Flat Spectrum Radio Quasars.

- Luminous radio quiet AGNs do not have relativistic jets; they may emit weakly in the radio band (compared to their optical luminosity) through aborted jets or non relativistic outflows (e.g. the Blandford & Payne mechanism) or other mechanisms. The (weak) radio power may still correlate with the luminosity of the accretion due to the common dependence on
the accretion rate, but their ratio should be $< 10^{-2}$.

- For accretion rates $\dot{m} < 10^{-2}$ the appearance of the AGN nucleus in the optical-UV-X-ray changes, due to the transition to a different, radiatively inefficient, accretion regime (RIAF). If the central BH has high spin, the jet power (still proportional to $\dot{m}$) can be larger than the observed thermal luminosity. These objects may therefore be very radio loud, but their absolute powers both thermal and non-thermal will be less than those of the first two classes for the same mass of the SMBH. If viewed along the jet axis these objects would likely be classified as BL Lacs. The radio-quiet counterparts (low spin) could correspond to the LINERS AGN category.

A more detailed discussion of these ideas will be given elsewhere.

[1] Abdo A. A., et al., 2009, ApJ, 700, 597
[2] Abdo A. A., et al., 2010, ApJ, 716, 30
[3] Begelman M. C., Blandford R. D., Rees M. J., 1984, Rev. Mod. Phys., 56, 255
[4] Blandford R. D., 1990, Saas-Fee Advanced Course 20
[5] Blandford R.D. & Znajek R.L., 1977, MNRAS, 179, 433
[6] Blandford R. D., Payne D. G., 1982, MNRAS, 199, 883
[7] Cavaliere A., et al. 1985, ApJ, 296, 415
[8] Celotti A., Ghisellini G., 2008, MNRAS, 385, 283
[9] Ghisellini G., Celotti A., 2002, ASPC, 258, 273
[10] Ghisellini G., Maraschi L. & Tavecchio F., 2009, MNRAS, 396, L105
[11] Ghisellini G., et al., 2010, MNRAS, 402, 497 (G10)
[12] Ghisellini G., et al., 2011, MNRAS, 411, 901
[13] Komissarov S. S., 2001, MNRAS, 326, L41
[14] Komissarov S. S., 2004, MNRAS, 350, 1431
[15] Krolik J. H., 1999, ApJ, 515, L73
[16] Levinson A., 2010, IJMPD, 19, 649
[17] Li L.-X., Paczyński B., 2000, ApJ, 534, L197
[18] Li L.-X., 2000a, PhRvD, 61, 084016
[19] Li L.-X., 2000b, ApJ, 533, L115
[20] MacDonald D., Thorne K. S., 1982, MNRAS, 198, 345
[21] Maraschi L., 2001, AIPC, 586, 409
[22] Maraschi L., Tavecchio F., 2003, ApJ, 593, 667
[23] Martinez-Sansigre A., Rawlings S., 2011, MNRAS, 414, 1937
[24] McKinney J. C., Gammie C. F., 2004, ApJ, 611, 977
[25] McKinney J. C., 2005, ApJ, 630, L5
[26] McKinney J. C., 2006, MNRAS, 368, 1561
[27] Meier D. L., 1999, ApJ, 522, 753
[28] Meier D. L., 2002, NewAR, 46, 247
[29] Narayan R., Garcia M. R., McClintock J. E., 1997, ApJ, 478, L79
[30] Padovani P., 1992, A&A, 256, 399
[31] Sikora M., Stawarz Ł., Lasota J.-P., 2007, ApJ, 658, 815
[32] Tchekhovskoy A., Narayan R., McKinney J. C., 2010, ApJ, 711, 50
[33] Wilson A. S., Colbert E. J. M., 1995, ApJ, 438, 62