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The correlation between the total jet power and the Poynting flux at the jet base

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Abstract. The magneto hydrodynamic models of relativistic jets from active galactic nuclei predict the jet power transported by the Poynting flux at the jet base, setting the correlation between the jet power and the total magnetic flux. For highly collimated jets taking the transversal structure into account allows to rewrite this correlation through the observed jet properties such as spectral flux and core shift. Applying this method we find that, for the sample of 48 sources, their jet power distribution is well peaked at the theoretically predicted level.

Keywords. MHD, BL Lacertae objects: general, quasars: general, galaxies: jets

1. Introduction

It is established that the electromagnetic processes are governing in the relativistic jet launching from a super massive black hole (BH) in a center of active galactic nuclei. The ordered magnetic field $B_{\rm g}$ frozen into accreting disk matter is brought to the black hole by the accretion, with the total magnetic flux $\Psi_0 = \pi B_{\rm g} r_{\rm g}^2$ threading the BH ergosphere of radius of the order of Schwarzschild radius $r_{\rm g} = 2GM/c^2$. The spinning BH with a spin parameter $a_* \in [0;\, 1)$ and corresponding angular velocity of field lines $\Omega_{\rm F} = ca_*/2r_{\rm g}(1 + \sqrt{1-a_*^2})$ creates in the lab frame the electric magnetic field of the order of $\Omega_{\rm F} r_{\rm g} B_{\rm g}/c$. This electromagnetic field configuration drives the Poynting flux from a black hole (Beskin (2010)).

The energy density flux $E(\Psi)$, conserved on magnetic surfaces designated by the contained magnetic flux Ψ, can be written for the central part of a flow, connected with a black hole, as:

$$E(\Psi) = \frac{\Omega_0 \Psi}{4\pi^2} + E_{\rm part}, \tag{1.1}$$

where the constant angular velocity $\Omega_{\rm F} = \Omega_0$, and $E_{\rm part}$ is an initial particle energy flux. The first term in the Eq. 1.1 represents the Poynting flux at the jet base, while the second term — the particle kinetic energy flux. The ratio of two terms is equal (Tchekhovskoy *et al.* (2009); Nokhrina *et al.* (2015)) to the Michel's magnetization parameter $\sigma_{\rm M}$, which value may be safely taken as of the order of 10, as supported by analytical results by (Nokhrina *et al.* (2015)) and by the kinematics of bright features in jets on pc scales (Lister *et al.* (2009)). If the observed Lorentz factors represent the jet bulk motion, than the highest Γ corresponds to a half of the initial magnetization $\sigma_{\rm M}$. These arguments allow us to state that the first term in Eq. 1.1 with about 10% accuracy represents the total energy density flux in a jet. The total jet power in this case is approximately equal to the integral of the first term in 1.1:

$$W_\Psi = \frac{1}{c}\int_0^{\Psi_0} E(\Psi)d\Psi = \frac{c}{8}\left(\frac{\Psi_0}{\pi R_{\rm L}}\right)^2. \tag{1.2}$$

The result above means that within well-established model of jet launching, there must be a correlation between the total jet power and the total magnetic flux in a jet. Both values are estimated through the observation only implicitly.

2. Magnetic flux estimate

The magnetic flux contained in a jet is defined as

$$\Psi_0 = \int_S \mathbf{B}_{\rm P}\cdot \mathbf{dS}. \tag{2.1}$$

The analytical modeling (see, e.g., Lyubarsky (2009); Beskin (2010)) of relativistic MHD outflows provide that the ratio of the poloidal magnetic field that determines the magnetic flux to the toroidal magnetic field is

$$|\mathbf{B}_{\rm P}|/|\mathbf{B}_\varphi| = R_{\rm L}/r. \tag{2.2}$$

Thus, the toroidal magnetic field dominates on the scales greater than the light cylinder with typically unresolved dimension of $R_{\rm L} = 4\times 10^{-3}\left(M_{\rm BH}/10^9\,M_\odot\right)$ pc for the black hole spin parameter $a_* = 0.1$. Any measurements of a magnetic field provide the dominating toroidal magnetic field that does not determine explicitly the magnetic flux. The MHD modeling provides an instrument to correlate the toroidal and poloidal components of a magnetic field in a jet, as has been done by (Zamaninasab *et al.* (2014); Zdziarski *et al.* (2015); Nokhrina (2017B)). The jet magnetic field transversal structure comprises the central core with the characteristic scale of $R_{\rm L}$ with dominating constant poloidal magnetic field of a magnitude B_0 and the Poynting-carrying outer jet with the correlation given by Eq. 2.2 and approximate poloidal field profile $B_{\rm P}\propto r^{-2}$ (Nokhrina *et al.* (2015); Bromberg & Tchekhovskoy (2016)). It is important that the amplitudes of both poloidal and toroidal magnetic fields are of the same order B_0. Taking these estimate we obtain the jet magnetic flux

$$\Psi_0 = \pi B_0 R_{\rm L}^2\left(1 + 2\ln\frac{R_{\rm jet}}{R_{\rm L}}\right). \tag{2.3}$$

The field amplitude B_0 introduced into the expression 2.3 does not represent the magnetic field measured in a jet. The magnetic field in a jet may be estimated through core shift measurements (Lobanov (1998)) or the brightness temperature measurements (Zdziarski *et al.* (2015); Nokhrina (2017A)). Both methods provide the amplitude of a uniform model magnetic field in a bright feature.

The spectral flux from a jet with prescribed transversal structure may be readily estimated for the blazars (Nokhrina (2017A)), providing an instrument to obtain the magnetic field amplitude B_0 measuring the brightness temperature. A jet with uniform magnetic field $B_{\rm uni}$ has the same brightness temperature if the magnetic field amplitudes relate as

$$\frac{B_0}{B_{\rm uni}} = 0.86\frac{R_{\rm jet}}{R_{\rm L}}. \tag{2.4}$$

The value $B_{\rm uni}$ may be a magnetic field measured either using core shift method or brightness temperature measurements. Thus, the expression for the magnetic flux through the observables is

$$\frac{\Psi_0}{\pi R_{\rm L}} = 0.86 B_{\rm uni} R_{\rm jet}\left(1 + 2\ln\frac{R_{\rm jet}}{R_{\rm L}}\right). \tag{2.5}$$

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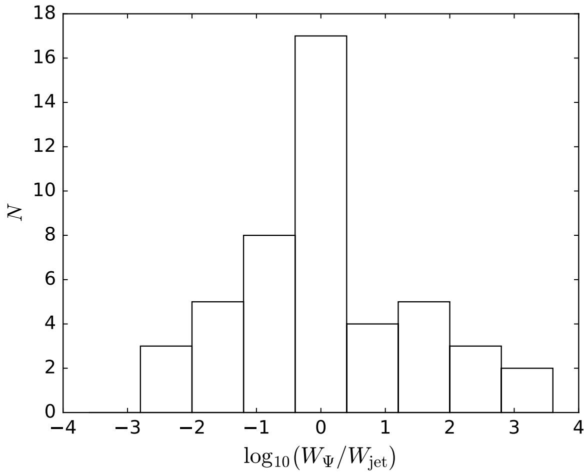

Figure 1. The distribution for the ratio $W_\Psi/W_{\rm jet}$ in log-scale for the sample of 48 blazars.

Here we write it so as to have in the l.h.s. the expression entering in the 1.2. The r.h.s. contains the values that may be estimated through the observables ($B_{\rm uni}$ and $R_{\rm jet}$). Here the light cylinder radius $R_{\rm L}$ is unknown, but the r.h.s. depends on it logarithmically weakly, so we may safely substitute for it the rough estimate $R_{\rm L} = 40 r_{\rm g}$ for the black hole spin parameter $a = 0.1$.

3. Power estimate

In order to check whether the sources obey the correlation

$$W_\Psi = \frac{c}{8}\left[0.86 B_{\rm uni} R_{\rm jet}\left(1 + 2\ln\frac{R_{\rm jet}}{R_{\rm L}}\right)\right]^2 \tag{3.1}$$

we use the averaged over lifetime jet power as a proxy for the jet power. The obtained by Cavagnolo *et al.* (2010) correlation of the average jet power needed to fill the cavities in a surrounding gas against the jet spectral flux at frequencies 200 – 400 MHz

$$\left(\frac{W_{\rm jet}}{10^{43}\,{\rm erg/s}}\right) = 3.5\left(\frac{W_{200-400}}{10^{40}\,{\rm erg/s}}\right)^{0.64} \tag{3.2}$$

allows to use the spectral flux data accumulated by the CATS (Verkhodanov *et al.* (1997)) database to obtain $W_{\rm jet}$.

We use the sample of 48 sources describe in Nokhrina (2017B). We calculate (see details in Nokhrina (2017B)) the uniform magnetic field magnitude $B_{\rm uni}$ and corresponding value for W_Ψ. We have also calculated the average jet power $W_{\rm jet}$ using the data accumulated by the CATS database. The histogram of ratio of these two values is presented in Fig. 1. The contrast with the result in Nokhrina (2017B) is more accurate formula for the jet power estimate using the total magnetic flux: the reasonable energy density flux integral $E(\Psi)$ provides the denominator 8, while the estimate used in Nokhrina (2017B) has the denominator 1.

4. Results and discussions

We observe that the total distribution is well peaked around the ratio $W_\Psi/W_{\rm jet} = 1$, with 17 sources falling in the central bin $\log_{10}(W_\Psi/W_{\rm jet}) \in [-0.4,\ 0.4]$, and 29 sources falling in the range $\log_{10}(W_\Psi/W_{\rm jet}) \in [-1.2,\ 1.2]$. Thus, we conclude, that for about 60% of the sources under consideration the total jet power can be explained purely by the

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power carried by the Poynting flux at the jet base, and there is no sufficient input from a possible outflow from a disk. The scatter of the distribution may be attributed to several factors. The uncertainties in the observed parameters estimation may lead to the observed scatter. The second factor may be our using the averaged jet power and the correlation (Cavagnolo *et al.* (2010)). We will address the correlation between W_Ψ and a momentary jet power that can be obtained for the number of sources (Ghisellini *et al.* (2014); Pjanka *et al.* (2017)) in the future work. The symmetry of the distribution might point to the absence of sufficient input of a jet originating from the disk into total jet power, or to correlation between these two sources of jet energy supply.

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