# PARTICLE ACCELERATION AND ENERGY SPECTRA IN EXTRAGALACTIC JETS

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**ABSTRACT.** The mechanism of particle diffusive acceleration by shocks produced by nonlinear fluid instabilities in supersonic collimated flows is discussed in the framework of the standard synchrotron model for extragalactic jets. With reference to the well-known case of the M87 jet, such model can reproduce the observed spectral uniformity independently from the non-uniform brightness distribution.

## 1. Introduction

The original difficulties of the standard synchrotron model on the global and specific energetics of extragalactic radiosources (Burbidge 1956) have become more critical after the discovery of superluminal blobs in their cores by the radio VLBI (Marscher 1993) and gamma-ray emission from AGNs by the CGRO (von Montigny *et al.* 1995): highly collimated relativistic jets with $\gamma_{bulk}$ up to 20 are required, carrying along a strong non-thermal electron component with $\gamma_{el}$ up to $10^7$. In addition, given the short emission lifetimes as compared with the propagation time from the central power source, a very efficient *in situ* reacceleration of relativistic electrons is required along the jet.

Acceleration by MHD turbulence at shock discontinuities is still the best candidate to produce a "universal" particle energy spectrum. Numerical simulations show quite clearly the formation of a rich variety of nonlinear dynamical structures in supersonic (relativistic) flows and some preliminary analysis of the level of turbulence and strength of shocks have been performed (Bodo *et al.* 1995).

Recently Massaglia *et al.* (1996), referring to the synchrotron model, have developed a self-consistent method to follow numerically the time evolution of the relativistic component in a supersonic jet exposed to adiabatic losses, synchrotron emission and acceleration at fluid discontinuities. Here we discuss some preliminary considerations of its application.

## 2. Multiple DSA and energy spectrum

The simplest version of the diffusive shock acceleration mechanism, DSA (Blandford & Ostriker 1980), shows that the downstream distribution function, $f_{down}(p)$ after the shock, is related to the upstream distribution function, $f_{up}(p)$ before the shock as follows:

$$f_{down}(p) = bp^{-b}\int_{p_c}^{p} dp'\, p'^{(b-1)} f_{up}(p'), \qquad b = \frac{3u_1}{u_1-u_2} = \frac{3r}{r-1} \tag{1}$$

where $p$ is the particle momentum, $u_1$, $u_2$ are the flow speeds upstream and downstream of the (parallel) shock, $r = \rho_2/\rho_1 = u_1/u_2$ is the density compression ratio across the shock, and $p_c$ is a lower cut-off such that $f_{up}(p) = 0$ for $p < p_c$. The Mach number, $M$, of the shock front is related to the compression ratio by

$$r = \frac{(\Gamma+1)\,M^2}{2+(\Gamma-1)\,M^2} \tag{2}$$

with $\Gamma$ the gas adiabatic index. For $\Gamma = 5/3$, Eq. (2) implies a maximum compression ratio $r = 4$ ($M \to \infty$), and hence a minimum spectral index $b = 4$.

In general, considering also injection of particles along the flow and post-shock decompresssion, DSA yields a power-law spectrum of relativistic particles $f(p) \propto p^{-b}$, with index $b = 3r/(r-1)$, which corresponds to $N(\gamma) \propto \gamma^{-a}$ with $a = b-2$.

In fact if an electron spectrum of the form $\propto p^{-c}$ encounters a shock whose strength is characterized by its value of $r$, or $b$, then:

$$f_{down}(p) \propto \begin{cases} p^{-c} & \text{for} b > c \\ p^{-b} & \text{for} b < c. \end{cases} \tag{3}$$

The final spectrum produced by a single shock is fixed either by the injection spectrum or by the strength $r$ of the shock, whichever produces the flatter spectrum.

DSA by an ensemble of shocks may be treated by taking the downstream distribution resulting from injection and acceleration at the first shock into a second shock, with the resulting downstream distribution used as the input distribution into a third shock, and so on: this leads to a hardening of the power-law distribution, reaching toward $f(p) \propto p^{-3}$ when all shocks are very strong (Melrose & Pope 1993).

### 3. Multiple DSA and spectral upper cut-off

Consider an electron cycling across a shock, moving with speed $u_s$ into the upstream medium. For highly relativistic electrons the change in energy is (Achterberg 1990):

$$\frac{d\gamma}{dt} = \frac{u_s^2}{c\lambda}\gamma - \left(\frac{d\gamma}{dt}\right)_{sync} \tag{4}$$

where the former term on the right hand side describes DSA and the latter synchrotron losses; $\lambda(\gamma)$ is the electron mean free path against scattering in the plasma. For synchrotron losses $(d\gamma/dt)_{sync} = (2/3)(\sigma^2 B^2)/(\mu_0 m_e c)\gamma^2$. For the acceleration term we use the expression for $\lambda$ given by Melrose (1986) for a turbulent plasma with power spectrum of magnetic fluctuations $W(k)$:

$$\lambda = \frac{1}{3\pi^2}\frac{m_e\Omega_e^2}{r_e k^2 W(k)}. \tag{5}$$

We adopt a power-law spectrum for the magnetic fluctuations, $W(k) = W_0(k/k_0)^{-\rho}$ for $k_0 < k < k_1$, normalized with $W_0 k_0 = (\delta B/B)^2 \left(B^2/2\mu_0\right)$, with $k_0 = m_e c/eB_0 = c/\Omega_0$ as the lower spectral cut-off.

The maximum energy $\gamma_{\rm max}$ stems from the acceleration and loss balance $d\gamma/dt = 0$:

$$\gamma_{\rm max} = \left[\frac{27\pi\,(\rho-1)}{16}\frac{u_s^2}{c^2}\frac{(k_0 r_0)^\rho}{k_0 r_e}\left(\frac{\delta B}{B}\right)^2\right]^{1/(3-\rho)}. \tag{6}$$

Other possible interpretations for the formation of a $\gamma_{\rm max}$ are that it is determined by the minimum $k_0$ for resonant scattering, or that it is limited by the time available for scattering $T = \int_{\gamma_0}^{\gamma_{max}} d\gamma(c\lambda)/(u_s^2\gamma)$.

## 4. The spectral characteristics of the M87 jet

Recently Meisenheimer *et al.* (1996a,b) have collected detailed data over a broad frequency range (from radio to X rays) on the jet in M87, showing that while the brightness distribution is highly non-uniform, showing bright knots separated by low luminosity regions, the shape of the spectral index is very uniform along the whole jet, $I(\nu) \propto \nu^{-0.6}$, and the high-frequency spectral cut-off is very nearly constant, $\gamma_c \sim 0.9\times 10^6$. These uniformities apply down to the smallest scale, $l \sim 10$ pc, observationally resolved. Therefore *in situ* reacceleration must be independent from the local physical parameters.

Without discussing the global jet energetics, we attempt a quantitative comparison with the model of formation of the electron spectrum by DSA.

*(a) Spectral shape and brightness ditribution.* In our model the power-law exponent is defined by the strongest shocks. For M87 an exponent $a = 2.3$ for the electron spectrum $N \sim \gamma^{-a}$ (corresponding to the observed synchrotron exponent 0.6) requires a dominant population of shocks with strength $r = 3.3$. Such requirement appears not to be contradicted by the results of the numerical nonlinear hydrodynamical simulations of (infinite) supersonic jets performed by Massaglia *et al.* (1996). Typically strong shocks with $r > 3$ do form along the jet and DSA can reach the same characteristics everywhere. The different brightness can be simply related to the extension of the emitting region due to the piling up of several shocks, although each of them does not overcome a limit $r \sim 3.3$. We conclude that there is no difficulty in principle in accounting for an electron spectrum with the same shape along the length of the M87 jet.

*(b) Upper energy cut-off.* One can envisage three possible models for the regular upper energy cut-off in the jet in M87: the synchrotron limit, the low-$k$ cut-off in the spectrum of resonant waves sustaining the acceleration process, and a limit from the time available for acceleration. The first condition is from Eq. (6); for $\rho = 5/3$ becomes:

$$\gamma_{\rm max} = \left[\frac{9\pi}{8}\frac{u_s^2}{r_e c\Omega_e}\left(\frac{\delta B}{B}\right)^2\right]^{3/4}(k_0 r_0)^{1/2} \tag{7}$$

The quantity inside the square brackets may be estimated using the typical values $u_s = 10^{-2}c$ and $B = 30$nT for M87 and for $(\delta B/B) \sim 1$. The remaining factor involves $r_0 \sim 6\times 10^4$ m for $B = 30$ nT and $k_0$, which is the minimum wavenumber of the turbulent spectrum. Assuming that this spectrum is formed in the conventional way, with energy input on a large scale $L_0 = k_0^{-1}$ and then cascading to smaller scales, if we measure $L_0$ in parsecs, then we have $k_0 \sim 1/(3 \times 10^{16} L_{0,pc})$ m$^{-1}$, giving $k_0 r_0 \sim 2 \times 10^{-12}/L_{0,pc}$. Then $\gamma_{\max} \sim 1 \times 10^6 / L_{0,pc}^{1/2}$, which for $L_{0,pc} \sim 1$ is close to the required value.

The other suggested interpretations for $\gamma_{\max}$ are that it is determined by the minimum $k_0$ for resonant scattering $\gamma_{\max} = 1/k_0 r_0$, or that it is limited by the time available for scattering. The former gives $\gamma_{\max} \sim 10^{12} L_{pc}$, an irrelevant condition. The latter is estimated from $T = \int_{\gamma_0}^{\gamma_{max}} d\gamma (c\lambda)/(u_s^2 \gamma)$ and yields:

$$\gamma_{\max} \sim \frac{1}{k_0 r_0} \left(\frac{u_s}{c}\right)^3 (k_0 u_s T)^3 \tag{8}$$

With $k_0 \sim 1/L_0$ and the available time estimated from the shock crossing time over a distance $1/k_0$, implying $k_0 u_s T \sim 1$, Eq. (8) gives $\sim 10^6 L_{0,pc}$, and for $L_{0,pc} \sim 1$ this is of the correct order of magnitude. However, the argument for $k_0 u_s T \sim 1$ is weak because the energetic particles drift along with the shock. A more plausible interpretation of Eq. (8) is that the time available is $T \geq 1/k_0 u_s$, and hence is adequate for acceleration to $\gamma \sim 10^6$. We conclude that the limit fixed by the balance between synchrotron losses and multiple shock acceleration provides the required value for the spectral cut-off and its independence from the brightness distribution.

These arguments warrant further analysis, including a self-consistent treatment of the dynamics of jets and relativistic component. This study is in progress with an appropriate numerical code.

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