The correlation between magnetic flux and jet power

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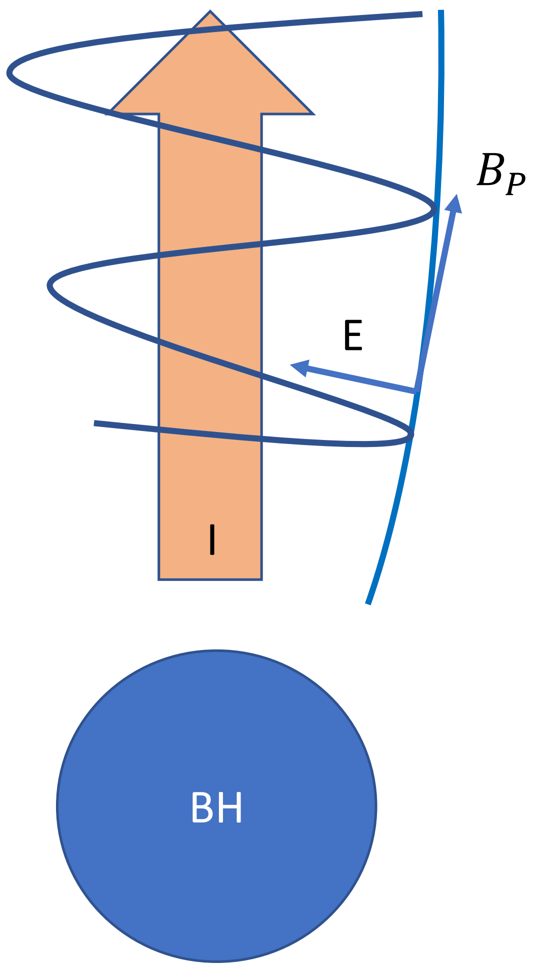
Outline

- The electromagnetic losses
- Magnetic field – core shift measurements
- Magnetic field – brightness temperature measurements
- Non uniform source – the simplest model
- Power vs. magnetic flux – results

The MHD flow (jet) works as a current system



The electromagnetic losses can be estimated through the following MHD outflow properties

$$P_{tot} \sim I \cdot \delta U$$

The electric potential drop

$$\delta U = ER = \frac{\Omega_F R}{c} BR$$

The current in a magnetosphere is carried by the Goldreich-Julian particle number density

$$\rho_{GJ} = -\frac{\Omega_F B}{2\pi c}$$

The electromagnetic losses

And the corresponding current

$$I = \frac{\Omega_F B R^2}{2}$$

The electromagnetic losses estimate

$$\boxed{P_{tot} = \frac{c}{2}\left(\frac{\Psi a}{\pi r_g}\right)^2}$$

Here

$$a = \frac{r_g \Omega_F}{c} = \frac{r_g}{R_L}$$

Of a – a rotational parameter

The very important scale in MHD models is the light cylinder $R_L = \frac{c}{\Omega_F}$, not the r_g.

In particular, for the flows collimated no worse than parabola the flow Lorentz factor scales as

$$\gamma = \frac{r}{R_L}$$

The natural scale for MHD models is R_L, and it is through introducing a that we relate it with r_g.

The MHD losses

The ideal axisymmetric MHD outflow is governed by the Grad-Shafranov equation (the force balance of magnetic surfaces Ψ) and by Bernoulli equation (along the magnetic surfaces)

There are 5 integrals conserved on the magnetic surfaces Ψ=const:

- Energy density flux E(Ψ)
- Angular momentum flux L(Ψ)
- Angular velocity $\Omega_F(\Psi)$
- Ratio of plasma flux to magnetic flux $\eta(\Psi)$
- Entropy s(Ψ)

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- Energy density flux $E(\Psi)$
- Angular momentum flux $L(\Psi)$
- Angular velocity $\Omega_F(\Psi)$
- Ratio of plasma flux to magnetic flux $\eta(\Psi)$
- Entropy $s(\Psi)$

The integrals are set at the jet base and must obey the conditions at the critical (fast magnetosonic) surface

The MHD losses

For the central flow the conditions of a smooth critical (Alfvenic and fast magnetosonic) sonic surfaces provides (Bogovalov 1995, Beskin & Okamoto 2000):

$$E(\Psi)=\frac{\Omega_0^2\Psi}{8\pi^2c^2}+\eta\mu_0\gamma_{in}$$

The ratio of two terms in rhs

$$\sigma_M=\frac{\Omega_0^2\Psi_0}{8\pi^2c^2\eta\mu_0\gamma_{in}}$$

The MHD losses

The typical σ_M is of the order of typical observed Lorentz factors of bulk motion => its value ~ 10-20 (also N+15) => the electromagnetic term dominates the losses.

The total power connected with the first term

$$P_{em} = c\int_0^{\Psi_0} E(\Psi)d\Psi = \frac{c}{8}\left(\frac{\Psi a}{\pi r_g}\right)^2$$

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Bias: the coefficient depends on whether the current is closed in a jet an in what manner

The MHD losses

$$P_{em} = \frac{c}{8}\left(\frac{\Psi a}{\pi r_g}\right)^2$$

Having this expression we need to calculated the magnetic flux

$$\Psi = \int \overrightarrow{B_P} \cdot d\vec{S}$$

Estimate for the magnetic field

The magnetic field measurements

- By core shift effect (Lobanov 1998, O'Sullivan & Gabuzda 2009, …)

  The field B~1G at 1 pc distance (uses the equipartition assumption)

- By brightness temperature measurements (Zdziarski+ 2015, N17)

  Applicable for the sources suspected to be in non-equipartition regime (extreme brightness temperatures)

The core shift magnetic field measurement

- Due to change in magnetic field and particle number density along the jet, the position of a surface with the maximum brightness for each frequency is situated at different distances along a jet
- Using standard synchrotron emission and absorption coefficients

$$\nu_{\mathrm{m}*}^{(5-2\alpha)} = \frac{c_\alpha^2(1-2\alpha)}{5(5-2\alpha)} \frac{e^4}{m^2c^2} \left(\frac{e}{2\pi mc}\right)^{3-2\alpha} R_*^2 B_*^{3-2\alpha} k_{\mathrm{e}*}^2$$

- +Blandford-Konigl scalings

$$B(r) = B_1 \left(\frac{r}{r_1}\right)^{-1}$$

$$n_{\mathrm{e}}(r) = n_1 \left(\frac{r}{r_1}\right)^{-2}$$

The core shift magnetic field measurement

- + (specific) equipartition = the bulk flow has a magnetization ~ 1 and about 1% of particles have the relativistic temperatures (Sironi, Spitkovsky, Arons 2013)

$$B^2 = \sigma_\xi 4\pi m c^2 n_e \Gamma$$

=>

$$\left(\frac{B_{cs}}{G}\right) = 0.17 \left(\frac{\eta_{cs}}{\text{mas GHz}}\right)^{0.75} \left(\frac{D_L}{\text{Gpc}}\right)^{0.75} \frac{\Gamma}{\chi^{0.25}(1+z)^{0.75} \sin^{0.5}\varphi \, \delta^{0.5}}$$

NB: the toroidal magnetic field dominates the jet, so it is the toroidal field we measure

The brightness temperature magnetic field

- The brightness temperature definition

$$S_\nu = \frac{2\pi\nu^2\theta^2}{c^2} k_{\mathrm{B}} T_{\mathrm{b}}$$

- The spectral flux for the self-absorbed spherically symmetric source (Gould 1979)

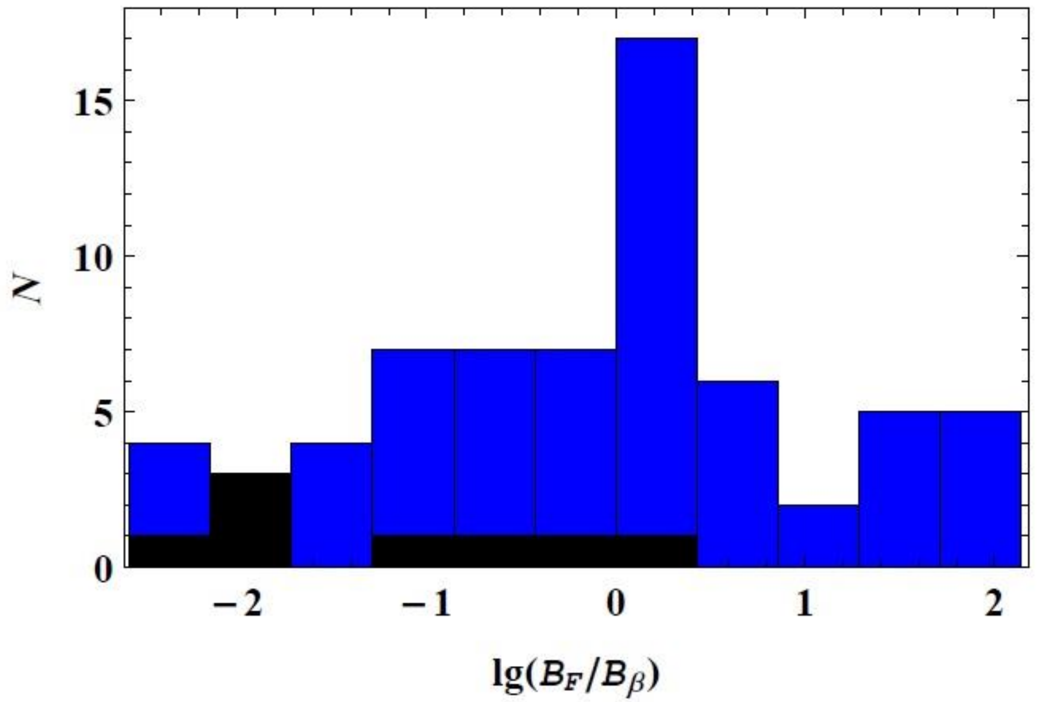
$$S_\nu = \pi\hbar\nu \frac{\rho_\nu}{æ_\nu} \frac{R^2}{d^2} u(2Ræ_\nu)$$

- =>

$$\left(\frac{B_{\mathrm{uni}}}{\mathrm{G}}\right) = 7.4 \cdot 10^{-4} \frac{\Gamma\delta}{1+z} \left(\frac{\nu_{\mathrm{obs}}}{\mathrm{GHz}}\right) \left(\frac{T_{\mathrm{b,\,obs}}}{10^{12}\mathrm{K}}\right)^{-2}$$

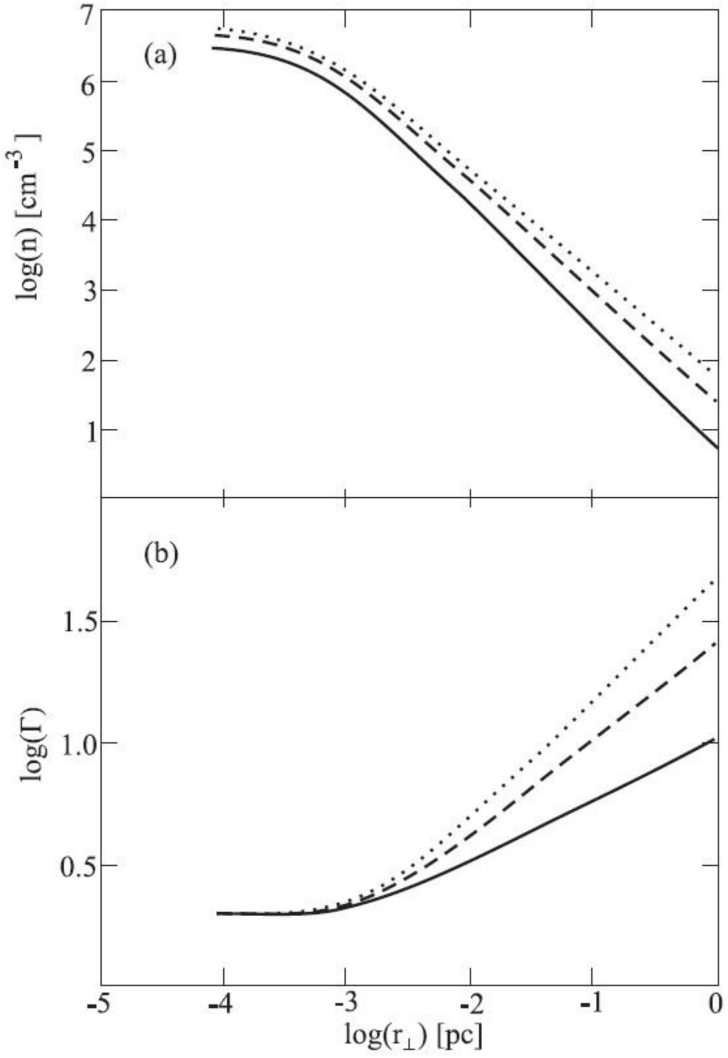
(Zdziarski+2015, N17)

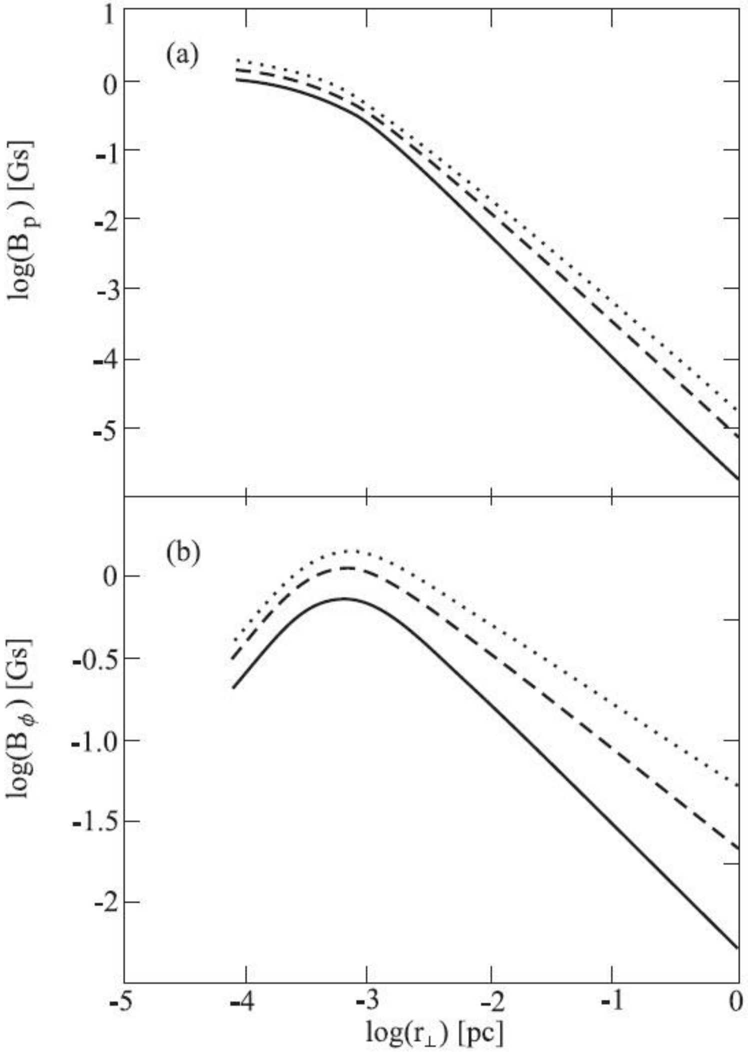
Zdziarski, Sikora, Pjanka & Tchekhovskoy, 2015: the distribution of ratio of magnetic field is peaked around its equipartition value:



In both cases it is the toroidal magnetic field we get from observations, not the poloidal

Non-uniform model: semi-analytical results

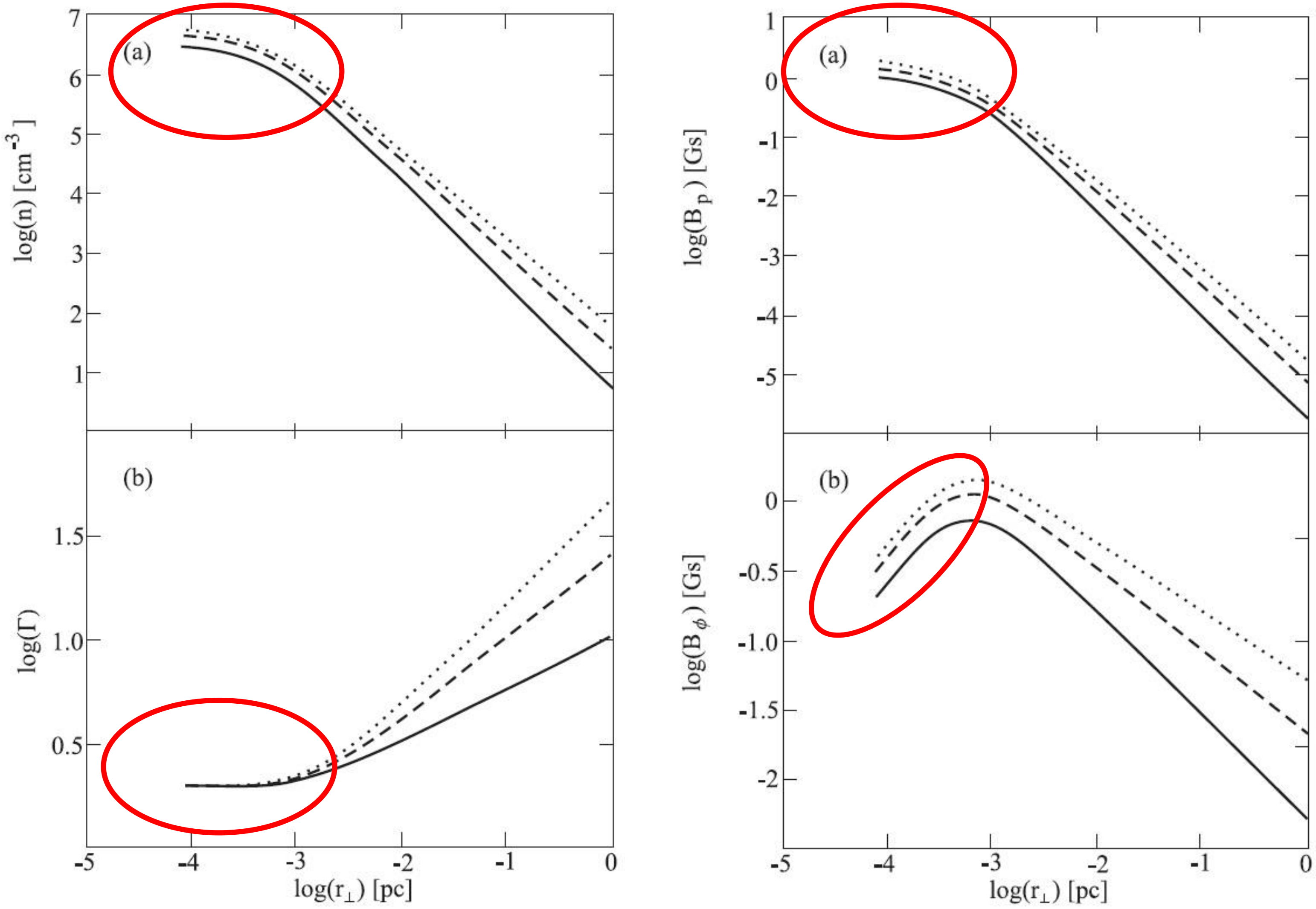




The principal behavior of *B* and *n* is obtained in many analytical, semi-analytical, and numerical works: Lyubarsky 2009, Tchekhovskoy & Bromberg 2016, and many others

Nokhrina+ 2015

Non-uniform model: analytical results



The central core:

$n \approx const$

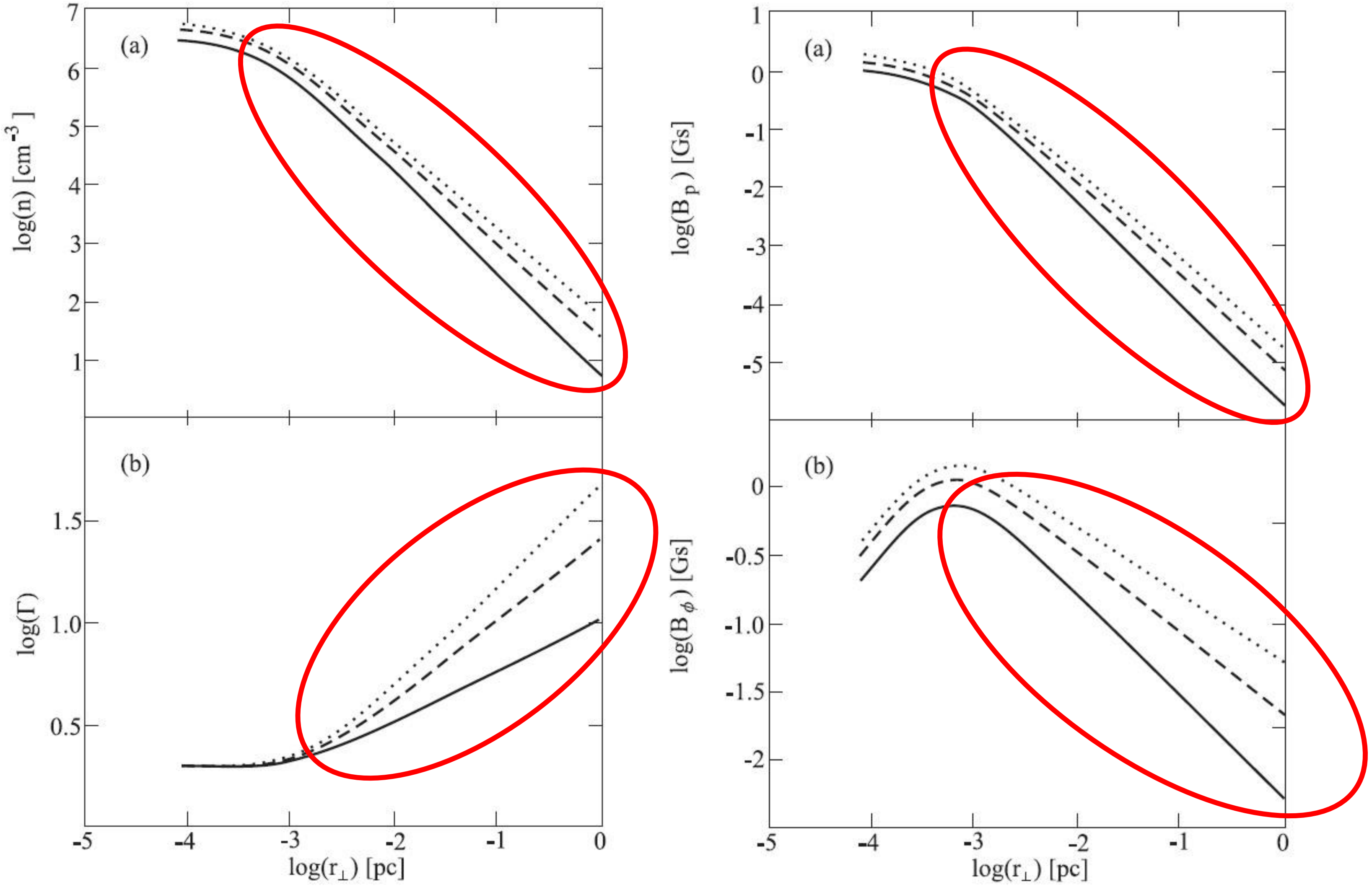
$B_P \approx const$

$B_\varphi \propto r$

$\Gamma \approx const$

Nokhrina+ 2015

Non-uniform model: analytical results



The central core:

$n \propto r^{-2}$

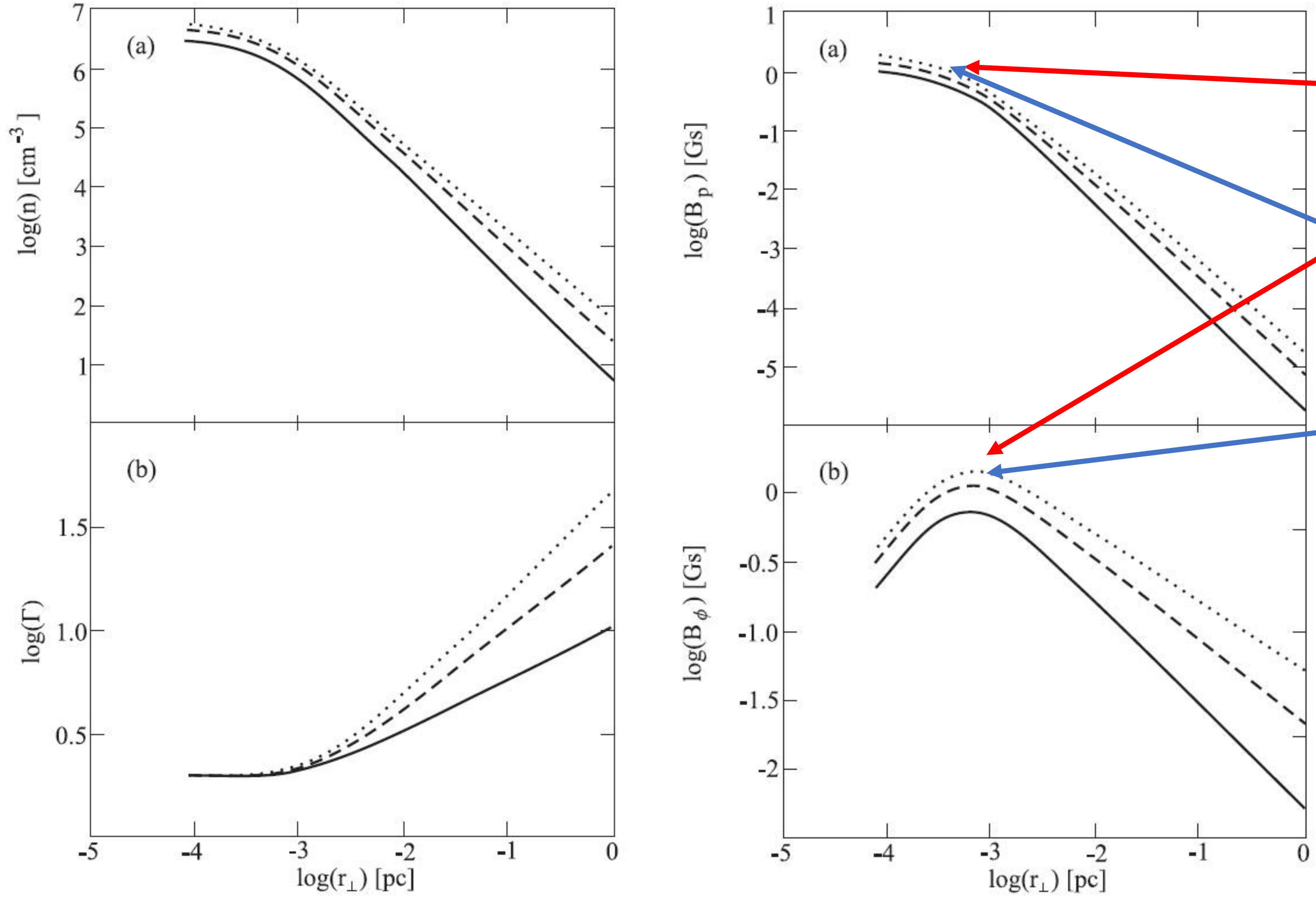
$B_P \propto r^{-2}$

$B_\varphi \propto r^{-1}$

$\Gamma \propto r$

Nokhrina+ 2015

Non-uniform model: analytical results



The central core size

$R_0 \approx 5R_L$

The magnetic field amplitude

B_0

Nokhrina+ 2015

The magnetic flux

Using these profiles it is easy to calculate the total magnetic flux

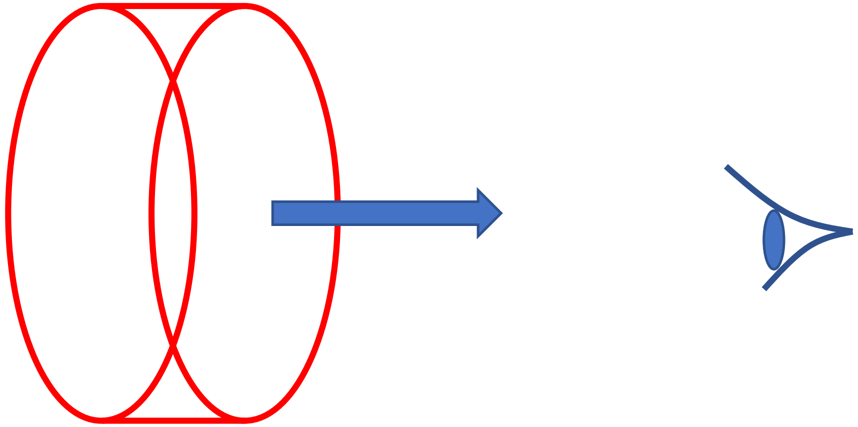
$$\Psi = \pi B_0 R_{\rm L}^2 \left(1 + 2\ln\frac{R_{\rm j}}{R_{\rm L}}\right)$$

First has been estimated by Zamaninasab+ (2014):

$$\Phi_{\rm jet} = \frac{2\pi(\Gamma\theta_{\rm j}) r_{\rm H} z B'_{\varphi}}{\ell a_* (1 - \Gamma/\mu)}$$

Here the important scale is a light cylinder (the estimate for the central jet core size), and the problem is – we don't know R_L

The non-uniform magnetic field



The spectral flux may be easily calculated for such a geometry of a self-absorbed source with prescribed transversal profiles for *B* and *n*

We use the magnetic field and particle number density profiles for the simplest case of calculation of the spectral flux for the blazars and AGN with small viewing angles (the radiating cylinder seen from its top)

$$\left(\frac{B_0}{\mathrm{G}}\right) = 6.4 \times 10^{-4} \frac{R_\mathrm{j}}{R_\mathrm{L}} \frac{\Gamma\delta}{1+z} \left(\frac{\nu_\mathrm{obs}}{\mathrm{GHz}}\right) \left(\frac{T_{\mathrm{b,\,obs}}}{10^{12}\,\mathrm{K}}\right)^{-2}$$

$$\left(\frac{B_0}{\mathrm{G}}\right) = 6.4 \times 10^{-4} \frac{R_\mathrm{j}}{R_\mathrm{L}} \frac{\Gamma\delta}{1+z} \left(\frac{\nu_\mathrm{obs}}{\mathrm{GHz}}\right) \left(\frac{T_\mathrm{b,\,obs}}{10^{12}\,\mathrm{K}}\right)^{-2}$$

$$\left(\frac{B_\mathrm{uni}}{\mathrm{G}}\right) = 7.4 \cdot 10^{-4} \frac{\Gamma\delta}{1+z} \left(\frac{\nu_\mathrm{obs}}{\mathrm{GHz}}\right) \left(\frac{T_\mathrm{b,\,obs}}{10^{12}\mathrm{K}}\right)^{-2}$$

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B_{uni} is a magnetic field assuming the spherically symmetric source,
B_0 is an amplitude magnetic field given the prescribed transversal source structure, the spectral flux is the same

The magnetic flux

- The magnetic flux may (?) be calculated by

$$\Psi = 2.7 B_{\mathrm{uni,\,cs}} R_{\mathrm{j}} \frac{r_{\mathrm{g}}}{a} \left[1 + 2 \ln \frac{R_{\mathrm{j}}\, a}{r_{\mathrm{g}}} \right] = \frac{\Psi_a}{a}$$

- We do not know the parameter *a*
- But the total power for electromagnetic losses has a term Ψa

$$P_{em} = \frac{c}{8} \left(\frac{\Psi a}{\pi r_g} \right)^2$$

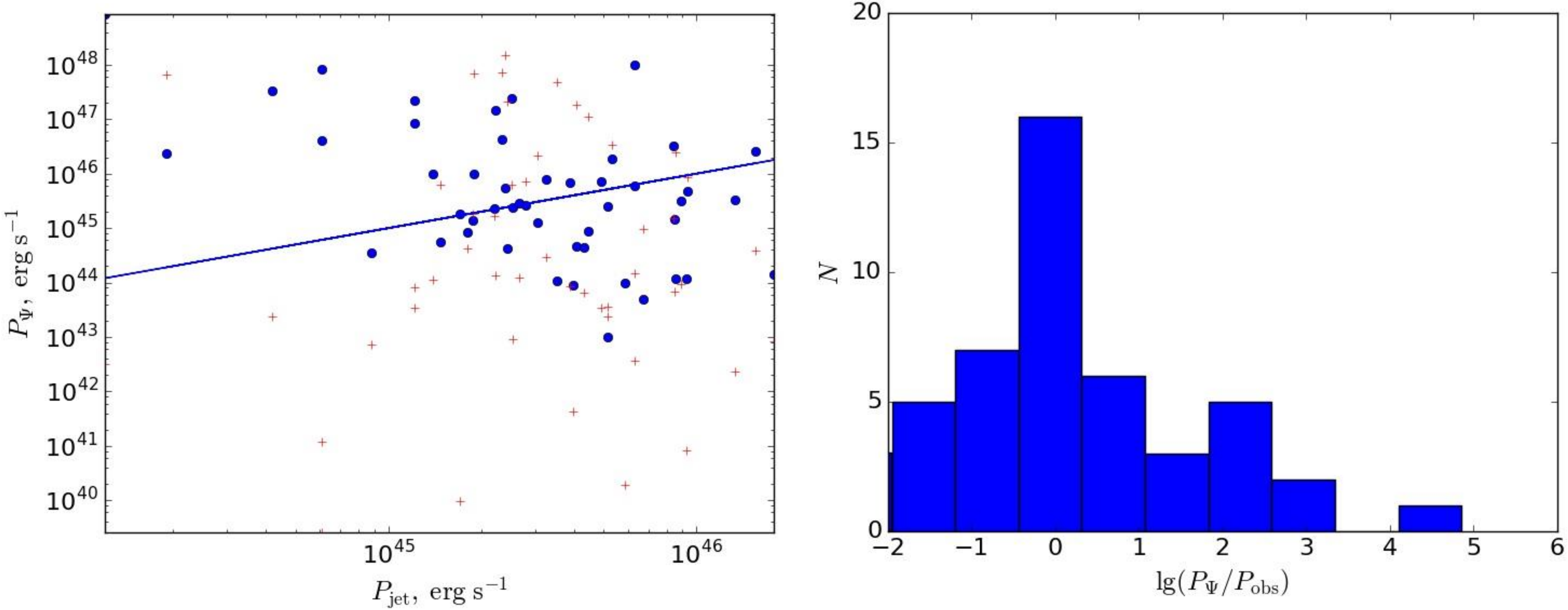
The result

- We use 48 sources with small viewing angles and measured core shift and opening angles
- For the jet power estimate we use the correlation between P_{jet} and the jet luminosities in 200 – 400 MHz band (Cavagnolo+ 2010):

$$\left(\frac{P_{\rm jet}}{10^{43}\,{\rm erg\,s^{-1}}}\right) = 3.5\left(\frac{P_{200-400}}{10^{40}\,{\rm erg\,s^{-1}}}\right)^{0.64}$$

The result

Source	z	Ψ_{MAD} G cm^2	Ψ_{br} G cm^2	Ψ_{cs} G cm^2	P_{Ψ} [erg s^{-1}]	P_{jet} [erg s^{-1}]
(1)	(2)	(3)	(4)	(5)	(6)	(7)
0133+476	0.859	5.51×10^{33}	1.17×10^{31}	5.34×10^{32}	1.92×10^{46}	2.54×10^{45}
0212+735	2.367	5.77×10^{35}	5.97×10^{32}	8.93×10^{32}	8.10×10^{43}	5.17×10^{45}
0234+285	1.206	5.71×10^{34}	1.24×10^{34}	5.31×10^{32}	8.65×10^{44}	3.52×10^{45}
0333+321	1.259	9.36×10^{34}	6.00×10^{32}	3.81×10^{32}	3.88×10^{44}	6.72×10^{45}
0336−019	0.852	1.55×10^{34}	1.45×10^{32}	2.12×10^{33}	6.31×10^{46}	3.26×10^{45}
0403−132	0.571	3.00×10^{34}	4.34×10^{33}	1.09×10^{33}	6.89×10^{45}	4.45×10^{45}
0528+134	2.070	6.05×10^{34}	1.61×10^{30}	3.24×10^{32}	7.75×10^{44}	5.85×10^{45}
0605−085	0.870	1.68×10^{34}	9.94×10^{33}	1.70×10^{33}	4.45×10^{46}	2.39×10^{45}
0736+017	0.189	6.94×10^{32}	3.86×10^{30}	1.29×10^{33}	2.68×10^{48}	4.20×10^{44}
0738+313	0.631	1.48×10^{35}	3.22×10^{33}	2.71×10^{33}	4.51×10^{45}	1.48×10^{45}
0748+126	0.889	4.33×10^{34}	1.39×10^{32}	1.90×10^{33}	2.31×10^{46}	2.65×10^{45}
0827+243	0.943	1.81×10^{34}	1.72×10^{32}	6.87×10^{32}	6.62×10^{45}	1.80×10^{45}
0836+710	2.218	1.78×10^{35}	7.19×10^{31}	8.30×10^{32}	1.11×10^{45}	1.78×10^{46}
0906+015	1.026	9.81×10^{33}	5.66×10^{32}	3.90×10^{32}	1.02×10^{46}	3.05×10^{45}


10^{48}
10^{47}
10^{46}
10^{45}
10^{44}
10^{43}
10^{42}
10^{41}
10^{40}
P_{Ψ}, erg s^{-1}
10^{45}
10^{46}
$P_{\rm jet}$, erg s^{-1}
20
15
10
5
0
N
−2
−1
0
1
2
3
4
5
6
$\lg(P_{\Psi}/P_{\rm obs})$

Conclusions

- The may estimate the total magnetic flux from the magnetic field measurements (differently for different models) if given the rotation parameter $a = {}^{r_g}/_{R_L}$
- The electromagnetic losses by a BH depend on a logarithmically, other values may be estimated from the observations
- For the chosen 48 sources the distribution of electromagnetic power to total power is peaked at 1 with large dispersion (the model uncertainties, the measurements uncertainties, the underlying physics)