On particle acceleration in turbulent shear boundary layers of relativistic jets

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ABSTRACT. We discuss processes accelerating cosmic ray electrons at boundaries of relativistic jets. The resulting spectrum is expected to possess two characteristic components: a power-law distribution at lower energies and a harder high energy component preceding the high energy cut-off. An example of high energy spectrum from such electron distribution is presented, including the synchrotron and the inverse-Compton components. A characteristic feature of the synchrotron spectrum of such electrons is its highest frequency part which occurs above the power-law fitted to the low frequency spectral range.

1. Introduction

Radio and optical polarimetry of the large scale jets in radio galaxies usually suggest strong velocity shearing effects at the jet edges, resulting in a magnetic field being parallel to the jet axis (see, e.g., Perlman et al. 1999 for M 87, Attridge et al. 1999 for 1055+018). Acceleration of radiating particles within a boundary region is required to explain the observed jet radial profile (e.g. in M87, Owen et al. 1989), or details of the spectral maps, like flattening of the radio spectrum near the jet surface in Mkn 501 (Edwards et al. 2000). One should mention, that the HST studies of the optical counterparts of large scale radio jets emphasize the necessity of the continuous electron reacceleration in a jet body (and not only in shock regions), as the lifetime of the synchrotron electrons is often much shorter than the light-travel time along the optical structure (cf. Jester et al. 2001 for the case of 3C 273). On the other hand, the broad band spectral properties of BL Lacs and FR I radio galaxies indicate a jet stratification. By comparing the multiwavelength observations of these two classes of AGNs in a framework of a unification scheme, Chiaberge et al. (2000) found evidences for a significant boundary layer emission, dominating the radiative jet output in FR Is. The inferred velocities of such boundary regions are significantly lower as compared to velocities of central spines, but are still relativistic, in order to explain anisotropic emission observed in the FR Is’ cores.

3D hydrodynamical simulations of relativistic jets reveal a highly turbulent cocoon and a shear layer surrounding the jet spine (Aloy et al. 1999). The reason for the presence of a turbulent medium effects in these simulations is numerical viscosity, which is not a real physical process. However, theoretical considerations support the model of a turbulent medium at the jet edges (cf. Bicknell & Melrose 1982). Such regions are therefore the promising places for particle acceleration, as discussed previously by Ostrowski (1998, 2000). The jet boundary layer acceleration, when applied to protons, was considered to provide ultra high energy cosmic rays, influence the jet dynamics, and significantly increase a pressure in the radio lobes of FR II sources (Ostrowski & Sikora 2001). Electrons accelerated at the jet boundary were considered to provide important contribution for the jet radiative output, including the large scale X-ray emission and its possible time (spatial) variation (Stawarz & Ostrowski 2002, 2001).

2. Radiating boundary layer

For illustration let us consider a relativistic large scale jet consisted of a spine surrounded by the boundary layer with a velocity shear. In order to specify the velocity structure,
we assume a uniform flow Lorentz factor $\Gamma_j$ inside the jet spine, and a linear radial profile $1 < \Gamma < \Gamma_j$ within the boundary transition region. Below we put the thickness of the boundary layer to be of order of the jet radius, $D \sim 1 \text{kpc}$. Furthermore, we assume, that due to shearing effects the magnetic field is parallel on average to the jet axis inside the highly turbulent boundary layer, and that its intensity is the same as the one estimated for the spine, $B = 10^{-5} \text{G}$.

The electrons injected into the jet boundary region can be accelerated due to cosmic ray viscosity connected with the flow velocity radial gradient within the shear layer and due to stochastic Fermi acceleration in the turbulent medium. For the assumed large scale jet parameters (with $D \gg r_g$, where $r_g$ is the electron gyroradius) the later mechanism acts more efficiently and, hence, the electrons gain energy mostly due to $V$, protons, magnetic field to the turbulent one. For the jet dynamicaly dominated by nonrelativistic $D$, of the boundary layer to be of order of the jet radius, $D$ large scale jet parameters (with and due to stochastic Fermi acceleration in the turbulent medium. For the assumed $< 1$ profile $1$, $T_{\text{th}}$ on average assume, that due to shearing effects the magnetic field is parallel of the emitting region, and hence – in our case of a shear layer – on the distance from the jet axis. For simplicity, we limit our calculation to the upper limits of both $u_{\text{cmb}}$ and $u_{\text{agn}}$, and neglect cosmological redshift corrections. Then the energy density of the CMB background with intrinsic luminosity $L'_{\text{cmb}} = u_{\text{cmb}} = a T^4_{\text{cmb}} \Gamma^2 < a T^4_{\text{cmb}} \Gamma_j^2$, and the energy density of the core emission $\propto \Gamma_j^{-1}$, $L'_{\text{agn}}$ is $u_{\text{agn}} = L'_{\text{agn}} / 4\pi c z^2 < L'_{\text{agn}} / 4\pi c z^2$, where $\Gamma$ is the bulk Lorentz factor of the (sub-) parsec scale jet, and $z$ is the distance from the galactic nucleus. The electrons’ escape from the shear layer with the assumed magnetic field configuration proceeds through the cross-field diffusion process. The appropriate time scale for this process can be estimated as $T_{\text{esc}} \sim D^2 \eta / c$, $\propto \eta / c$, is an effective cross-field diffusion coefficient, with the numerical scaling factor $\eta \leq 1$, $T_{\text{esc}}$ is much longer than the time scale for radiative losses, $T_{\text{loss}}$. As a result, the electrons pile-up at highest energies below the maximum energy $\gamma_{\text{eq}} mc^2$, where $\Gamma_{\text{esc}} \approx T_{\text{loss}}$. Below we will model the formed hard component in the electron spectrum with a monoenergetic bump at the highest energy ($\propto \delta (\gamma - \gamma_{\text{eq}})$, cf. Ostrowski 2000). For the parameters $L'_{\text{agn}} \sim 10^{37} \text{erg/s}$, $\eta = 1$ and $\Gamma_0 \sim \Gamma_j \sim 10$, the maximum energy the electrons can reach due to turbulent acceleration in a Bohm limit – at distances $z \geq 10 \text{kpc}$ where $u_{\text{agn}} < u_{\text{cmb}}$ – corresponds to the electron Lorentz factor $\gamma_{\text{eq}} \sim 10^8$.

In the case of efficient particle injection, the acceleration process acting continuously within the whole jet boundary layer leads to the distribution approximated here as a flat power-law spectrum $n_\gamma(\gamma) \propto \gamma^{-\sigma}$ finished with the pile-up bump at the maximum energies near $\gamma_{\text{eq}}$. The detailed evolution of the highest energy electrons needs careful analysis of the momentum diffusion of the accelerating particles within turbulent layer with velocity and density gradients (work in preparation). Below, in order to discuss main consequences of the boundary layer acceleration for the radiative jet output, we consider a case of forming the stationary two-component electron energy distribution with $\sigma \sim 2$ and the high energy bump modeled as a monoenergetic peak (c.f. discussion in Stawarz & Ostrowski 2002). The observed multiwavelength radiation of such electrons, including synchrotron radiation, synchrotron self-Compton emission and external Compton scattering of CMB photons is plotted on figure 1 for different jet
Fig. 1. The observed spectral energy distributions of the radiation generated within the shear boundary layer for $\gamma_{eq} = 10^8$ and different jet inclinations, as indicated near the respective curves. The presented spectra are integrated over the assumed linear flow Lorentz factor profile with $D \sim 1$ kpc and $\Gamma_j \sim 10$. A distance to the observer is assumed to be 10 Mpc, and the absorption of VHE $\gamma$-rays during the propagation to the observer is neglected. The dotted vertical lines indicate the Chandra energy band, 0.1 keV - 10 keV. The dashed vertical line indicates the observed photon energy 1 TeV.

inclinations. In order to find the normalization constants for the particle distribution, we assumed the energy equipartition between the magnetic field and each one of the electron spectral components. The presented spectra are integrated over the assumed bulk flow Lorentz factor profile within the boundary layer, with the appropriate beaming pattern for synchrotron/self-Compton and external Compton radiation (Dermer 1995).

3. Discussion - X-ray emission of the large scale jets

After Chandra discovery that the large scale jets in quasars and radio galaxies are strong X-ray emitters, the question of the origin of such radiation became an important issue. For the jets observed at small angles, the inverse Compton scattering of the CMB photons by the low-energy tail of the non-thermal electron distribution flowing with high bulk Lorentz factor is the most likely explanation (Tavecchio et al. 2000). However, strong beaming effects exclude this process in case of the jets in radio galaxies. Celotti et al. (2001) proposed instead, that the X-ray radiation detected from such objects can be explained as the SSC emission of the slower (and therefore less beamed) boundary layer electrons, or as the inverse Compton scattering of the core emission. This, however, requires a departure from the energy equipartition between the magnetic field and radiating particles, at least if the X-ray flux is of the same order of magnitude as the synchrotron one. As illustrated on figure 1, the boundary layer acceleration at the tens-of-kpc scale jets can generate high energy synchrotron radiation peaking at the keV
energy band. Luminosity of such radiation is high enough to account for the Chandra observations without departures from the equipartition condition (Stawarz & Ostrowski 2002). Continuous acceleration acting within the whole boundary layer volume compensates radiative losses of high energy electrons, and therefore the diffusive character of their X-ray emission is a natural consequence of the presented model (but of course any compressive perturbation – a shock – in the jet can disturb this smooth intensity variation). One should note that recent HST observations of the jet in 3C 273 (Jester et al. 2002) with a smooth spectral transition from optical, through UV, up to X-ray frequencies are consistent with our model.

The low energy (radio-to-optical) component of the boundary layer synchrotron emission can affect the jet-counterjet brightness asymmetry measurements, ‘hiding’ the highly relativistic spine. Thus the bulk Lorentz factor of the jet spine at large scales can be comparable to the one at VLBI scales. This has several consequences for the jet energetics (cf. Ghisellini & Celotti 2001).

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