On the Deceleration of Relativistic Jets in Active Galactic Nuclei

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Abstract

Relativistic jets deceleration detected recently by MOJAVE team is discussed in connection with the interaction of the jet material with the external photon field. Both radiation drag and particle loading are considered in detail on the ground of standard MHD approach. Appropriate energy density of the isotropic photon field and the number density of the loading pairs which is necessary to decelerate the jet material are determined.

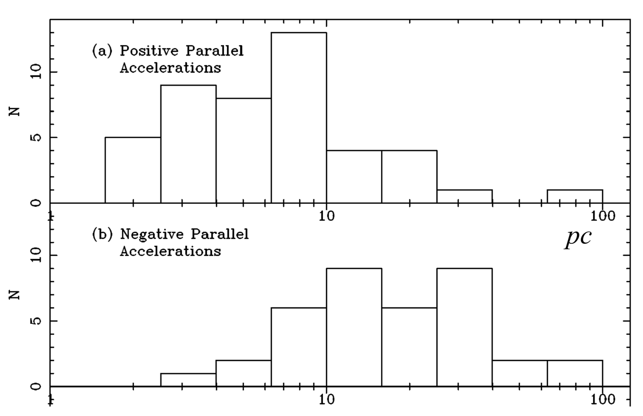

Fig.1. Histograms of jet with positive parallel accelerations (left) and deceleration (right) [1].

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 two possible effects that can account for such a deceleration: the direct radiation drag reducing the energy flux of a jet, and particle loading resulting in the increase of the particle number density. As a zero approximation we consider ideal MHD cylindrical jet [2]. Indeed, within last several years more observational evidence supporting MHD models has been found. Among them are the presence of the electron-positron plasma [3,4] and the toroidal magnetic field [5]. Numerical simulations [6-8] demonstrate very nice agreement with analytical asymptotic MHD solutions as well.

The first step to combine ideal MHD and the radiation field together was done by Li, Begelman & Chiueh [9]. It was demonstrated how general equations can be integrated for conical geometry. But the integration was performed in given poloidal field geometry when the fast magnetosonic surface locating at infinity. So, the approach does not allow us to analyze the radiation drag effects in the supersonic region. The self-consistent disturbance of magnetic surfaces was included into consideration in [10] for high enough particle energy (when the radiation pressure is ineffective for particle acceleration). It was demonstrated that for magnetically dominated flow the drag force actually does not change the particle energy. It was shown as well that the disturbance of magnetic surfaces becomes large only if the drag force changes significantly the total energy flux. Finally, recently in [11,12] it was considered the drag action on the magnetized outflow in gamma-bursters where the radiation pressure can play important role in particle acceleration.

As to the particle loading, several aspects of this process were considered in [13-15]. Even if the electron-positron pairs are produced at rest (i.e., they do not change the total energy and angular momentum flux), the increase in particle density flux inevitably decreases the mean particle energy. Thus, the particle loading also can be an effective mechanism of the deceleration of the jet bulk motion.

Radiation Drag

Following [10], we analyze the set of time-independent Maxwell equations and two-fluid equations of motion for electron-positron plasma. As a zero approximation we consider ideal force-free cylindrical jet:

$$
\begin{aligned}
n^{+} &= \frac{\Omega_0 B_0}{2\pi c e}\left[\lambda - \frac{1}{4r_\perp}\frac{\mathrm{d}}{\mathrm{d}r_\perp}\left(r_\perp^2\frac{\Omega_{\mathrm F}}{\Omega_0}\right) + \eta^{+}(r_\perp, z)\right],\\
n^{-} &= \frac{\Omega_0 B_0}{2\pi c e}\left[\lambda + \frac{1}{4r_\perp}\frac{\mathrm{d}}{\mathrm{d}r_\perp}\left(r_\perp^2\frac{\Omega_{\mathrm F}}{\Omega_0}\right) + \eta^{-}(r_\perp, z)\right],\\
\Psi &= \pi B_0 r_\perp^2\left[1 + \varepsilon f(r_\perp, z)\right],\\
v_z^{\pm} &= c\left[1 - \xi_z^{\pm}(r_\perp, z)\right],\\
v_r^{\pm} &= c\xi_r^{\pm}(r_\perp, z),\\
v_\varphi^{\pm} &= c\xi_\varphi^{\pm}(r_\perp, z),\\
B_r &= -\frac{\varepsilon}{2} r_\perp B_0 \frac{\partial f}{\partial z},\\
B_\varphi &= \frac{\Omega_0 r_\perp}{c} B_0\left[-\frac{\Omega_{\mathrm F}}{\Omega_0} - \zeta(r_\perp, z)\right],\\
B_z &= B_0\left[1 + \frac{\varepsilon}{2r_\perp}\frac{\partial}{\partial r_\perp}\left(r_\perp^2 f\right)\right],\\
E_r &= \frac{\Omega_0 r_\perp}{c} B_0\left[-\frac{\Omega_{\mathrm F}}{\Omega_0} - \frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}(r_\perp^2\delta)\right],\\
E_z &= -\frac{\Omega_0 r_\perp^2}{c} B_0 \frac{\partial \delta}{\partial z}.
\end{aligned}
$$

$$
\begin{aligned}
&-\frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}(r_\perp^2\zeta) = 2(\eta^{+}-\eta^{-}) - 2\left[(\lambda-K)\,\xi_z^{+} - (\lambda+K)\,\xi_z^{-}\right],\\
&2(\eta^{+}-\eta^{-}) + \frac{1}{r_\perp}\frac{\partial}{\partial r_\perp}\left[r_\perp\frac{\partial}{\partial r_\perp}\left(r_\perp^2\delta\right)\right] + r_\perp^2\frac{\partial^2\delta}{\partial z^2} = 0,\\
&r_\perp\frac{\partial\zeta}{\partial z} = 2\left[(\lambda-K)\,\xi_r^{+} - (\lambda+K)\,\xi_r^{-}\right],\\
&-\varepsilon r_\perp^2\frac{\partial^2 f}{\partial z^2} - \varepsilon\frac{\partial^2}{\partial r_\perp^2}\left(r_\perp^2 f\right) = 4\frac{\Omega_0 r_\perp}{c}\left[(\lambda-K)\,\xi_\varphi^{+} - (\lambda+K)\,\xi_\varphi^{-}\right],\\
&\frac{\partial}{\partial z}\left(\xi_r^{+}\gamma^{+}\right) = -\xi_r^{+}F_{\mathrm d}^{+} + 4\frac{\lambda\sigma_{\mathrm M}}{r_{\mathrm{jet}}^2}\left[-\frac{\partial}{\partial r_\perp}(r_\perp^2\delta) + r_\perp\zeta - r_\perp\frac{\Omega_{\mathrm F}}{\Omega_0}\xi_z^{+} + \frac{c}{\Omega_0}\xi_\varphi^{+}\right],\\
&\frac{\partial}{\partial z}\left(\xi_r^{-}\gamma^{-}\right) = -\xi_r^{-}F_{\mathrm d}^{-} - 4\frac{\lambda\sigma_{\mathrm M}}{r_{\mathrm{jet}}^2}\left[-\frac{\partial}{\partial r_\perp}(r_\perp^2\delta) + r_\perp\zeta - r_\perp\frac{\Omega_{\mathrm F}}{\Omega_0}\xi_z^{-} + \frac{c}{\Omega_0}\xi_\varphi^{-}\right],\\
&\frac{\partial}{\partial z}\left(\gamma^{+}\right) = -F_{\mathrm d}^{+} + 4\frac{\lambda\sigma_{\mathrm M}}{r_{\mathrm{jet}}^2}\left[-r_\perp^2\frac{\partial\delta}{\partial z} - r_\perp\frac{\Omega_{\mathrm F}}{\Omega_0}\xi_r^{+}\right],\\
&\frac{\partial}{\partial z}\left(\gamma^{-}\right) = -F_{\mathrm d}^{-} - 4\frac{\lambda\sigma_{\mathrm M}}{r_{\mathrm{jet}}^2}\left[-r_\perp^2\frac{\partial\delta}{\partial z} - r_\perp\frac{\Omega_{\mathrm F}}{\Omega_0}\xi_r^{-}\right],\\
&\frac{\partial}{\partial z}\left(\xi_\varphi^{+}\gamma^{+}\right) = -\xi_\varphi^{+}F_{\mathrm d}^{+} + 4\frac{\lambda\sigma_{\mathrm M}}{r_{\mathrm{jet}}^2}\left[-\frac{\varepsilon}{2}\frac{c r_\perp}{\Omega_0}\frac{\partial f}{\partial z} - \frac{c}{\Omega_0}\xi_r^{+}\right],\\
&\frac{\partial}{\partial z}\left(\xi_\varphi^{-}\gamma^{-}\right) = -\xi_\varphi^{-}F_{\mathrm d}^{-} - 4\frac{\lambda\sigma_{\mathrm M}}{r_{\mathrm{jet}}^2}\left[-\frac{\varepsilon}{2}\frac{c r_\perp}{\Omega_0}\frac{\partial f}{\partial z} - \frac{c}{\Omega_0}\xi_r^{-}\right].
\end{aligned}
$$

Here $F_{\mathrm d}^{\pm} = \frac{4}{3}\frac{\sigma_{\mathrm T} U_{\mathrm{iso}}}{mc^2}(\gamma^{\pm})^2$, $\sigma_{\mathrm M} = \frac{\Omega e B_0 r_{\mathrm{jet}}^2}{4\lambda m c^3}$ is the Michel magnetization parameter, and $\lambda = n_{\mathrm e}/n_{\mathrm{GJ}}$.

Radiation drag force results in the diminishing of the energy flux $E(\Psi)$ [9]. The drag force generates also the drift motion of charged particles resulting in the appearance of the additional electric field. Our analysis allows us to include both processes into consideration.

As a result, on can obtain for the Lorentz-factor of the bulk MHD flow

$$2\Gamma^3 - 2\left(K' - \int_0^z F_{\mathrm d}\Gamma^2(z')\mathrm{d}z'\right)\Gamma^2 + \frac{x_r^2}{x_{\mathrm{jet}}^2}\sigma_{\mathrm M} = 0,$$

where

$$K' = \Gamma_0 - \frac{x_r^2}{x_{\mathrm{jet}}^2}\sigma_{\mathrm M}\, r_\perp\frac{\mathrm d}{\mathrm d r_\perp}\left(\frac{\delta}{\Omega_{\mathrm F}/\Omega_0}\right) + \frac{1}{2x_{\mathrm{jet}}^2}\sigma_{\mathrm M},$$

and $x = \Omega_{\mathrm F} r_\perp / c$. It gives for the supersonic flow

$$\Gamma(z) \approx \frac{\Gamma_0}{1 + \Gamma_0\int F_{\mathrm d}\mathrm{d}z'}.$$

Thus, the essential diminishing of the energy of the bulk particle motion on the scale L along the jet takes place for $U_{\mathrm{iso}} \approx U_{\mathrm{cr}}$, where

$$U_{\mathrm{cr}} = \frac{m_{\mathrm e}c^2}{\sigma_{\mathrm T} L \Gamma}$$

This relation is true not only for particle dominated flow (when this evaluation is trivial), but for magnetically dominated outflow as well.

Particle Loading

For simplicity we suppose that the electron-positron pairs are created at rest. This implies that the energy $E(\Psi)$ and the angular momentum flux $L(\Psi)$ remain constant [13]. It is obvious that in the comoving reference frame the particle trajectories are two tangent circles. But this inevitably results in two important effects that has not been considered before.

1. The particles rotate in the (*rz*)-plane. For this reason the energy-momentum tensor of the loading component should have anisotropic pressure. In other words, $P_n = 0$ in the well-known anisotropic parameter $\beta = 4\pi\frac{P_n - P_s}{b^2}$ .This results in the additional term in the last bracket of the energy-momentum tensor

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

Here four-velocity U^i corresponds to the bulk motion of the wind, and

$$\varepsilon_{\mathrm{ld}} = n_{\mathrm{ld}}^{\mathrm{com}} m_{\mathrm e} c^2\Gamma, \qquad P_s = \frac{1}{2}n_{\mathrm{ld}}^{\mathrm{com}} m_{\mathrm e} c^2\Gamma,$$

where Γ is the mean energy of the individual particle. As a result, even for constant anisotropic pressure, the nonzero radial force is to appear:

$$\mathcal{F} = -\frac{P_s}{r}\mathbf{e}_r.$$

2. Radial displacement of electrons and positrons in the opposite directions inevitably results in the screening of the poloidal electric field. It is this screening that finally reduces the bulk particle velocity corresponding to electric drift in the laboratory reference frame.

The critical number density which is necessary to decelerate the bulk motion can be estimated in four different ways:

1. By direct calculation of the disturbances of the electric and magnetic fields determining the drift velocity.
2. By the condition $\delta E \sim E$.
3. By comparison of the anisotropic pressure force with the appropriate forces in the anisotropic GS equation [16].
4. From the condition $|\beta| \approx 1$ for the anisotropic parameter $\beta = 4\pi\frac{P_n - P_s}{b^2}$.

Indeed, as one can find, $|\beta| = \frac{n_{\mathrm{ld}}}{n_{\mathrm{cr}}}.$

As a result, we obtain for the critical number density of the loading plasma (in the laboratory reference frame)

$$n_{\mathrm{cr}} = \frac{B_\varphi^2}{m_{\mathrm e}c^2\Gamma^2}$$

which is necessary to decelerate significantly the bulk motion of a jet material.

Concluding Remarks

Radiation drag

1. The drift current resulting from the drag force is to be included into consideration.
2. U_{cr} is even lower than CMB energy density. Does it mean that the radiation drag is really so important?

Particle loading

1. The loading process results in the formation of media with highly anisotropic pressure.
2. The obtained critical particle number density is certainly too high, but it changes the dynamics of a jet dramatically. The estimates will be made for needed n_{ld} to explain the observed jet decelerations.

A problem

In both cases the longitudinal electric field inevitably appears. This results from the radial drift motion of charged particles for the radiation drag and the radial displacement of particles during their acceleration for particle loading. This implies that time-dependent (i.e. PIC) simulation is necessary to clarify the interaction of the MHD flow with photon field.

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