



Blazar jets as the most efficient persistent engines

Gabriele Ghisellini¹

Received: 31 August 2018 / Accepted: 1 August 2019 / Published online: 8 August 2019
© Accademia Nazionale dei Lincei 2019

Abstract

We have not identified for sure what is the mechanism launching, accelerating, and collimating relativistic jets. The two most likely possibilities are the gravitational energy of the accreting matter or the rotational energy of a spinning black hole. Even the evaluation of the jet power is not trivial, since the radiation from the jet is enhanced by relativistic beaming, and there are fundamental uncertainties concerning the matter content of the jet (electron–proton or electron–positron plasma). However, in recent years, there have been crucial advances mainly driven by the richness of data in the γ -ray band. This is the band, where blazars emit most of their electromagnetic power. Furthermore, there are now large sample of γ -ray loud blazars covered by optical spectroscopy. For the blazar sub-class of flat spectrum radio quasars, these data provide measurements of the main emission lines and of the underlying continuum. From these data, it is relatively easy to infer the bolometric luminosity of the accretion disk. The relativistic jet emission on one hand, and the disk luminosity on the other hand, allows us to compare the jet power and the accretion luminosity. Although the inferred jet power is subject to a few assumptions and is somewhat model-dependent, it is possible to derive a lower limit to the jet power that is assumption-free and model-independent. Since this lower limit is of the order of the accretion luminosity, we infer that the true jet power is larger.

Keywords Relativistic jets · BL Lac objects · Galaxies: quasars: general · Radiative processes: general

1 Introduction

BL Lac objects and flat spectrum radio quasars (FSRQs) form the class of blazars, radio-loud active galactic nuclei (AGN), whose jet is pointing toward us (for recent reviews, see, e.g., Böttcher 2007; Ghisellini et al. 2011; Dermer 2014). FSRQs are powerful sources, with broad emission lines, contrary to BL Lacs, that are less powerful and often line-less. The observational distinction among them is in fact the equivalent width (EW) of their broad emission lines: BL Lacs have $EW < 5\text{\AA}$ (rest frame, Urry and Padovani 1995). This divide is purely observational: objects that do have strong emitting lines could then be classified as BL Lacs

if their jet emission is particularly enhanced (see Ghisellini et al. 2011; Sbarrato et al. 2012 for an alternative definition).

Blazars emit most of their electromagnetic power by the synchrotron and the inverse Compton processes. Their spectral energy distribution (SED) is in fact characterized by two broad humps. The SED follows a sequence controlled by the bolometric luminosity: when this is increasing, the peaks of the two main radiation mechanisms shift to smaller frequencies, and the inverse Compton component becomes more dominant (Fossati et al. 1998; Donato et al. 2001; Ghisellini et al. 2017).

At the largest luminosities, the synchrotron peaks in the IR-sub-mm band, and the slope above it is as steep as the slope in the γ -ray band covered by *AGILE* and *Fermi/LAT*. This makes the accretion disk clearly visible, and at high redshifts, the observed accretion disk peak falls in the optical band. In these cases, we can directly measure its total luminosity. Otherwise, we have to rely on the observed broad emission lines. Phenomenological relations between their relative weight (Francis et al. 1991; Vanden Berk et al. 2001) allow to calculate the total luminosity emitted by the broad lines. Using an average covering factor of ~ 10 , we have an estimate of the accretion disk luminosity.

This paper is the peer-reviewed version of a contribution selected among those presented at the Conference on Gamma-Ray Astrophysics with the *AGILE* Satellite held at Accademia Nazionale dei Lincei and Agenzia Spaziale Italiana, Rome on December 11–13, 2017.

✉ Gabriele Ghisellini
gabriele.ghisellini@inaf.it

¹ INAF-Osservatorio Astronomico di Brera, Milan, Italy

In addition, from the broad line FWHM and the continuum, we can estimate the black hole mass. This is the so-called virial method, which relies on empirical correlations between the disk luminosity and the distance of the BLR from the central engine. The uncertainties of the method are quite large: a factor between 3 and 4 (Park et al. 2012), and they do not depend on the quality of data, but upon the dispersion of the empirical relations used. Alternatively, we can directly fit the spectrum with a disk model, such as the Shakura and Sunjaev optically thick and geometrically thin accretion disk model (Shakura and Sunyaev 1973; Calderone et al. 2013). This simple model assumes zero black hole spin, and does not take into account relativistic effects. Kerr models including all effects have been studied by, among others, (Li et al. 2005) for binaries, and extended by Campitiello et al. (2018) to AGNs.

Blazars are among the strongest γ -ray emitting sources. The third catalog of AGNs detected by *Fermi*/LAT lists $\sim 1,500$ sources, of which the vast majority are blazars (Ackermann et al. 2015). This made possible to make population studies, such as the γ -ray blazar luminosity function and their contribution to the γ -ray background (Ajello et al. 2012, 2014).

Figure 1 shows the γ -ray luminosities of BL Lacs and FSRQs as a function of their redshift. We have also drawn three lines indicating the approximate limiting sensitivity of EGRET, AGILE and *Fermi*/LAT. It is approximate, because the same spectral index is used for all sources. This figure shows the improvement that AGILE and especially LAT

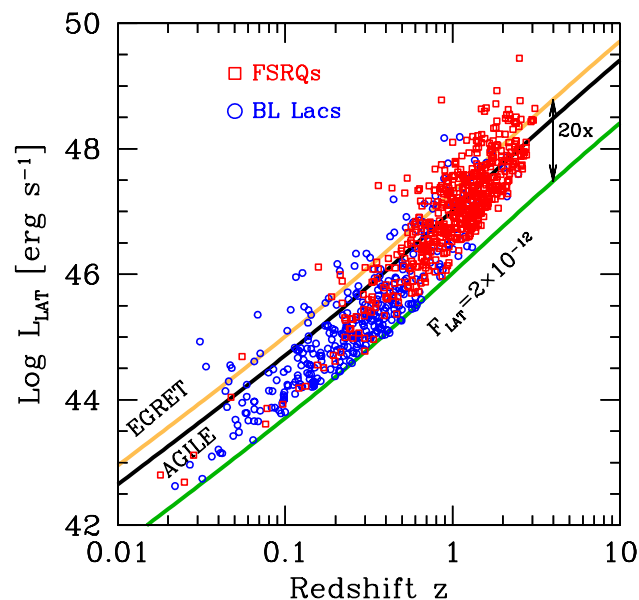


Fig. 1 γ -ray luminosity of blazars detected by *Fermi*/LAT as a function of their redshift. We also plot three solid curves, corresponding (roughly) to the LAT, AGILE, and EGRET sensitivity assuming for simplicity that the γ -ray spectrum is the same

made possible in our knowledge of blazars. It also makes clear that EGRET could explore only the tip of the iceberg of the entire blazar population. Furthermore, since all blazars vary greatly especially in γ -rays, EGRET probably detected most blazars only when they are in high state. LAT returns instead a more balanced view.

2 Comparing jet power and accretion luminosity

The first attempt to derive the relation between the jet and the accretion disk power was made by Rawlings and Saunders (1991). They estimated the average jet power considering the extended radio emission, calculating their minimum energy through equipartition considerations, and estimating their lifetime considering the time needed to expand and the presence of a cooling break in the spectrum. Then, they collected for all the sources the luminosity of the narrow lines. They found a strong correlations between jet power and line luminosity, but this, per se, is not unexpected, since both quantities depend on distance. What is interesting was that the narrow line luminosity was always a factor 100 less than the jet power. Since the covering factor of the narrow lines is $\sim 10^{-2}$, they concluded that the average jet power energizing the lobes and the accretion luminosity was of the same order.

Stimulated by this result, Celotti and Fabian (1993) tried to improve the estimate of the jet power by considering the jet emission at the parsec (e.g., VLBI) scale to find the number of particles needed to account for the emission and the Lorentz factor needed not to overproduce the X-ray emission through the synchrotron-self-Compton (SSC) process. They confirmed the earlier results. Later, the same was performed using broad line luminosities instead of the narrow ones (Celotti et al. 1997).

At the same time of these pioneering studies, EGRET discovered that blazars are very strong γ -ray emitters and that this emission is the most variable. The first models thought that the γ -rays were SSC emission (Maraschi et al. 1992; Bloom and Marscher 1992; Bloom et al. 1993). Soon, it became clear that variability at different frequencies was correlated, strongly suggesting that the same population of particles, in only one region, was responsible for the emission. This was the birth of the leptonic, one-zone model. The location of this one-zone is still controversial: early suggestions located it close to the accretion disk (Dermer et al. 1992), or within the BLR (Sikora et al. 1994), or beyond the BLR but within the molecular torus size (Sikora et al. 2002). In these models, the seed photons for the inverse Compton process are produced externally to the jet (External Compton, EC for short). This process is highly efficient, since the radiation energy density, as seen in the comoving frame, is enhanced by Γ^2 . In general, we have two constraints that

limit the location of the emitting region: i) if too close to the disk, the produced γ -rays are absorbed in γ - γ collisions and ii) if very distant from the black hole, the dimension of the emitting region becomes too large to account for the observed short variability. Distances of the order of $\sim 10^3$ Schwarzschild radii are suggested, see the cartoon in Fig. 2.

The one-zone model had the advantage to greatly simplify the modelling while reducing the number of free parameters. For low power blazars, lacking broad lines, and thermal components, the SSC model is still the leading model, and has the virtue of having no degeneracies: given some basic observables, the solution is unique (Tavecchio et al. 1998). EC models, on the other hand, can offer a unique solution if some extra information is supplied or can be derived from the fitting, such as the black hole mass and the disk luminosity (see Ghisellini and Tavecchio 2009).

3 Electrons and positrons

If we calculate the jet power estimating how many leptons are necessary to produce the received flux, we face a crucial problem. Any particle distribution fitting the data has to be relatively steep: $N(\gamma) \propto \gamma^{-p}$, with $p \geq 2$, so that the total number of the emitting particles depends strongly on the minimum particle energy, or their minimum random Lorentz factor γ_{\min} . The synchrotron emission is self-absorbed for values of $\gamma \lesssim 50 - 100$ and the SSC flux is always hidden by the synchrotron one at low energies. In these condition,

we cannot estimate γ_{\min} that corresponds to an uncertainty on the jet power of the order of $\sim \gamma_{\min}^{p-1}$. However, for powerful blazars, the soft X-ray emission is produced by the EC process. In this case, we do see the effects of changing γ_{\min} , since the soft X-ray shape should become harder below $v_{Ly\alpha} \gamma_{\min}^2 \Gamma^2 \sim 1 \text{ keV} \times \gamma_{\min}^2 (\Gamma/10)^2$. Usually, we do not see a break in the soft X-ray spectrum, corresponding to $\gamma_{\min} < \text{a few}$. This agrees with the typical values estimated by the radiative cooling occurring in the emitting region.

The other uncertainty concerns the presence of protons, or, equivalently, the number of electron–positron pairs. This is because, at least in powerful blazars, the bulk motion of protons, even if cold in the comoving frame, dominates the jet power if we assume that there is one proton for emitting electron. If instead, there are no protons, i.e., for a pure pair jet, the jet power estimate is a factor $\langle \gamma \rangle m_e / m_p \approx 10^{-2}$ smaller. The presence of both protons and pairs corresponds to intermediate values of the jet power. The counter arguments concerning the presence of e^-e^+ pairs are:

- It is not easy to produce pairs in the first place. If we are using even a relatively small fraction of the γ -ray photons produced in the emitting region, we are nevertheless using a large power. The produced pairs, that are born relativistic, emit efficiently, mostly in the X-rays, where the SED of powerful blazars has a “valley” (Ghisellini and Madau 1996), see the right panel of Fig. 3. We do not see any sign of this reprocessed emission.
- If pairs are produced at the start, very close to the jet apex, there is a maximum number of them that can survive. In fact, if their optical Thomson optical depth is larger than unity and they are cold, they annihilate efficiently until the optical depth is below unity. If they are hot, annihilation is reduced, but they are bound to cool in a short time.
- Pairs can be the result of hadronic cascades, but in this case, we have to account for the bulk motion of ultra-relativistic protons, and this increases the power demand.
- In powerful blazars relativistic pairs efficiently cool on external radiation and recoil, braking the jet (Sikora et al. 1996), (Ghisellini and Tavecchio 2010) if there are more than ~ 10 – 20 pairs per proton.
- The total power in radiation (integrated over the entire solid angle) often exceeds the power in the relativistic emitting particles, because the radiative cooling time is shorter than the light crossing time. This requires continuous injection of new fresh particles or re-acceleration. If these processes are the result of the dissipation of a fraction of the jet kinetic or magnetic power, they must be larger than the radiated power. The jet Poynting flux is constrained by the observed synchrotron luminosity that is smaller than the inverse Compton one. Bulk motion of protons is, therefore, required.

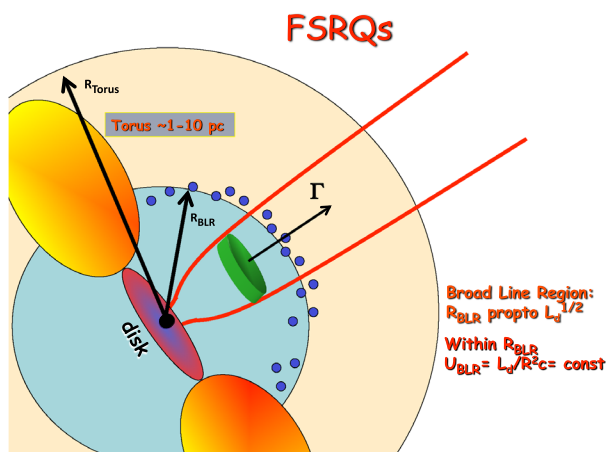


Fig. 2 Cartoon of the assumed geometry for the model, see (Ghisellini and Tavecchio 2009). At some distance R_{diss} from the black hole, the jet produces most of its radiation. This region can be inside the BLR or within R_{torus} , the dimension of the molecular torus. The radiation energy densities within the BLR and the torus are constant, since both R_{BLR} and R_{torus} scale as $L_d^{1/2}$. This structure is valid for FSRQs only, since BL Lacs have a radiatively inefficient disk, unable to photo-ionize the BLR

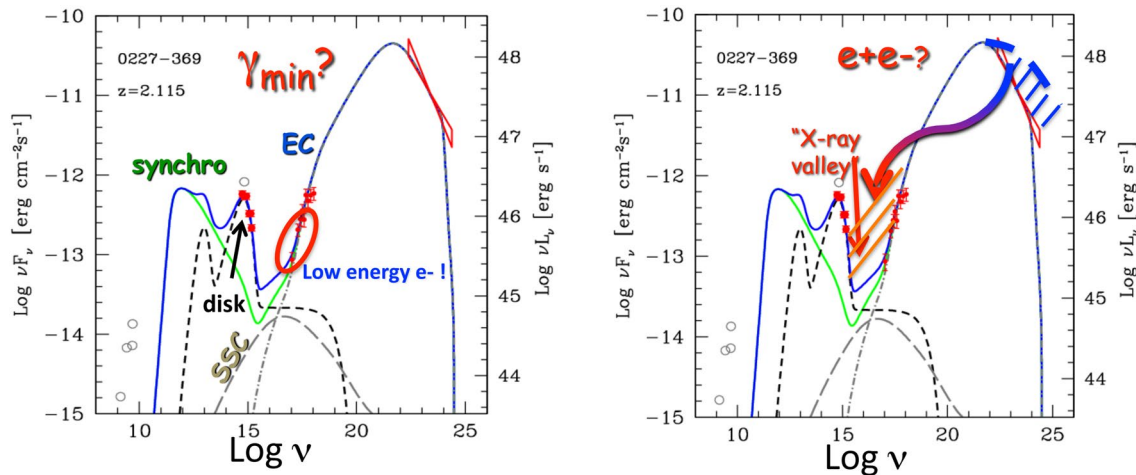


Fig. 3 In the past, there were two major uncertainties concerning the estimate of the jet power. The first was the difficulty to estimate the lowest electron energies, but now, we do have information about it looking at the soft X-rays, where, in the EC scenario, the lowest

energy electron contributes to the emission. The second is the importance of pairs. As illustrated in the right panel, if part of the γ -rays do form pairs, we expect that they emit in the X-ray band, filling the “valley” between the synchrotron and the Compton humps

We conclude that e^-e^+ pairs can be present in jets, but their number is severely limited to be a few per proton. A slightly larger number (i.e., 15 per proton) has been invoked by Sikora (2016) to explain the different median power of a sample of FR II and FSRQs calculated through radio-lobe calorimetry. Such a number of pairs corresponds to a jet kinetic power of the same order of the radiated luminosity, implying that jets are highly efficient radiators. Alternatively, radio-lobes may contain hot protons, not accounted for by calorimetry.

4 Jet power

Jets can carry energy in different forms:

- **Radiation** The observed emission has been produced in the jet that spent part of its power to produce it. This is not merely the luminosity measured in the comoving frame, because it needs some extra power to move the emitting particles to blue-shift the photons we receive and to account for the different rate of arrival. Both these effects are measured by the relativistic Doppler factor $\delta \equiv [\Gamma(1 - \beta \cos \theta_v)]^{-1}$, where θ_v is the viewing angle. The observed (L) and the comoving (L') jet bolometric luminosity are linked by $L = \delta^4 L'$. If the luminosity is isotropic in the comoving frame, as can be the case for synchrotron and SSC:

$$P_r = 2 \times \int_{4\pi} \frac{L'}{4\pi} \delta^4 d\Omega = 2 \frac{L'}{2\Gamma^4} \int_{-1}^1 \frac{d \cos \theta}{(1 - \beta \cos \theta)^4} = 2 \frac{\Gamma^2 L}{\delta^4} \left(1 + \frac{\beta^2}{3}\right). \tag{1}$$

The factor 2 accounts for the presence of two jets. If the radiation is not isotropic in the rest frame, as in the EC process, we have (Ghisellini and Tavecchio 2010):

$$P_r = 2 \times \frac{\langle L' \rangle}{4\pi} \int_{4\pi} \frac{\delta^6}{\Gamma^2} d\Omega \sim \frac{32}{5} \frac{\Gamma^4}{\delta^6} L \tag{2}$$

When $\Gamma = \delta$, implying that the viewing angle $\theta_v = 1/\Gamma$, the two expressions differ by a factor 5 / 12. There is an alternative way to calculate P_r , that is useful also for calculating the other the forms of carried energy. It consists to calculate the flux across a cross section (of radius r) of the jet:

$$P_r = 2 \times \pi r^2 \Gamma^2 U'_r c \sim \pi r^2 \Gamma^2 \frac{L}{\delta^4 4\pi r^2 c} c = \frac{\Gamma^2}{2\delta^4} L. \tag{3}$$

The reason of the Γ^2 term is due to the transformation of the energy density from the comoving to the observer frame: one term for the blue-shift and the other term for the different number density in the two frames.

- **Magnetic field** The Poynting flux is

$$P_B = 2 \times \pi r^2 \Gamma^2 U'_B c, \tag{4}$$

where $U'_B \equiv (B')^2 / (8\pi)$ and the factor 2 accounts again for the presence of two jets.

- **Relativistic leptons** The power in the bulk motion of relativistic leptons is

$$P_e = 2 \times \pi r^2 \Gamma^2 U'_e \beta c = 2\pi r^2 \Gamma^2 \beta \langle \gamma \rangle m_e c^3 n'_e, \tag{5}$$

where $U'_e = m_e c^2 \int_{\gamma_{\min}}^{\gamma_{\max}} N(\gamma) \gamma d\gamma = \langle \gamma \rangle m_e c^2 n'_e$. Usually, n_e and $\langle \gamma \rangle$ are calculated through the properties of the observed emission. There could be other leptons not

participating to the emission and, therefore, not accounted for when we estimate the $N(\gamma)$ distribution.

- *Protons* The power in the bulk motion of protons is

$$P_p = P_e \frac{n_p}{n_e} \frac{\langle \gamma_p \rangle m_p}{\langle \gamma \rangle m_e}. \tag{6}$$

If protons are cold, then $\langle \gamma_p \rangle = 1$, but if there is a hot component, possibly highly relativistic, then the power increases. This is indeed a possibility, especially after the discovery of the likely association of one high-energy neutrino detected by Icecube with the BL Lac TXS 0506+056 (Aartsen et al. 2018). For the rest of this paper, we will assume cold protons, and one proton for each emitting electron. With these working assumptions, note that the presence of protons, even if cold, is very important when $\langle \gamma \rangle$ of the leptons is small, namely, for FSRQs. On the other hand, TeV emitting BL Lacs can have $\langle \gamma \rangle > m_p/m_e$. In these sources, protons (if cold) do not contribute much to the total jet power.

5 Results

To compare the jet power with the accretion luminosity, we need blazars that have been detected in the γ -ray band and that have been observed spectroscopically, with detected broad emission lines. The high-energy emission allows us to know the entire bolometric luminosity, and the broad emission lines allow us to estimate the disk luminosity.

To this aim, we have used the sample of blazars studied by Shaw et al. (2012) (FSRQs) and Shaw et al. (2013) (BL Lacs). Only very few BL Lacs were selected, only those showing the presence of broad lines. We have collected for all blazars of the total sample the available archival data, and we have applied the one-zone leptonic model described in Ghisellini and Tavecchio (2009). The results concerning the 217 blazars of this sample were presented in Ghisellini et al. (2014) and Ghisellini and Tavecchio (2015).

The SED coverage was much better than in the past, because for all blazars in the sample, we had: i) the spectroscopic data (that are used to find the disk luminosity and the black hole mass); ii) the γ -ray luminosity (used to infer the jet radiated power); iii) the far IR data given by *WISE* satellite (that help to shape the jet+torus continuum); and iv) the high-frequency radio data from the *WMAP* and *Planck* satellites helping to define the synchrotron peak.

Then, we have added a sample of $z > 2$ blazars detected by *Swift*/BAT (Ghisellini et al. 2010), a sample of $z > 4$ blazars selected from (Sbarrato et al. 2013), and two powerful FSRQs detected by *NuSTAR* (Sbarrato et al. 2016).

We find $P_r \sim L_d$. These results are model independent, since $P_r \sim L/\Gamma^2$, and while Γ is indeed found through modelling, the typical values found agree with independent estimates given by superluminal motion and other beaming indicators (such as the radio brightness temperature).

This is a lower limit to the jet power and does not depend on the uncertainties regarding the particle distribution and the importance of electron–positron pairs. This result is solid.

Then, to go from P_r to $P_j = P_r + P_e + P_p + P_B$, we do have to apply a model. We used the model described in Ghisellini and Tavecchio (2009). Figure 4 shows P_j as a function of L_d assuming one cold proton per emitting electron. This gives, on average, $P_j \sim 10L_d$.

6 Discussion

How can the jet power be proportional to L_d , but larger than it? We have two possibilities. The first, suggested by the fact that the two powers are proportional, is that it is accretion that powers the jet. The gravitational energy dissipated by the accreting \dot{M} is transformed into heat only partly, while the rest goes to power the jet (Jolley and Kunzic 2008; Jolley et al. 2009). The total accretion efficiency

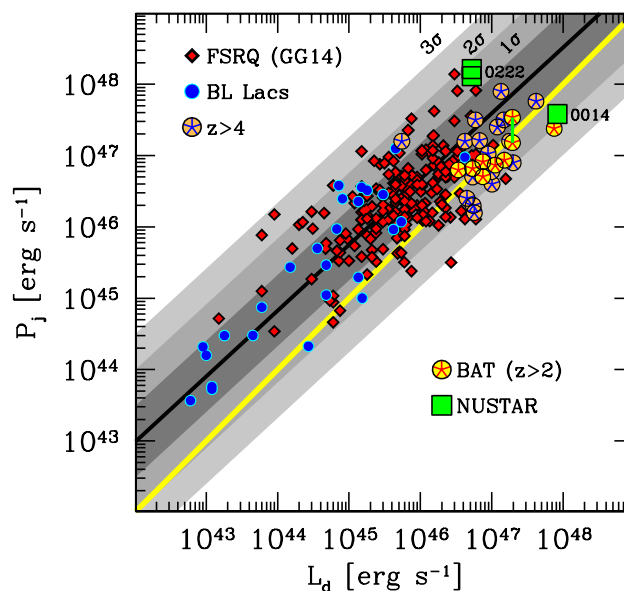


Fig. 4 Jet power as a function of the accretion luminosity for different blazar samples. In addition, the BL Lacs shown in this figures had some broad lines in their spectrum. The sources belong to the sample studied by Shaw et al. (2012), Shaw et al. (2013), and Ghisellini et al. (2014); two powerful FSRQs detected by *NuSTAR* (Sbarrato et al. 2016); a sample of $z > 2$ blazars detected by *Swift*/BAT (Ghisellini et al. 2010) and a sample of $z > 4$ blazars selected from (Sbarrato et al. 2013). The yellow line is the equality line, and the black line is the best fit

η is used to power the jet with an efficiency η_j , and to heat the disk with an efficiency η_d :

$$P_j = \eta_j \dot{M} c^2; \quad L_d = \eta_d \dot{M} c^2; \quad \eta = \eta_j + \eta_d. \quad (7)$$

Then, $P_j = 10L_d$ requires $\eta_j = 10\eta_d$. This has an important consequence: if there is a jet, the disk efficiency can be smaller (even by a factor 10) than what is foreseen for standard accretion models. To produce a given L_d , \dot{M} must, therefore, be larger, and this helps jetted sources to have black holes that grow faster (especially at large redshifts Ghisellini et al. 2013).

The second possibility is that jets are powered not by accretion, but by the rotational energy of the black hole, by the Blandford–Znajek process (Blandford and Znajek 1977). The total energy that can be extracted by a maximally spinning black hole is 29% of its mass, namely, 5×10^{62} erg for a $10^9 M_\odot$ black hole. This is enough to power a jet with $P_j = 10^{47}$ erg s⁻¹ for 166 million years. As (Cavaliere and D’Elia 2002) and (Ghisellini and Celotti 2002) proposed in 2002, this can be the engine for powering blazars. This has also been confirmed by numerical simulations (Tchekhovskoy et al. 2012) finding an average jet power corresponding to $\sim 1.5 \dot{M} c^2$ that obviously indicates that the power of the jet does not come from direct accretion, but from the rotational black hole energy (in turn originated by the previous accretion, and now released in a efficient way).

The fact that $P_j \propto L_d$ in this scenario can be explained if the magnetic field energy density necessary to tap the rotational energy of the black hole is proportional to \dot{M} and hence to L_d . This is possible if $B^2 \simeq \rho c^2$, where ρ is the disk density.

Furthermore, when the accretion disk is radiatively efficient, it produces most of its luminosity in the optical-UV, ionizing the gas of the BLR, that can indeed emit broad emission lines, but allows rates of accretion, the disk becomes radiatively inefficient (ADAF (Rees et al. 1982; Narayan and Yi 1994), ADIOS (Blandford and Begelman 1999), and so on), and most of its (already reduced) luminosity is not emitted in the UV (Mahadevan 1997). The clouds of the BLR are not photo-ionized, and no broad line is produced. This explains the divide between FSRQs and BL Lacs (Ghisellini et al. 2009) and possibly their different cosmic evolutions (Cavaliere and D’Elia 2002).

Acknowledgements I thank ASI 1.05.04.95 for funding.

Compliance with ethical standards

Conflict of interest I declare that there is no conflict of financial or non-financial interests.

Research involving human and animal participants This research did not involve animals, nor other human participants.

References

- Aartsen MG, Ackermann M, Adams J et al (2018) Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube. *Science* 361:1378
- Ackermann M, Ajello M, Atwood WB et al (2015) The third catalog of active galactic nuclei detected by the fermi large area telescope. *ApJ* 810:14
- Ajello M, Shaw MS, Romani RW et al (2012) The luminosity function of fermi-detected flat-spectrum radio quasars. *ApJ* 751:108
- Ajello M, Romani RW, Gasparri D et al (2014) The cosmic evolution of fermi BL lacertae objects. *ApJ* 780:73
- Blandford RD, Znajek RL (1977) Electromagnetic extraction of energy from Kerr black holes. *MNRAS* 179:433
- Blandford RD, Begelman MC (1999) On the fate of gas accreting at a low rate on to a black hole. *MNRAS* 303:L1
- Bloom SD, Marscher AP (1992) Expected level of self-Compton scattering in radio loud quasars. In NASA. Goddard Space Flight Center, The Compton Observatory Science Workshop, p 339
- Bloom SD, Marscher AP, Gear WK (1993) Multiwavelength observations of flat radio spectrum quasars and active galaxies. *AAS* 182:7007
- Böttcher M (2007) Modeling the emission processes in blazars. *Astrophys Sp Sci* 309:95. [arXiv:astro-ph/0608713](https://arxiv.org/abs/astro-ph/0608713)
- Calderone G, Ghisellini G, Colpi M, Dotti M (2013) Black hole mass estimate for a sample of radio-loud narrow-line Seyfert 1 galaxies. *MNRAS* 431:210
- Campitiello S, Ghisellini G, Sbarrato T, Calderone G (2018) How to constrain mass and spin of supermassive black holes through their disk emission. *A&A* 612:59
- Cavaliere A, D’Elia V (2002) The Blazar Main Sequence. *ApJ* 571:226
- Celotti A, Fabian AC (1993) The kinetic power and luminosity of parsec-scale radio jets—an argument for heavy jets. *MNRAS* 264:228
- Celotti A, Padovani P, Ghisellini G (1997) Jets and accretion processes in Active Galactic Nuclei: further clues. *MNRAS* 286:415
- Dermer CD, Schlickeiser R, Mastichiadis A (1992) High-energy gamma radiation from extragalactic radio sources. *A&A* 256:L27
- Dermer CD (2014) proc. of “High Energy Astrophysics in Southern Africa”, [arXiv:astro-ph/1408.6453](https://arxiv.org/abs/astro-ph/1408.6453)
- Donato D, Ghisellini G, Tagliaferri G, Fossati G (2001) Hard X-ray properties of blazars. *A&A* 375:739
- Fossati G, Maraschi L, Celotti A, Comastri A, Ghisellini G (1998) A unifying view of the spectral energy distributions of blazars. *MNRAS* 299:433
- Francis J, Hewett PC, Foltz CB, Chaffee FH, Weymann RJ, Morris SL (1991) A high signal-to-noise ratio composite quasar spectrum. *ApJ* 373:465
- Ghisellini G, Madau P (1996) On the origin of the gamma-ray emission in blazars. *MNRAS* 280:67
- Ghisellini G, Celotti A (2002) Blazars, Gamma Ray Bursts and Galactic Superluminal Sources, Blazar Astrophysics with BeppoSAX and Other Observatories, Proc. of the international workshop, December 2001, ASI, Italy. Edited by P. Giommi, E. Massaro, G. Palumbo. ESA-ESRIN, p 257. [arXiv:astro-ph/0204333](https://arxiv.org/abs/astro-ph/0204333)
- Ghisellini G, Tavecchio F (2009) Canonical high-power blazars. *MNRAS* 397:985
- Ghisellini G, Maraschi L, Tavecchio F (2009) The Fermi blazars’ divide. *MNRAS* 396:L105
- Ghisellini G, Tavecchio F (2010) Compton rockets and the minimum power of relativistic jets. *MNRAS* 409:L79

- Ghisellini G, Della Ceca R, Volonteri M et al (2010) Chasing the heaviest black holes of jetted active galactic nuclei. *MNRAS* 405:387
- Ghisellini G, Tavecchio F, Foschini L, Ghirlanda G (2011) The transition between BL Lac objects and flat spectrum radio quasars. *MNRAS* 414:2674
- Ghisellini G, Haardt F, Della Ceca R, Volonteri M, Sbarrato T (2013) The role of relativistic jets in the heaviest and most active supermassive black holes at high redshift. *MNRAS* 432:2818
- Ghisellini G, Tavecchio F, Maraschi L, Celotti A, Sbarrato T (2014) The power of relativistic jets is larger than the luminosity of their accretion disks. *Nature* 515:376
- Ghisellini G, Tavecchio F (2015) Fermi/LAT broad emission line blazars. *MNRAS* 448:1060
- Ghisellini G, Righi C, Costamante L, Tavecchio F (2017) The Fermi blazar sequence. *MNRAS* 469:255
- Jolley EJD, Kuncic Z (2008) Jet-enhanced accretion growth of supermassive black holes. *MNRAS* 386:989
- Jolley EJD, Kuncic Z, Bicknell GV, Wagner S (2009) Accretion discs in blazars. *MNRAS* 400:1521
- Mahadevan R (1997) Scaling laws for advection-dominated flows: applications to low-luminosity active galactic nuclei. *ApJ* 477:585
- Maraschi L, Ghisellini G, Celotti A (1992) A jet model for the gamma-ray emitting blazar 3C 279. *ApJ* 397:L5
- Narayan R, Yi I (1994) Advection-dominated accretion: a self-similar solution. *ApJ* 428:L13
- Li L-X, Zimmerman ER, Narayan R, McClintock JE (2005) Multitemperature blackbody spectrum of a thin accretion disk around a Kerr black hole: model computations and comparison with observations. *ApJS* 157:335
- Park D, Woo JH, Treu T et al (2012) The Lick AGN monitoring project: recalibrating single-epoch virial black hole mass estimates. *ApJ* 747:30
- Rawlings S, Saunders R (1991) Evidence for a common central-engine mechanism in all extragalactic radio sources. *Nature* 349:138
- Rees MJ, Begelman MC, Blandford RD, Phinney ES (1982) Ion-supported tori and the origin of radio jets. *Nature* 295:17
- Sbarrato T, Ghisellini G, Maraschi L, Colpi M (2012) The relation between broad lines and γ -ray luminosities in Fermi blazars. *MNRAS* 421:1764
- Sbarrato T, Ghisellini G, Nardini M., Tagliaferri G, Greiner J, Rau A (2013) Blazar candidates beyond redshift 4 observed with GROND. *MNRAS*, 433, 2182
- Sbarrato T, Ghisellini G, Tagliaferri G et al (2016) Extremes of the jet-accretion power relation of blazars, as explored by NuSTAR. *MNRAS* 462:1542
- Shakura NI, Sunyaev RA (1973) Black holes in binary systems. Observational appearance. *A&A* 24:337
- Shaw MS, Romani RW, Healey SE et al (2012) Spectroscopy of broad-line blazars from 1LAC. *ApJ* 748:49
- Shaw MS, Romani RW, Cotter G et al (2013) Spectroscopy of the Largest Ever γ -Ray-selected BL Lac Sample. *ApJ* 764:135
- Sikora M, Begelman MC, Rees MJ (1994) Comptonization of diffuse ambient radiation by a relativistic jet: the source of gamma rays from blazars? *ApJ* 421:153
- Sikora M, Blazejowski M, Moderski R, Madejski GM (2002) On the nature of MeV blazars. *ApJ* 577:78
- Sikora M (2016) Powers and magnetization of blazar jets. *Galaxies* 4:12
- Sikora M, Sol H, Begelman MC, Madejski GM (1996) Radiation drag in relativistic active galactic nucleus jets. *MNRAS* 280:781
- Tavecchio F, Maraschi L, Ghisellini G (1998) Constraints on the physical parameters of TeV blazars. *ApJ* 509:608
- Tchekhovskoy A, McKinney JC, Narayan R (2012) General relativistic modeling of magnetized jets from accreting black holes. *J. Phys Confer Ser* 372(1):012040
- Urry CM, Padovani P (1995) Unified schemes for radio-loud active galactic nuclei. *PASP* 107:803
- Vanden Berk DE, Richards GT, Bauer A (2001) Composite quasar spectra from the Sloan Digital Sky Survey. *AJ* 122:549

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.