Precursor shocks and cosmic ray acceleration

A Meli
IFPA, Institute of Astrophysics and Geophysics, University of Liege, Belgium
Web Institute of Physics, www.wiph.org
E-mail: ameli@ulg.ac.be

Abstract. Cosmic ray acceleration takes place in shocks of relativistic jets in Active Galactic Nuclei (AGN). The diffusive or stochastic acceleration are believed to be the main responsible mechanisms. Additionally, it is known that the back-reaction of accelerated cosmic rays in shock fronts in astrophysical environments, may lead to the formation of a precursor shock with a length scale which corresponds to the diffusive scale of the energetic particles. In this work we will investigate the properties of relativistic, parallel and perpendicular precursor shocks, via numerical test-particle simulations, allowing diffusive and stochastic acceleration.

1. Introduction
There is no doubt that cosmic ray acceleration takes place in shocks of relativistic astrophysical jets [2]. In principle, for the particle acceleration treatment the shock should not be considered always as an immaterial surface, because if a reasonable amount of energy is transferred to the accelerated particles (i.e. > 10%) they can play a dynamic role interacting with the shock, modifying its thickness and consequently the acceleration process. The modified shock (namely precursor shock) [3], will consequently have a finite width $L$, where its length scale can be expressed and will correspond to the diffusive length scale of the energetic particles.

Additionally, two kinds of Fermi acceleration mechanisms, the first-order Fermi acceleration (i.e. diffusive) downstream and upstream the shock front [1] and the second-order Fermi acceleration (i.e. stochastic) in the turbulent plasma [5], can be taken under account. Although these two mechanisms produce the required power-law particle spectrum $N(E) \propto E^{-\sigma}$, and in the non-relativistic regime our understanding is certainly more straightforward, questions still remain regarding the role of both mechanisms at work to the produced particle spectra and attained energies, in the relativistic regime. Albeit one can neglect the second-order Fermi mechanism when calculating the particle spectra right at a shock front, it is nevertheless not appropriate to neglect its effect on the spectrum, for example, of radiating particles (e.g. electrons) in astrophysical shocks further away from the shock front downstream. In this work the diffusive and stochastic particle acceleration behaviour will be examined for precursor, relativistic, parallel and perpendicular shocks using Monte Carlo test-particle simulations.

2. Particle acceleration and precursor shocks
The actual sources of particle acceleration are the shocks and plasma turbulence in the relativistic jets of Active Galactic Nuclei (AGN) due to high super-alfvenic plasma speeds. Observations of electron synchrotron radiation in the radio regime indicate that relativistic shocks of boost factors $\Gamma = (1 - V^2/c^2)^{-1/2} \geq 10 - 50$ are present in the jets of AGN [2].
It has been shown that over a limited momentum range the non-relativistic time scale for acceleration of particles can be expressed as \( t = \frac{\kappa}{V_1 V_2} \left[ \kappa_1 V_1 + \kappa_2 V_2 \right] \) where, 1 and 2 refer to upstream and downstream side of the shock, \( V \) is the flow velocity, the diffusion coefficient is \( \kappa = (1/3) \lambda v \), where \( \lambda \) is the particle’s scattering mean free path and \( v \) its velocity, \( \sim c \) [4]. In relativistic cases though it has been shown that the acceleration rate can be decreased resulting in a ‘speed-up’ of the process, as is shown in e.g. [6], [7].

In the second-order Fermi mechanism (stochastic) [5], one assumes collision-less magnetised plasmas and in the observer-frame individual test-particles are reflected by magnetic-mirrors associated with irregularities in the turbulent magnetised media, following stochastically a net energy gain. When one transforms back into the wave-rest frame one finds that there is no change in energy of particles (i.e. collision-less elastic scattering) but the direction of cosmic rays is randomised by the wave-particle collisions, and so forth. If particles remain in the acceleration region for time \( t \) then this leads to a power law distribution of the particles such as \( N(E) \propto E^{-\sigma} \) where \( \sigma = 1 + 1/\alpha t \) and \( \alpha \propto (V/c)^2 \), with an average energy gain, \( < \Delta E/E > = (V/c)^2 \).

The theory of first-order Fermi (diffusive) acceleration [1], is about a mechanism where cosmic rays gain an amount of energy by crossing a shock front -formed in a super-Alfvénic plasma flow- in consecutive cycles, while scattering off the irregularities of the magnetic field frozen into the plasma media. For the non-relativistic regime, the diffusive acceleration mechanism can produce particle momentum distributions as \( f(p) \propto p^{-\sigma} \) with spectral index \( \sigma \) which depends only on the compression ratio of the shock, \( r = V_1/V_2 \), as \( \sigma = 3r/(r - 1) \). Nevertheless in the past it was shown (e.g. [12] [9]) that in relativistic shocks \( \sigma \) is inconstant, being sensitive to shock parameters such as upstream velocity, scattering mode, magnetic field strength and inclination. For example it was shown that relativistic oblique and parallel shocks result in flatter particle power-law distributions than what their non-relativistic counterparts e.g. [10].

Furthermore, in a non-relativistic modified shock - i.e., of a finite shock thickness \( L = \kappa/V \)- it was shown that the acceleration efficiency drops as the thickness increases (e.g., [11] [13]). Drury et al. [3] showed for the non-relativistic case that the resulting spectral index as a function of shock thickness and compression ratio can have a simple analytical solution, whereas in relativistic cases matters get more complicated (e.g. [11]). It was also shown that the spectral index \( \sigma \) tends to the well known step-shock limit when the shock thickness approaches zero and the high energy part of the spectrum is a power-law even when the transition is large compared to mean free path of the accelerated particles. It was found that the spectral index \( \sigma \) depends on the thickness of the transition region and the compression ratio can be expressed as, \( \sigma = \frac{3V_1}{V_1 - V_2} \left( 1 + \frac{1}{\xi \left( \frac{V_1}{V_2} - 1 \right)} \right) = \frac{3r}{r - 1} \left( 1 + \frac{1}{\xi \left( r^{-1} - 1 \right)} \right) \). Here \( \xi = 1 \left( 1 + \gamma c \right) \) is a parameter inversely proportional to the shock thickness \( \left( \xi \propto L^{-1} \right) \), where \( \gamma c \) is the adiabatic index of the cosmic-ray gas. So in principle, the last equation about \( \sigma \) shows, given a known \( r \), that the efficiency of acceleration is proportional to the thickness of the shock. As [11] analytically showed for the relativistic case, the spectral index increases linearly in respect to the shock width, a trend that will be also shown numerically here.

3. Simulations
We modified the established test-particle Monte Carlo code described extensively in [9], for calculating spectra and acceleration rates for thick relativistic, parallel and perpendicular shocks, monitoring the acceleration rates and the produced spectral index of the differential spectrum of the accelerated particles. A large number of relativistic test-particles (i.e. of negligible mass), \( N_t = 10^3 \), was injected upstream a shock of width \( L \), allowing shock Lorentz factor values of \( 10 \leq \Gamma \leq 50 \), for direct comparison with previous work on thin relativistic shocks, and as an application to relativistic shocks observed in AGN jets. The width of the shock was given values of \( L = 100 \lambda, 10 \lambda \), or no width was assumed, allowing fine pitch-angle scattering within the precursor region as \( \theta < 1/\Gamma \) -assuming high turbulence- and \( \theta < 10/\Gamma \) for the
**Figure 1.** Spectral indexes for diffusive and stochastic acceleration in parallel shocks with shock widths $L=10\lambda$, $100\lambda$ and no width, for comparison purposes, versus shock speed. All the values shown in the plots were measured at the shock-rest-frame at the downstream side, at a distance $D=250\lambda$ from the precursor area.

**Figure 2.** The acceleration time ratio of the simulation time to the theoretical acceleration time versus the shock Lorentz factor. $L$ denotes shock thickness expressed in mean free paths ($\lambda$).
upstream and downstream shock regions. For extensive discussion on the pitch angle scatter mode in relativistic shocks see [9]. The scattering off the magnetic fluctuations was simulated by making small random displacements of the tip of the particle’s momentum vector. If $\theta$ (initial pitch angle) is the angle between the velocity $v$ of the particle and the magnetic field $B$ then $\cos \theta' = \cos \theta \cos \delta \theta + \sin \delta \theta \sqrt{(1 - \cos^2 \theta)} \cos \phi$, where $\phi \in (0, 2\pi)$. Since in the simulations we assume stochastic acceleration as well, in the code algorithm we allow the particles in the downstream region of the shock to scatter twice, using a random number generator, for each time step until reaching a far point from the precursor area at a distance $D = 250\lambda$. This means that instead of a single scattering (i.e. for the diffusive mechanism) off the plasma frozen-in centres, the process of the double scattering simulates the condition of a particle scattered in a forward-fluid-rest frame and immediately after in a backward-fluid rest frame. No losses are taken into account at this stage, assuming protons in an environment of low photon fields or mild enough magnetic fields, most likely to be found in tenuous AGN jets, far downstream the AGN black hole. Fully relativistic Lorentzian transformations (reference frames i.e. shock-rest frame, fluid-rest frame, E=0 frame) are applied as extensively discussed in [7]. All the values shown in the plots were measured at the shock-rest-frame at the downstream side immediately after escaping the downstream boundary at $D = 250\lambda$ or by reaching a fixed sufficient maximum energy.

The simulation results are given in the five graphs of figures 1-2, where spectral indexes and acceleration rates are shown, versus shock Lorentz factors, for parallel or perpendicular shock inclinations and precursor widths ($L$) or no widths, for appropriate comparison purposes. Below the concluding remarks of the results are given.

4. Results - Conclusions

The impact of precursor (thick) relativistic shocks on the produced particle distributions was investigated, and in addition two acceleration mechanisms were allowed to occur, the first- and second-order Fermi, using Monte Carlo test-particle numerical simulations, as an application to relativistic shock environments observed in AGN jets. We compared the results with their thin relativistic counterparts (an extensive study for thin relativistic shocks is given in [9], [10]). The results conclude as follows:

(i) Relativistic precursor (thick) shocks give steeper spectral indexes in contrast to their thin relativistic counterparts.

(ii) A speed-up effect of acceleration, firstly observed by [7] in thin relativistic shocks, still holds for precursor relativistic shocks but not as strongly.

(iii) The parallel thick shocks seem to be more efficient accelerators than perpendicular ones, following the trends of thin relativistic shock acceleration of [9].

(iv) When two kinds of acceleration mechanisms occur (first- and second-order Fermi) simultaneously downstream, the resulting particle spectra have comparable particle distributions to the sole first-order mechanism for parallel shocks, but flatter distributions for the perpendicular ones.

These results could shed further light into understanding irregular or flat x-ray and gamma-ray spectra emitted by accelerated electrons or protons in blobs or shocks of AGN jets (e.g. M87) or decelerating shocks in Gamma Ray Bursts.

References
[1] Bell A R 1978a MNRAS 182 147
[2] Biermann P L and Strittmatter P A 1987 ApJ 322 643
[3] Drury L O’C Axford W I and Summers D 1982 MNRAS 198 833
[4] Drury L O’C 1983 Rep. Prog. Phys. 46 973
[5] Fermi E 1949 Phys. Rev. 75 1169
[6] Lieu R and Quenby J J 1990 ApJ 350 692
[7] Meli A and Quenby J J 2003b APh 19 649
[8] Meli A and Biermann P L 2006 A&A 454 687
[9] Meli A Becker J and Quenby J J 2008 A&A 492 323
[10] Meli A 2011 Astr. Sp. Sc. 7 287
[11] Schneider P and Kirk J G 1989 A&A 217 344
[12] Stecker F W Baring M G and Summerlin E J 2007 ApJ 667L 29
[13] Virtanen J J P and Vainio R 2005 A&A 439 461
[14] Zank G P Axford W I and McKenzie J F 1990 A&A 233 275