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On 'cosmic ray cocoons' separating relativistic jets from the ambient medium

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Abstract

In the acceleration process at a jet side boundary a flat cosmic ray distribution can be created. As a result the cosmic rays are expected to cause viscous and dynamic effects in a cylindrical-like volume - a 'cosmic ray cocoon' - separating the jet from the ambient medium. The considered cosmic ray particles provide an additional jet breaking force and lead to a number of consequences for the jet structure and its radiative output. In AGNs the involved dynamic and acceleration time scales are comparable to the values observed.

1 Particle acceleration at the jet boundary

Shock waves are widely considered to be sources of cosmic rays in relativistic jets ejected from active galactic nuclei. In the present paper we consider an alternative, till now hardly explored mechanism involving particle acceleration at the velocity shear layer, formed at the interface between the jet and the ambient medium. We point out possible regimes of turbulent second-order Fermi acceleration at low particle energies, next dominated by the 'viscous' acceleration at larger energies, and by acceleration at the tangential flow discontinuity at highest energies. Till now, besides casual remarks, the considered complicated physical phenomenon was hardly discussed in the literature (cf. a discussion of radiation-viscous jet boundary layers by Arav & Begelman (1992) and a discussion of possible UHE cosmic ray acceleration by Ostrowski (1998; $\equiv$ 'O98')).

For particles with sufficiently high energies the transition layer between the jet and the ambient medium can be approximated as a surface of discontinuous velocity change, a tangential discontinuity ('TD'). Any high energy particle crossing the boundary from gains or looses its energy, E, according to the respective Lorentz transformation. In the case of uniform magnetic field near TD the successive transformation at the next boundary crossing changes the particle energy back to the original value. However, in the presence of perturbations acting at the particle orbit a mean energy gain results:

$$< \Delta E > \; = \eta_{\rm E} \, (\Gamma - 1) \, E \tag{1}$$

where $\Gamma \equiv (1 - U^2)^{-1/2}$ is the flow Lorentz factor. The numerical factor $\eta_{\rm E}$ depends on particle scattering near TD. For mildly relativistic flows, in the strong scattering limit particle simulations give values of $\eta_{\rm E}$ as substantial fractions of unity (Ostrowski 1990). This value increases with the growing magnetic field perturbations' amplitude and slowly decreases with the growing flow velocity. Thus, for large Γ we will assume the following scaling

$$\eta_{\rm E} = \eta_0 \frac{2}{\Gamma} \qquad , \tag{2}$$

where η_0 is defined by the magnetic field perturbations at Γ 2 and, in general, it depends also on particle energy. During the acceleration process, on average, a single particle with the momentum p transports across the jet's boundary the following momentum:

$$< \Delta p_{\rm z} > = \eta_p \, (\Gamma - 1) \, U \, p \qquad , \tag{3}$$

where the z-axis is chosen along the flow velocity and the value of p is given as the one before transmission. The numerical factor η_p depends on scattering conditions near the discontinuity and in highly perturbed conditions (in mildly relativistic shocks) it can reach values being a fraction of unity also and $\eta_p \approx \eta_{\rm E}$. As a result, there acts a drag force *per unit surface* of the jet boundary and the opposite force at the medium along the jet, of the magnitude order of the accelerated particles' energy density. Independent of the exact value of $\eta_{\rm E}$, the acceleration process can proceed very fast due to the fact that a substantial fraction of particles is not able to diffuse – between the successive energizations – far from the accelerating interface.

The simulations (Ostrowski 1990, $\equiv$ 'O90') show that in favourable conditions the formation of the flat particle distribution can be very rapid, with the time scale given in the observer frame as

$$\tau_{\rm TD} \sim 10 \frac{r_{\rm g}}{c} \qquad , \tag{4}$$

where $r_{\rm g}$ is the characteristic value of particle gyroradius. One should note, that formation of a somewhat flatter stationary distribution would require infinite time for the applied model. Also, the expression (4) and the following discussion is valid for an average accelerated particle. A small fraction of external particles reflected from the jet can reach large energy gains, $\Delta E / E \sim \Gamma^2$.

For low energy cosmic ray particles the velocity transition zone at the boundary is expected to become a finite-width turbulent shear layer. We do not know of any attempt in the literature to describe the internal structure of such layer on the microscopic level. Therefore, we limit our discussion of the acceleration process within such a layer to quantitative remarks only. There, two processes can accelerate low energy particles, i.e. the ones with the mean radial free path λ much smaller than the transition layer thickness, D. The first one is due to velocity shear and is called 'cosmic ray viscosity' (Berezko 1990; Earl et al. 1988). The second one is the ordinary Fermi process in the turbulent medium. The acceleration time scale, $\tau_{\rm II}$, can not be evaluated with accuracy for these processes, but we can give an estimate

$$\tau_{\rm II} \sim T_{\rm g} \frac{c^2}{V^2 + \left(U \frac{\lambda}{D} \right)^2} \qquad , \tag{5}$$

where $T_{\rm g} \equiv 2\pi r_{\rm g}/c$ and V is the turbulence velocity ($\sim$ the Alfvén velocity for subsonic turbulence). The first term in the denominator representing the second-order Fermi process can dominate $\tau_{\rm II}$ at low particle energies, while the second one due to the viscous acceleration will dominate at larger energies, with $\tau_{\rm II}$ approaching the value given in Eq. (4) for $\lambda \sim D$. Depending on the choice of parameters $\tau_{\rm II}$ can be comparable or longer than the expansion and internal evolution scales for relativistic jets.

The loss time scale for UHE protons can be evaluated with the Rachen & Biermann's (1993) formula

$$T_{\rm loss} \simeq 5 \cdot 10^9 \, B_{\rm g}^{-2} \, (1 + Xa)^{-1} \, E_{\rm EeV}^{-1} \quad [s] \qquad , \tag{6}$$

where $B_{\rm g}$ is the magnetic field in Gauss units, a is the ratio of the energy density of the ambient photon field relative to that of the magnetic field and X is a relative strength of $p\,\gamma$ interactions compared to synchrotron radiation; $E_{\rm EeV} \equiv E/(10^{18} {\rm eV})$. For cosmic ray protons the acceleration dominates over the losses (Eq-s 4, 6) up to the maximum energy $E_{\rm EeV} \approx 20 \, [B_{\rm g}(1 + Xa)]^{-1/2}$.

2 Energy spectra and spatial distributions of accelerated particles

The acceleration process acting at the tangential discontinuity of the velocity field produces a flat particle energy spectrum and a perpendicular spatial distribution increasing its extension with particle energy. Below we propose a simple acceleration and diffusion model describing these features. Let us consider particles accelerated at the *plane* tangential discontinuity surrounded with infinite regions for particle diffusion. For the assumed perpendicular (to the discontinuity) diffusion coefficient being proportional to particle energy, $\kappa_\perp \propto E$ and for relativistic particles with $p = E$, the mean time between the successive particle interactions with the discontinuity is also proportional to particle energy in conditions close to stationarity at a given energy. Thus the mean rate of particle energy gain is $< \dot{p} >_{\rm gain}$ = const (cf. O90 for a more realistic model describing

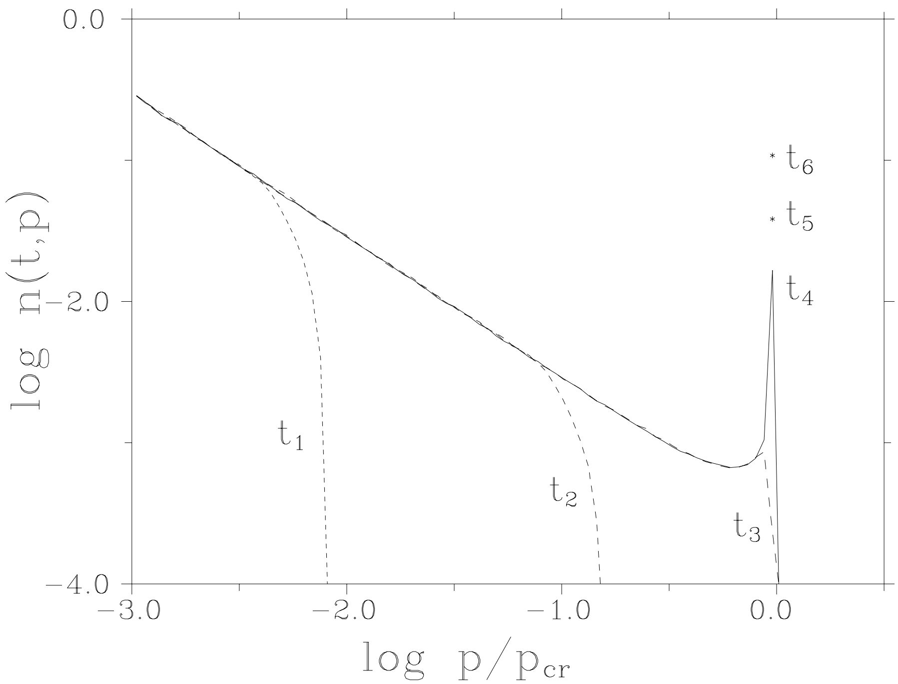

Figure 1: Spectra of accelerated particles at the jet boundary in a sequence of times $t_1 < t_2 < t_3 < t_4 < t_5 < t_6$, for continues particle injection at small momentum $p_0 << p_{\rm cr}$. For the times t_5 and t_6 only the last points at $p \approx p_{\rm cr}$ are shown, the remaining part of the spectrum nearly coincides with the one for $t = t_4$.

a discrete nature of TD acceleration). Next, let us take a simple expression for the synchrotron energy losses, $< \dot{p} >_{\rm loss} \propto p^2$ (cf. Eq. 6), to represent any real process acting near the discontinuity.

The particle spectra derived within the above model are presented in Fig. 1, with the critical momentum, $p_{\rm cr}$, defined by $\tau_{\rm loss}(p_{\rm cr}) = \tau_{\rm gain}(p_{\rm cr})$. It also defines a cut-off when it is smaller than the escape momentum, $p_{\rm escape}$. At the figure one may observe time evolution of the spectrum for $p_{\rm cr} < p_{\rm escape}$. At small momenta it has a power-law form – in our model $n(t,p) \propto p^{-1}$ – with a cut-off momentum growing with time. However, at long time scales, when particles reach momenta close to $p_{\rm cr}$, losses lower the value of $< \dot{p} >$ leading to spectrum flattening and pilling up particles at p close to $p_{\rm cr}$. Let us also note that for efficient particle escape, $p_{\rm escape} < p_{\rm cr}$, the resulting spectrum would be similar to the one for t_1 or t_2 (cf. O98).

For $\kappa_\perp$ growing with particle momentum the spatial extension of accelerated particles also grows with p and the distribution function at the discontinuity is lowered by, approximately, a factor $\propto \kappa_\perp^{-1}(p)$, with respect to the model involving constant $\kappa_\perp$. One should also note that at $p \approx p_{\rm cr}$ the spatial extension of the spectrum grows slowly with time, $\propto t^{1/2}$, allowing for continues increase of particle density at $x = 0$.

3 Consequences of the jet's cosmic ray cocoon

Inspection of Fig. 1 reveals a few possible scenarios of cosmic ray acceleration at the jet boundary. If, at small particle energies, the acceleration time scale is much longer than the jet expansion time or the escape time (and no efficient external injection is present), the formed energetic particle population cannot reach a sufficiently high energy density to allow for dynamic effects in the medium near the interface. Then, it acts only as a small viscous agent near the boundary, decreasing slightly gas density and magnetic field (cf. Arav & Begelman 1992). In such cases we call the occurring cylindrically distributed cosmic ray population a '*weak* cosmic ray cocoon'. Then, if accelerated particles are electrons or can transfer energy to electrons, a cosmic ray electron population may be formed along the jet leading to the synchrotron component with slowly varying spectral index and break frequency.

If the acceleration is fast and dominates over losses at small (injection) energies, then the time dependent high energy part of the spectrum may be a power-law with growing cut-off energy for weak radiative losses (like the distributions denoted with 't_1' and 't_2' in Fig. 1), or a power-law with a growing mono-energetic spike proceeding a cut-off energy (the distributions '$t_3 - t_6$'). In such cases the increasing cosmic ray pressure in a cocoon may reach values comparable to the medium (gas and magnetic field) pressure, $P_{\rm ext}$, and result in a substantial modification of the jet boundary layer – the '*dynamic* cosmic ray cocoon'. Then a possible scenario of dynamic interaction of high energy cosmic rays with the jet and the ambient medium involves a growing number of particles forming the cosmic ray pressure gradient outside the jet pushing the ambient medium apart. Additionally, an analogous gradient may be formed directed into the jet, helping to keep it collimated. In this situation the cosmic ray energy density may build up only to the value comparable to $P_{\rm ext}$, when it is able to push the magnetized plasma away from the jet and form a cylindrical cocoon filled preferentially with photons and energetic cosmic rays. Because the diffusive escape of charged particles from the cosmic ray cocoon can not be efficient, in some cases the blown out volumes could be substantial, reaching values comparable to the jet radius $R_{\rm j}$ or even to the local vertical gas scale. Then the accumulated cosmic rays can be removed by advection in the form of cosmic rays filled bubbles, the process characterized with the respective RT instability time scale.

The jet moving in space filled with photons and high energy cosmic rays is subject to the braking force due to scattering this species. For cosmic rays with $\lambda \sim R_{\rm j}$ both types of particles penetrate relatively freely inside the jet and the breaking force is exerted more or less uniformly within its volume, in rough proportion to the electron density for the photon breaking and to the turbulent magnetic field energy density for the cosmic ray breaking. If the cosmic ray cut-off energy is lower, with the equivalent $\lambda < R_{\rm j}$, the breaking force acts within the boundary layer of width λ. From Eq. (3) we estimate the cosmic ray breaking force *per unit jet length* to be $f_{\rm b,cr} = 2\pi \, \eta_{\rm p} \, (\Gamma - 1) \, P_{\rm cr} \, R_{\rm j}$, where we consider $\lambda \leq R_{\rm j}$ and we put $U = 1$. For the jet with a (relativistic) mass density ρ_j and $P_{\rm cr} \approx P_{\rm ext}$, with Eq-s (2, 3) and $\eta_{\rm p} = \eta_{\rm E}$, the jet breaking length due to cosmic rays is $L_{\rm b,cr} = R_{\rm j} \, \frac{\Gamma}{4\eta_0} \, \frac{\rho_j c^2}{P_{\rm ext}}$. Because of dynamic form of pushing out the ambient medium and the following it cosmic rays escape, the back-reaction of this process at particle acceleration is expected to make the full process unstable, with an intermittent behaviour seen in longer time scales. The presented discussion assumed the cylindrical symmetry of the unstable flow, which may be not true. However, any *large* amplitude perturbation of the conditions near/in the jet can not be much smaller than the spatial scale $R_{\rm j}$ and the respective observer's time scale shorter than $R_{\rm j}/c$.

Let us finally note that our discussion deals with a possibly ultra-relativistic section of the jet close to the active galaxy nucleus. However, analogous phenomena should also occur at larger scales, provided at least mildly relativistic jet velocity.

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