Jet power estimators in blazars

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Introduction

Jets are common in modern astrophysics. They can be found in young stars, X-ray binaries, as well as accompanying super-massive black holes in the cores of galaxies. At the same time, little can be said with confidence about their ejection and acceleration processes. Constraints following reliable estimations of the jet kinetic power could substantially improve our understanding of these effects.
This work is concerned with AGN jets, being one of the most powerful. Due to blazars' precise alignment towards Earth, they are an attractive sub-sample of AGNs to investigate the range of their jet powers.
Here, I present the current state of jet power measurement methodology, as a starting point of my study of jet energetics in blazars.

Time-averaged jet power

Radio lobes

The jet power is estimated as ratio of the energy content within radio lobes and age of the AGN. The minimum energy content required to produce observed surface brightness $\left(\frac{S}{\sigma}\right)_\nu$ (Willott et al. (1999)):

$$u_{min} \simeq ((1+k) f_{geom} f_{lowE}/\eta)^{4/7}\, u_{base}\left(\left(\frac{S}{\sigma}\right)_\nu, \nu, z\right)$$

, where: $(1+k)$, f_{geom}, f_{lowE} and η are the correction factors to account for ion content, deviations from assumed geometry, lower spectrum cut-off and volume filling factor, respectively, and u_{base} is a generalized function.

Then, the jet kinetic power:

$$\tilde{P}_j = g_{exp} g_{ke}\left(\frac{((1+k) f_{geom} f_{lowE}/\eta)^{4/7}\, f_{min} u_{base} \eta\, V}{t}\right) = \frac{f U_{base}}{t}$$

, where: g_{exp}, g_{ke} are the correction factors to account for expansion work and bulk motions within a lobe, V is the lobe volume, t – its age. All correction factors are then enclosed in the f-factor.

From feasibility studies, correction factor f can be constrained to be $\in (1, 20)$. Here $f = 10$ is assumed. As the bow-shock evolves self-similarly, the value of the age of a radio lobe can be calculated using dimensional analysis (Kaiser & Alexander (1997); Blundell et al. (1999)):

$$\frac{D}{\sin\theta} = 2c_1(f) a_0 t^{3/(5-\beta)}\left(\frac{P_j}{2a_0^5\rho_{100}}\right)^{1/(5-\beta)}$$

, where: D is the distance to the AGN, θ – inclination, c_1 – normalization factor, $a_0 = 100$ kpc, ρ_{100} – density normalization at a_0, β – density profile slope and P_j – radio lobe (jet) mechanical power.

Finally, using considerations of observations from Scheuer (1995), Willott et al. (1999) calibrates the final jet kinetic power formula (L_{151} being the luminosity at 151 MHz):

$$P_{j,W} \simeq 3\times 10^{38}\ \mathrm{W}\ f^{3/2}\left(\frac{D}{110\ \mathrm{kpc}}\right)^{-4/7+\beta/2}\left(\frac{c_1(f)}{5.4}\right)^{7/4} \times \left(\frac{\rho_{100}}{3000\ m_P/\mathrm{m}^3}\right)^{-1/2}\left(\frac{L_{151}}{10^{28}\ \frac{\mathrm{W}}{\mathrm{m^2\ sr\ Hz}}}\right)$$

X-ray cavities

Large quantities of energy are predicted to be deposited in the Inter Cluster Medium (ICM). One of results of this effect are X-ray cavities – regions of matter, where cooling is suspended by the ongoing energy transport from AGN.
During its lifetime, the jet "drills" a channel through the environment, depositing substantial amounts of energy in it. An estimate on the power required to sustain X-ray cavities surrounding a given galaxy is also an estimate of its jet power. Bîrzan et al. (2004, 2008) calculated volumes for a total of 24 X-ray cavities observed with both *VLA* and *Chandra*, as well as the average pressure within each cavity. The energy content of a cavity was then estimated as the enthalpy of gas within it, $4pV$. Both acoustic and buoyancy time have been estimated, as possible estimates of the cavity age.
A correlation has been found between radio (1.4 GHz or $200-400$ MHz) luminosities and the mechanical power (energy content divided by age estimate) – a useful tool since radio data provide larger samples than X-ray, especially for high-z sources. This correlation was further expanded by Cavagnolo et al. (2010) by 21 gEs at the low-luminosity end, yielding:

$$log\left(P_{j,C}/\frac{\mathrm{erg}}{\mathrm{s}}\right) \approx \log\left(P_{cav}/\frac{\mathrm{erg}}{\mathrm{s}}\right) = 0.35(\pm 0.07)\log\left(\frac{P_{1.4}}{10^{24}\frac{\mathrm{W}}{\mathrm{Hz}}}\right) + 43.85(\pm 0.10)$$

, where $P_{j,C}$ is the estimated jet power, P_{cav} – the cavity mechanical power and $P_{1.4}$ – the radio monochromatic luminosity at 1.4 GHz.

Instantaneous jet power

SED modelling

Ghisellini et al. (2014) designed a self-consistent composite model of AGN emission, composed of:

- one-zone jet leptonic model
- multicolor blackbody accretion disk
- broad-line region and the dusty torus

Once a fit to a blazar spectrum was made (jet composition assumptions), the jet power resulted from the model parameters.

Note: due to high blazar variability and observational biases related to it, the calculated jet power corresponds to the hard state of the source and the average jet power is predicted to be ~ 3 times lower.

γ-ray emission

From the scaling relations reported by Ghisellini et al. (2014), we can also construct an estimate of the jet power from γ-ray observations alone. Advantages:

- a single observable suffers less from sparse coverage of the SED in hard X-ray to soft γ-ray region
- lower importance of the pair content

From calculations:

$$P_{j,F} = \frac{K_\gamma L_\gamma^{(Fermi)}}{\eta_{j,rad}\Gamma^2}$$

, where the angle between the jet spine to the line of sight is assumed to be $\theta_{obs} = 1/\Gamma$, Γ is the bulk Lorentz factor of the jet, $K_\gamma \sim 2$ is the bolometric correction factor, $L_\gamma^{(Fermi)}$ – the observed luminosity and $\eta_{j,rad}$ – the jet radiative efficiency. The Lorentz factors Γ are found by Ghisellini et al. (2014) to be 13 ± 1.4.

Radio core shift

In the steady-state jet model of Blandford & Königl (1979) the synchrotron spectrum is divided into two regimes: partially optically thick at low energies and optically thin at high energies. Due to this effect, the "height" of the radio emission core depends on the observation frequency as ν^{-1}. Such core shift's value from observation can be represented as (eq. (4) of Zdziarski et al. (2014)):

$$\Delta\, h = \frac{D_L \Delta\Theta}{(1+z)^2 \sin\ i} = r_g \nu_g (\nu_1^{-1} - \nu_2^{-1})$$

, where D_L is the luminosity distance, $\Delta\Theta$ – the angular core shift, z – redshift of the source, i – its inclination, r_g – gravitational radius of the central black hole, ν_g – normalization of the turnover frequency (as defined in Zdziarski et al. (2014)). ν_1 and ν_2 are the observation frequencies.

Normalization ν_g is a proxy to obtain normalizations of electron distribution K_g and (poloidal) magnetic field B_g, e.g. with eq. (23) of Zdziarski et al. (2012):

$$\left[\frac{(1+z) h_P \nu_g}{m_e c^2}\right]^{\frac{p+4}{2}} = \frac{\pi C_2(p) \sigma_T K_g r_g \tan\Theta_j}{\alpha_f \sin\ i}\left(\frac{\delta\ B_g}{B_{cr}}\right)^{\frac{p+2}{2}}$$

An additional assumption or observable is needed:

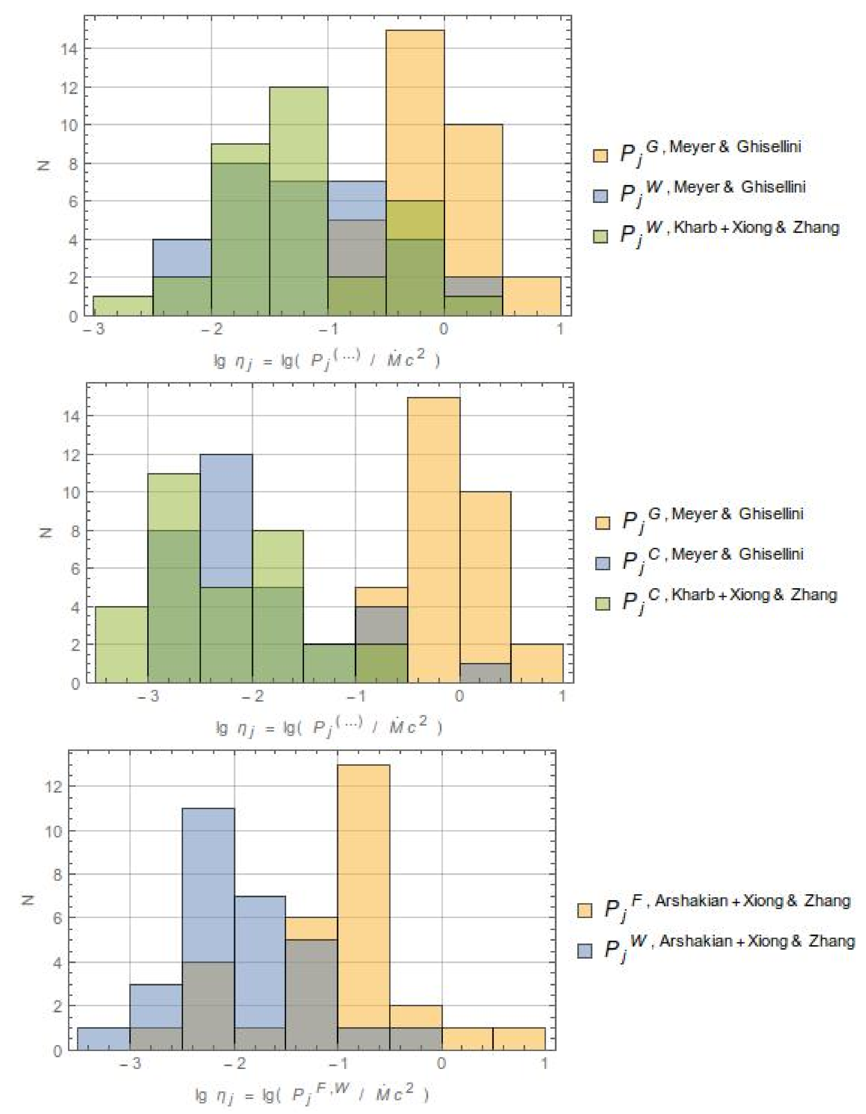
- equipartition between the magnetic field and relativistic electrons within the jet (e.g. Zamaninasab et al. (2014))
- radio flux in $\alpha\ = 0$ regime (e.g. Zdziarski et al. (2014))
- utilization of a measurement of angular size of the source (e.g. Hirotani (2005))

Regardless of the option used, inputting normalizations K_g and B_g into a jet model such as the one of Zdziarski et al. (2012), one can determine the jet physical parameters σ and β, as well as the total jet power (for details see Zdziarski et al. (2014)):

$$P_{j,core} = \frac{(Bhs)^2}{2} c\beta_j (1+\sigma) = \frac{\phi_{BH}^2 \sigma \dot{M} c^2 r_g^2 l^2 a^2 \beta_j}{16\pi^2 r_H^2 (1+\sigma)}\left(1 + \frac{\eta\beta}{2\Gamma_j} + \frac{\Gamma_j - 1}{\sigma\Gamma_j}\right)$$

, where β_j is the jet speed in units of c, $\dot{M}$ is the accretion matter flux, $l \lesssim 0.5$ – the ratio of field lines to BH angular frequency, a – the black hole spin, $r_H = r_g(1+\sqrt{1-a^2})$, $\eta \in (4/3, 5/3)$ is the particle adiabatic index of the jet matter and Γ_j is the jet bulk Lorentz factor. $\phi_{BH} = \Phi_{BH}/(r_g\sqrt{\dot{M}c})$ is the ratio of the magnetic flux threading a hemisphere of the BH horizon (conserved along the jet as the poloidal flux) to $r_g\sqrt{\dot{M}c}$, proportional to the ram pressure of the accretion flow, where it was assumed that $\dot{M} = L/\epsilon$ with L being the bolometric luminosity and $\epsilon \simeq 0.2$.

Jet production efficiency



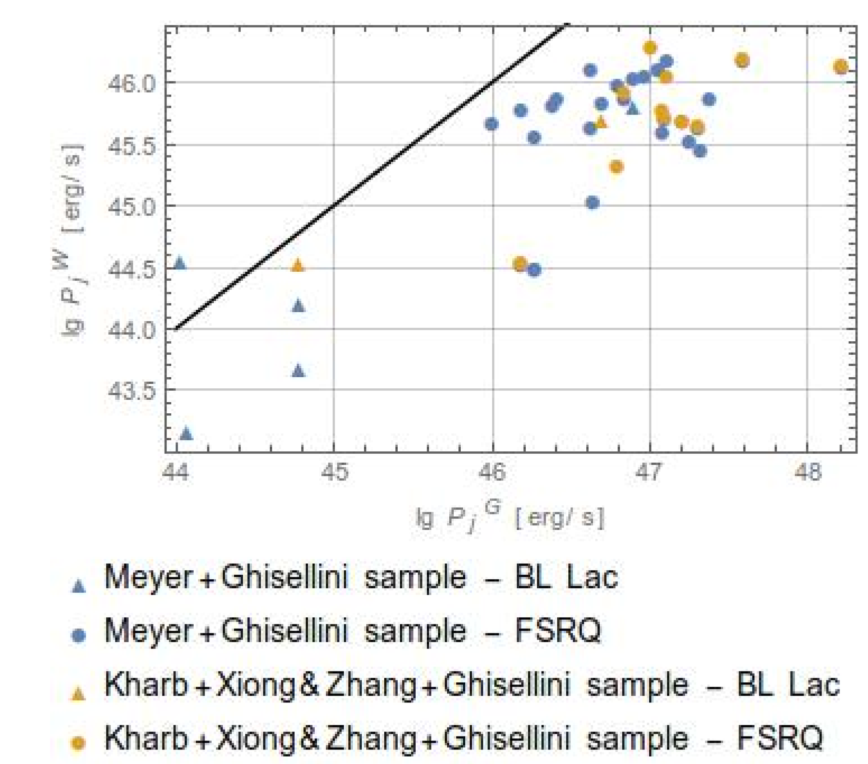
Discussion and conclusions

- The different methods of jet power estimation give substantially different ranges of jet production efficiency; from lowest to highest efficiencies, respectively:
  - X-ray cavities power radio scaling relations of Cavagnolo et al. (2010): $< \log\eta_j >\sim -2.5$
  - jet power from γ-ray emission: $< \log\eta_j >\sim -2.0$
  - radio lobe energy content method (by Willott et al. (1999)): $< \log\eta_j >\sim -1.0$
  - SED modelling (Ghisellini et al. (2014)): $< \log\eta_j >\sim 0.0$
- Consequently, while jet powers from Ghisellini et al. (2014) require the black hole spin to be utilized in jet ejection process, other estimators are not decisive in this matter.
- Jet production efficiencies suffer significant scatter on samples investigated for all estimators.
- The jet powers from energy content methods and modelling seem to differ systematically by a ~ 10 factor, regardless (small sample!) of the object morphology.

Future plans

- Enlarging the sample, utilization of the radio core shift method in jet power measurement
- Comparison with other methods leading to the derivation of magnetization σ parameter within the jet
- Forming conclusions concerning the plausibility of the Magnetically Arrested Accretion Disk scenario in blazars
- New clues regarding the composition of jets

Radio lobe vs modelling methods



The sample

The results presented here utilize data published in the following literature: Ghisellini et al. (2014); Meyer et al. (2011); Kharb et al. (2010); Xiong & Zhang (2014); Arshakian et al. (2012).

References

Arshakian, T. G., León-Tavares, J., Böttcher, M., et al. 2012, A&A, 537, A32

Bîrzan, L., McNamara, B. R., Nulsen, P. E. J., Carilli, C. L., & Wise, M. W. 2008, ApJ, 686, 859

Bîrzan, L., Rafferty, D. A., McNamara, B. R., Wise, M. W., & Nulsen, P. E. J. 2004, ApJ, 607, 800

Blandford, R. D., & Königl, A. 1979, ApJ, 232, 34

Blundell, K. M., Rawlings, S., & Willott, C. J. 1999, AJ, 117, 677

Cavagnolo, K. W., McNamara, B. R., Nulsen, P. E. J., et al. 2010, ApJ, 720, 1066

Ghisellini, G., Tavecchio, F., Maraschi, L., Celotti, A., & Sbarrato, T. 2014, Nature, 515, 376

Hirotani, K. 2005, ApJ, 619, 73

Kaiser, C. R., & Alexander, P. 1997, MNRAS, 286, 215

Kharb, P., Lister, M. L., & Cooper, N. J. 2010, ApJ, 710, 764

Meyer, E. T., Fossati, G., Georganopoulos, M., & Lister, M. L. 2011, ApJ, 740, 98

Scheuer, P. A. G. 1995, MNRAS, 277, 331

Willott, C. J., Rawlings, S., Blundell, K. M., & Lacy, M. 1999, MNRAS, 309, 1017

Xiong, D. R., & Zhang, X. 2014, MNRAS, 441, 3375

Zamaninasab, M., Clausen-Brown, E., Savolainen, T., & Tchekhovskoy, A. 2014, Nature, 510, 126

Zdziarski, A. A., Lubiński, P., & Sikora, M. 2012, MNRAS, 423, 663

Zdziarski, A. A., Sikora, M., Pjanka, P., & Tchekhovskoy, A. 2014, ArXiv e-prints, arXiv:1410.7310

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