On the magnetization of relativistic jets with radial velocity shear

Dominika Król, Łukasz Stawarz
Jagiellonian University, Kraków, Poland

Introduction

Relativistic jets found in various types of astrophysical sources of high-energy radiation such as active galactic nuclei (AGN), microquasars, or gamma-ray bursts, are most likely to be formed via an efficient extraction of the energy and angular momentum from the rotating black hole/accretion disk system in the form of the Poynting flux [1]. The released electromagnetic energy is expected to be gradually converted to the bulk kinetic energy of the outflowing matter, and partly to the internal energy of jet particles via hardly understood dissipative processes. The exact evolution of such relativistic outflows has been subjected to the ongoing debate [4], recently involving also numerical simulations ([3],[5]), but as of yet there is no consensus on the properties — and in particular on the magnetization — of 'fully formed' (i.e., collimated and accelerated to terminal bulk velocities) jets.
Here we are considering the simplest model of magnetised, current carrying jet. We assume that jet: **(1)** is in the magnetohydrodynamical equilibrium, **(2)** is magnetized and magnetic field has only a toroidal component **(3)** has a radial velocity shear without an anomalous boundary layer **(4)** has cylindrical axisymmetric shape. Jet is in the hydrostatic equilibrium with the ambiguous medium and plasma consist of ultra relativistic particles.
This model can be relevant at big distance from the black hole. Motivated by the results of ([2]), for such a jet we show, once it is in MHD equilibrium it is dominated by a energy flux associated with jet particles not the Poyting flux.

Jet model

Equilibrium condition gives following equation for the jet pressure profile:

$$\partial_r P = -\frac{1}{8\Pi r^2}\partial_r\left(\frac{r^2 B_\phi^2}{\Gamma^2}\right) \tag{1}$$

in the lab frame. Solution of (1) gives:

$$p(x) = 1 + q - q\frac{b^2(x)}{\Gamma^2(x)} - 2q\int_0^x \mathrm{d}y \frac{b^2(y)}{x\Gamma^2(x)}, \tag{2}$$

where $x \equiv \frac{r}{R_j}$, $b(x) = \frac{B(x)}{B(1)}$ and $\Gamma(x) = \frac{\Gamma_{old}(x)}{\Gamma(1)}$, $x = 1$ is the jet boundary. q parameter is given as $\frac{B(1)/8Pi}{P(1)} = \frac{P_B(1)}{P(1)} = \beta_{pl}^{-1}(1)$ being the inverse of β parameter value at the jet boundary. Please note, that since $\forall_{x\in[0;1]} p(x) \geq 0$ we have a some limitations on $b(x)$ and $\Gamma(x)$ profiles.
Hence assuming $B(r)$ and $\Gamma(r)$ profiles allows to calculate $p(r)$ profile from the equilibrium condition (1) for a given q value.
Magnetization of the jet can be described using σ parameter. In this purpose let us define the energy flux associated with jet particles as:

$$L_p = 2\pi c \int dr\, r\,\Gamma^2\beta\, w = 8\pi c \int dr\, r\,\beta\,\Gamma^2\, P\,, \tag{3}$$

while the jet magnetic flux is

$$L_B = 2\pi c \int dr\, r\frac{E_r B_\phi}{4\pi} = \frac{1}{2}c\int dr\, r\,\beta\, B_\phi^2\,, \tag{4}$$

. Therefore σ parameter can be written as:

$$\sigma = \frac{q}{2}\frac{\int_0^1 \mathrm{d}x x\beta(x)\Gamma^2(x)}{\int_0^1 \mathrm{d}x x\beta(x)\Gamma^2(x)p(x)} \tag{5}$$

Inequality $\sigma < 1$ can be proofed analytically for some classes of $b(x)$ and $\Gamma(x)$ profiles (Król et al. in prep). **Here we show examples of profiles which not necessary are included in those classes, but still calculated σ parameters are smaller than 1**

Models

We would like to present **calculations for three exemplary cases** chosen to illustrate some general ideas. They are described by a formulas:

$$G(x, G_0, k_0) = 1 + (G_0 - 1) * (1 - x^{k_0}) \tag{6}$$

$$b(x, a, k_1, k_2) = (1 + a)\frac{x^{k_1}}{1 + (a * x^{k_2}) + (b * \cos(11\Pi x/2)^2)} \tag{7}$$

With following parameters values:

- (a): $G_0 = 10$, $a = 80$, $b = 0$, $k_0 = 2$ $k_1 = 3$, $k_2 = 3$
- (b): $G_0 = 10$, $a = 80$, $b = 0$, $k_0 = 2$ $k_1 = 1$, $k_2 = 4$
- (c): $G_0 = 10$, $a = 80$, $b = 1.3$, $k_0 = 2$ $k_1 = 1$, $k_2 = 4$

In the Fig. (1) we present profiles of $b(x)$, $\Gamma(x)$ and calculated $p(x)$. For all models $p(x)$ was calculated for two q values: 0.1 and 100. Our models consist of a $b(x)$ profile which is monotonically increasing (a), has one maximum in $x \in (0;1)$ range (b) and has three maximums (c).

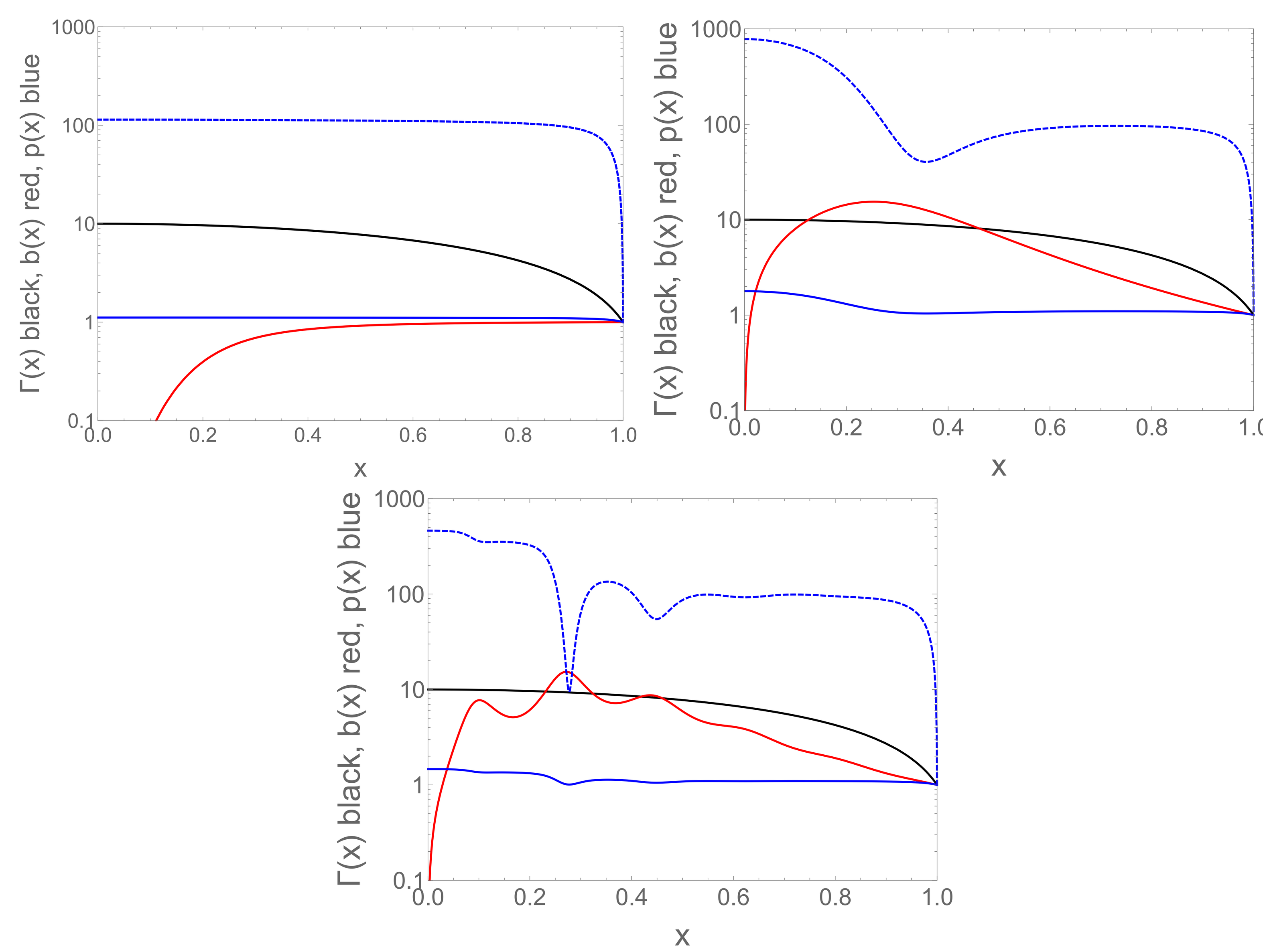

Figure 1: Normalized profiles of magnetic field ($b(x)$), $\Gamma(x)$ and calculated $p(x)$. Black colour – $\Gamma(x)$, red colour – $b(x)$, blue colour – $p(x)$. Dashed line denotes $q = 100$, continuous line $q = 0.1$. Upper-left panel – model a, upper-right panel – model b and lower panel – model c.

For every model we calculated sigma value, showed in Fig. (2). In every tested case σ value rise with q, but then goes to limiting value which is smaller than 1.

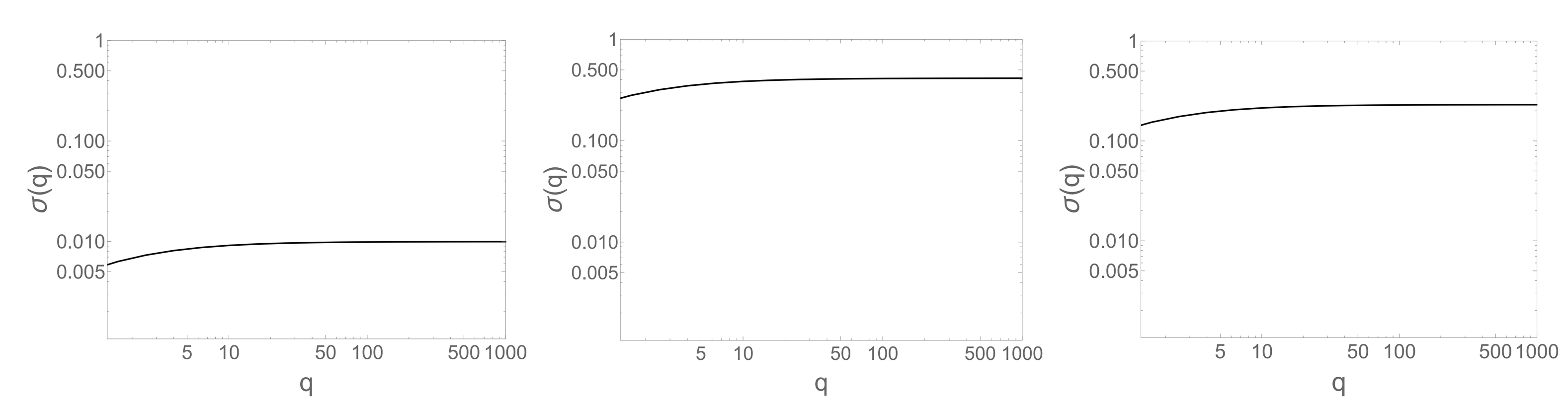

Figure 2: Sigma as a function of q value. Left panel model (a), middle panel model (b) and right panel model (c)

Models

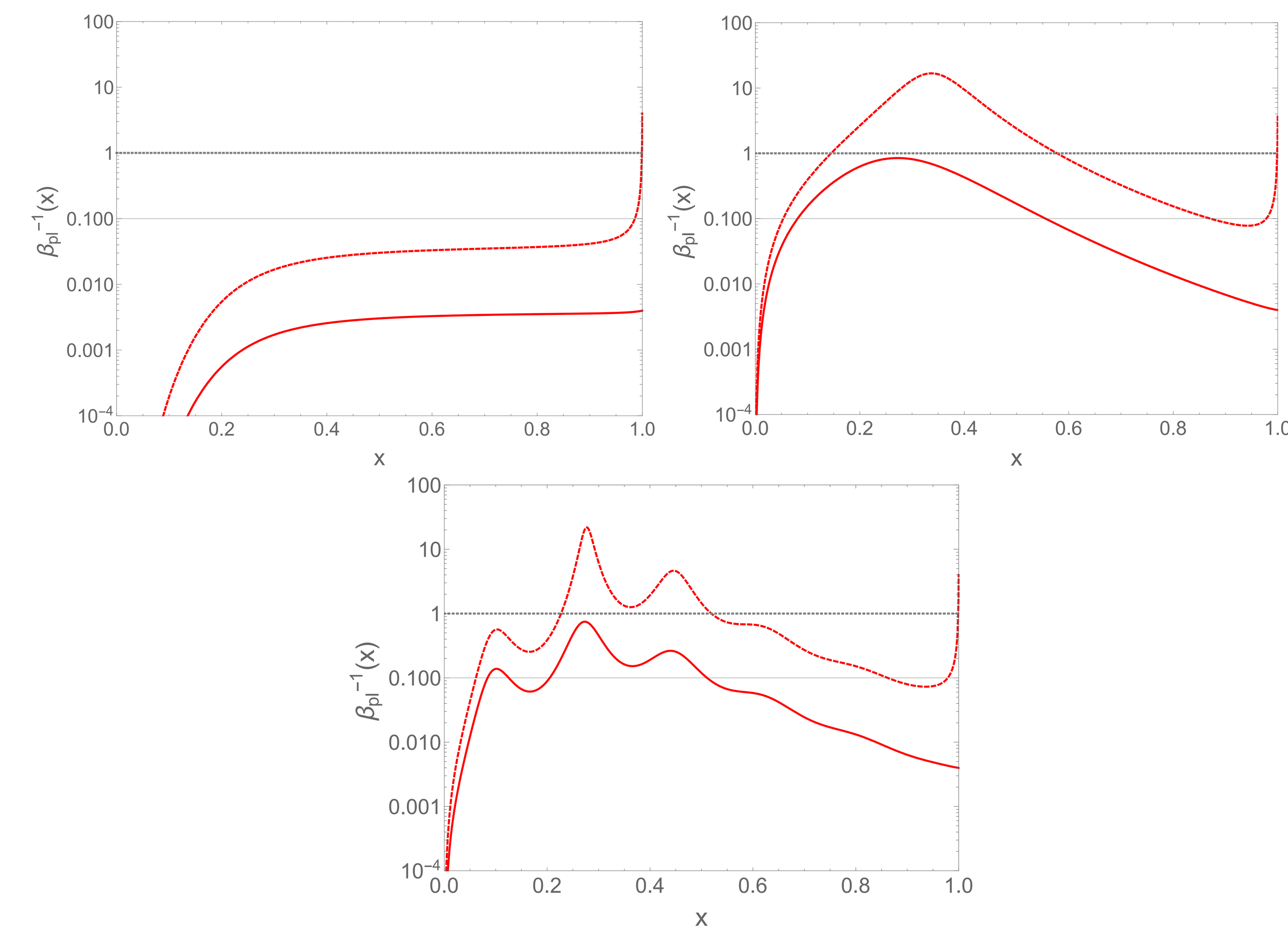

Figure 3: β parameter as a function of x calculated for two values of of q: 0.1 and 100. Upper-left panel – model (a), upper-right panel – model (b), lower panel – model (c).

In the Fig. (3) we show profiles of $\beta^{-1}(x) = \frac{p_B(x)}{p(x)}$ for two q values: 0.1 and 100 and all three models. We see that even for the simplest case (a) β_{pl} changes drastically from gas pressure dominated in the middle of the jet to given q value. For models (b) and (c) change of the β_{pl}^{-1} profile is non-monomaniacal. We see local maximas within the jet, meaning different layers of jet can be gas pressure or magnetically dominated. Due to the relativistic effects different layers of jet can dominate emission depending on the angle of observations. Therefore even for $\sigma < 1$ so jet dominated with a kinetic energy of the particles rather than Poyting flux, it is possible to observe emission from regions at which magnetic pressure dominates gas pressure.

Summary

On this poster we presented calculation of σ parameter for the simple jet model with only toroidal component of magnetic field, normal velocity profile in magnetohydrostatic equilibrium with ambient medium. We show that for different classes of $b(x)$ and $\Gamma(x)$ profiles we consistly get $\sigma < 1$ for the jet regardless of q value. Moreover we showed that even if jet is dominated by the kinetic energy of the particles there can be still some part of the jet where it is magnetic pressure dominated.

References

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