The Jet Magnetic Flux

Elena Nokhrina
(Moscow Institute of Physics and Technology)

Moscow, Russia

September 13, 2017

What we need to produce jets?

- The ordered magnetic field
- The rotating black hole
- The accreting material

Blandford-Znajek process

BH rotational energy extraction

What we need to produce jets?

- The ordered magnetic field
- The rotating black hole
- The accreting material

$$P_{tot} = \frac{\Omega^2}{\pi^2 c} \Psi_{tot}^2$$

(Beskin 2010)

$$\Psi_{tot} \propto 50\left(\dot{M} r_g^2 c\right)^{1/2}$$

(Zamaninasab+ 2014)

↓

Blandford-Znajek process → BH rotational energy extraction

What we need to produce jets?

- The ordered magnetic field
- The rotating black hole
- The accreting material

Need estimates for
magnetic field B
particle number density n

Blandford-Znajek process → BH rotational energy extraction

Core-shift measurement

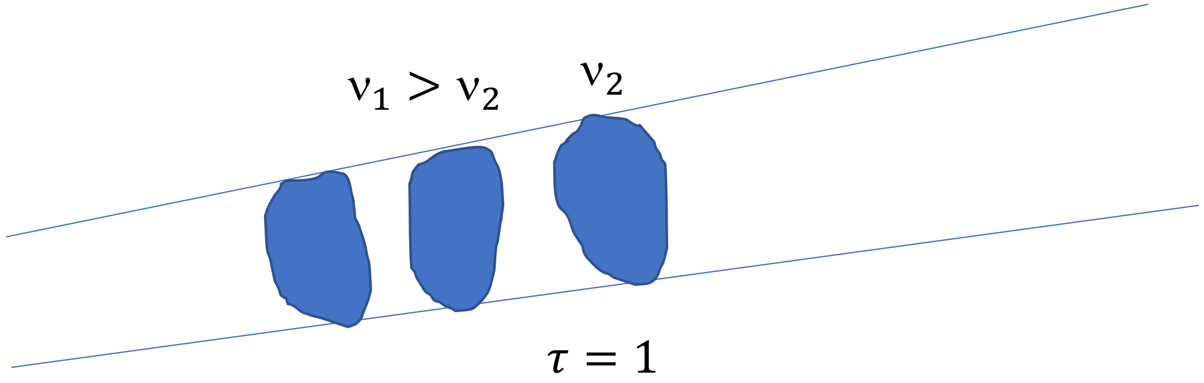
Equipartition assumption

Blandford-Konigl scalings

(Lobanov 1998, see also Hirotani 2005, O'Sullivan & Gabuzda 2009, Nokhrina+ 2015)

Which physical parameters we can imply basing on the observations?

Core-shift effect:



Can be measured, for instance, in mas GHz

Which physical parameters we can imply basing on the observations?

Equipartition:

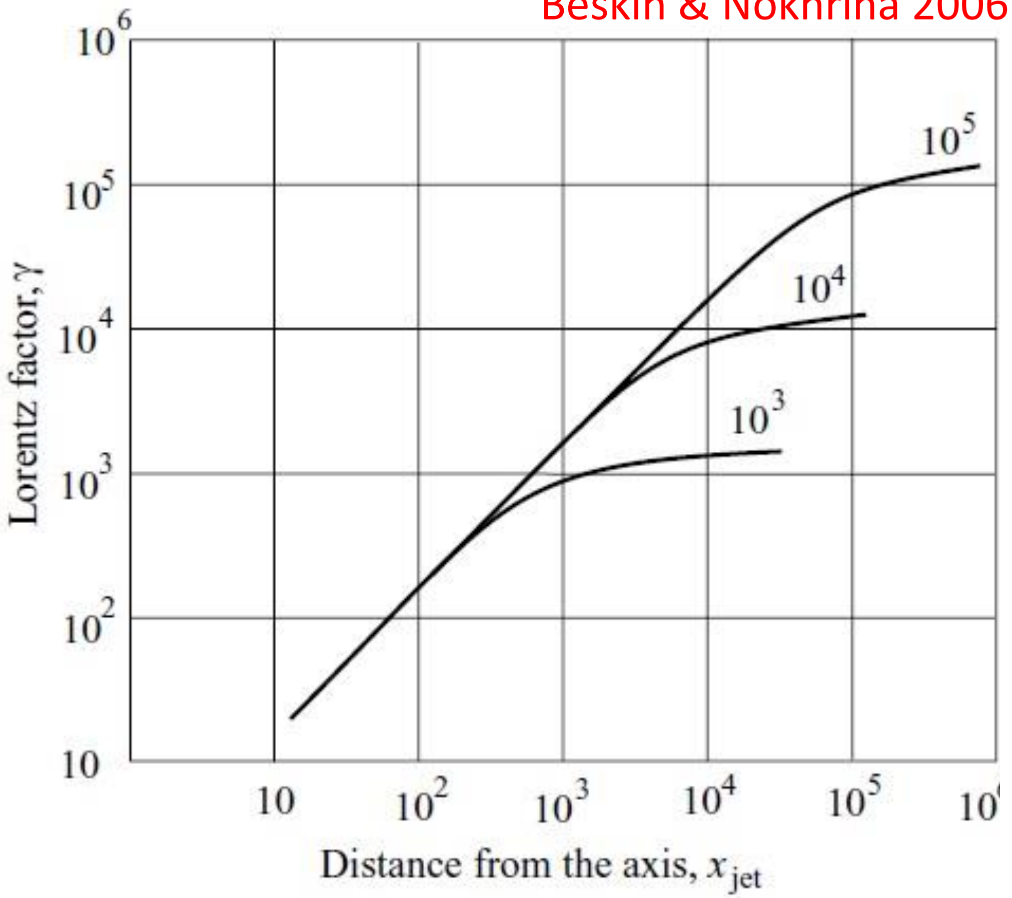
$$\sigma = \frac{B^2}{4\pi n m c^2 \Gamma^2}$$

$$dn = k_e \gamma^{-p} d\gamma$$

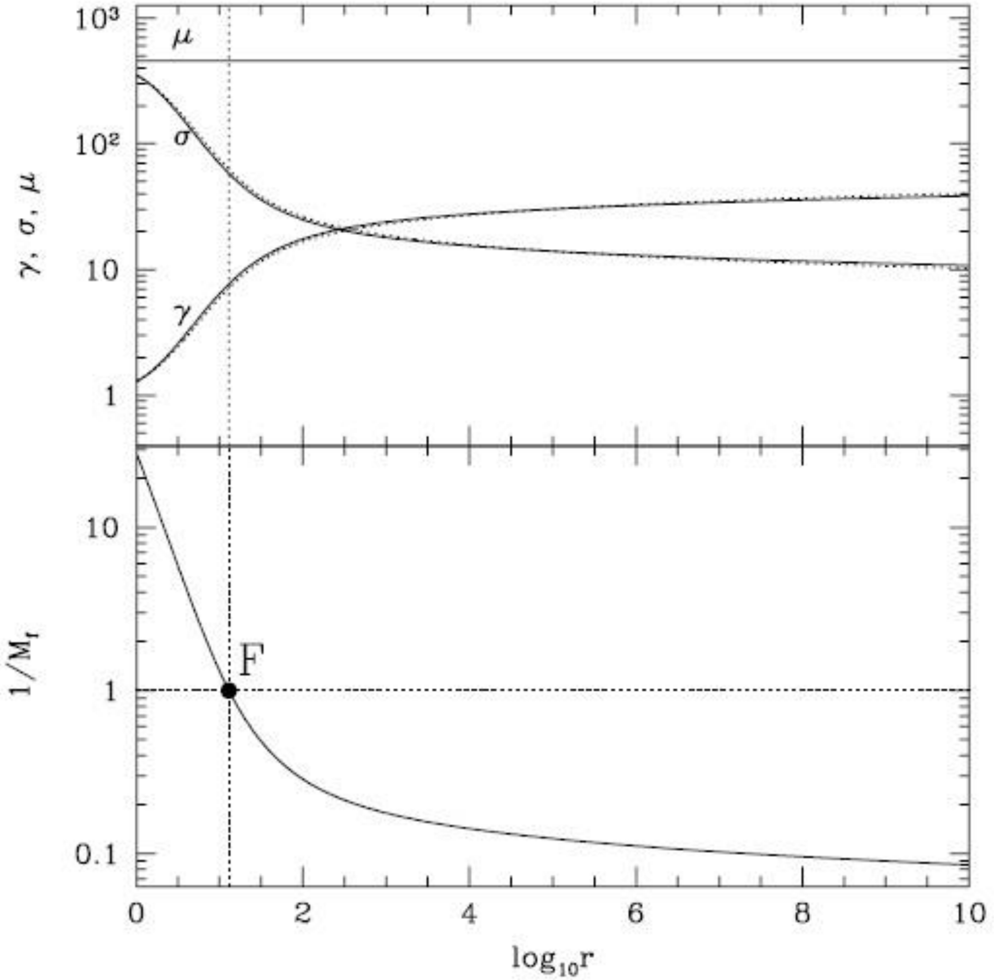
$$\Sigma = \frac{\Gamma B^2 f(2)}{4\pi n_{rad} m c^2 \ln(\gamma_{max}/\gamma_{min})}$$

Which physical parameters we can imply basing on the observations?

Beskin & Nokhrina 2006

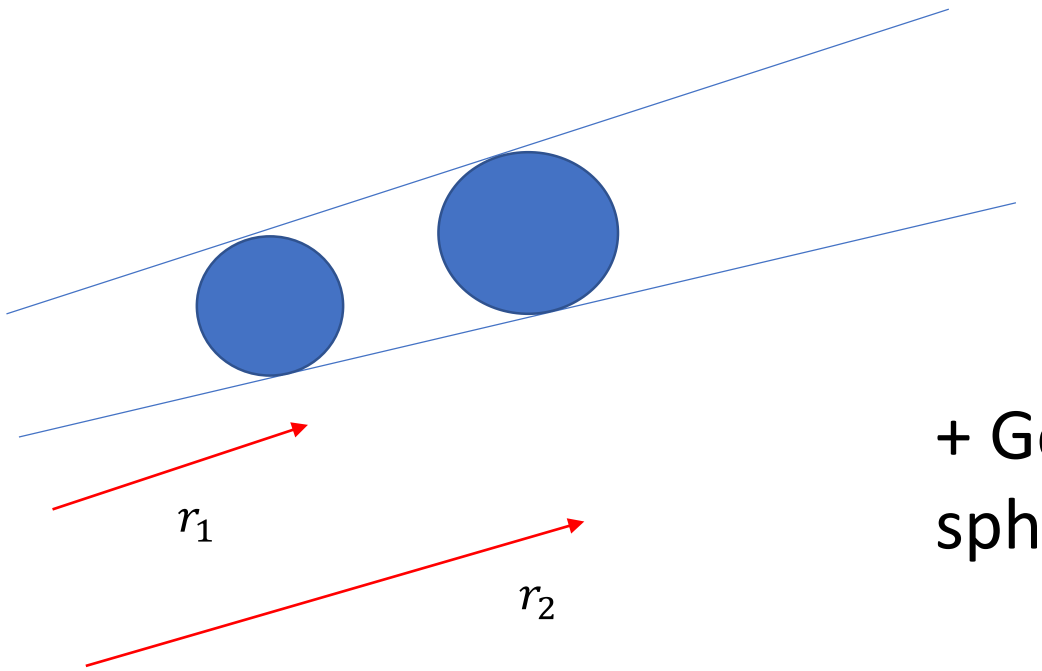


Tchekhovskoy, McKinney & Narayan 2009



Which physical parameters we can imply basing on the observations?

Blandford-Konigl (1979) model $B \propto r^{-1}$ and $\mathrm{n} \propto r^{-2}$



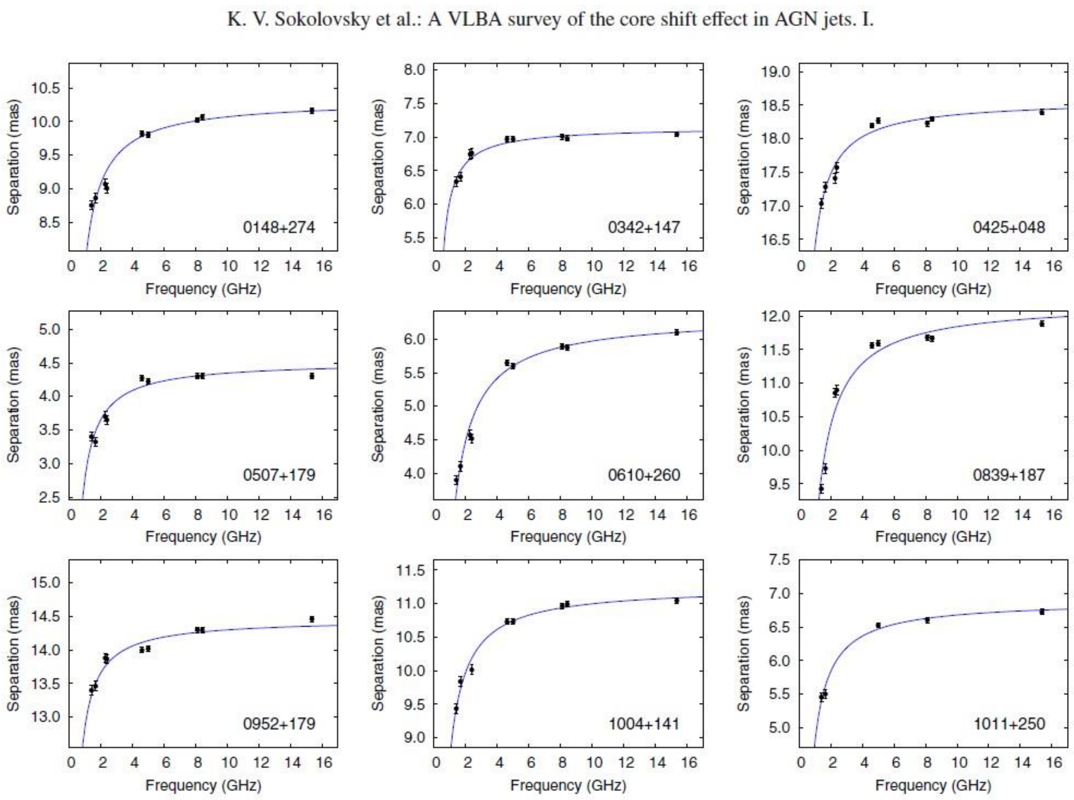
+ Gould (1979) model for the spherical self-absorbed sources

Which physical parameters we can imply basing on the observations?

Blandford-Konigl model + synchrotron self-absorbed source model provides

$$\nu_{obs} \propto r^{-1}$$

Sokolovsky+ 2011 supports it.



Core-shift measurement

Equipartition assumption

Blandford-Konigl scalings

$B \sim 1G$

$n \sim 10^3\ cm^{-3}$

(Lobanov 1998, see also Hirotani 2005, O’Sullivan & Gabuzda 2009, Nokhrina+ 2015)

Why non-equipartition is probably not valid?

- Kellermann & Pauliny-Toth 1969: the idea of the inverse Compton catastrophe and the limiting intrinsic brightness temperature

$$T_{br} \approx 10^{12}\mathrm{K}$$

- Readhead 1994: the equipartition brightness temperature

$$T_{br} \approx 10^{11.5}\mathrm{K}$$

- However: recent observations of radio cores by Gomez+ 2016, Kovalev+ 2016, Lisakov+ 2017 provide

$$T_{br} > 7 \times 10^{12}\mathrm{K}$$

Why non-equipartition is probably not valid?

- Kellermann & Pauliny-Toth 1969: the idea of the inverse Compton catastrophe and the limiting intrinsic brightness temperature

$$T_{br} \approx 10^{12}\text{K}$$

- Readhead 1994: the equipartition brightness temperature

$$T_{br} \approx 10^{11.5}\text{K}$$

- However: recent observations of radio cores by Gomez+ 2016, Kovalev+ 2016, Lisakov+ 2017 provide

$$T_{br} > 7 \times 10^{12}\text{K}$$

Core-shift measurement

Equipartition assumption

Blandford-Konigl scalings

Core-shift measurement

~~Equipartition assumption~~

Blandford-Konigl scalings

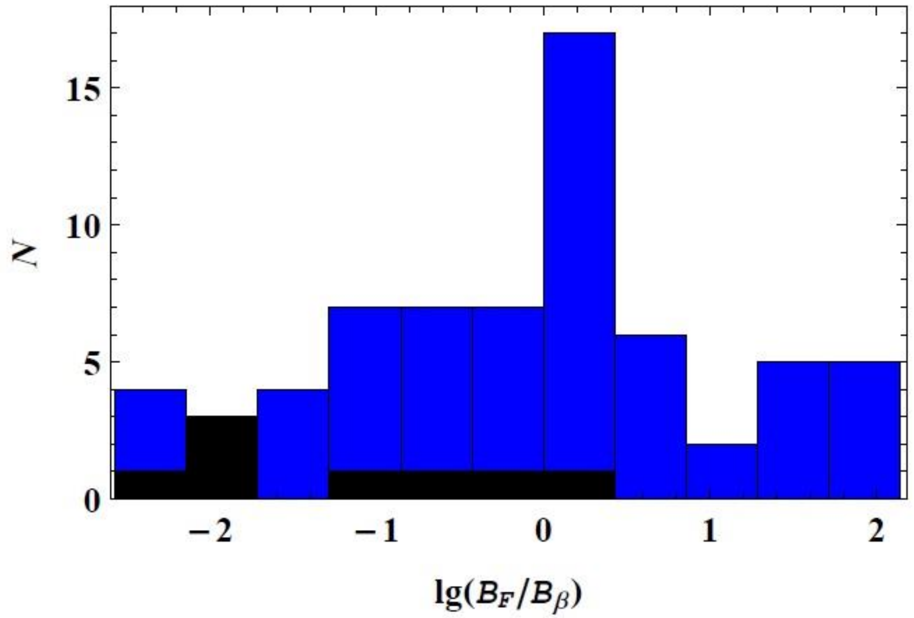
Core-shift measurement

Flux (Tb) measurement

Blandford-Konigl scalings

Can we estimate independently the B and n?

Zdziarski, Sikora, Pjanka & Tchekhovskoy, 2015: let us use the flux measurement + core-shift measurement => independent evaluation of B and n in the radio core region. The result is that the magnetic field is nearly equipartition. However, the flux measurements correspond to the sub-equipartition limit.



1. Core-shift effect;
2. Brightness temperature measurement;
3. Blandford-Konigl model.

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

$$\left(\frac{n}{cm^{-3}}\right) = 8.2 \times 10^{3} \frac{\Gamma sin^{2}\varphi(1+z)^{7}}{2\chi\delta^{4}} f(2) \times$$

$$\times \left(\frac{D_L}{Gpc}\right)^{-1} \left(\frac{\Phi}{mas\ GHz}\right)^{-1} \left(\frac{\nu_{obs}}{GHz}\right)^{2} \left(\frac{T_{b,obs}}{10^{12} K}\right)^{4}$$

Magnetization of the radiating region: the ratio of magnetic energy flux to the plasma particle energy flux

$$\Sigma = 7.7 \times 10^{-5} \frac{2\chi\Gamma^2\delta^6}{sin^2\varphi(1+z)^9} \frac{F(2)}{f(2)} \times$$

$$\times \left(\frac{D_L}{Gpc}\right)\left(\frac{\Phi}{mas\ GHz}\right)\left(\frac{T_{b,obs}}{10^{12}K}\right)^{-8}$$

These are the upper limits for B and Σ, and the lower limit for n.

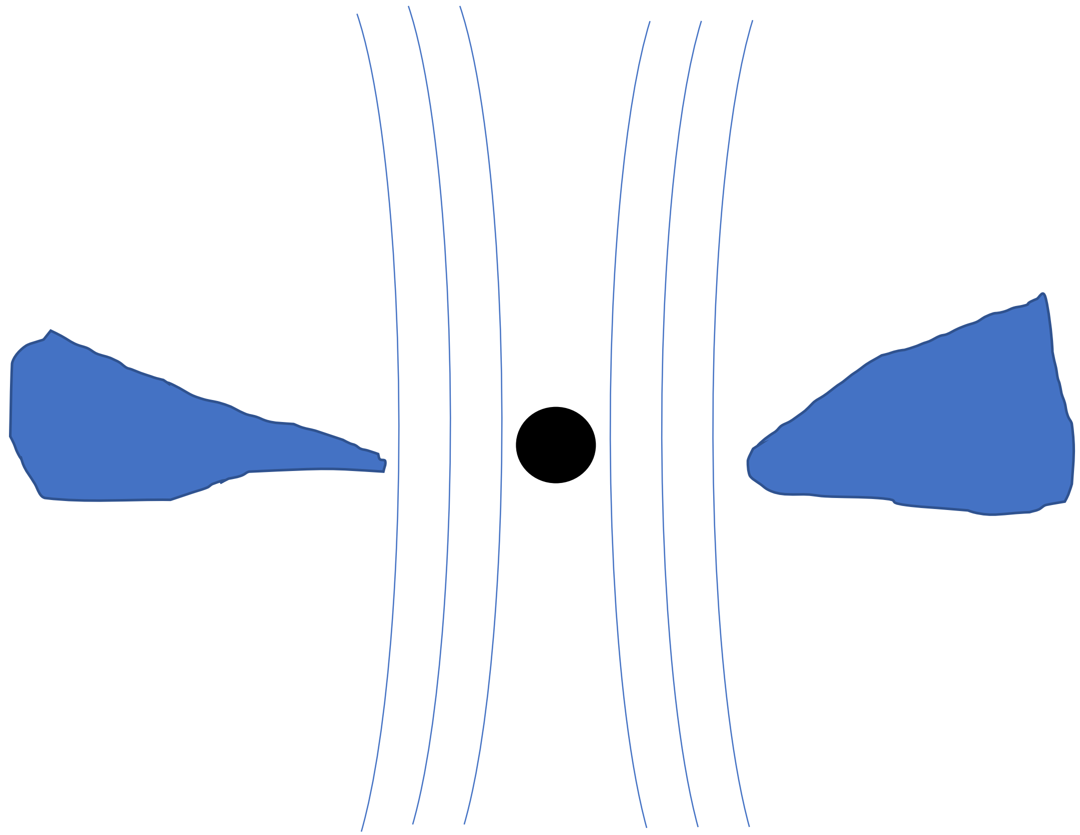
BL Lac and 3C273

- BL Lac (Gomez+ 2016)
- $T_{b,obs} = 7.9 \times 10^{12}$K at $\nu_{obs} = 15$ GHz
- $B_{uni} = 3.3 \times 10^{-2}$G

- 3C273 (Kovalev+ 2016)
- $T_{b,obs} = 13 \times 10^{12}$K at $\nu_{obs} = 4.8$ GHz
- $B_{uni}(high) = 8.1 \times 10^{-3}$G
- $B_{uni}(low) = 0.13$ G (for Tb=4×10^{12}K at $\nu_{obs} = 16.7$ GHz)

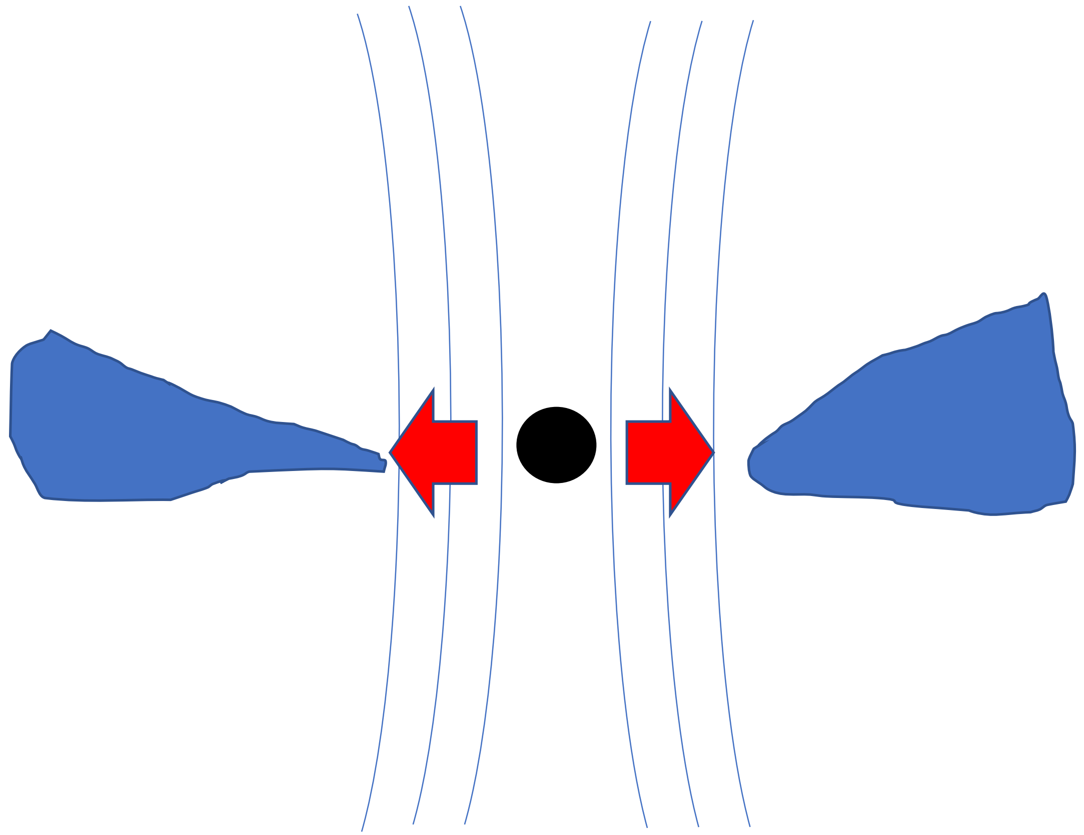
What about the total magnetic flux in a jet?

- MADs – magnetically arrested disks (Narayan+ 2003, Tchekhovskoy+ 2011, McKinney+ 2012).
- Dynamically important magnetic field – regulate the accretion rate



What about the total magnetic flux in a jet?

- MADs – magnetically arrested disks (Narayan+ 2003, Tchekhovskoy+ 2011, McKinney+ 2012).
- Dynamically important magnetic field – regulate the accretion rate
- $\Psi_{MAD} \sim 50\sqrt{\dot{M} r_g^2 c}$



What about magnetic flux in a jet?

Zamaninasab+ 2014:

$$\frac{B_P}{B_\varphi} \propto a\,\frac{R_j}{r_g}$$

From CS+BK+E the measured field

B_φ, and the flux

$$\Psi \propto R_j^2 B_P \propto M R_j B_\varphi$$

Let us account for the transversal jet structure.

Non-uniform model

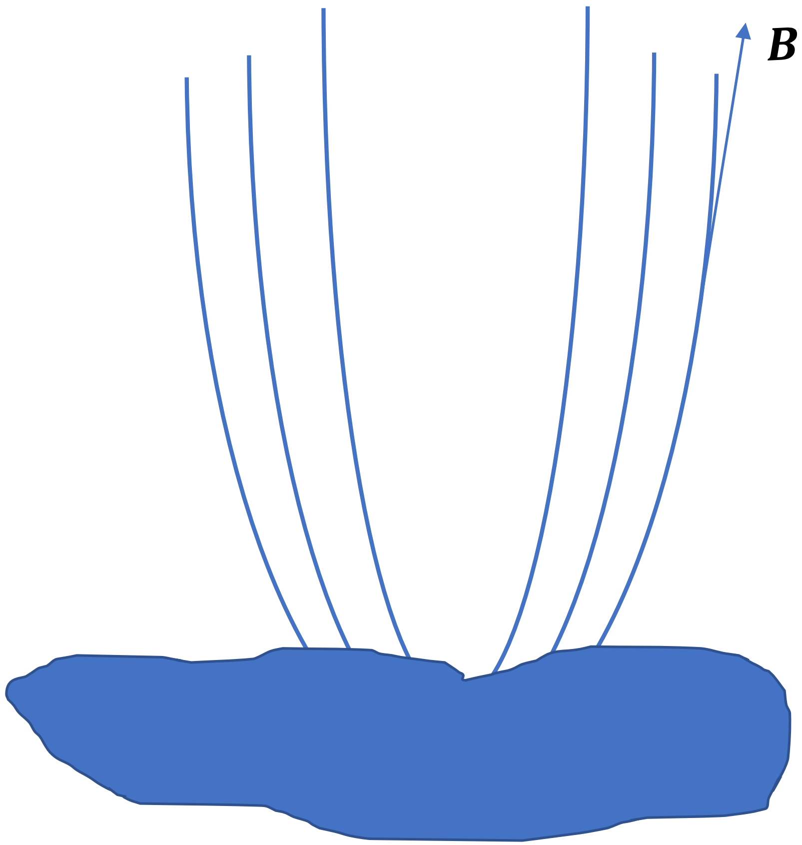
- Can be obtained solving the non-linear Grad-Shafranov equation on the flux function Ψ. It can be done analytically under certain assumptions: self-similarity, or force-free flow (plasma inertia = 0), or effectively 1D – the cylindrical magnetic surfaces configuration.
- The latter is a good approximation for the well-collimated jets, or a slice of a jet where we may neglect by the opening angle on the interesting for us scales.

Non-uniform model: some analytical results

$$B_P = \frac{\nabla\Psi \times e_\varphi}{2\pi r}$$

$$B_\varphi = -\frac{2I}{r} e_\varphi$$

$$E = -\frac{\Omega_F}{2\pi}\nabla\Psi$$



Non-uniform model: some analytical results

$$B_P = \frac{\nabla\Psi \times e_\varphi}{2\pi r}$$

$$B_\varphi = -\frac{2I}{r} e_\varphi$$

$$E = -\frac{\Omega_F}{2\pi} \nabla\Psi$$

Useful relations:

$$E = B_P \Omega_F r$$

Non-uniform model: some analytical results

$$B_P = \frac{\nabla\Psi \times e_\varphi}{2\pi r}$$

$$B_\varphi = -\frac{2I}{r} e_\varphi$$

$$E = -\frac{\Omega_F}{2\pi} \nabla\Psi$$

Useful relations:

$$E = B_P \Omega_F r$$

From the condition of flux freezing one may obtain (Lyubarsky 2009):

$$B_\varphi \approx B_P \Omega_F r$$

Non-uniform model: some analytical results

$$B_P = \frac{\nabla\Psi \times e_\varphi}{2\pi r}$$

$$B_\varphi = -\frac{2I}{r} e_\varphi$$

$$E = -\frac{\Omega_F}{2\pi} \nabla\Psi$$

Useful relations:

$$E = B_P \Omega_F r$$

From the condition of flux freezing one may obtain (Lyubarsky 2009):

$$B_\varphi \approx B_P \Omega_F r$$

$$\boxed{B_\varphi^2 - E^2 \approx \frac{B_\varphi^2}{\Gamma^2}}$$

Non-uniform model: some analytical results

$$B_P = \frac{\nabla\Psi \times e_\varphi}{2\pi r}$$

$$B_\varphi = -\frac{2I}{r} e_\varphi$$

$$E = -\frac{\Omega_F}{2\pi} \nabla\Psi$$

For the constant current density j

$$I = \int jrdr \propto r^2$$

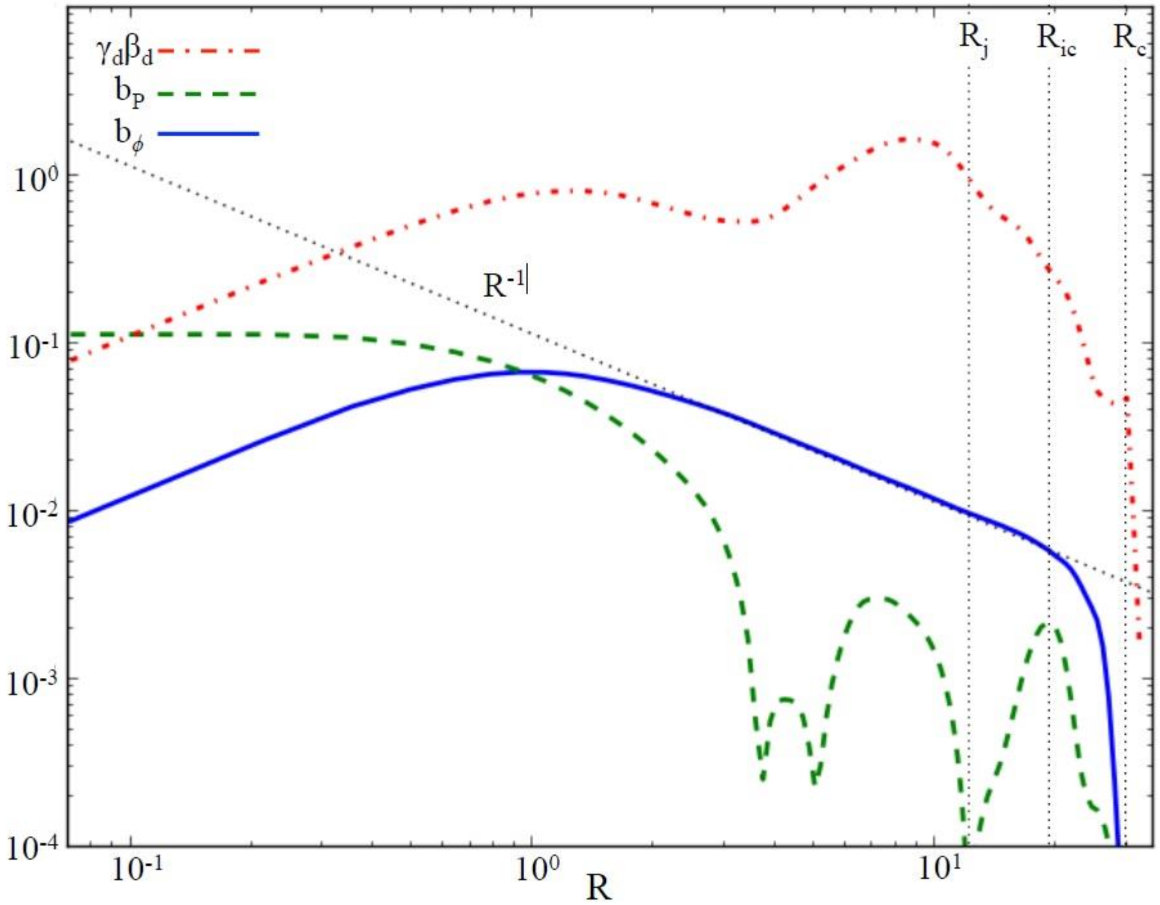
$$B_\varphi \propto r$$

For the zero current density

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

Non-uniform model: numerical results

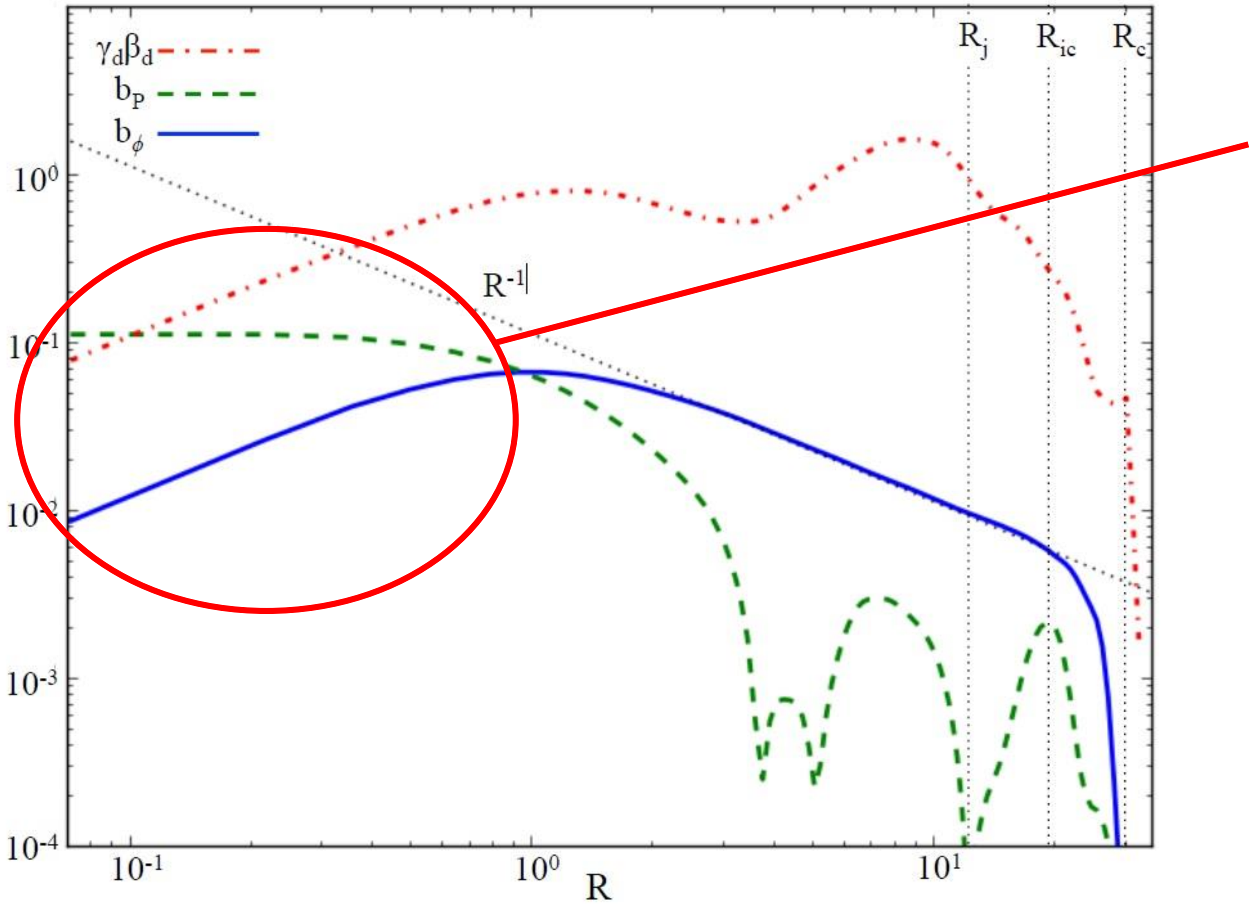
The solution may be obtained doing the numerical simulations:



Tchekhovskoy & Bromberg 2016

Non-uniform model: numerical results

The solution may be obtained doing the numerical simulations:

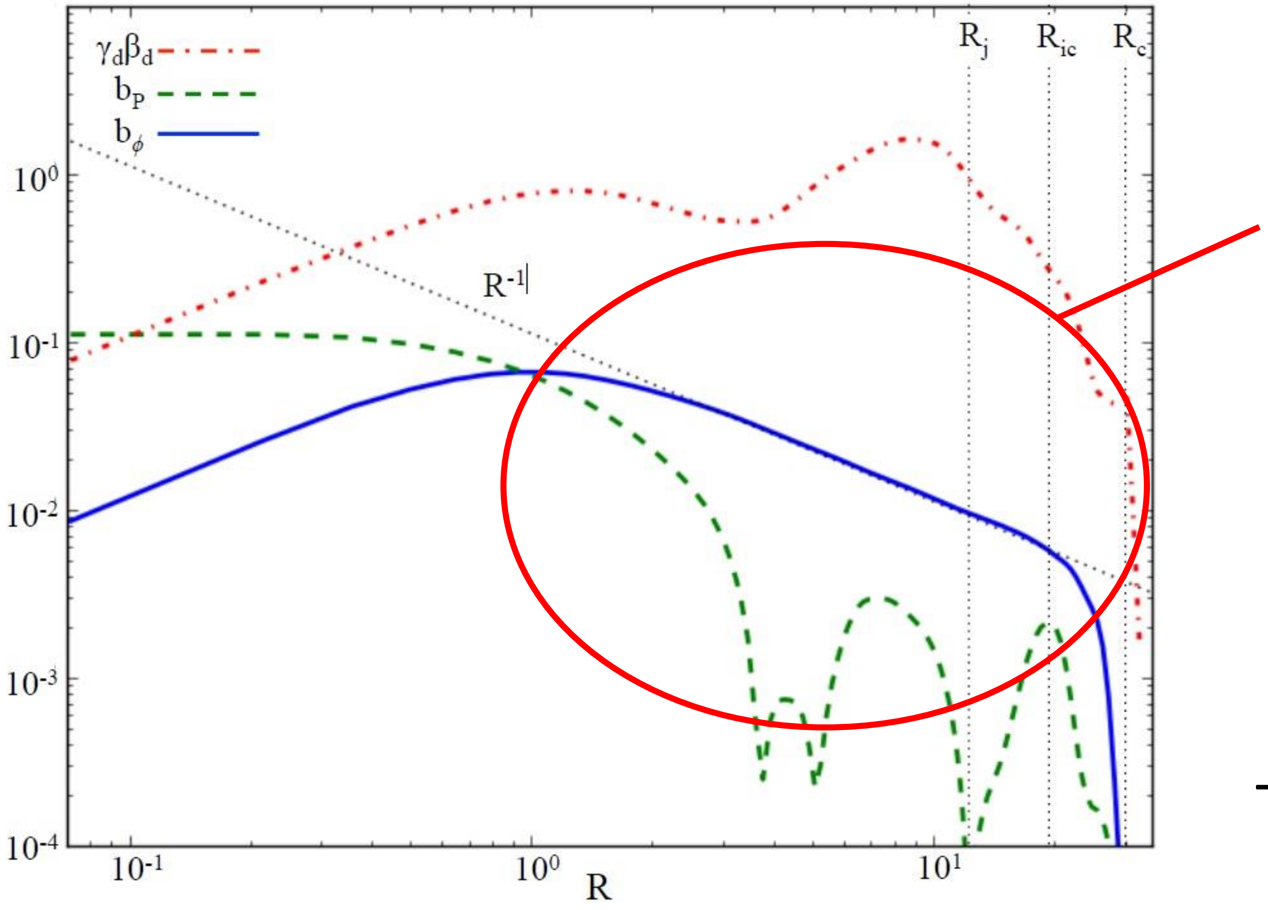


The central core with constant poloidal magnetic field B_P and linearly growing toroidal magnetic field B_φ.

Tchekhovskoy & Bromberg 2016

Non-uniform model: numerical results

The solution may be obtained doing the numerical simulations:

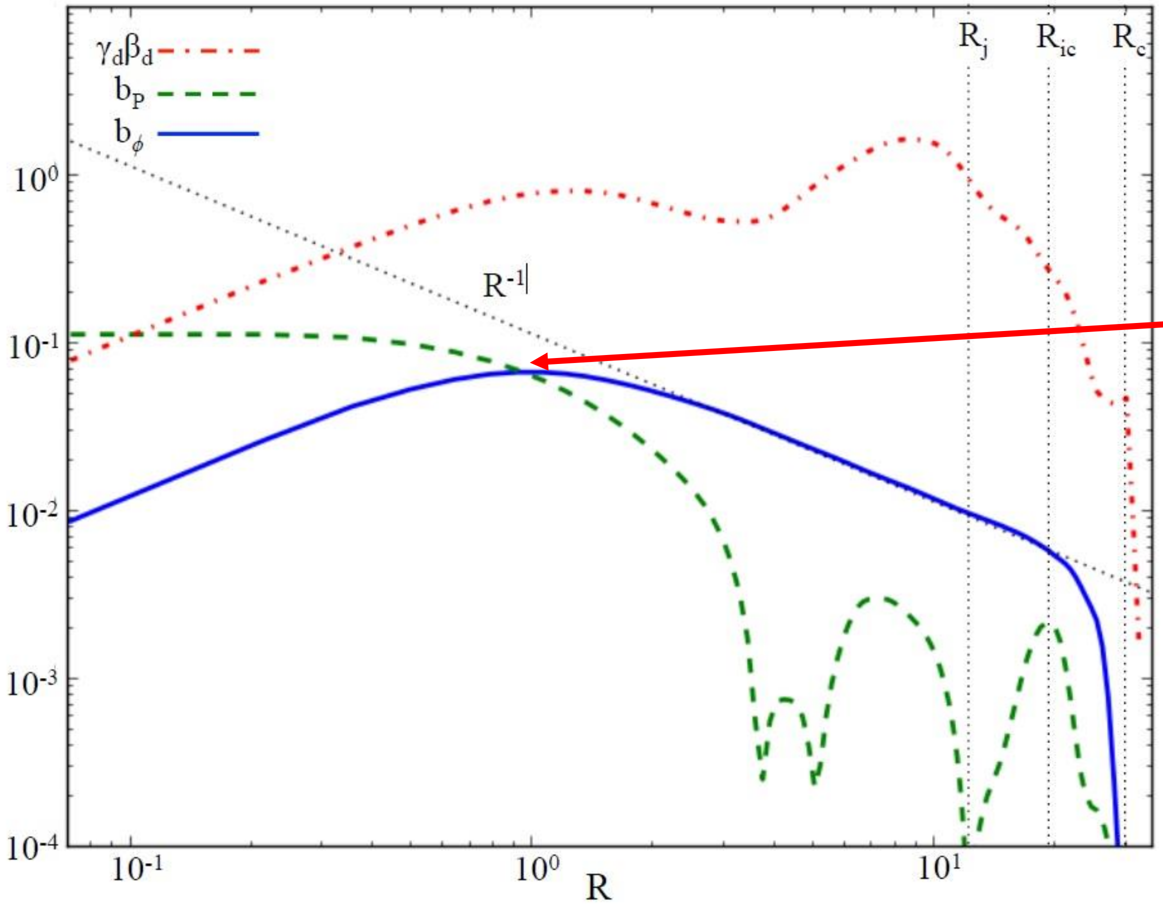


The outer flow with the poloidal magnetic field $B_P \propto r^{-2}$ and the toroidal magnetic field $B_\varphi \propto r^{-1}$.

Tchekhovskoy & Bromberg 2016

Non-uniform model: numerical results

The solution may be obtained doing the numerical simulations:



The size of a central core

$$R_0 \approx R_L$$

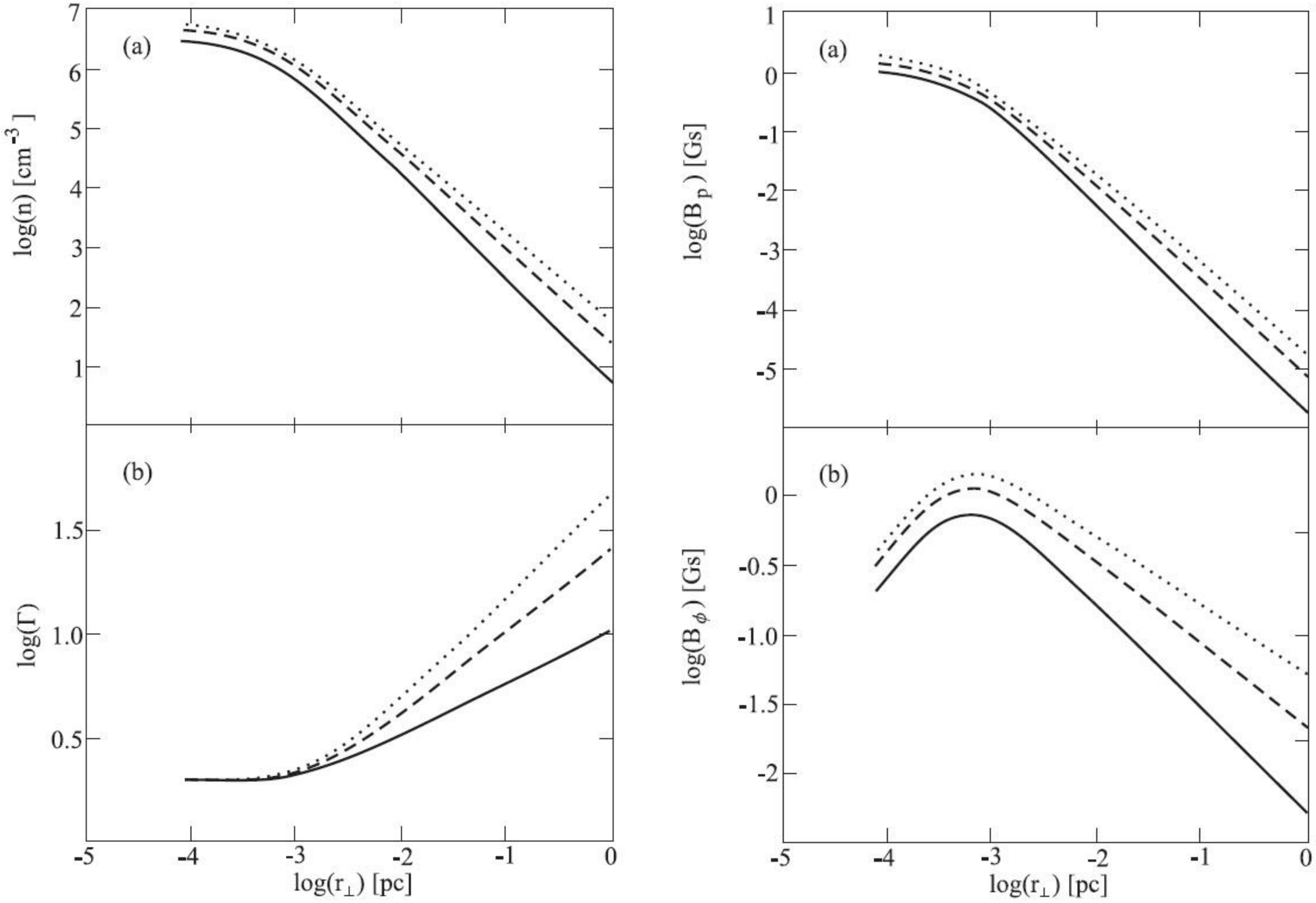
At the central core boundary

$$B_P = B_\varphi = B_0$$

and we call it the magnetic field amplitude.

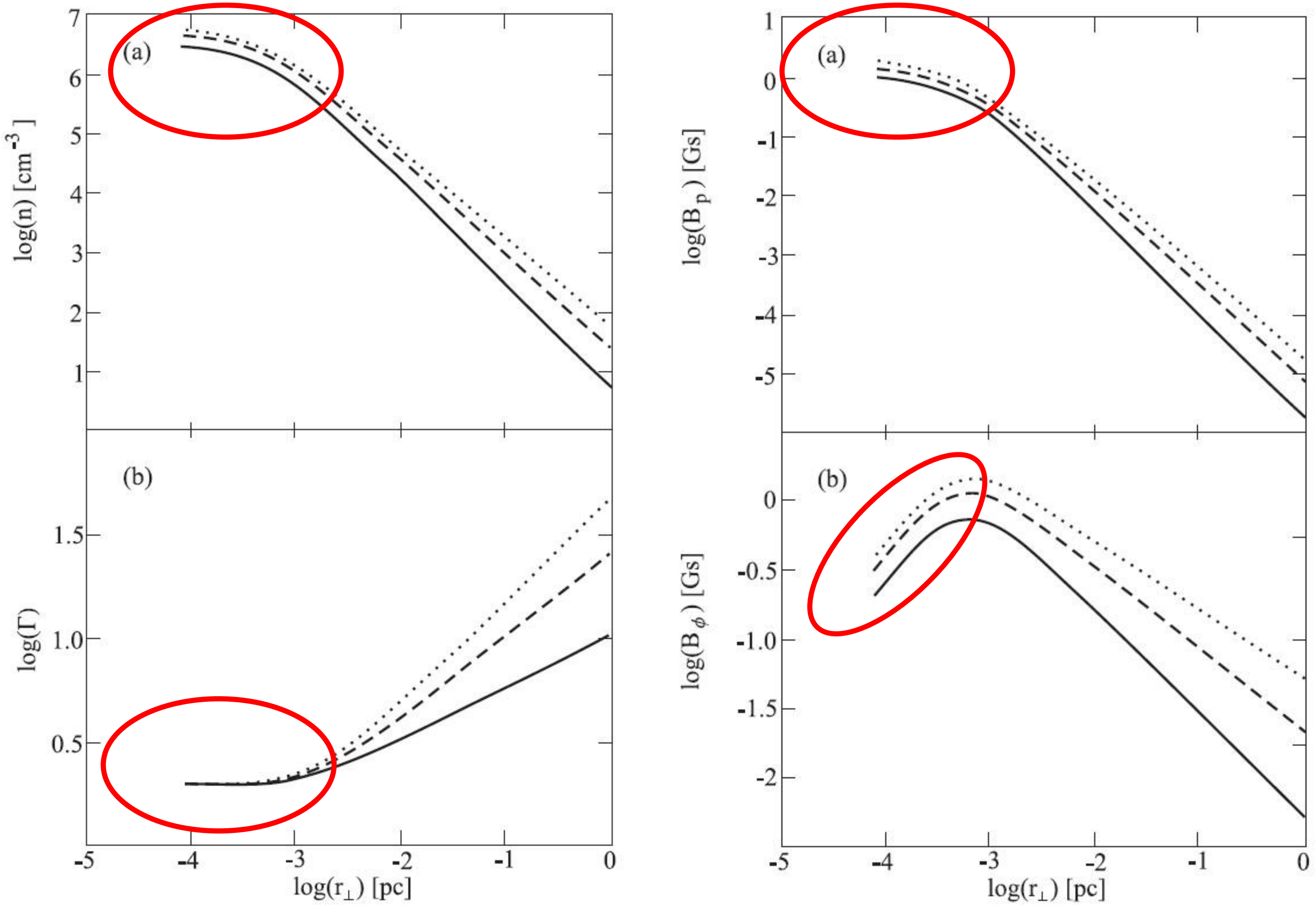
Tchekhovskoy & Bromberg 2016

Non-uniform model: analytical results



Nokhrina+ 2015

Non-uniform model: analytical results



The central core:

$n \approx const$

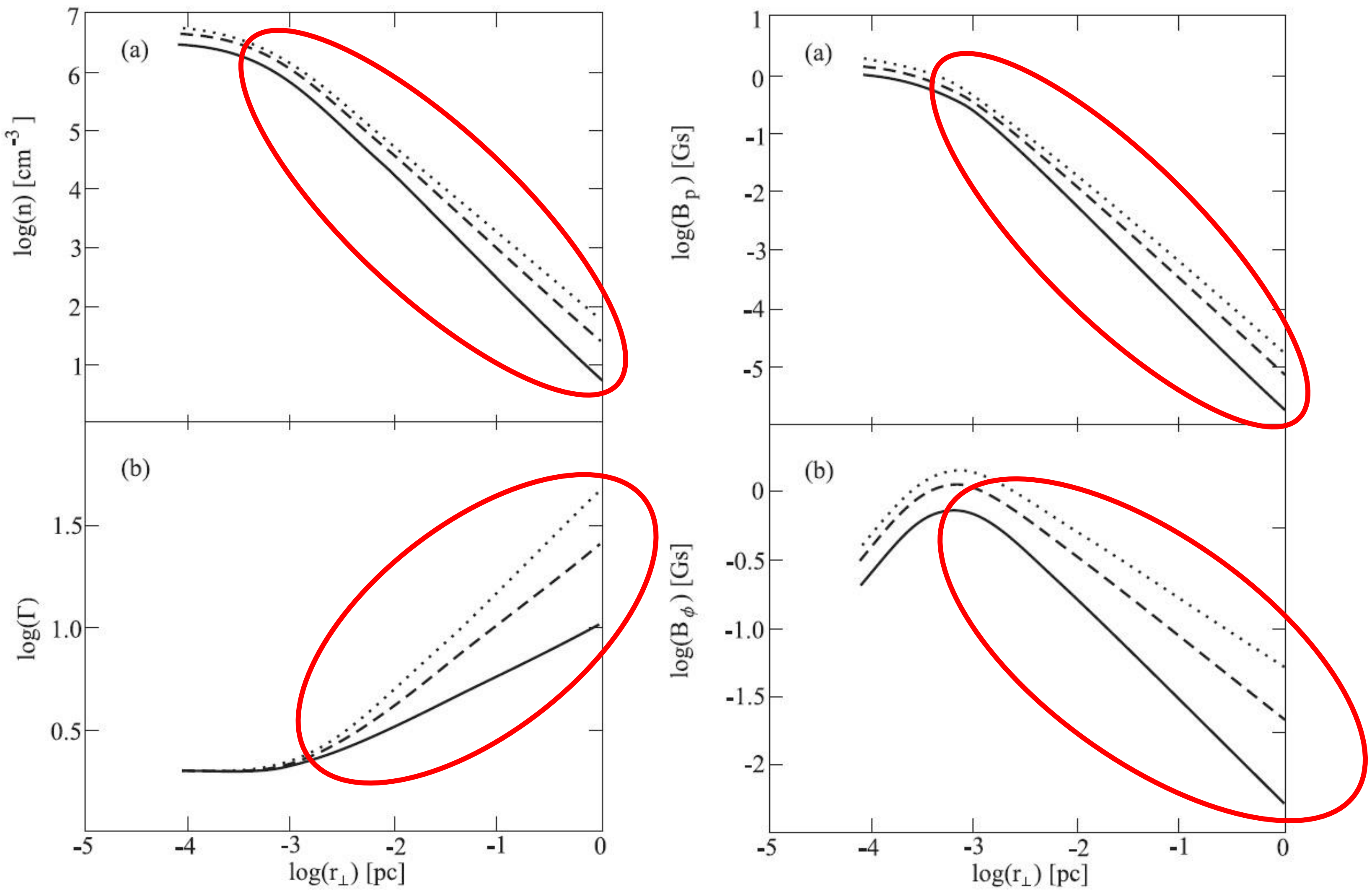
$B_P \approx const$

$B_\varphi \propto r$

$\Gamma \approx const$

Nokhrina+ 2015

Non-uniform model: analytical results



The outer flow:

$n \propto r^{-2}$

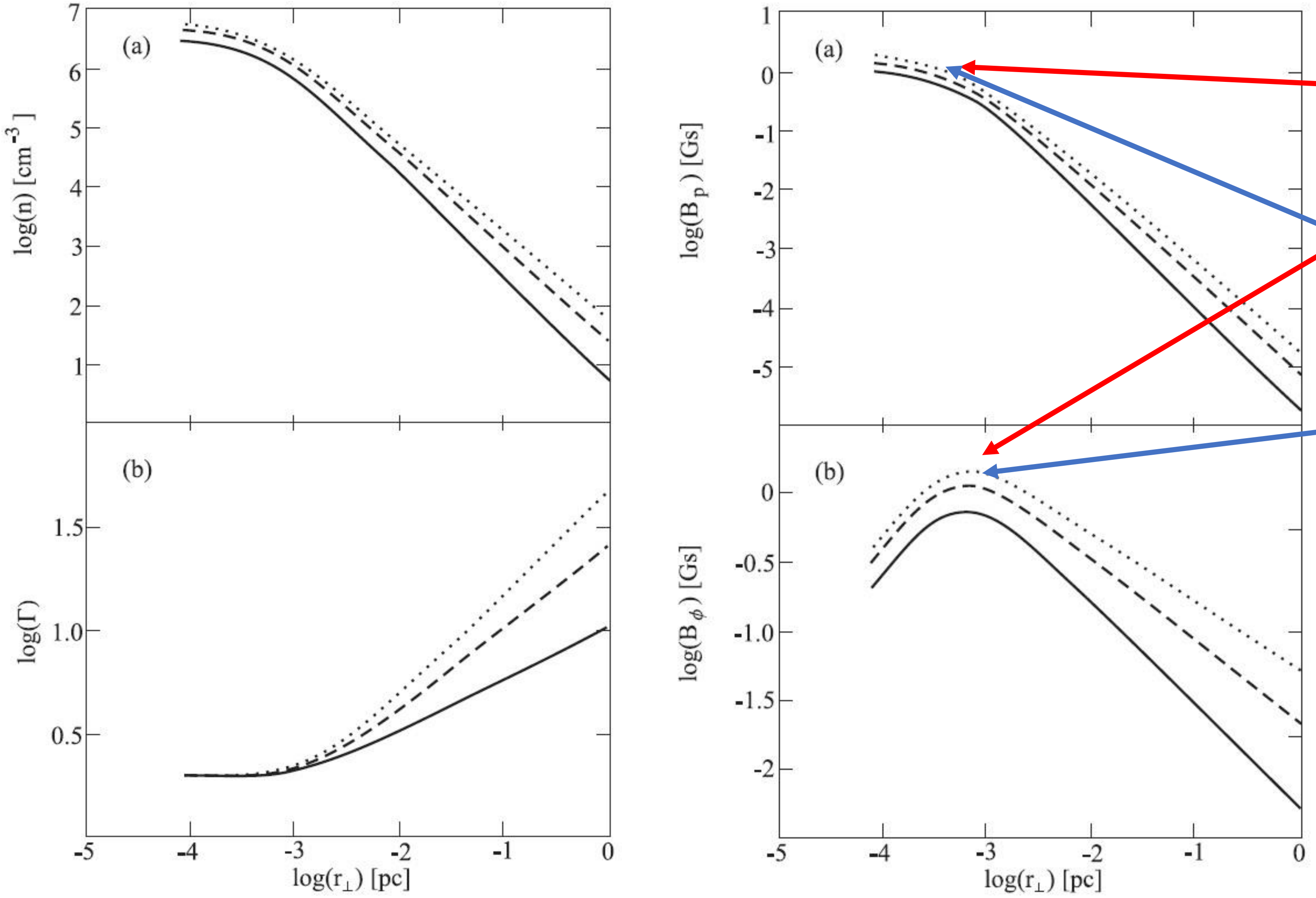
$B_P \propto r^{-2}$

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

$\Gamma \propto r$

Nokhrina+ 2015

Non-uniform model: analytical results



The central core size

$R_0 \approx 5R_L$

The magnetic field amplitude

B_0

Nokhrina+ 2015

Non-uniform model

- The non-uniform n and B distribution leads to non-uniform synchrotron emission

$$\rho = 4\pi(1.5)^{\frac{p-1}{2}} a(p) \alpha k'_e \left(\frac{\nu'_B}{\nu'}\right)^{(p+1)/2}$$

and effective absorption

$$\varkappa = c(p) r_0^2 k'_e \left(\frac{\nu_0}{\nu'}\right) \left(\frac{\nu'_B}{\nu'}\right)^{(p+1)/2}$$

coefficients (important).

- Different boosting Lorentz factors across the jet cross-section (not important, Nokhrina 2017).

Non-uniform model – B-field

For jets with small viewing angles calculation of the observed flux

$$S_\nu = \frac{\delta^3}{d^2}\int_{\Omega'} \hbar\nu' \rho' dV' e^{-\int \varkappa' ds'}$$

can be done analytically. We use the measurements of the brightness temperature for BL Lac (Gomez+ 2016) and 3C273 (Kovalev+ 2016).

BL Lac → $\varphi = 0.1$

3C273 → $\varphi = 0.067$

(using measurements of β_{app} by Lister+ 2013, and Doppler factor by Jorstad+ 2005 and Cohen+ 2007).

Non-uniform model – B-field

Finally, we obtain the following expression for the magnetic field amplitude

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

Compare with the uniform source

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

Non-uniform model – B-field

Finally, we obtain the following expression for the magnetic field amplitude

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

Compare with the uniform source

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

The expression for the amplitude of non-uniform magnetic field depends on unknown radius of the light cylinder, which is defined by the field lines rotation rate

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

Thus, the amplitude magnetic field is not known directly from the observations (unlike uniform non-equipartition magnetic field amplitude).

However, one may calculate the flux in a jet and compare it with the MAD flux, thus estimating the lower limit for Ω_F and rotational rate

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

The non-uniform jet model provides readily the expression for the flux

$$\Psi = 2.7 B_{uni} R_j \frac{r_g}{a}\left[1 + 2ln\frac{R_j}{ar_g}\right]$$

Here we used the proportionality of amplitude field B_0 (can not be estimated independently of a) and uniform field B_{uni} (can be estimated independently of a).

The weak dependence of the expression in square brackets of a allows to use it to estimate a comparing the observed flux and MAD flux.

- Magnetic flux predicted by MAD seems to be the flux upper limit
- MAD flux:

$$\Psi_{MAD} \sim 50 \sqrt{\frac{L_{acc} r_g^2}{\eta c}}$$

$$a \geq \frac{2.7 B_{uni} R_j r_g [\ldots]}{\Psi_{MAD}}$$

- However R_j may be underestimated through observed angular size

$$R_j = \frac{\theta_{obs} D_L}{(1+z)^2}$$

BL Lac

$M = 1.7 \times 10^8 M_\odot$ (Woo & Urry 2002)

$L_{acc} = 1.5 \times 10^{45}\ \mathrm{erg}\ s^{-1}$ (Zamaninasab+ 2014)

$\Psi_{MAD} = 9.2 \times 10^{32}\ G\ cm^2$

$B_{uni} = 3.3 \times 10^{-2}\ G$ (Nokhrina 2017)

$\theta_{obs} \geq 21\ mas$ (Gomez+ 2016)

$a = 0.5$

3C 273

$M = 10^9\ M_\odot$ (Woo & Urry 2002)

$L_{acc} = 1.38\ \times 10^{48}\ \mathrm{erg}\ s^{-1}$ (Punsley & Zhang 2011, Torrealba+ 2012)

$\Psi_{MAD} = 1.6 \times 10^{35}\ G\ cm^2$

$B_{uni} = 0.13\ G$

$\theta_{obs} \geq 275\ mas$ (Kovalev+ 2016)

$a = 0.01$

Conclusions

- Using the extreme brightness temperatures we obtain the non-equipartition magnetic field for the uniform model

$$B_{uni} \approx 10^{-2}\ G$$

- The non-uniform transversal jet structure provides the estimate for the magnetic flux through observable values and effective rotational rate

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

- Comparison of the flux depending on a and the flux predicted by MAD may give a clue on how fast the black hole rotates.

Thank you!