The physical parameters of jets - the non-uniform transversal model

Elena Nokhrina

(Moscow Institute of Physics and Technology)

arXiv:1702.08676, accepted by MNRAS

Padova, Italy

April 4, 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

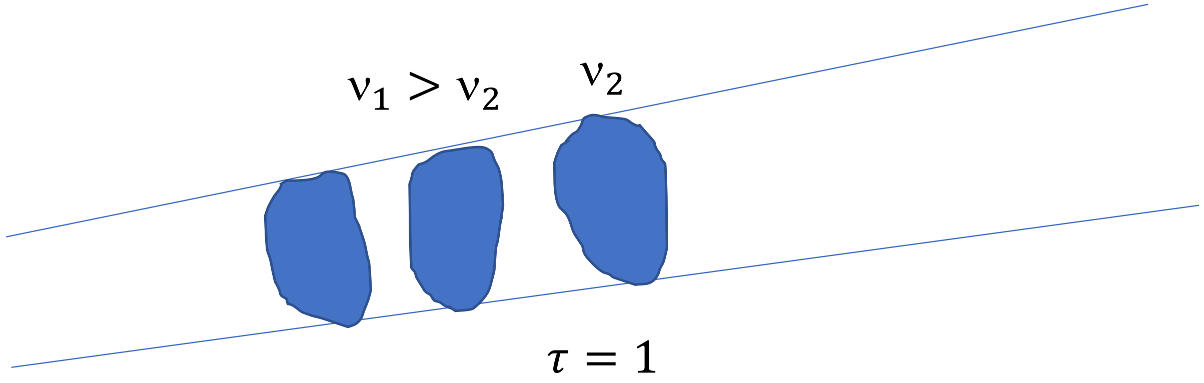
Equipartition assumption

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:

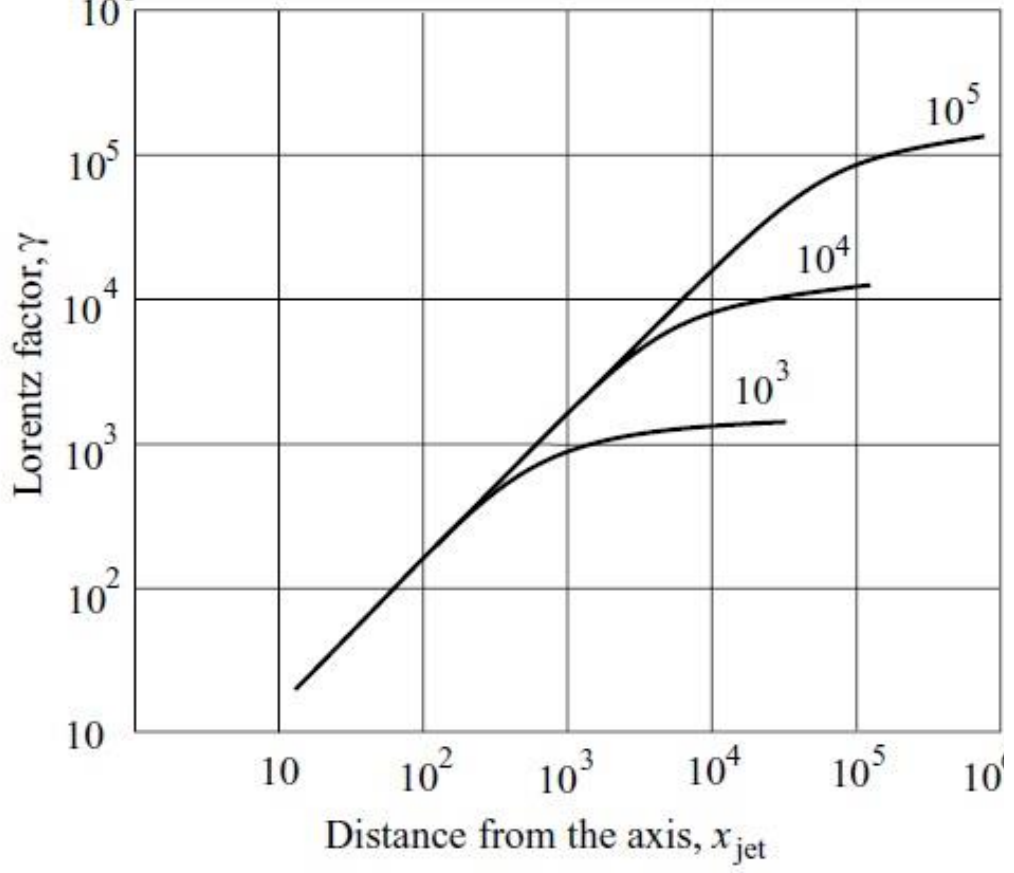
$$\sigma = \frac{B^2}{4\pi n m c^2 \Gamma^2}$$

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

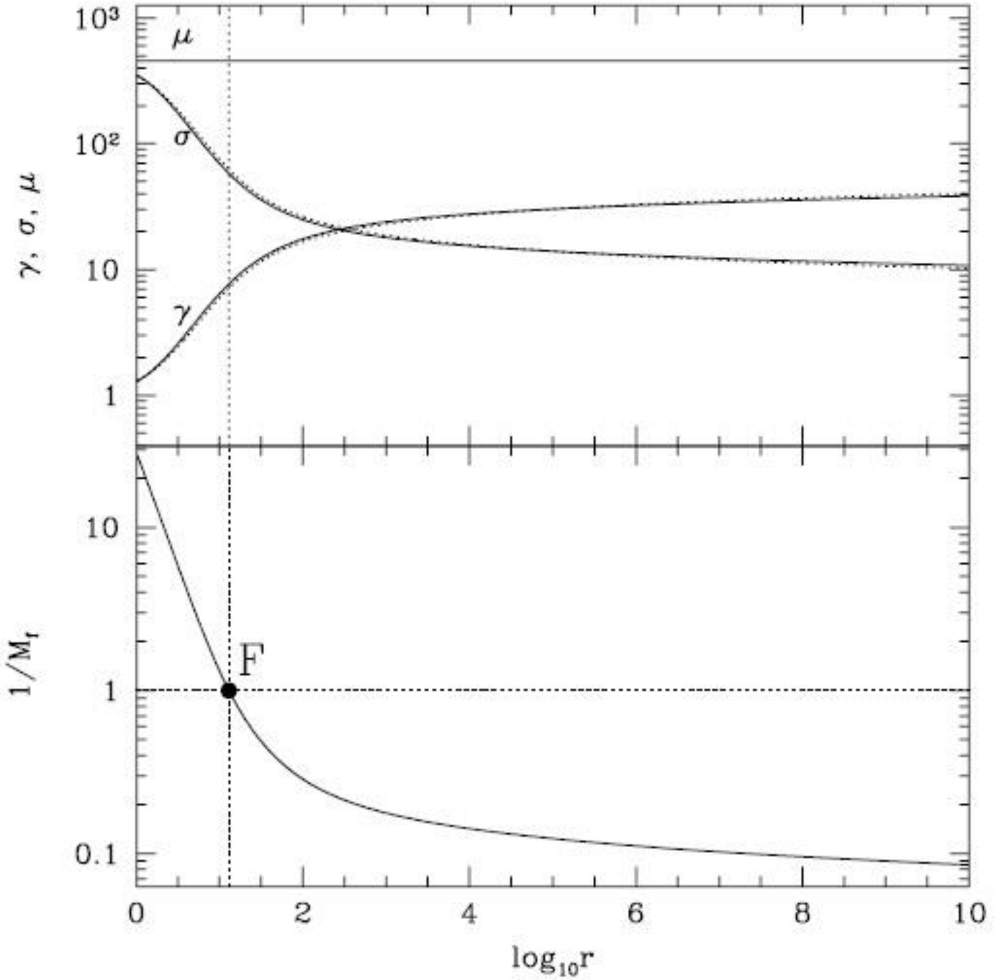
$$\Sigma = \frac{\Gamma B^2 f(2)}{4\pi n_{rad} m c^2 \ln(\gamma_{max}/\gamma_{min})}$$

Which physical parameters we can imply basing on the observations?

Beskin & Nokhrina 2006

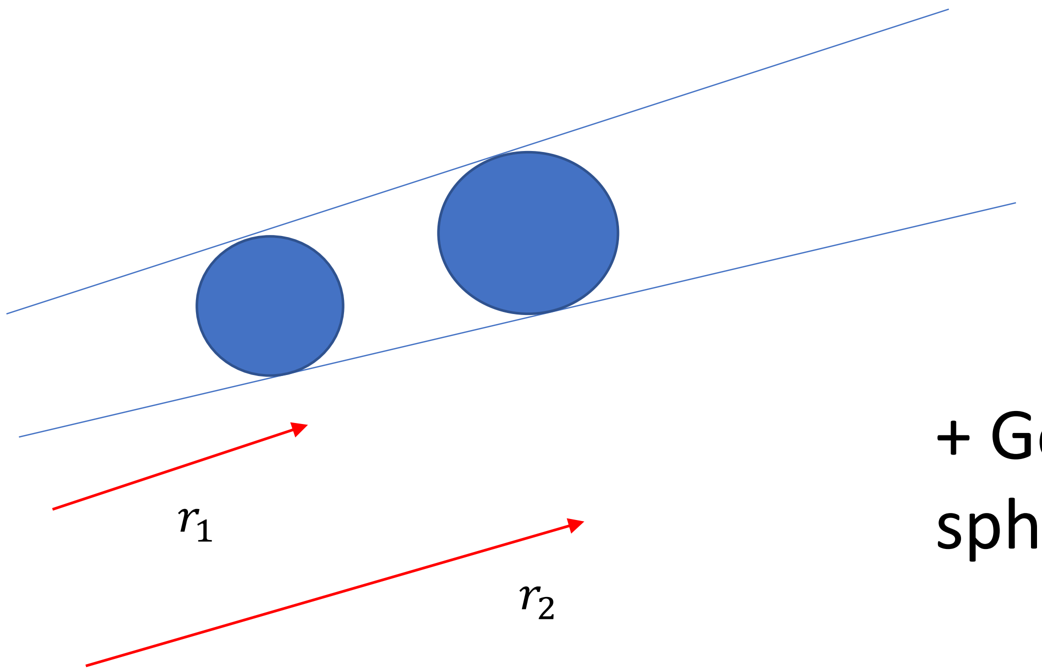


Tchekhovskoy, McKinney & Narayan 2009



Which physical parameters we can imply basing on the observations?

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



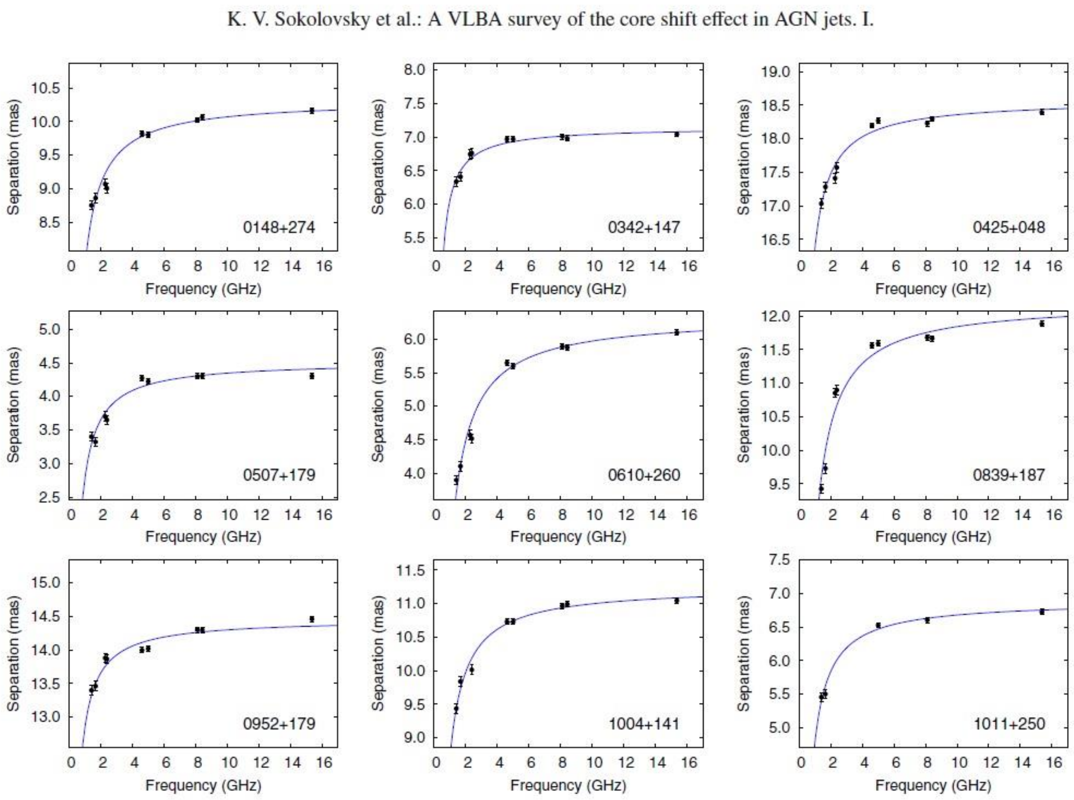
+ Gould (1979) model for the spherical self-absorbed sources

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

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

- 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

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

Core-shift measurement

~~Equipartition assumption~~

Blandford-Konigl scalings

Core-shift measurement

~~Equipartition assumption~~

Blandford-Konigl scalings

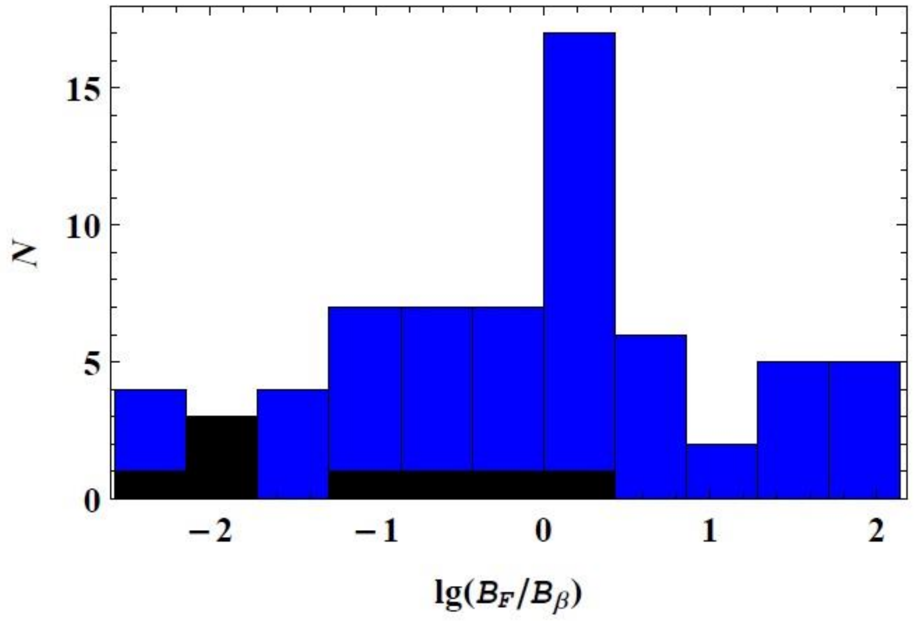
Core-shift measurement

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
- $n = 3.4 \times 10^{7} cm^{-3}$
- $\Sigma = 1.3 \times 10^{-5}$

- 3C273 (Kovalev+ 2016)
- $T_{b,obs} = 13 \times 10^{12}$K at $\nu_{obs} = 4.8$ GHz
- $B_{uni} = 8.1 \times 10^{-3}$G
- $n = 1.4 \times 10^{7} cm^{-3}$
- $\Sigma = 2.9 \times 10^{-6}$

What about the total magnetic flux in a jet?

- MADs – magnetically arrested disks (Tchekhovskoy+ 2011).
- For $M_{BH} = 10^9 M_{\odot}$

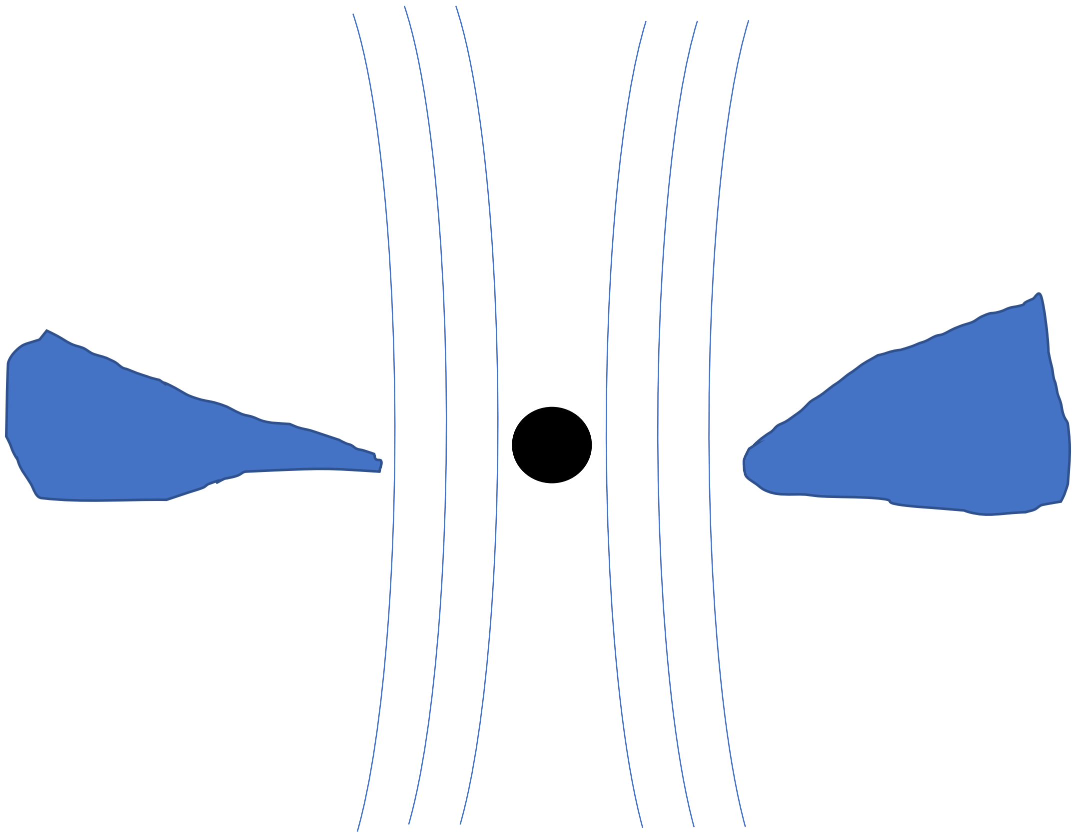
  the total magnetic flux in a jet

  $$\Psi_{MAD} = 3 \times 10^{33}\ \mathrm{G}\ cm^2$$

What about the total magnetic flux in a jet?

- MADs – magnetically arrested disks (Tchekhovskoy+ 2011).
- For $M_{BH} = 10^9 M_{\odot}$ the total magnetic flux in a jet

$$\Psi_{MAD} = 3 \times 10^{33}\ \mathrm{G}\ cm^2$$

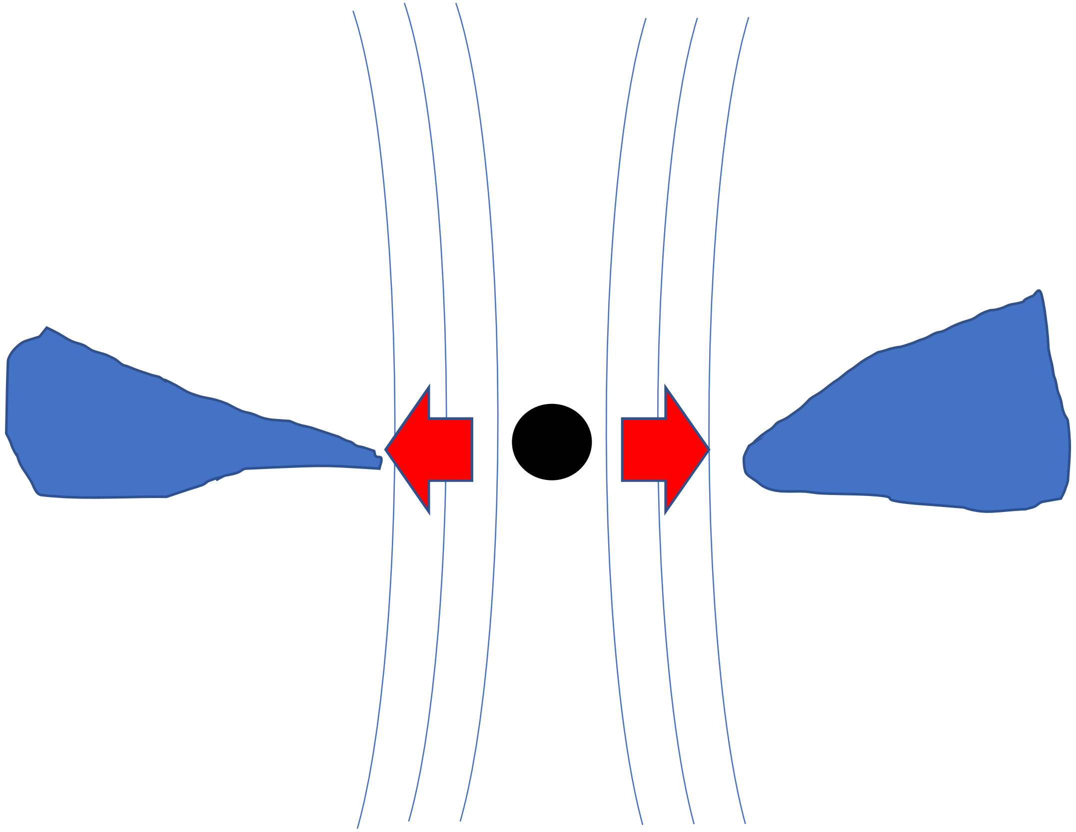


What about the total magnetic flux in a jet?

- MADs – magnetically arrested disks (Tchekhovskoy+ 2011).
- For $M_{BH} = 10^9 M_{\odot}$

  the total magnetic flux in a jet

  $$\Psi_{MAD} = 3 \times 10^{33} \text{ G } cm^2$$



What about the total magnetic flux in a jet?

- MADs – magnetically arrested disks (Tchekhovskoy+ 2011).
- For $M_{BH} = 10^9 M_{\odot}$

  the total magnetic flux in a jet

$$\Psi_{MAD} = 3 \times 10^{33}\ \mathrm{G}\ cm^2$$

- Equipartition magnetic field provides

$$\Psi_{jet} = 3 \times 10^{35}\ \mathrm{G}\ cm^2$$

- Non-equipartition magnetic field provides

$$\Psi_{jet} = 3 \times 10^{33}\ \mathrm{G}\ cm^2$$

What about the total magnetic flux in a jet?

- MADs – magnetically arrested disks (Tchekhovskoy+ 2011).
- For $M_{BH} = 10^9 M_{\odot}$

  the total magnetic flux in a jet

  $$\Psi_{MAD} = 3 \times 10^{33}\ \mathrm{G}\ cm^2$$

- Equipartition magnetic field provides

  $$\Psi_{jet} = 3 \times 10^{35}\ \mathrm{G}\ cm^2$$

- Non-equipartition magnetic field provides

  $$\Psi_{jet} = 3 \times 10^{33}\ \mathrm{G}\ cm^2$$

Probably, the equipartition magnetic field overestimates the flux we can accrete. The non-equipartition field reproduces well the dynamically important magnetic field in MADs.

Non-uniform model

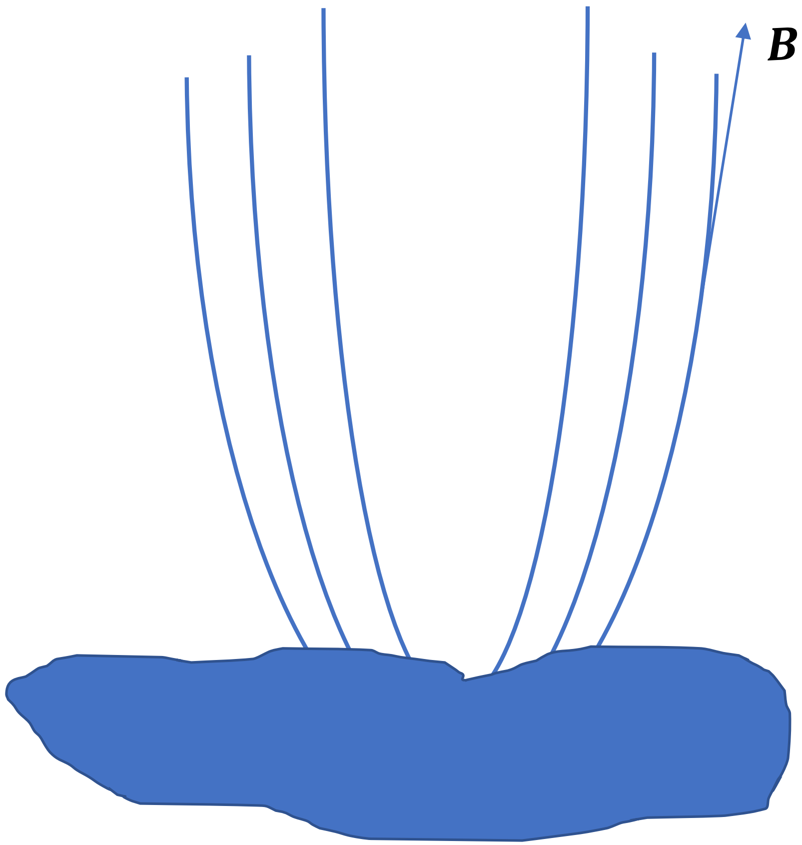
- Can be obtained solving the non-linear Grad-Shafranov equation on the flux function Ψ. It can be done analytically under certain assumptions: self-similarity, or force-free flow (plasma inertia = 0), or <u>effectively 1D – the cylindrical magnetic surfaces configuration</u>.
- The latter is a good 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

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

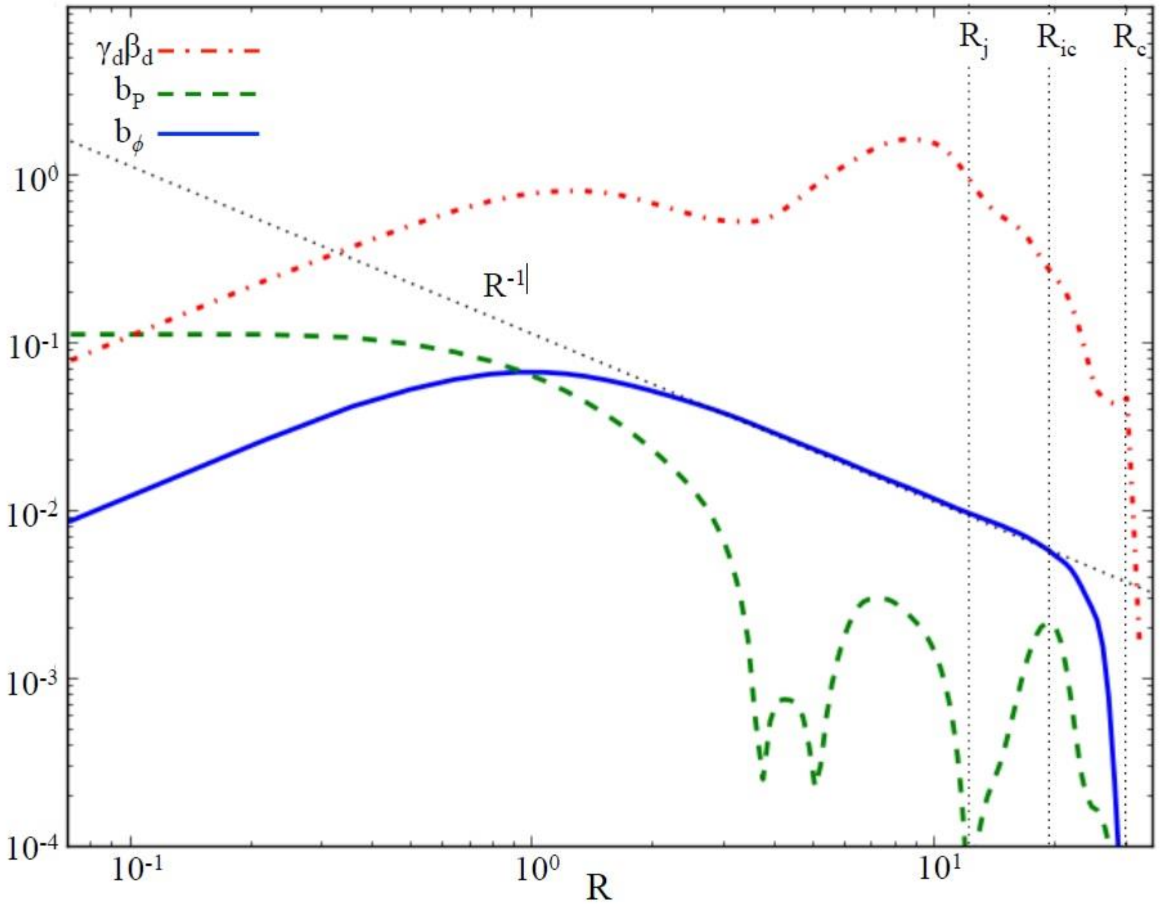
$$B_\varphi \propto r$$

For the zero current density

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

Non-uniform model: numerical results

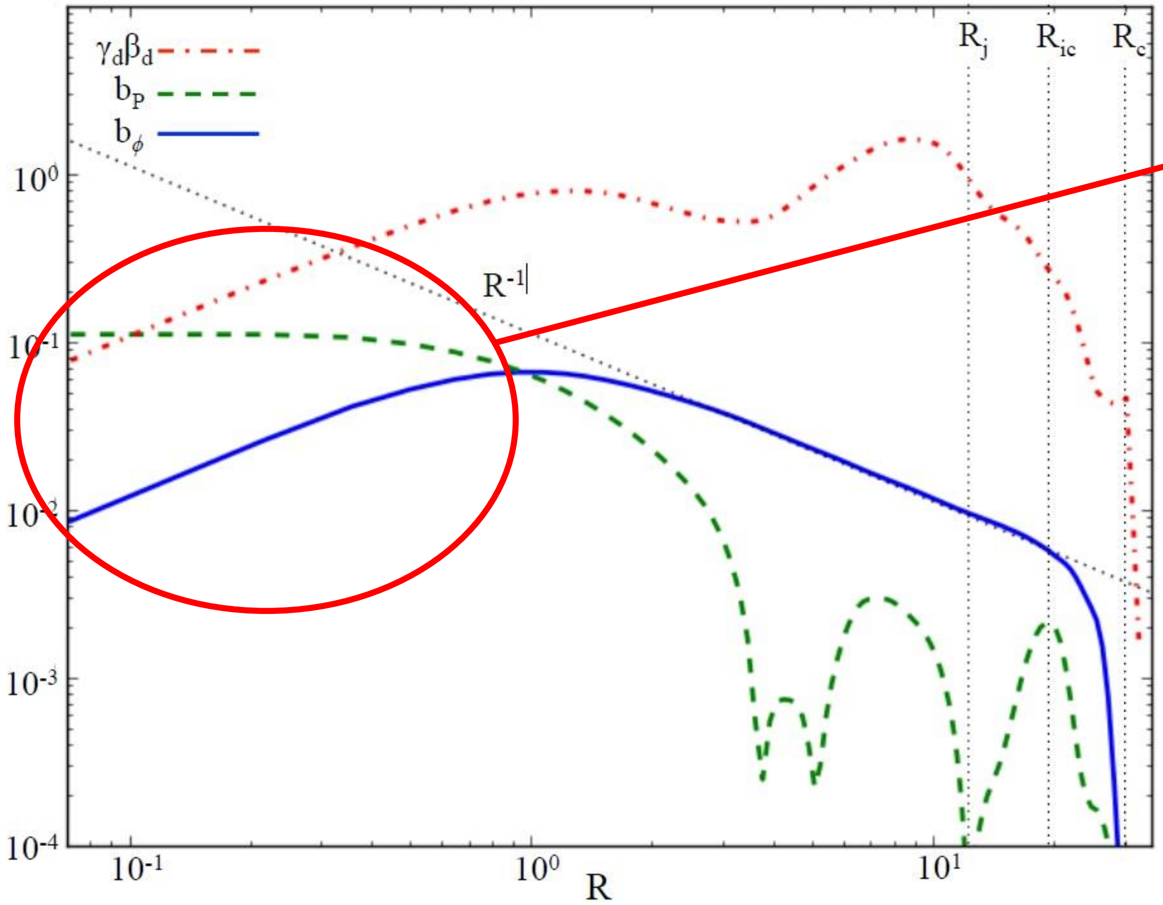
The solution may be obtained doing the numerical simulations:



Tchekhovskoy & Bromberg 2016

Non-uniform model: numerical results

The solution may be obtained doing the numerical simulations:

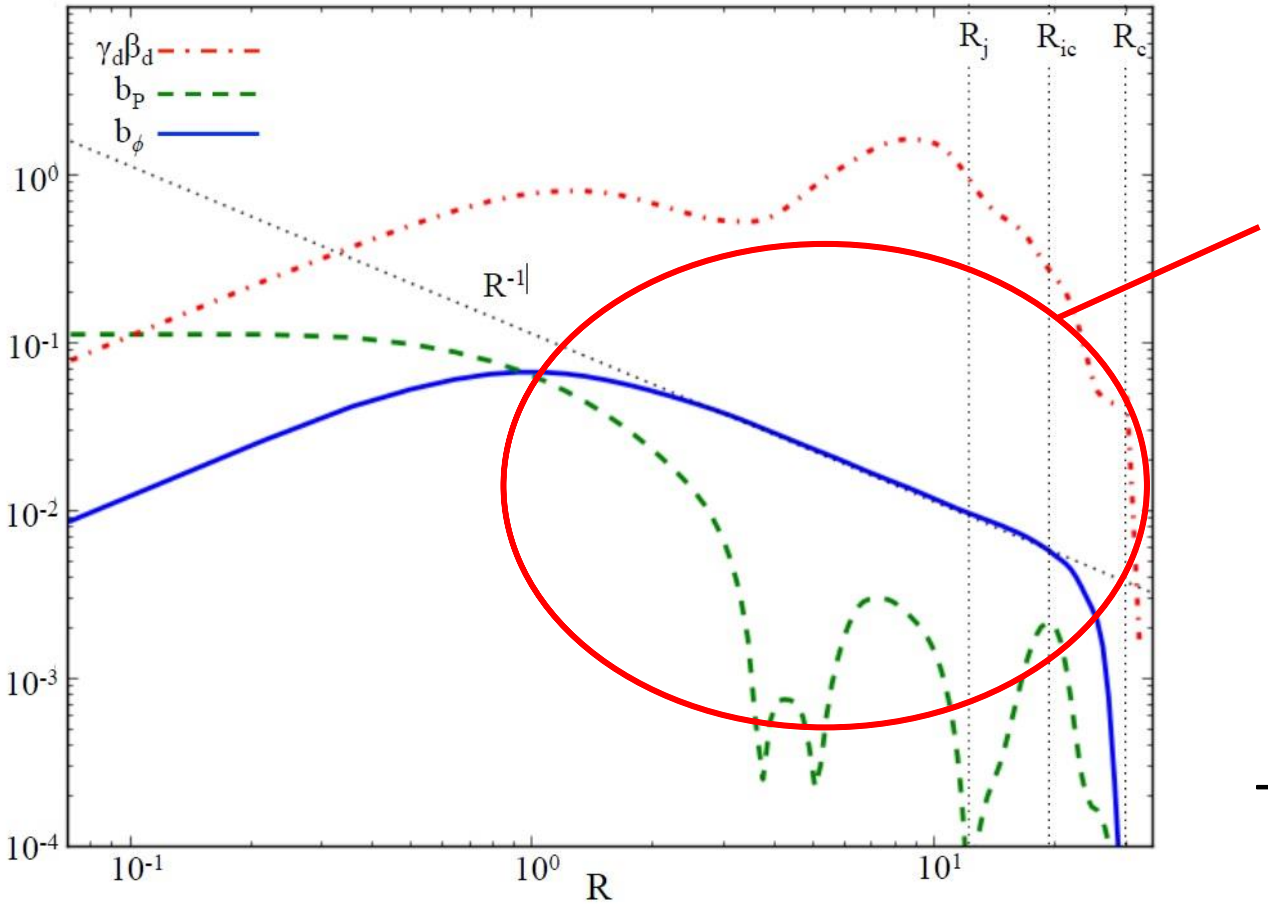


The central core with constant poloidal magnetic field B_P and linearly growing toroidal magnetic field B_φ.

Tchekhovskoy & Bromberg 2016

Non-uniform model: numerical results

The solution may be obtained doing the numerical simulations:

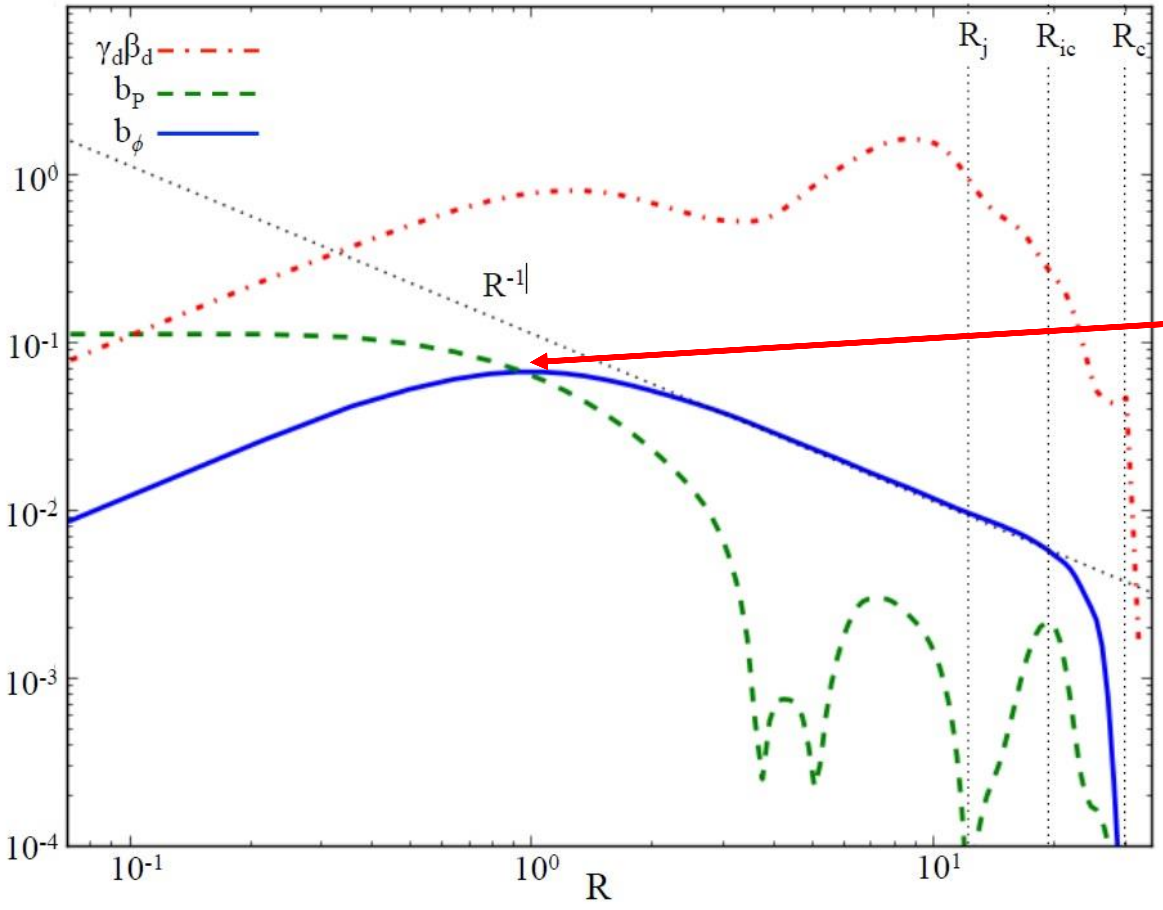


The outer flow with the poloidal magnetic field $B_P \propto r^{-2}$ and the toroidal magnetic field $B_\varphi \propto r^{-1}$.

Tchekhovskoy & Bromberg 2016

Non-uniform model: numerical results

The solution may be obtained doing the numerical simulations:



The size of a central core

$$R_0 \approx R_L$$

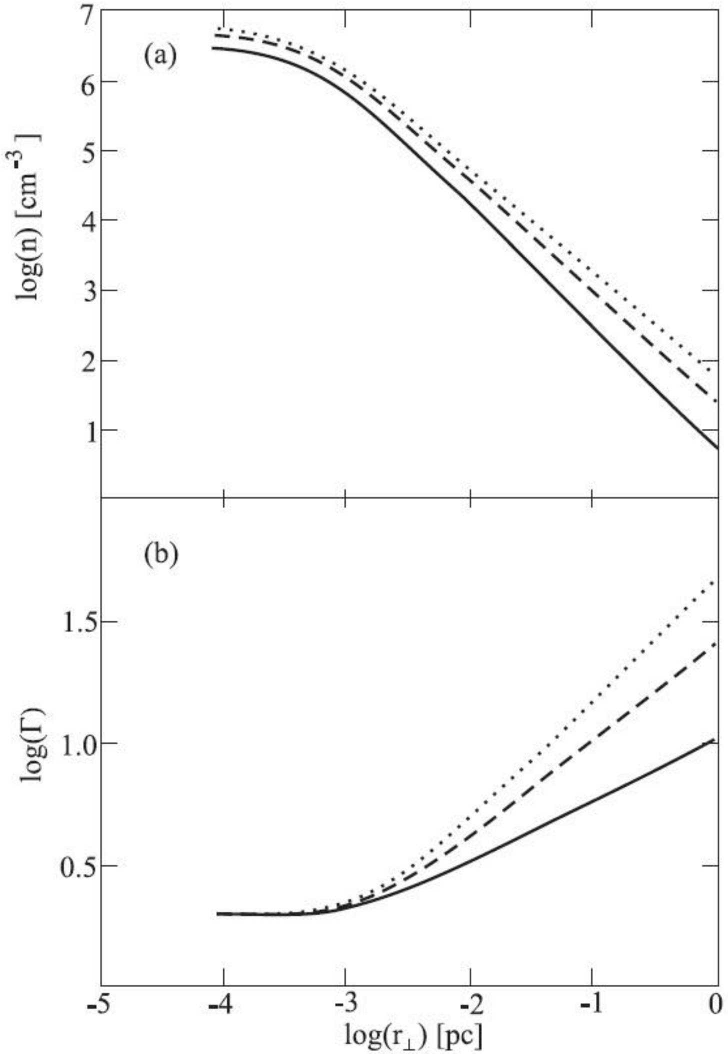
At the central core boundary

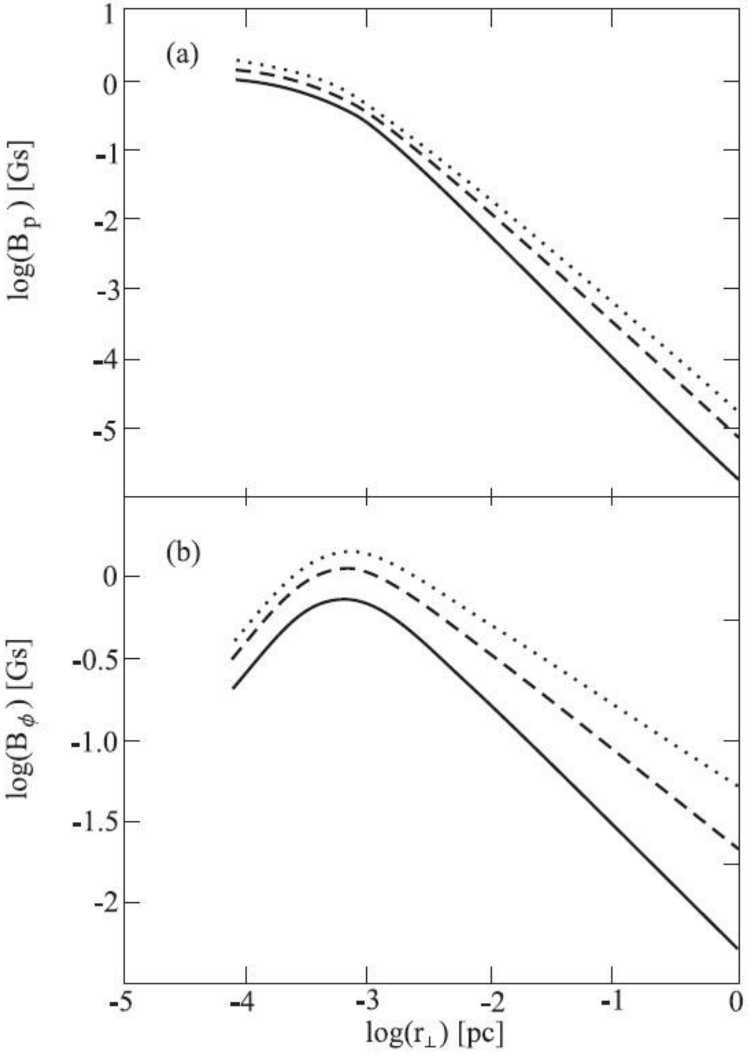
$$B_P = B_\varphi = B_0$$

and we call it the magnetic field amplitude.

Tchekhovskoy & Bromberg 2016

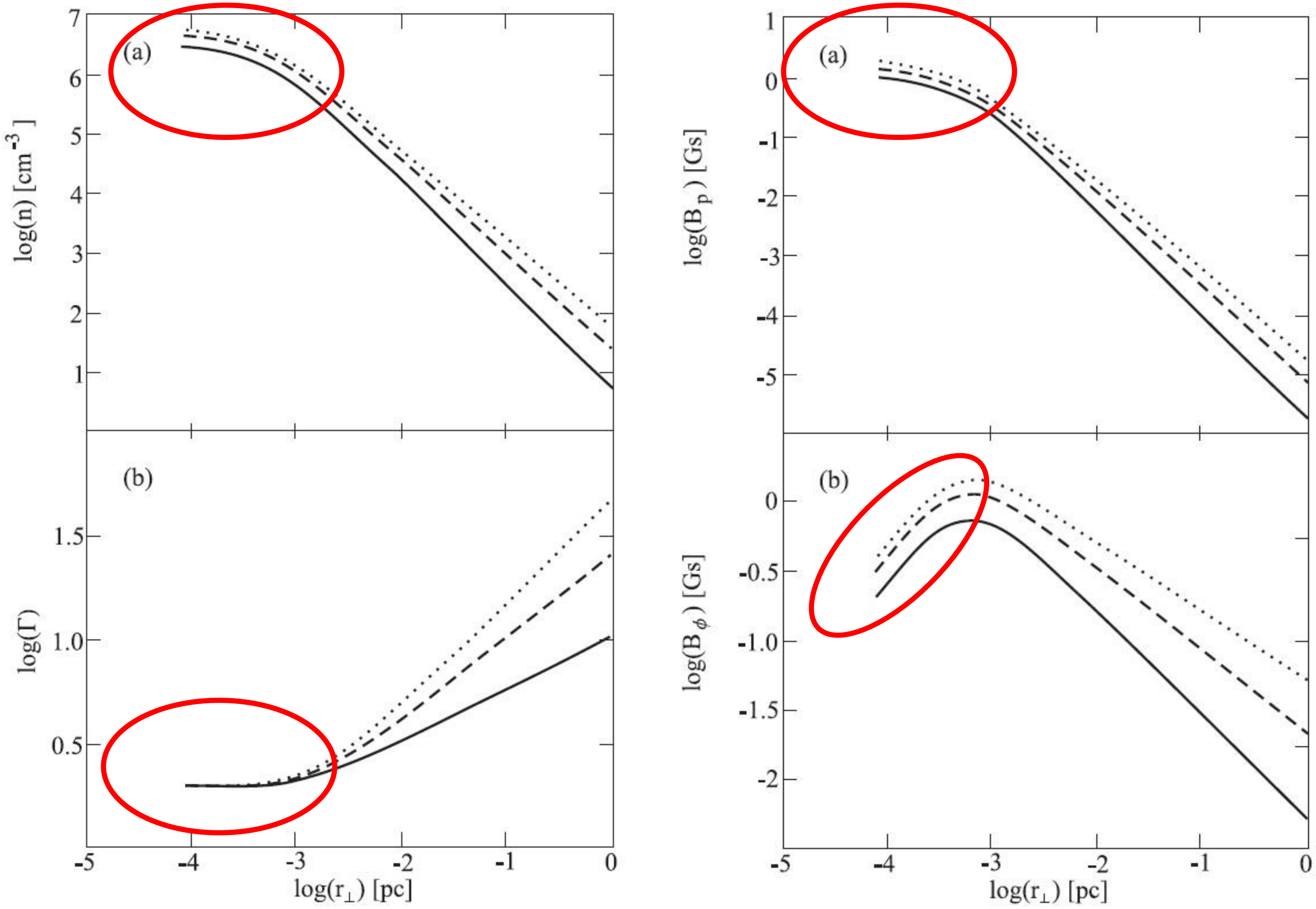
Non-uniform model: analytical results





Nokhrina+ 2015

Non-uniform model: analytical results



The central core:

$n \approx const$

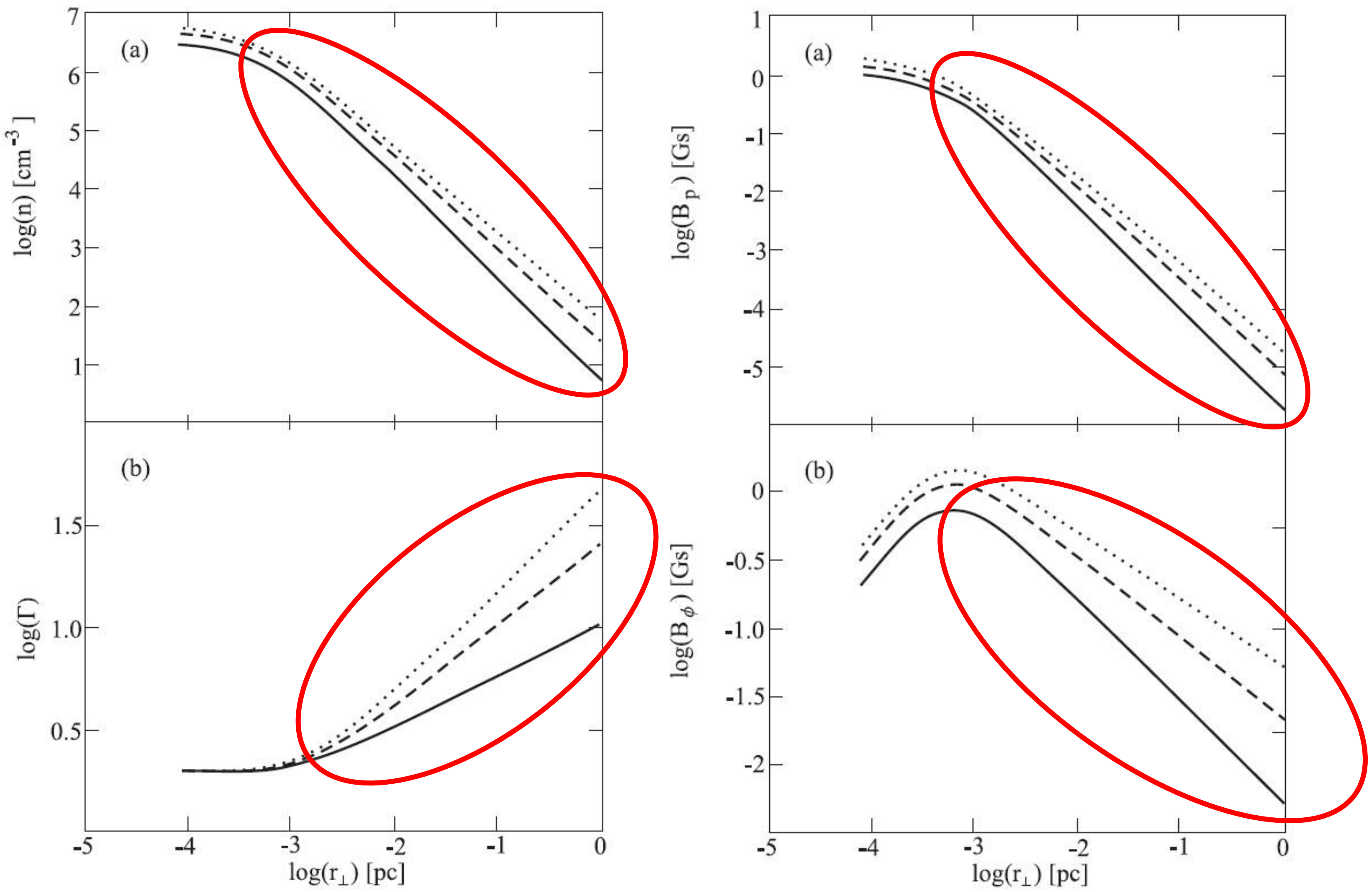
$B_P \approx const$

$B_\varphi \propto r$

$\Gamma \approx const$

Nokhrina+ 2015

Non-uniform model: analytical results



The central core:

$n \propto r^{-2}$

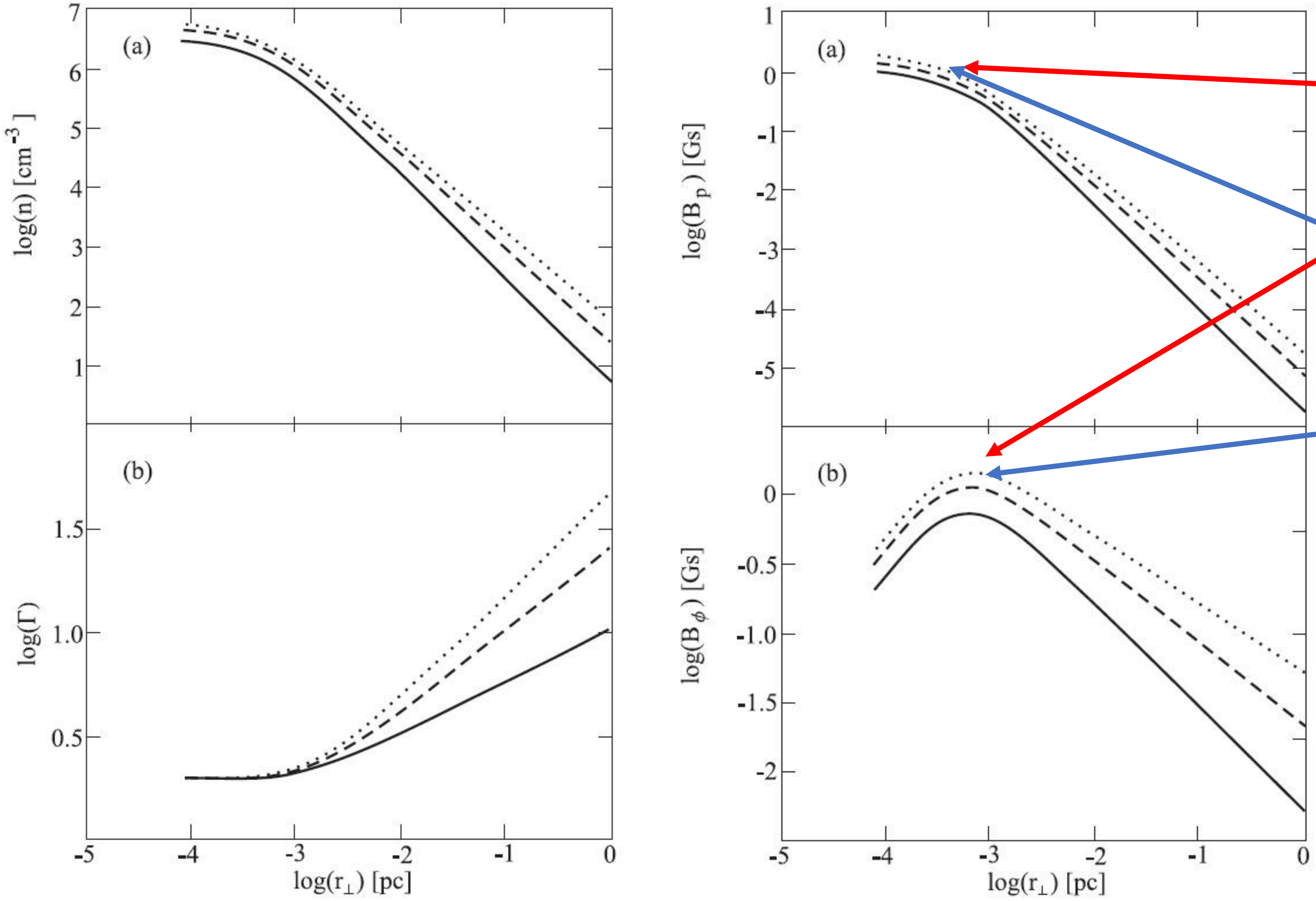
$B_P \propto r^{-2}$

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

$\Gamma \propto r$

Nokhrina+ 2015

Non-uniform model: analytical results



The central core size $R_0 \approx 5R_L$

The magnetic field amplitude B_0

Nokhrina+ 2015

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).

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

$$\left(\frac{B_0}{G}\right) = 6.4 \times 10^{-4} \Gamma \left(\frac{R_{jet}}{R_0}\right) \frac{\delta}{1+z} \left(\frac{\nu_{obs}}{GHz}\right) \left(\frac{T_{b,obs}}{10^{12} K}\right)^{-2}$$

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

$$\left(\frac{B_0}{G}\right) = 6.4 \times 10^{-4} \Gamma \left(\frac{R_{jet}}{R_0}\right) \frac{\delta}{1+z} \left(\frac{\nu_{obs}}{GHz}\right) \left(\frac{T_{b,obs}}{10^{12} K}\right)^{-2}$$

Compare with the uniform source

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

Estimates for R_{jet} and R_0

- Zamaninasab+ 2014:

$$\Omega_{BH} \approx 0.1\Omega_{cr}$$
$$R_L \approx 10r_g$$

Taking $R_0 \approx R_L$ we have for $M_{BH} = 10^9 M_\odot$

$$R_0 = 10^{-3}\text{pc}$$

- Mertens+ 2016:

The measured visible R_{jet} for M87 is 10^{-1}pc.

$$\boxed{\frac{R_{jet}}{R_L} = 10^2}$$

B-field for 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
- $B_0 = 3$ G

- 3C273 (Kovalev+ 2016)
- $T_{b,obs} = 13 \times 10^{12}$K at $\nu_{obs} = 4.8$ GHz
- $B_{uni} = 8.1 \times 10^{-3}$G
- $B_0 = 0.7$ G

What about the total magnetic flux in a jet?

- MADs – magnetically arrested disks (Tchekhovskoy+ 2011).
- For $M_{BH} = 10^9 M_{\odot}$

  the total magnetic flux in a jet

$$\Psi_{MAD} = 3 \times 10^{33}\ \mathrm{G}\ cm^2$$

- Non-uniform magnetic field distribution with an amplitude of the order of G provides

$$\Psi_{jet} = 10^{33}\ \mathrm{G}\ cm^2$$

- Uniform distribution provides

$$\Psi_{jet} = 3 \times 10^{33}\ \mathrm{G}\ cm^2$$

Conclusions

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

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

- It corresponds to the dynamically important magnetic field (MADs)
- The measure of non-equipartition for the flow is $\Sigma \approx 10^{-5}$ => we need come up with the idea which process can transform Poynting flux into plasma kinetic energy so effectively (reconnection?)
- For the non-uniform transversal model the peak magnetic field (on the scales of $10^{-3} pc$ from the jet axis) is

$$B_0 \approx 1\ G$$

- The work on how the non-uniform structure affects the T_b and core-shift effect – going on.

Thank you!