Relativistic Jets Deceleration – Effects of Mass-loading

V.S. Beskin [1,2], *E.E. Nokhrina* [2]

[1]Lebedev Institute, Moscow, Russia; [2]Moscow Institute of Physics and Technology, Dolgoprudny, Russia

P.N.Lebedev Physical Institute of the Russian Academy of Science

1. Abstract

Relativistic jets deceleration detected recently by MOJAVE team [1] is discussed in connection with possible mass loading of relativistic jets. Particle loading is considered in details as a possible mechanism for both plasma deceleration and Poynting flux diminishing. It has been shown that moderate loaded particle number density can lead to a noticeable jet deceleration. The magnetization is to drop due to mass loading.

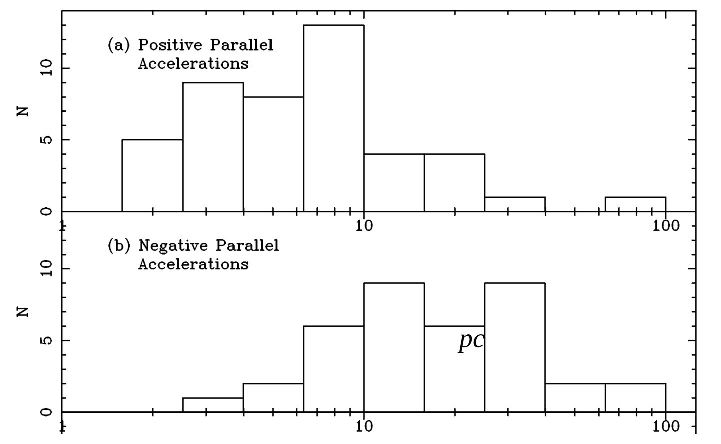

Fig. 1 Histograms of jet with positive parallel accelerations (upper panel) and deceleration (lower panel) [1].

2. Introduction

Recently the MOJAVE team has found statistically significant deceleration of the jet material on the scale 50-100 pc [1] (see Fig.1). Its possible nature can be attributed to the interaction of the jet material with the internal and external photon field. We consider here possible effect of mass-loading that can account for such a deceleration.

The effects of mass-loading for pulsar winds has been considered by [2]. The main result is that the mass-loading works as a nozzle and leads to acceleration of the flow in a super-magnetosonic regime. The different aspects of mass-loading such as possible mechanism for particle acceleration by stochastic mechanism on the jet shear layer [3], and formation of high energy spectrum by cascade mechanisms connected with two-photon pair conversion and subsequent radiation of high energy gamma-quanta [4], have been considered.

We propose a model of mass-loading of a relativistic jets with electron-positron pair produced at rest in a nucleus rest frame. Such pairs, coupling with bulk MHD flow are not cold, but highly relativistic, contributing the anisotropic pressure into the energy-momentum tensor of a flow. The main effect of such loading is partial screening of electric and magnetic fields and consequent deceleration of the plasma bulk motion.

The screened electric and magnetic fields are determined self-consistently for the mass loaded outflow. The appropriate Lorenz factor is obtained. We show that even for moderate mass loading the flow decelerates with diminishing of Poynting flux in greater degree than losses in particle kinetic energy flux. The effect of jet deceleration due to charged mass loading is more pronounced for the faster jets.

2. Mass loading

Let us regard the following problem: there is some source of plasma in a relativistic jet from AGN, which we expect to affect the bulk motion of a jet. We need to find a possible jet acceleration / deceleration and appropriate change in a flow magnetization given the rate of pair production. One of the possible sources of such a mass loading may be two-photon pair conversion [7-10]. As a first model which captures the principal effects we propose pairs produced at rest in a nucleus frame. This implies that the energy flux $E(\Psi)$ and the angular momentum flux $L(\Psi)$ remain constant along the flow [2,3]. In the jet plasma proper frame the particle trajectories are two cycloids for each pair. The most important consequence of this is a screening of electric field *E* and magnetic filed *B*. It is this screening that leads to diminishing of Lorenz factor of a jet bulk motion and thus may account for the observed jet deceleration.

For the problem of pair production at rest in nucleus frame the four-vectors of each charge motion can be found. The loading plasma is relativistic with mean Lorenz factor

$$\langle\gamma\rangle = \Gamma^2\left(1+\frac{\beta^4}{2}\right),$$

where Γ is the initial Lorenz factor of a jet bulk motion. The effect of pair rotation in *rz*-plane leads to appearance of anisotropic pressure in an energy-momentum tensor of loading plasma [5]

$$T^{ik}_{\rm ld} = \left(\varepsilon_{\rm ld}+P_s+\frac{\mathbf{b}^2}{4\pi}\right)U^iU^k + \left(P_s+\frac{\mathbf{b}^2}{8\pi}\right)g^{ik} - \left(\frac{P_s-P_n}{\mathbf{b}^2}+\frac{1}{4\pi}\right)b^ib^k.$$

Here $\varepsilon_{\rm ld} = mc^2 n_{\rm ld}\Gamma$ and $P_s = mc^2 n_{\rm ld}\Gamma\frac{\beta^2}{2}$, with $P_n=0$.

Radial displacement of electrons and positrons, produced uniformly over some jet domain, creates the surface charge and surface current which screen the initial fields. The field disturbance may be found knowing the charges trajectories:

$$\delta E = \frac{4\pi m_{\rm e}c^2 n_{\rm ld}\tilde\beta^3\tilde\Gamma^3}{\tilde E} \quad \text{and} \quad \delta B = \frac{4\pi m_{\rm e}c^2 n_{\rm ld}\tilde\beta^3\tilde\Gamma^3}{\tilde B}.$$

Here $n_{\rm ld}$ is loaded plasma particle number density in jet proper frame. We find the disturbed fields $\tilde E$ and $\tilde B$ self-consistently, as we describe the loaded particle motion in the screened fields. As a result, the bulk Lorenz factor determined by the drift motion in crossed fields changes. One may see that the disturbance of magnetic field is smaller than that of electric field, and so the jet have to decelerate (see Fig.2).

We see that that even for fairly moderate loaded particle number density the Lorenz factor drops noticeably. The effect should be more pronounced for the faster jets.

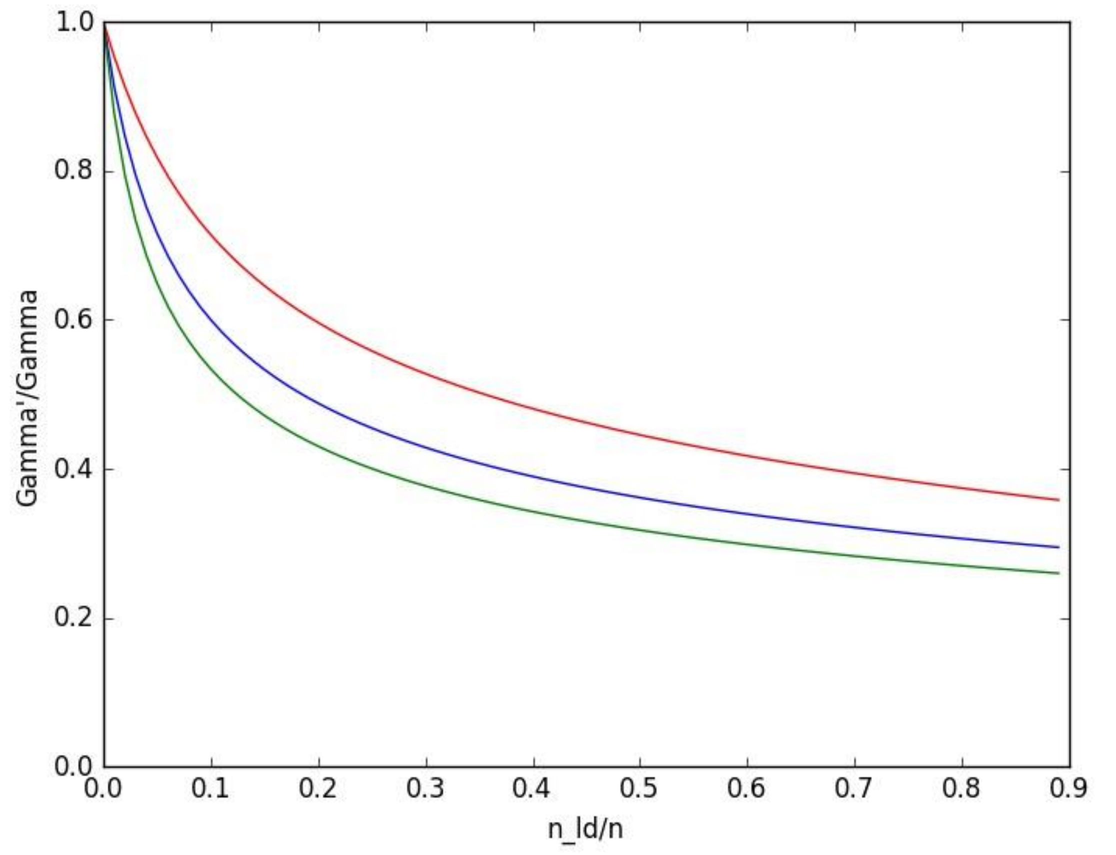

Figure 2. The ratio of loaded Lorenz factor to the initial one with respect to relative loaded particle number density. The red curve corresponds to Γ=5, the blue one to Γ=10, and the green one to Γ=15.

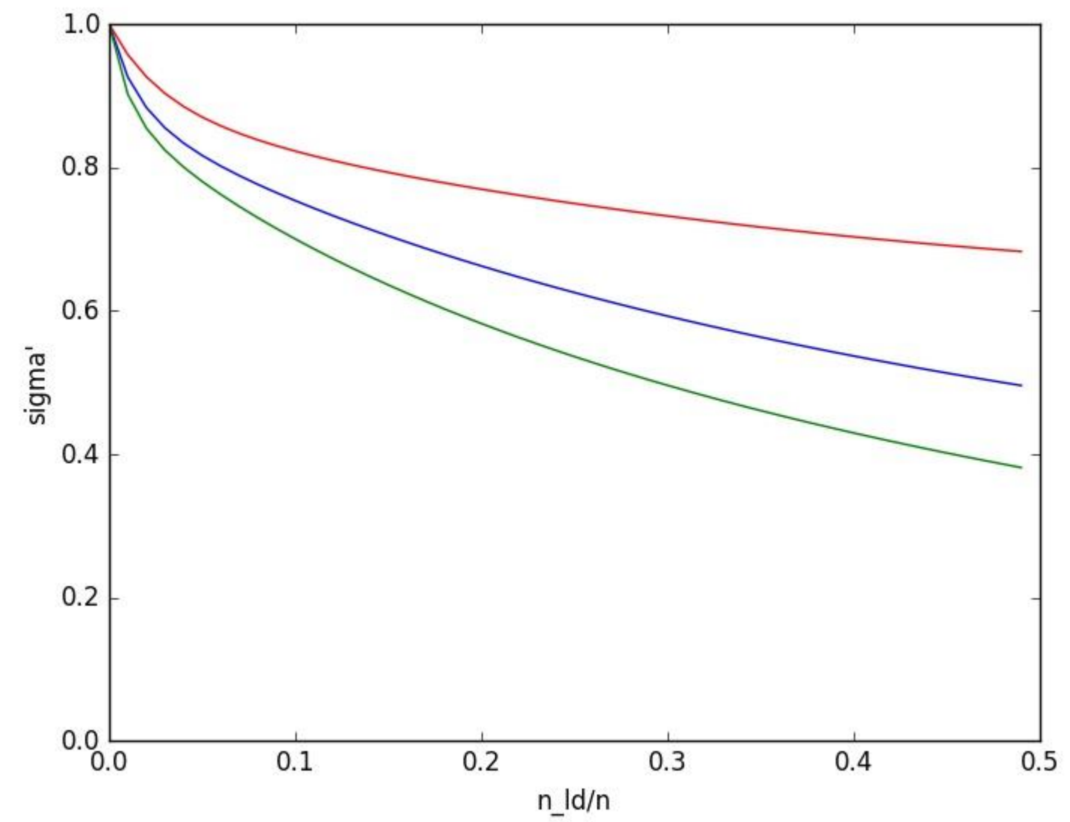

Figure 3. The loaded magnetization is plotted as a function of relative loaded particle number density. The coloured curves corresponds as in Fig.2 to Γ=5, Γ=10, and Γ=15.

3. Magnetization

The energy flux conservation allows to determine the loaded jet magnetization given that before loading the jet was in equipartition, i.e. σ=1. Indeed, the zeroth component of energy-momentum conservation equation can be readily integrated for the cylindrical jet, and we obtain the energy integral for loaded outflow

$$E(\Psi) = \frac{\tilde\Omega_{\rm F}\tilde I}{2\pi c}(1+|\beta_{\rm a}|) + \mu_{\rm ld}\eta_{\rm ld}\tilde\Gamma + \mu\eta\tilde\Gamma.$$

Here the anisotropy parameter [5] $\beta_{\rm a} = 4\pi\frac{P_n-P_s}{b^2}$.

The magnetization after loading can be related to the calculated parameters through

$$\tilde\sigma = \frac{\sigma+1-\frac{\tilde\Gamma}{\Gamma}\left(1+\frac{3}{2}\frac{n_{\rm ld}}{n}\tilde\Gamma\right)}{\frac{\tilde\Gamma}{\Gamma}\left(1+\frac{3}{2}\frac{n_{\rm ld}}{n}\tilde\Gamma\right)}.$$

The result presented in Figure 3. We see that the loaded flow magnetization is less than unity with a drop in magnetization greater for the faster jets. This means that the diminishing of Poynting flux due to charged mass loading is greater than for kinetic energy flux.

4. Concluding Remarks

The important consequence of particle loading is partial screening of the electric and magnetic fields in a jet, which leads to a jet deceleration. The effect will hold for the particles produced with initial velocities in a nucleus frame. The latter is a realistic scenario for photon-photon pair production as a plausible source of pairs [7,9,10]. For pairs produced with initial velocity the main difference in comparison with the regarded problem is in final magnetization, that might change due to change in energy integral.

5. References

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