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PARTICLES ACCELERATION AT RELATIVISTIC SHOCKS AND HIGH ENERGY ASTROPHYSICS

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Abstract. High energy astrophysical phenomena stem from the generation of powerful flows emanating from Super Nova explosions, Gamma Ray Bursts, from ejections in the environment of Black Holes or Neutron Stars that lead to the formation of very strong shocks where particle acceleration takes place. The new developments in these issues are based on the interdependence between the shock structure, the generation of supra-thermal particles and the generation of turbulence. This view started with the studies of Super Nova Remnants, both with X-ray observations and with theoretical investigations, that concluded that the magnetic field is largely amplified by MHD instabilities in the precursor. It is thought, and numerical simulations support that view, that the penetration of supra-thermal particles in the shock precursor generates a magnetic turbulence which in turn produces the scattering process needed for particle acceleration through the Fermi process. This successful development inspired similar investigations for the termination shock of Gamma Ray Bursts. However in ultra-relativistic shocks, difficulties arise with the transverse magnetic field that puts a limitation to particle penetration upstream and that drags particles in the downstream flow and makes shock recrossing difficult. It turns out that only fast enough micro-turbulence can make the Fermi process operative when its level is high enough. This very challenging requirement can nevertheless be fulfilled naturally, as proved by recent numerical simulations. These points are briefly discussed in the presentation and astrophysical consequences are drawn. In particular, it is shown that ultra-relativistic shocks are very efficient electron accelerators and radiation emitters, but poor proton accelerators. It turns out that mildly relativistic shocks inside relativistic flows are better candidates for the generation of UHE-Cosmic Rays. The acceleration performance depends essentially of two parameters: the conversion factor of incoming energy at a shock into magnetic turbulence (this number is provided by the numerical simulations) and the jet power. The Pierre Auger Observatory suggests that the UHECR spectrum is enriched with heavy elements at high energies. What we know about the closest Radio-jets, as those of Centaurus A, together with the theoretical view, indicates that UHECRs can be accelerated up to a few $Z \times 10^{18} eV$, and iron nuclei (Z=26) from these nearby radio galaxies can populate the UHE-Cosmic Rays, as long as they are not photo-dissociated. Nevertheless a significant proton contribution can come from GRB internal shocks as well.

Keywords: high energy astrophysics, Fermi acceleration, turbulence, UHE-cosmic rays, SNRs, GRBs, jets

1 Introduction

Strong shocks occurring in astrophysical flows often generate power law distributions of very high energy particles. This is the origin of most high energy phenomena in astrophysics. The favored mechanism for that supra-thermal particle generation is the famous Fermi process. It works with the scattering of high energy particles off magnetic disturbances that allows them to cross the shock back and forth and thus to gain energy. Many works have been done in the 80-ties and 90-ties by assuming a pre-existing magnetic turbulence. However, it turns out that the pre-existing turbulence is generally not strong enough to account for the acceleration performance. The X-ray observations with the satellites XMM and Chandra of Super Nova Remnants (Cassam-Chenaï et al. 2004) have stimulated the studies of particle acceleration at shocks by revealing an important fact, namely that the magnetic field is largely amplified in the vicinity of the forward shock. New developments of the theory of magnetic field amplification by Cosmic Rays have shown that the penetration of accelerated

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particles in the shock upstream flow can generate a magnetic turbulence that reaches a level much larger than the intensity of the ambient mean field (Bell 2004; Pelletier et al. 2006). In producing turbulence the cosmic rays component loses a fraction of its global energy but increases the maximum energy of its spectrum. Roughly the maximum energy achieved by the Fermi process is close to $\epsilon_{max} = Ze\bar{B}r_s$, where r_s is the shock radius (typically of a few pc at the beginning of the Sedov phase) and $\bar{B}$ is the rms turbulent field that can reach an intensity of few hundreds of μ Gauss, much larger than the value of $2-3\,\mu$ Gauss of the ambient magnetic field in the Galaxy, which allows Super Nova Remnants to generate cosmic rays that cover the various "knees" of the spectrum from the proton knee around $10^{15}-10^{16}$eV up to the iron knee 26 times higher. According to theory and numerical simulations, one expects that a SNR shock converts 10 percent of its incoming energy flux into cosmic rays and a few percent into magnetic turbulence.

These results incited similar investigations for the termination shock of GRBs with the expectation of getting a much larger efficiency and of solving the enigma of UHE-Cosmic Ray generation. However several difficulties raised in the physics of relativistic shocks. Very encouraging results were obtained at the beginning of the century which extended the theory of Fermi process to the case of relativistic shocks and predicted the formation of a power law energy spectrum with an index $s = 2.2 - 2.3$ and an acceleration time as fast as the Larmor time (Gallant et al. 1999; Kirk et al. 2000; Achterberg at al. 2001; Bednarz & Ostrowsky 1998; Ellison & Double 2002; Pelletier 2003). But disappointment came once the effect of the ambient magnetic field had been taken into account, because it inhibits the Fermi process even when one considers a strong Kolmogorov turbulence (Niemiec et al. 2006; Lemoine et al. 2006).

In the following, it will be shown how the paradigm of the three interdependent aspects of collisionless shock physics works successfully in the absence of any mean field: structure with a partial reflection on a barrier, supra-thermal particle generation, magnetic turbulence generation. Then the scattering issue in the presence of a mean magnetic field will be addressed and the requirement for circumventing the inhibition effect will be stated. Then an unusual fact in astrophysics will be emphasized, namely the necessity of considering some unavoidable micro-physics, that turns out to be crucial not only for the relativistic shock formation but also for making the Fermi process operative and producing high energy particles. The termination shocks of Gamma Ray Bursts will be discussed together with the determination of its performance for electron acceleration and gamma-ray emission, and for proton acceleration. Finally the generation of UHE-Cosmic Rays will be addressed.

2 Successful Fermi process at very low magnetization

The most favored process for the generation of supra-thermal power law distributions is the Fermi process at shocks. The plasma flow that experiences a shock is supposed to carry a frozen in turbulent magnetic field under astrophysical conditions. High energy particles (some injection mechanism is expected at non-relativistic shocks) scatter off magnetic perturbations with a mean free path much larger than the shock thickness, so that they can cross the shock front back and forth. They undergo elastic interactions with magnetic disturbances with respect to their proper frame, however upstream magnetic perturbations move forward faster than downstream ones, and thus a particle that undergoes a Fermi cycle– i.e. a cycle upstream-downstream-upstream or downstream-upstream-downstream – because of its scattering, gains energy.

At a non-relativistic shock of speed, $\beta_s = V_s/c \ll 1$, the average gain per cycle is small, $G = 1 + \frac{4}{3}\frac{r-1}{r}\beta_s$ (where r is the compression ratio, that reaches the value 4 when the shock is adiabatic and strong). However this is compensated by a large number of shock crossings; indeed the escape probability (i.e. the probability for a particle to be entrained by the downstream flow and to not come back to the shock front) is weak, $P_{\rm esc} = 4\beta_s/r$; the return probability $P_{\rm ret}$ is thus large. A power law distribution of energy is set up with an index that is a simple function of the compression ratio, in the non-relativistic case:

$$s = 1 - \frac{\ln P_{\rm ret}}{\ln G} \simeq 1 + \frac{3}{r-1} \ . \tag{2.1}$$

Strong adiabatic shocks provide a particle spectrum with an universal index, $s \simeq 2$, which is modified by losses, radiation losses for the electrons, expansion or escape for protons. For instance protons accelerated in a Super Nova Remnant gain energy until their Larmor radius becomes larger than the shock radius during the Sedov phase, which leads to $\epsilon_{max} = Ze\bar{B}r_s$, where $\bar{B}$ is the rms field intensity at the shock. The spectrum is then steepened by the effect of diffusive propagation and escape of particles from the Galaxy.

A sizable fraction of the incoming energy flux is converted into cosmic ray pressure:

$$P_{\rm cr} = \xi_{\rm cr}\rho_u V_s^2 \text{ with } \xi_{\rm cr} \sim 0.1 \ . \tag{2.2}$$

The successive Fermi cycles produce a precursor of supra-thermal particles (mostly protons) of large extension (the diffusion length increases with the particle energy) and this penetration in the upstream medium (the ambient medium for an external shock) triggers an MHD turbulence through two types of streaming instability, one is resonant and has been considered for many years (see for instance Kenzie & Völk 1982), the other is non-resonant and has been considered more recently (Bell 2004; Pelletier et al. 2006). That latter case is quite interesting, first because it is a simple and robust mechanism based on the supplementary Lorentz force associated with the plasma current that compensates the cosmic ray current, second because it leads to a turbulent field of large intensity; indeed this latter can become much larger than the ambient magnetic field. The theory indicates that the fraction of incoming energy flux converted into magnetic energy can reach $\xi_B \sim \beta_s$, which is a few percent in Super Nova Remnants, where one defines

$$\frac{\bar{B}^2}{4\pi} = \xi_B \rho_u V_s^2 \ . \tag{2.3}$$

A very important remark is that the efficiency of the Fermi process depends on the efficiency of the scattering process. By the way, the mechanism of Fermi acceleration is a simple process, but the scattering is the main issue for particle acceleration.

As for relativistic shocks, there are similarities and some differences with the non-relativistic ones, as summarized in Table 1. There are strong arguments that there is a significant generation of magnetic turbulence at the external shock of a Gamma Ray Burst (Li & Waxman 06) and there is an obvious power law distribution of ultra-relativistic electrons that synchrotron radiate, with an index compatible with the theory of Fermi process at ultra-relativistic shocks ($s = 2.2 - 2.3$). The ambient magnetic field is very low and at first approximation can be neglected. A remarkable work was published in 2008 by A. Spitkovsky(Spitkovsky 2008) that fully validates the paradigm that combines three fundamental processes: the formation of a collisionless relativistic shock front with reflected particles, the generation of magnetic turbulence and the generation of a power law distribution through Fermi process. This is a PIC (Particles In Cell) simulation of the development of a collisionless shock in a pair plasma (electrons and positrons) that runs with a Lorentz factor Γ_s of a few tens ($\Gamma_s \equiv (1-\beta_s^2)^{-1/2}$). The flow of reflected particles interacts with the flow of passing particles leading to streaming type instabilities, and the Weibel branch of instability describes the formation of intense small scale magnetic filaments. The relevant scale of the physics is the inertial length (or skin depth) $\delta \equiv \frac{c}{\omega_p}$. The spatial growth of the magnetic micro-turbulence produces a partial reflection of the incoming particles, which allows the formation of a shock front, and self-consistently, the reflected particles generate the required level of micro-turbulence. Similarly as the non-relativistic case, conversion parameters $\xi_{\rm cr}, \xi_B$ can be defined in the ultra-relativistic case:

$$P_{\rm cr} = \xi_{\rm cr} \rho_u \Gamma_s^2 c^2 \tag{2.4}$$

$$\frac{\bar{B}^2}{4\pi} = \xi_B \rho_u \Gamma_s^2 c^2 \tag{2.5}$$

And the simulations indicate that $\xi_{\rm cr} \sim 0.1$ and $\xi_B \sim 1 - 10\%$, similarly to the non-relativistic case. However a parameter scan needs to be done. Actually the physics is being developed in the two extremes, non-relativistic and ultra-relativistic, that allows some approximations, but not yet in the case of mildly relativistic shocks. The supra-thermal spectrum obtained in the simulation is close to the theoretical prediction with an index $s \simeq 2.4$.

Table 1. Comparison non-relativistic shocks and relativistic shocks.

At non-relativistic shocks	**At relativistic shocks**
weak escape probability	significant escape probability
many cycles of weak energy gain	few cycles of large energy gain
power law distribution ϵ^{-s} with $s \simeq 2$	power law distribution ϵ^{-s} with $s \sim 2.3$
upstream distribution weakly anisotropic	upstream distribution strongly anisotropic
partial reflection at shock front	partial reflection at shock front
generation of MHD turbulence upstream	generation of e.m. micro-turbulence upstream
acceleration time $t_{acc} \sim \tau_s/\beta_s^2$	acceleration time $t_{acc} \sim \tau_s$

Similar results were obtained later with PIC simulation involving a plasma of electrons and ions of $10 - 100 m_e$ (Sironi & Spitkovsky 2009).

3 Opening phase space with finite magnetization

Many astrophysical shocks form in a plasma having a significant magnetization. The physics becomes more complex with a finite ambient mean field; it is controlled by the important "magnetization" parameter σ:

$$\sigma \equiv \frac{B_{t,f}^2}{4\pi\rho_u\Gamma_s^2c^2} = \frac{B_0^2\sin^2\theta_B}{4\pi\rho_u c^2} \ , \tag{3.1}$$

where B_0 is the field measured in the upstream flow frame (generally the ambient field), and $B_{t,f}$ is the transverse component of the mean field measured in the front frame. Like in non-relativistic shocks, the angle of the field lines with respect to the shock normal is very important. But whereas most non-relativistic chocks are in the so-called "sub-luminal" configuration, i.e. that the angle θ_B is not too close to 90^0 and thus particles can flow along the field lines, in ultra-relativistic shocks, it suffices that the field angle θ_B be larger than $1/\Gamma_s$ to stop the motions of particles returning upstream. A generic ultra-relativistic shock is thus "supra-luminal", and the magnetic field in the front frame can be considered as almost perpendicular, because its transverse component is amplified by a factor Γ_s. This field orientation is a serious hindrance for the development of Fermi cycles. A particle that enters the downstream flow of speed $c/3$ is dragged by the frozen in magnetic field and cannot easily come back upstream; it can be shown that it can come back just one time (Lemoine et al. 2006). Once upstream, it eventually comes back downstream, but in a subset of phase space that does not allow it to make a second cycle. It might be thought that a strong turbulence could make an efficient scattering allowing it to make several cycles. But an usual turbulent MHD state with a large scale coherence length behaves like an ordered magnetic field for such particles, because their penetration length upstream ($\ell_p = m_pc^2/\Gamma_s eB_0$, measured in co-moving upstream frame) is much shorter than the coherence length of turbulence (Lemoine et al. 2006). The coherence length ℓ_c is formally defined as the range of the field correlation; the field self-correlation function being $C(r)$, assuming an isotropic turbulent state (it can easily be properly modified in the case of anisotropic turbulence):

$$\ell_c \equiv \int_0^\infty C(r)dr \ ; \tag{3.2}$$

this can be expressed in term of an integral over the turbulence spectrum, and one finds that for a spectrum in $k^{-\beta}$ the correlation length is located in the large wavelengths part for $1 < \beta < 2$, as is the case of a Kolmogorov spectrum; for $0 \leq \beta \leq 1$, the coherence length is in the shortest wavelengths part of the spectrum.

Moreover the expected duration of the cycle would be much shorter than the eddy turn over time of large scale vortices. The requirement for a scattering process off magnetic turbulence is quite challenging (Pelletier et al. 2009), for not only the intensity of the turbulent field must be much larger than the mean field, but also the coherence length must be shorter than a Larmor radius. When a scattering process develops, the opening of phase space for getting an operative Fermi process is achieved if the scattering frequency is larger than the Larmor pulsation in the mean field. Short scale turbulence leads to a scattering frequency $\nu_s \propto \epsilon^2$, whereas the Larmor pulsation $\omega_L \propto \epsilon$; thus the range of particle energies for which the phase space is unlocked and Fermi process operative, is such that $\epsilon < \epsilon_{scatt} \equiv Ze(\bar{B}^2/B_0)\ell_c$.

The investigation of ultra-relativistic collisionless shocks started at the beginning of the 90-ties with J. Arons and co-workers, in the case of high magnetization ($\sigma > 0.03$ say). The results, obtained mostly in 1D-PIC simulations, revealed the interesting physics of those shocks (Gallant et al. 1992;). The loop of particles reflected by a magnetic barrier is responsible for a Synchrotron Maser Instability that generates an intense electro-magnetic wave propagating upstream and downstream. The shock radiates a coherent wave upstream with an energy flux, which corresponds to the conversion of the incoming energy by a factor $\sim 0.1\sigma$. The downstream wave is absorbed at synchrotron resonance and heats the plasma that displays a Maxwell-Jüttner distribution. These studies have been done for electron positron plasma first, which is relevant for the termination shock of the pulsar wind nebulae. When the plasma is composed of electrons and protons, the upstream coherent waves exerts a ponderomotive force on electrons which locally separates them from protons and so generates an electrostatic wake-field. The electrons undergo relativistic oscillations in this wave-field and are thus strongly heated until equipartition with protons that are slowed down. These physics has been confirmed by more precise 2D-PIC simulations, performed recently (Sironi & Spitkovsky 2011).

At lower magnetization, nothing happens except the thermalization of protons ($T_p \simeq 0.2\,\Gamma_s m_pc^2$), until one comes to a very low critical value of the magnetization where the Fermi process starts. Actually one needs a very low magnetic field to get a penetration length of supra-thermal particles upstream large enough for having a significant interaction of those particles with the incoming plasma and having a growth of micro-instabilities.

Fermi process works with the magnetic component of micro-turbulence at inertial scale $\sim \delta \equiv c/\omega_{pi}$. In principle it starts at even smaller scale, the inertial scale of electrons, however electrons are efficiently heated by the electric component of micro-turbulence and then the precursor becomes composed of electrons and protons of similar mass, like a pair plasma. This is a very interesting outcome that simplifies these physics which rapidly evolves towards physics similar to that occurring in a pair plasma. Thus the PIC simulations developed in a pair plasma are also valuable to understand the physics of shocks in electron-proton plasmas. Then a distribution function displaying a thermal part and a supra-thermal part with a power law is obtained.

The transition towards the Fermi process is determined by the micro-instabilities that can grow when the upstream penetration of reflected particles is long enough. The fastest instabilities (Buneman instability, Oblique Two Stream instability, see Bret et al. (2005)) seem to essentially pre-heat the incoming electrons almost up to equipartition with protons. However more simulations are necessary to clarify this important point. Also laboratory experiments are envisaged to check the capability of the micro-turbulence excited by a beam of protons to efficiently heat the electron population (V. Tikhonchuk). The generation of magnetic micro-turbulence by Weibel instability, which is also studied in laboratory experiments, is thought to be the main ingredient to form the collisionless shock and to produce the Fermi process; however this is also under study by PIC simulations. The generation of magnetic micro-turbulence occurs when the magnetization parameter goes below the following critical value (Lemoine & Pelletier 2009), as confirmed by numerical simulations (Sironi & Spitkovsky 2011):

$$\sigma < \sigma_{crit} \equiv \frac{\xi_{cr}}{\Gamma_s^2} \ . \tag{3.3}$$

Numerical simulations show that the level reached by that Weibel turbulence is such that $\xi_B = 1 - 10\%$, which insures shock formation and Fermi process. Then there exists a large energy range for particle scattering when $\sigma \ll \xi_B^2$.

The main issue with Fermi process based on scattering off micro-turbulence is that the scattering frequency decreases as ϵ^{-2}. The performance of Fermi process at non-relativistic shocks is that the scattering off large scale, say Kolmogorov, turbulence is fairly low (much weaker than the Larmor pulsation in the mean field) but decreases slowly, like $\epsilon^{-1/3}$. Thus if we compare the Fermi process at relativistic shocks with the process at non-relativistic shock, this is like the hare and the tortoise: the scattering, and thus the acceleration rhythm, at relativistic shocks is very fast at low energy and decreases rapidly as energy increases, whereas, at non-relativistic shocks, it is slow at low energy but continues at higher energies with a moderate decline of its efficiency.

4 Electron acceleration at relativistic shocks and radiation (GRBs)

The external shock that starts the afterglow emission of Gamma Ray Bursts (GRBs) gives rise to an efficient acceleration of electrons. If they thermalize with protons (as reasonably expected), their temperature is already very high at the beginning of the afterglow:

$$T_e \sim T_p = \frac{\Gamma_s}{3\sqrt{2}} m_p c^2 \ ; \tag{4.1}$$

which corresponds to a few tens of GeV. Intense short scale magnetic turbulence develops because the interstellar magnetization parameter is very low, $\sigma \sim 10^{-9}$, whereas the critical value $\sigma_{\rm crit} \sim 10^{-6}$, with $\Gamma_s \sim 300$.

What kind of radiation can be expected in such small scale field, much more intense than the mean field? This depends on a so-called “wiggler” parameter a:

$$a \equiv \frac{e\bar{B}\ell_c}{m_e c^2} \sim \xi_B^{1/2} \Gamma_s \frac{m_p}{m_e} \ . \tag{4.2}$$

This parameter measures the capability of the magnetic force to deviate a relativistic electron of Lorentz factor γ by an angle $1/\gamma$ (this is the reason for which γ does not appear in the definition). When $a > 1$ the magnetic field produces a single deviation of the electron in the emission cone of half angle $1/\gamma$, whereas when $a < 1$ the electron can undergo several wiggles in the emission cone. When a is large, the emission behaves like a normal synchrotron radiation in a mean field, except that there is no polarization. When a is small, the emission is of “jitter” type (Medvedev 2000). Thus the emission caused by shocked and accelerated electrons at a relativistic shock is “synchrotron-like”, and the analysis of the emitted spectrum provides a diagnosis of the magnetic turbulence.

It is quite remarkable that there exists an almost universal energy limit for the electron radiating in the intense small scale field (in agreement with (Kirk & Reville 2010):

$$\gamma_{\max} \sim (\frac{4\pi e^2 \ell_c}{\sigma_T m_e c^2})^{1/3} \sim (\frac{m_p/m_e}{n r_e^3})^{1/6} \sim 10^6 \ . \tag{4.3}$$

The corresponding maximum energy for the emitted photons is

$$\epsilon_{\gamma,\max} = \sqrt{\pi}\xi_B \frac{\Gamma_s^2}{\gamma_{\max}} \frac{m_p c^2}{\alpha_f} \simeq 2 \times (\frac{\xi_B}{10^{-2}})^{1/2} (\frac{\Gamma_s}{300})^2 \mathrm{GeV} \ . \tag{4.4}$$

Thus a single synchrotron-like spectrum extending up to several GeV, even possibly a few tens, can be expected and thus is compatible with observations. So the performance of relativistic shocks for electron acceleration and radiation is excellent. The conversion factor into radiation is $\xi_{\mathrm{rad}} \sim \xi_B \sigma_T n_0 r_s < \gamma_e^2 >$, and at the beginning of the afterglow $\xi_{\mathrm{rad}} \sim \xi_B \sim 1 - 10\%$.

5 Relativistic shock and supra-thermal protons in GRBs

As mentioned previously, because the scattering time and thus the acceleration time increase with ϵ^2, the Fermi process at relativistic shocks is not expected to be an efficient accelerator of protons towards the highest energies. That acceleration is limited by expansion losses of time scale r_s/c in observer frame. At the terminal shock of GRBs at the beginning of the afterglow, the maximum energy achieved is

$$\epsilon_{\max} = Z\Gamma_s^{3/2} \xi_B^{1/2} \sqrt{\frac{r_s}{\delta_i}} m_p c^2 \sim Z \times 1.7 \times 10^7 \mathrm{GeV} \ . \tag{5.1}$$

This has to be compared with the scattering limit $\epsilon_{\mathrm{scatt}} = Z \frac{\xi_B}{\sqrt{\sigma}} \Gamma_s^2 m_p c^2 \sim Z \times 3 \times 10^7$ GeV. These numbers are not much better than the Hillas limit in the ambient mean field: $\epsilon_{\mathrm{Hillas}} = Z\Gamma_s e B_0 r_s \sim Z \times 0.3 \times 10^7 GeV$. Thus although an energy of order 10^{16} eV is achieved, which is something, the result is far from the goal of UHE-range. The relativistic shocks are poor protons or nuclei accelerators.

6 About the origin of UHE-Cosmic Rays

Precise performances of mildly or sub-relativistic shocks are not yet known and require more numerical simulations. However some reasonable guess are permitted by extrapolating what we know about the two extremes: non-relativistic and ultra-relativistic shocks. The main guess is that we can expect a magnetic field amplification at shocks with a conversion factor $\xi_B = 1 - 10\%$, occurring in MHD regime without severe limitation due to the super-luminal configuration, especially for oblique internal shocks (termination shocks in the hot spots of FR2 jets might be super-luminal). These assumptions can be applied to internal shocks of AGN jets (in particular in Blazars jets), and to internal shocks of GRBs; the limitation of the acceleration of protons and nuclei is essentially the escape of particles at the edge of the flow. For a relativistic jet of radius r_j, with a large bulk Lorentz factor Γ_j and a kinetic power $P_{jet} \simeq \rho_0 c^3 \Gamma_j^2 \pi r_j^2$ (ρ_0 being the co-moving density), the maximum energy given by assuming acceleration at the Bohm limit, i.e. an acceleration timescale $t_{\mathrm{acc}} = r_L/c$ in the co-moving frame, the maximum energy in the observer frame reads (in agreement with Lemoine & Waxman 2009):

$$\epsilon_{\max} \simeq \Gamma_j Z e \bar{B} r_j \simeq Z \times 10^{19} \left(\frac{\xi_B}{10^{-2}} \frac{P_{\mathrm{jet}}}{10^{45}\,\mathrm{erg/s}}\right)^{1/2} \ \mathrm{eV} \ . \tag{6.1}$$

Here we assumed that $\gamma_s(\gamma_s - 1) \simeq 1$ so that $\bar{B}^2/4\pi \simeq \xi_B \rho_0 c^2$.

The jets of FR2 radiogalaxies have a power $P_{\mathrm{jet}} = 10^{44} - 10^{46}$erg/s, hence they might produce UHECRs. GRBs flows carrying internal shocks can be even more efficient accelerators, depending of the duration of the flow for a given energy. For instance, a GRB of apparent isotropic luminosity $P_{jet}/(\theta_j^2/4) \sim 10^{52}$erg/s ($\theta_j$ being the half opening angle of the flow $> 1/\Gamma_j$) with $\Gamma_j \sim 100$ may produce particles with energy as high as $Z \times 10^{21}$eV for a similar conversion factor $\xi_B = 0.01$. Thus mildly or sub-relativistic shocks in a relativistic flow are more efficient accelerators of protons than ultra-relativistic shocks and are excellent candidates for being sources of UHECRs, thanks to the magnetic field amplification at shocks.

Now if we consider FR1-jets, they are less powerful than the FR2, with $P_{jet} = 10^{42} - 10^{43} erg/s$ and they are sub-relativistic. The maximum energy achieved in those jets is one order of magnitude lower than that achieved in FR2-jets. This can be compensated by the generation of UHECRs in the form of iron nuclei (Z=26) For instance, we have fairly precise VLBI measurement of the radius of Centaurus A at several distances from the nuclei, together with estimate of the magnetic field responsible for synchrotron emission; this leads to an estimate of the product $\bar{B}r_j \simeq 2 \times 10^{-3} G \times pc$. The Hillas criterium leads to $\epsilon_{\max} \simeq Z \times 2 \times 10^{18} eV$ (see (Lemoine & Waxman 2009), which is consistent with a significant amplification of the magnetic field at internal shocks. The most recent VLBI map of Centaurus A, done by the TANAMI project, reveals structures in the flow, suggesting internal shocks. The recent data analysis of Pierre Auger Observatory suggests an enrichment of the UHECR spectrum with heavy elements at higher energies and also a possible correlation with Centaurus A. However it is very difficult to understand the observed pattern of anisotropy if one assumes that the observed particles are heavier than hydrogen (Lemoine & Waxman 2009). In this sense, a contribution of protons coming from more remote and more powerful sources appears unavoidable. A recent spectrum fitting ((Aloisio at al. 2011)) strongly suggests that the spectrum displays a proton cut off around $10^{18} eV$ and another one around $3 \times 10^{19} eV$ associated with iron nuclei. Another recent work ((Ptuskin et al. 2011)) strongly suggests that local radio-galaxies can contribute to the UHE spectrum with iron nuclei.

7 Conclusion and prospect

The triangular dependence of collisionless shock structure with a reflecting barrier for a part of incoming particles, with generation of supra-thermal particles and the generation of magnetic turbulence is a successful paradigm that applies to astrophysical shocks, both non-relativistic and relativistic. Numerical and theoretical works are making significant progress for both understanding the physics and providing quantitative results useful for astrophysical investigations. This includes not only the spectrum index and cut off of the distribution of accelerated particles, but also the conversion factors into cosmic rays, magnetic turbulence and radiation. This is the only beginning of these studies, that require more PIC simulations and new types of hybrid codes involving relativistic MHD coupled with PIC codes for cosmic rays.

The new results that have already been obtained with these approaches are important. First the strong amplification of the magnetic field at SNRs received theoretical and numerical support; the astrophysical consequences are interesting, especially for understanding of the galactic contribution of the Cosmic Ray spectrum. Secondly it has been understood and confirmed by PIC simulations that the Fermi process does not work at relativistic shocks with magnetization of order unity, which is supposed to be a frequent situation in high energy astrophysics, as for instance in FR2 hot spots, in Blazars, in Pulsar Wind Nebulae (we will discuss again this point further on). Thirdly the radiation process that takes place in most high energy astrophysical sources is produced by relativistic electrons scattered in an intense short scale magnetic turbulence; this leads to reconsider the radiation physics in this context and to use it as a diagnosis of the magnetic turbulent state.

There are many opened questions in that field, that can be organized as follows.

- We do not understand yet the process of electron heating and also we have to check whether the electron temperature reaches equipartition with the proton one (we recall that in GRB termination shocks, at the beginning of the afterglow, the electron temperature could reach a few tens of GeV!). This will require more PIC simulations. Moreover experiments with powerful lasers are envisaged: intense protons beam can be produced by high energy laser like LMJ in Bordeaux (however still subrelativistic), and it would be possible to look whether triggering electronic turbulence can leads to a thermalization process (V. Tikhonchuk) during the interaction with a target plasma.

- Till now the shock fronts have been considered as stationary, whereas we know from space plasma physics that most shocks are experiencing a reformation process, which has an impact on particle acceleration (Lembège & Savoini 1992). This issue is currently under investigation for relativistic shocks (Lembège, Plotnikov).

- The physics of mildly or sub-relativistic shocks is not yet done. Even if we might draw some hints by knowing what happens in non-relativistic strong shocks and in ultra-relativistic shocks, for which analytical studies can be developed, we need quantitative results. This is important because those shocks are frequently encountered in high energy astrophysics and are probably the sources of UHE Cosmic Rays. Not only PIC, but also Relativistic MHD code (Casse & Marcowith) and special hybrid codes will be useful for these investigations.

- The classification of relativistic shocks as a function of their magnetization is still very recent, and we need to explore more completely the properties of each class. For instance at high magnetization we know that the Fermi process is impossible and that an intense coherent wave is generated. When the plasma is composed of protons and electrons, a wake field is also generated; this has been studied by two simulations only, and one shows a thermalization process only, whereas the other one indicates also the formation of a power law tail. At intermediate magnetization, a simulation says that nothing happens but the thermalization of protons. This needs to be checked by other simulations and other codes. At low magnetization, where micro-turbulence develops together with the Fermi process, many opened questions remain that could be clarified by appropriate codes (PIC and hybrid RMHD+PIC).
- A special investigation of magnetic reconnections occurring downstream a relativistic shock is a new topic, motivated by at least three reasons. First at high magnetization, in Blazars for instance, we can observe power law distributions with an index smaller ($s \simeq 1.5$) than the one predicted by Fermi process. In the termination shock of Pulsar Wind Nebulae (Y. Gallant, private communication), we can also observe broken spectra with a low energy part with an index $s \simeq 1.5$ and a high energy part compatible with a Fermi process with an index $s \simeq 2.2$. It is thought that the hard spectra are produced by reconnections driven by the compression of a relativistic shock. This is particularly relevant in the case of a Pulsar Wind Nebula (Petri & Lyubarsky 2007) because of the striped structure of the flow where the magnetic field changes its orientation periodically. Moreover dramatic gamma-ray flares have recently been observed in the Crab Nebula (Lemoine-Goumard, this meeting).

The new trend in these topics is the important role imputed to micro-physics phenomena, which have a direct astrophysical impact, as this talk is supposed to show. These developments incite some interests in several communities including Space Plasma Physics and Laser-Plasma Physics communities, Astro-Particle and High Energy Astrophysics communities. This is a very stimulating phase of research.

References

Achterberg, A., Gallant, Y., Kirk, J. G., Guthmann, A. W. 2001, MNRAS 328, 393

Aloisio R., Berezinsky V., Gazizov A., 2011, Astroparticle Phys., 34, 620

Bednarz, J., & Ostrowski, M. 1998, Phys. Rev. Lett., 80, 3911

Bell, A. 2004, MNRAS, 353, 550

Bret, A., Firpo, M.-C., Deutsch, C. 2004, Phys. Rev. E, 70, 046401

Cassam Chenaï G.; Decourchelle, A.; Ballet, J.; Hwang, U.; Hughes, J. P.; Petre, R., et al. 2004, A&A, 414, 545

Ellison, D., & Double, G. 2002, Astroparticle Physics, 18, 213

Gallant, Y. A., & , A. 1999, MNRAS, 305, L6

Gallant, Y.A., Hoshino M., Langdon A.B., Arons J., Max C.E. 1992, ApJ, 391, 73.

Hoshino, M., Arons J. 1991, Phys. Fluids B, 3, 818

Kirk, J., Guthmann, A., Gallant, Y., & Achterberg, A. 2000, ApJ, 542, 235

Kirk J., Reville B. 2010, ApJ, 710, 16

Lembège, B., Savoini P. 1992, Phys. Fluids, 4, 3533

Lemoine, M., Pelletier, G. 2003, ApJ, 589, L73

Lemoine, M., Pelletier, G., Revenu, B. 2006, ApJ, 645, L129

Lemoine, M., Waxman E. 2009, JCAP, 11, 009

Lemoine, M., & Waxman, E. 2009, JCAP, 11, 9

Mc Kenzie, J.F., Völk, H.J. 1982, A&A, 116, 191

Medvedev, M. V. 2000, ApJ, 540, 704

Niemec, J., Ostrowski, M., Pohl, M. 2006, ApJ, 650, 1020

Pelletier G., Lemoine M., & Marcowith A. 2006, A&A, 453,181
393, 587

Pétri, J., Lyubarsky Y. 2007, A& A, 473, 683

Ptuskin V.S., Rogovaya S.I., Zirakashvili V.N., 2011, astro-ph, arXiv:1105.4491

Spitkovsky, A., 2008, ApJ, 673, L39

Sironi, L., Spitkovsky, A. 2011, ApJ, 726, 75