Particle-Acceleration and Radiation in the Turbulent Flow of a Jet

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Abstract. We present a numerical model for electron acceleration and radiation inside the body of an extragalactic jet. We model the jet environment as a turbulent medium generating non-linear structures (eddies and/or shocks) through a cascading process. These structures act like in-situ accelerators for the electrons that are initially injected from the central engine. Two types of acceleration processes are considered: second order Fermi-acceleration and shock-drift acceleration, depending on the velocity of the turbulent eddies encountered. We study the modulation of the energy distribution of electrons in such an environment, by incorporating synchrotron radiation losses in the time intervals between successive interactions of the particles with the turbulent structures. By performing a parametric study with respect to the level of turbulent activity and the time intervals between interactions, we calculate the temporal evolution of the cut-off frequency of the synchrotron radiation spectrum of the particles and discuss our results in connection with recent observations.

1 Introduction

It is widely accepted that the radio emission of jets is synchrotron radiation from an ensemble of relativistic electrons (or e^+) embedded in a magnetic field (e.g. Begelman [3]). In almost all cases the spectrum of the radiation can be fitted by one or the superposition of a number of power laws in frequency, ($F_\nu \sim \nu^{-\alpha}$), thus implying a power-law distribution for the emitting electrons ($dN \sim E^{-x} dE$). The index x is related to the spectral index α through the relation $x = 2\alpha + 1$. The values of α come in a surprising narrow range: $0.5 \leq \alpha \leq 1.0$, even for different astrophysical systems. This yields for the particles' distribution index values $2.0 \leq x \leq 3.0$ (Scheuer [17]).

The linear dimensions of jets can reach values up to ~ 1 Mpc in some cases. Particles somehow seem to be able to maintain their high energies — otherwise lost due to synchrotron radiation losses — until very far from the central engine (Achterberg [1]). In order to account for the observed radiation at such long distances, particles should be accelerated *in situ* (e.g. [10]).

The recent observations, as well as numerical simulations (e.g. [5]) suggest that the jet-environment may be more complex than it has been considered so far. A turbulent flow can generate local discontinuities throughout the jet, which may act as in situ particle accelerators [16].

Following the above scenario, we introduce a numerical model for permanent electron acceleration in a turbulent jet, where a particle's energy may vary due to collisions with small-scale structures (eddies) or/and encounters with shock fronts. In addition, particles are assumed to be subject to synchrotron losses during time intervals between successive interactions. Our goal is to study the influence of the jet environment on a power law energy distribution of electrons initially injected at the beginning of the jet. We construct a turbulent environment, which will be the generator of the turbulent structures which will act as accelerators for the particles. We calculate the final energy distribution of the particles and the corresponding synchrotron radiation spectrum, and perform a parametric study with respect to the level of turbulent activity and the time intervals between successive encounters. The evolution of the cut-off frequency as a function of time is also considered and compared to the case of no in-situ acceleration, where only synchrotron losses are active.

2 Model Description

The values of the physical parameters of the jet are taken to be: $L = 1$ Mpc, $n_o = 10^{-4}\text{cm}^{-3}$, $B_o = 10^{-5}$G, and $T = 10^6$K (Ferrari [7]). These are the linear dimension of the jet, the particle density of the medium, the magnetic field strength, and the temperature of the plasma, respectively. The corresponding value of the Alfven velocity is $V_A = 2.18 \times 10^8$ cm sec^{-1}. We assume that the flow velocity of the jet is non-relativistic and of the order $V_{\text{jet}} \approx 4V_A$. We also define the time $\tau \approx L/V_{\text{jet}} \sim 1.2 \times 10^8$ yrs as the minimum time for the transport of a turbulent structure from the beginning of the jet to the outer edge of the system.

In order to simulate the turbulent flow inside the jet we use the Simple Stochastic Selfsimilar Branching (SSSB) model introduced by Kluiving and Pasmanter [12]. This seems to be one of the most successful cascade models, mimicking the break-up of structures along a one-dimensional cut through the isotropic turbulent velocity field. A detail description of the SSSB model as well as the basic advantages that this model combines compared to other cascade models (e.g. [15]) are given in Kluiving and Pasmanter [12]. This model provides the energy dissipation rate as a function of the internal subrange of turbulence ($\epsilon(r)$). From that we calculate the velocity of the eddies $V(r)$ (see [14]).

We use this environment to accelerate electrons via two types of acceleration mechanisms: the second order Fermi mechanism and the shock drift mechanism. For both cases the eddies act as accelerators. We introduce a threshold in the value of the velocity of the eddies, $V_{\text{thr}} = 1.5V_A$, above which the shock mechanism is applied, otherwise Fermi acceleration is taking place. The reason is that the higher velocity structures (eddies) create discontinuities of larger sizes as they compress effectively the ambient flow locally. Thus we assume that the higher velocity eddies produced by the SSSB model introduce shocks in the jet flow.

As an electron moves inside the jet flow it encounters both the above mentioned discontinuities (eddies and/or shocks). If the electron interacts with a structure with velocity $V < V_{\rm thr}$, it changes its energy according to the **second order Fermi mechanism** (Fermi [8; 9]). The increment of the total energy of the particle is given by the relation (Longair [13]):

$$\Delta E = \pm 2\gamma^2 E_1 V(u \pm V)/c^2 \tag{1}$$

where γ is the Lorentz factor: $\gamma = [1 - (V/c)^2]^{-1/2}$, u and E_1 are the velocity and the total energy of the particle before the collision and c is the velocity of light. The plus (minus) sign stands for head-on (following) collisions of the electrons with eddies. From Eq. 1, it is evident that an electron can be accelerated or decelerated depending on the direction of the encounter.

In the case that an electron interacts with a structure having velocity $V \geq V_{\rm thr}$, it undergoes acceleration by a shock front. Particles can in general be accelerated in shock waves by either the *drift* or the *diffusive* acceleration mechanism (for a review see [11]). In our model we make use of the **shock drift acceleration mechanism** (e.g. [2, 4]). We apply this specific mechanism because we are able to calculate analytically the energy change of the electrons during the interaction using the adiabatic treatment (for details see Decker [6]).

For each shock front we assume that the upstream plasma values are: $U_1 = V$, $1.5 \leq M_{A_1} \leq 4.0$, $20^o \leq \theta_{Bn_1} \leq 60^o$, $B_1 = 10^{-5}$ G and $\beta_1 = 0.35$, where U_1 is the plasma flow velocity, $M_{A_1} = U_1/V_A$ is the Alfvenic Mach number, θ_{Bn_1} is the angle between the shock normal and the direction of the upstream magnetic filed B_1, and β_1 is the plasma parameter beta. The angle θ_{Bn_1} is chosen randomly from the above given range, while the Alfvenic Mach number is provided by the model for the environment we have used (SSSB model). We evaluate the downstream plasma parameters from the upstream ones using the MHD jump conditions known as *Rankine-Hugoniot* conditions [18].

We consider only the case of those electrons which before the shock encounter are upstream of the shock front and are transmitted into the downstream region after the shock encounter. We do not follow the evolution of the pitch angle at the end of each electron-shock encounter. The kinetic energy, T_2, of the downstream transmitted electrons, is given by the relation (Decker [6]):

$$\frac{T_2}{T_1} = 1+\gamma_1(\gamma_1-1)^{-1}\beta_1 R_1 \left\{ \frac{1}{2}(1+f^2)\varepsilon_1 + \mu_1 - f[(\varepsilon_1+\mu_1)^2 - (b-1)(1-{\mu_1}^2)]^{1/2} \right\}, \tag{2}$$

where γ is the Lorentz factor of an electron, $\beta = u/c$ (u is the electron's velocity), μ is the cosine of the electron's pitch angle, $b = B_2/B_1$ is the ratio of the downstream to upstream magnetic field, r is the compression ratio of the shock wave, $f = b/r$, $R = V \sec\theta_{Bn}/c$ and $\varepsilon = Rc/u$. Finally, we must state here that the subscripts 1 and 2 stand for the upstream and downstream regions of a shock front, respectively.

In addition to the acceleration processes described above, we include synchrotron radiation losses for the electrons during the time intervals between successive interactions with the turbulent structures [14]. We must emphasize here that the acceleration of electrons is a localized process in our model, but the losses due to synchrotron radiation are active continuously along the trajectories of the electrons and play a very important role for the formation of their final energy distribution.

3 Numerical Results

We perform a parametric study on the modulation of an initial power-law energy-distribution of electrons injected at the beginning of the turbulent jet, and calculate the corresponding synchrotron radiation spectrum after time $\sim \tau$. In addition, the temporal evolution of the cut-off frequency is calculated for the same time $\sim \tau$ and compared to the case where only synchrotron losses are active along the electrons' trajectories.

The free parameters of our model are (1) the level of turbulent activity of the jet flow, and (2) the time intervals between successive interactions of the electrons with the turbulent structures (eddies and/or shocks). For the first parameter we studied two distinct cases: lower level (environment A) and higher level (environment B) of turbulent activity. Concerning the second parameter we considered three values for the mean time interval between successive interactions of the electrons with the eddies and/or shock waves: $\sim 2.5 \times 10^5 (T_1\text{-case}), \sim 5 \times 10^4 (T_2\text{-case})$ and $10^3 (T_3\text{-case})$ yrs, respectively. More details about the role of these parameters can be found in [14].

In the case that the injected energy distribution of the particles is a power law with index $s = 2.0$ and $s = 3.0$ in the energy range 10^7 eV $\leq E < 10^{11}$ eV, it turns out that for all three cases T_1, T_2 and T_3, both for environment A and B, the final energy distribution has also a power-law form. Moreover, the value of the final index, x is very close to the value of the injected index, s. The numerical fittings of the final distributions were tested by a χ^2-test and found to be acceptable on a 95% significance level. However we should note here that the highest value of the maximum energy is achieved for the T_3-case. Moreover, it turns out that environment A is a more efficient accelerator than environment B, since the number of shocks encountered by the electrons is higher [14]. The spectral index α ($\alpha = (x-1)/2$) of the intensity of the emitted radiation is of the order of $\alpha \sim 0.5$, for $x \sim 2.0$ ($s = 2.0$), and for $x = 3.0$, $\alpha \sim 1.0$ ($s = 3.0$). In Fig. 1 (left panel) we show the velocities of the eddies in environment A, as seen by an electron along its path for the T_3-case. For this case the number of shock waves encountered by an electron is higher than in the other cases, thus rendering the acceleration process more efficient. Again in Fig. 1 (right panel) we present the evolution of the cut-off frequency, ν_c, as a function of time, t, for the T_3-case of environment A ($s = 2.0$). The cut-off frequency is the frequency that corresponds to the maximum energy achieved by the electrons. Also shown there is the theoretically calculated curve for the time evolution of the cut-off frequency for the case that no acceleration is included in the model [14]. The numerically calculated temporal evolution of the cut-off frequency (curve (a) in Fig. 1) was performed by estimating the time evolution of the initially injected power-law distribution, as it is transported down the jet. It turned out that the power-law form of the electron energy distribution (equivalently of the radiation spectrum) is preserved as we move down the jet.

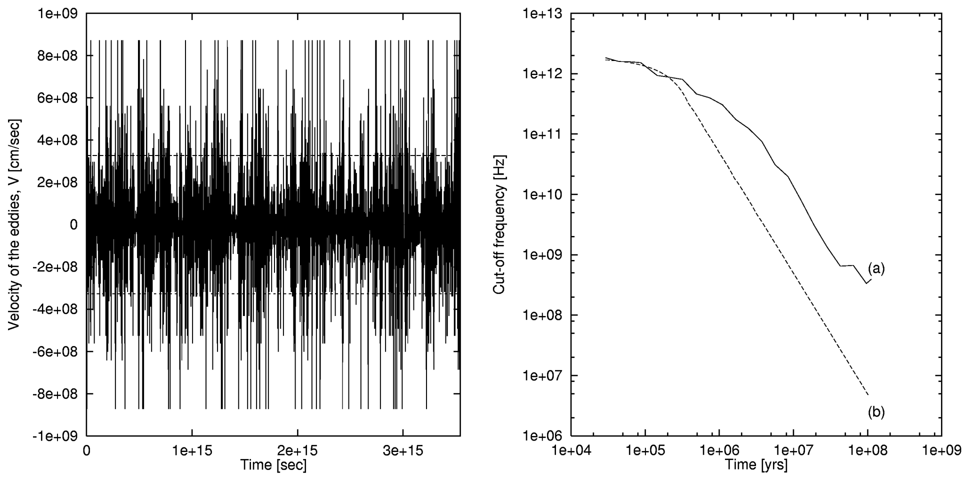

Fig. 1. Left panel: The velocity time series of the structures produced by the SSSB model, for the case of environment A, as seen by an electron moving random time intervals with mean value 10^3 yrs (T_3-case). The dashed lines correspond to the threshold velocity, $|V_{\rm thr}| = 3.27 \times 10^8$ cm/sec. Right panel: The cut-off frequency of the emitted radiation as a function of time, for the T_3-case of environment A ($s = 2.0$). The continuous curve (a) corresponds to the case of environment A, while the dashed one (b) to the case where only synchrotron losses are included in the model.

From Fig. 1 (right panel) we also see that the cut-off frequency deduced from the acceleration model (environment A) is *always* higher than the corresponding value of the cases where only synchrotron losses are active in the trajectories of the electrons. For $t \sim \tau$ we have $\Delta\nu_c \sim 100$ MHz That means that the model is able to preserve a part of the spectrum even at large distances (down the jet). We wouldn't be able to observe this part of the spectrum without in-situ acceleration due to synchrotron cooling of the particles.

Another external parameter of our model is the value of the threshold velocity, $V_{\rm thr}$. This parameter does not change the form of the distribution of the electrons, but contributes only to the efficiency of the process. Indeed, by raising its value (for e.g. $V_{\rm thr} = 2.5V_A$), we lower the number of shocks encountered by the electrons (see Fig. 1-left panel), thus rendering the process less efficient.

4 Summary and Discussion

We have introduced a one dimensional numerical model for permanent acceleration and radiation of electrons in extragalactic jets. We have modeled the non-relativistic flow inside the body of a jet as a turbulent one, able to produce eddies depending upon the level of activity.These structures accelerate electrons via second order Fermi acceleration or shock drift acceleration. If the velocity of the structures (eddies) encountered by the particles is less than a threshold value ($V_{\rm thr}$), the former acceleration mechanism is applied (see Eq. 1), otherwise the latter one (see Eq. 2). Thus the acceleration mechanism used here is a mixed one. Synchrotron losses were included between the successive interactions of the electrons with the turbulent structures.

Concluding, we might say that in the case that the injected distribution is of power-law form ($s = 2.0$ or $s = 3.0$) the power-law is preserved with very minor differences in the spectral index. Moreover the level of turbulent activity has minor or no impact on the spectral index α, but contributes only to the efficiency of the acceleration process. Finally, the model is able to sustain a part of the spectrum even at large distances down the jet, otherwise lost due to synchrotron cooling of the particles.

In our opinion, more attention should be paid in the acceleration mechanisms used here. The Fermi acceleration mechanism proved inadequate in accelerating electrons in energies high enough to account for the radiation losses, as well as the the observations of the radiation spectrum of the jets in higher frequencies ($\nu > 1$ GHz). The choice of shock acceleration mechanisms (e.g. shock drift and diffusive shock acceleration) acting exclusively in the jet, might give a better approach to the problem.

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References

[1] Achterberg A., 1986, Particle Acceleration in Astrophysical Jets. In: W. Kundt (ed.) NATO ASI Series, vol. C 208, Astrophysical Jets and their Engines. Reidel Dordrecht, p. 223.
[2] Anastasiadis A., Vlahos L. (1993) *Astron. Astrophys.* **275**, 432.
[3] Begelman M.C., Blandford R.D., Rees M.J. (1984) *Rev. Mod. Phys.* **56**, 255.
[4] Begelman M.C., Kirk G.J. (1990) *Astrophys. J.* **353**, 66.
[5] Bodo G., Rossi P., Massaglia S., Ferrari A., Malagoli A., Rösner R. (1998) *Astron. Astrophys.* **333**, 1117.
[6] Decker R.B. (1988) *Space Sci. Rev.* **48**, 195.
[7] Ferrari A. (1983) in: Kundu M.R., Holman G.D. (eds.) IAU Symposium No 107, Unstable Current Systems and Plasma Instabilities in Astrophysics. Reidel, Dordrech, p. 393.
[8] Fermi E. (1949) *Phys. Rev.* **49**, 1169.
[9] Fermi E. (1954) *Astrophys. J.* **119**, 1.
[10] Hargrave P.J., Ryle M. (1974) *Mon. Not. R. Astron. Soc.* **166**, 305
[11] Jones F.C., Ellison D.C. (1991) *Space Science Rev.* **58**, 259.
[12] Kluiving R., Pasmanter R.A. (1996) *Phys.* A **228**, 273.
[13] Longair M.S *High Energy Astrophysics* (Cambridge Univ. Press, Cambridge 1983).
[14] Manolakou K., Anastasiadis A., Vlahos L. (1999) *Astron. Astrophys.* **345**, 653.
[15] Menneveau C., Sreenivasan K.R. (1987) Phys. Rev. Lett. **59**, 1424.
[16] Pelletier G., Zaninetti L. (1984) *Astron. Astrophys.* **136**, 313.
[17] Scheuer P.A.G. (1984) *Adv. Space Res.* **4**, 337.
[18] Tidman D.A., Krall N.A. *Shock Waves in Collisionless Plasmas* (Wiley, New York 1971).