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Ultimate energy particles in the Universe/Particules d'énergies ultimes dans l'Univers

Acceleration mechanisms 1: shock acceleration

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Abstract

Acceleration by shock waves is one of the favorite models envisaged to explain the origin of the highest energy cosmic rays. This view was developed in the framework of various astrophysical acceleration sites: hot spots of radio galaxies, clusters of galaxies, jets powered by supermassive black holes, gamma ray burst blast waves, etc. These mechanisms along with their limitations and specific signatures for each type are reviewed. ***To cite this article: M. Ostrowski, C. R. Physique 5 (2004).***

Résumé

Mécanismes d'accélération 1 : accélération par ondes de choc. L'accélération par des ondes de choc constitue l'un des modèles les plus en faveur envisagés pour expliquer l'origine des rayons cosmiques d'énergies extrêmes. Ce point de vue a été développé dans le cadre de multiples mécanismes astrophysiques : points chauds de radio-galaxies, amas de galaxies, jets alimentés par des trous noirs super-massifs, ondes de choc produites par les sursauts gamma, etc. Nous présentons une revue de ces mécanismes, de leurs signatures spécifiques ainsi que de leurs limites. ***Pour citer cet article : M. Ostrowski, C. R. Physique 5 (2004).***

Keywords: UHE cosmic rays; Acceleration mechanisms; Shock waves

Mots-clés : Rayons cosmiques ultra-énergétiques ; Mécanismes d'accélération ; Ondes de choc

1. Introduction

Energetic charged particles can be accelerated in the interstellar or intergalactic medium by interaction with ambient electric fields

$$\delta\mathbf{E} = \frac{\delta\mathbf{u}}{c} \wedge \mathbf{B} \tag{1}$$

generated in space by flow non-uniformities, $\delta\mathbf{u}$, of magnetized plasma carrying the magnetic field consisting – in general – of the regular ($\mathbf{B}_0$) and 'turbulent' ($\delta\mathbf{B}$) components, $\mathbf{B} = \mathbf{B}_0 + \delta\mathbf{B}$. These non-uniformities have compressive character at shocks, the non-compressive one at tangential flow discontinuities or shear layers occurring at boundaries of astrophysical jets or accretion discs, finally involve chaotic velocity fluctuations in volumes filled with magneto-hydro-dynamic (MHD) waves or turbulent wedges. The high amplitude turbulence is expected to accompany the above mentioned large scale flow non-uniformities. In each particular case derivation of considered charged particle energy changes requires integration of its equations of motion in the background electromagnetic field. Below we will shortly review the mentioned acceleration processes in the context of cosmic ray acceleration up to ultra high energies (UHE), above $\sim 10^{19}$ eV.

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In the present review we do not attempt to cover the full literature for the topics presented. Instead, we concentrate on essential physical problems, providing references to selected characteristic publications and review papers only.

2. Acceleration processes at flow non-uniformities of astrophysical plasmas

2.1. Acceleration processes at shock waves

A compressive flow discontinuity at the shock allows for the first order acceleration of energetic particles reflected on both its sides, in the magnetized plasmas approaching each other. The perturbed structure of the background magnetic field leads to particle scattering and randomising their trajectories to enable some particles for successive shock crossings and accompanying regular energy gains. Quite often the particle spectra resulting from such first-order Fermi acceleration take a simple power law form in a wide energy range. For high energy cosmic rays discussed in the present review one can neglect a detailed structure of the shock transition, which is important only for 'low' energy particle injection to the acceleration process and, thus, at high energies, for the spectrum normalization only. It is, however, a free parameter in the discussed test particle models and computations.

Below, we describe shock waves propagating along the mean magnetic field as the 'parallel' waves, and those with velocities inclined at some angles to the field as the 'oblique' waves.

2.1.1. Non-relativistic shocks

For shock waves propagating with non-relativistic velocities, $u_1 \ll c$,[1] velocities of the considered relativistic particles are $v \gg u_1$. In such conditions, in most studied cases, the particle distribution at the shock is nearly *isotropic* and the *spatial diffusion equation* can be applied for its description outside the shock (for a review see, e.g., [1] and [2]). For modelling of the test particle acceleration at high Mach number shocks the mentioned isotropy is the factor responsible for a weak dependence of the resulting energetic particle distribution on physical conditions near the shock. We mean here both the shock velocity, u_1, and the structure of the magnetic field characterized with the mean field value, $\mathbf{B}_0$, its inclination to the shock normal, ψ, and the power spectrum of the wave field, $F(\mathbf{k})$ ($\mathbf{k}$ – a wave vector). The resulting stationary phase space distribution function has a power-law form

$$f(p) \propto p^{-\alpha} \tag{2}$$

in the momentum range not-influenced by the boundary conditions. For the shock compression $R = u_1/u_2$ the spectral index $\alpha = 3R/(R-1)$; i.e., with a value of R only slightly below 4.0 for strong shocks the spectral index α becomes also only slightly above 4.0, equivalent to the energy spectral index $\sigma \equiv \alpha - 2$ slightly above 2.0.

Even within the test particle approach the background and boundary conditions are important (but often known only approximately) factors influencing the spectrum normalization and the upper energy cut-off. For example Ellison et al. [3] used a simple model to show that increasing the mean field inclination at the shock leads to less efficient injection of superthermal particles to the first-order Fermi acceleration process. The role of oblique magnetic field configuration in limiting the characteristic acceleration time scale was discussed by Ostrowski [4], who derived the acceleration time scale in oblique shocks in the form:

$$T_{\mathrm{acc}} = \frac{3}{u_1 - u_2}\left(\frac{\kappa_{n,1}}{u_1\sqrt{\kappa_{n,1}/(\kappa_{\|,1}\cos^2\psi_1)}} + \frac{\kappa_{n,2}}{u_2\sqrt{\kappa_{n,2}/(\kappa_{\|,2}\cos^2\psi_2)}}\right), \tag{3}$$

where the index 'n' denotes quantities normal to the shock and the index '$\|$' those parallel to the magnetic field, and the κ are corresponding diffusion coefficients. The above formula applies only for non-relativistic shocks with $u_1/\cos\psi_1 \ll c$. The terms $\sqrt{\kappa_n/\kappa_\| \cos^2\psi}$ represent the ratio of the mean normal particle velocity to such velocity in absence of the cross field diffusion. As discussed by a number of authors (e.g., [5]) the time scale (3) in some conditions can be much shorter than the one for parallel and/or highly turbulent shocks. The minimum acceleration time scale allowed in oblique shocks is

$$T_{\min} \sim \frac{2r_{g,1}}{u_1} \sim \frac{2r_{g,2}}{u_2}, \tag{4}$$

[1] The indices '1' and '2' indicate quantities measured in the upstream and downstream plasma rest frames, respectively. Additionally, we use the following notation: $v,\ p,\ E,\ \gamma$ indicate the particle velocity, momentum, energy, and the Lorentz factor; $\mathbf{B} = \mathbf{B}_0 + \delta\mathbf{B}$ is the magnetic field consisting of the background regular component $\mathbf{B}_0$ and the component $\delta\mathbf{B}$ representing the local field perturbation due to MHD waves or turbulence, the angle ψ is the mean field inclination to the shock normal $\mathbf{n}$ and the shock velocity projection on the mean field is $u_B = u/\cos\psi$.

where r_g is the particle gyroradius. One should remember that both derivation of Eq. (3) and validity of the above lower limit require small or moderate amplitude of the background turbulence. The limiting minimum acceleration time scale for highly turbulent conditions can be evaluated from Eq. (3) for $\psi = 0$ and $\kappa_n \to \kappa_B = r_g c/3$ (e.g., [6]), as

$$T_{\min}^{\psi=0} \sim \frac{r_g c}{u_1^2} \sim T_{\min} \frac{c}{u_1}. \tag{5}$$

In such shocks one requires the respective upstream and downstream plasma extensions to be larger than a few times the diffusive scale $L_{\rm diff} \approx \frac{c}{u} r_g$ to allow for the same value of the power law spectral index as that defined just after Eq. (2) in terms of the shock compression. The smaller diffusive regions lead to generation of steeper cosmic ray spectra.

2.1.2. Mildly relativistic shocks

The main factor changing characteristics of the acceleration process acting at shocks moving with a substantial fraction of the light velocity, $u_1 \sim c$, is particle anisotropy at the shock ([7]; see [8] for a review and also [9] for recent modelling). For highly turbulent ($\delta B \gg B_0$) conditions near the shock the magnetic field configuration at the shock can be considered equivalent to the parallel one and the spectral indices of accelerated particles are quite close to the ones derived from the non-relativistic formula given after Eq. (2) [10], at least in a limited energy range. The situation changes drastically for oblique shocks, where acceleration conditions – in particular the sub- or superluminal field configurations ($u_B <$ or $> c$, respectively) – can lead to qualitative variations of the resulting cosmic ray spectra (e.g., [11–13]).

In the presence of low amplitude turbulence, in subluminal shocks an anisotropic distribution of particles allows for many successive reflections of energetic upstream particles from the compressed magnetic field downstream of the shock. Each reflection increases particle energy. The involved acceleration process results in forming extremely flat particle spectra with the spectral index $\alpha \approx 3.0$. Additionally, in such a 'snow plough' scenario particle density upstream of the shock can be much higher than the one behind the shock [12]. Contrary to that the superluminal shocks lead to acceleration of the upstream particles through a single compression at the shock if there is not enough MHD turbulence to allow efficient particle cross field diffusion [13].

Increasing the turbulence amplitude in the acceleration model leads to steepening of the flat spectra in the subluminal shocks and to flattening of the steep spectra in the superluminal ones, to approach the parallel shock limit at $\delta B \gg B_0$. All these factors lead to substantial dispersion of the resulting spectral indices and the associated acceleration time scales, $T_{\rm acc}$. For illustration of the dependence of α and $T_{\rm acc}$ on the background conditions, in Fig. 1 we present results of numerical simulations of the acceleration process at oblique shocks propagating with velocity $u_1 = 0.5c$ (from [14]). In the figure the border between sub- and superluminal shocks corresponds to the curve for $\psi_1 = 60^\circ \equiv \psi_{1,L}$. The curves for $\psi_1 < \psi_{1,L}$ start with the minimum $\delta B \ll B_0$, while at $\psi_1 > \psi_{1,L}$ the presented minimum wave amplitude means $\delta B \sim B_0$, to allow for the index α within the presented range. One may note that the minimum acceleration time scale in the figure ($< 10 r_g/c$) is comparable to the upstream gyration time scale of the particle.

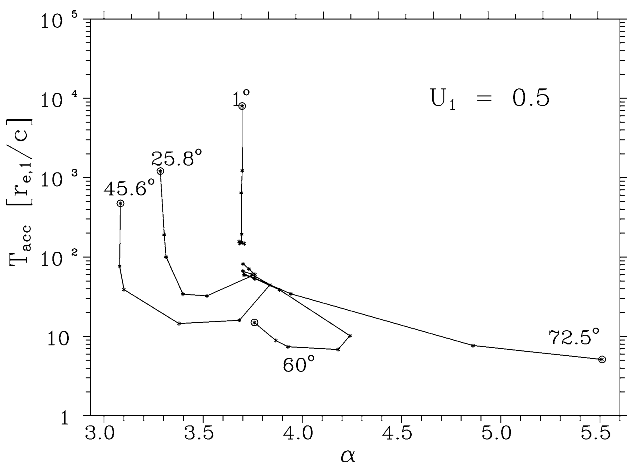

Fig. 1. The relation of the acceleration time scale, $T_{\rm acc}$, versus the particle spectral index α at different mean magnetic field inclinations, ψ_1, given near the respective curves. The *minimum* value of the magnetic field perturbation amplitude, δB, occurs at the encircled point of each curve and the wave amplitude monotonously increases along each curve up to $\delta B \gg B_0$. The difference between the $\delta B \gg B_0$ limit of $T_{\rm acc}$ for parallel ($\psi = 1^\circ$) and oblique shocks arises due to details of simplified simulations, in reality these values should coincide. $r_{e,1}$ is the particle mean gyroradius upstream of the shock.

2.1.3. Ultra-relativistic shocks

Shock waves propagating with large Lorentz factors, Γ, form superluminal configurations for nearly all background mean magnetic field inclinations. In such conditions, if the field perturbations are of limited amplitude, the acceleration process is only due to single interactions of upstream particles hitting the shock and being transmitted downstream. A small fraction of such particles can be reflected from the shock to increase their original energies by a factor of $\sim \Gamma^2$ (e.g., [15]).

In the presence of large amplitude magnetic field perturbations near the shock continuous shock acceleration forming the power-law particle spectrum is possible (see discussion by Ostrowski and Bednarz [16]). Bednarz and Ostrowski [17], Gallant and Achterberg ([15], see also [18]) and other authors proved that in this situation the spectrum reaches its asymptotic inclination with the index $\alpha - 2 \equiv \sigma \approx 2.2$. In this process, due to extreme particle anisotropy at the shock, the mean energy gain of particles interacting with the shock is comparable to the original particle energy, much below the Γ^2 factor expected for reflections. For decreasing perturbations amplitude the particle spectrum is expected to quickly steepen.

Quite recently a novel approach to acceleration at high Γ shocks was proposed by Derishev et al. ([19], see also [20]), which is applicable in dense environments, where particle–particle or photon–particle scattering plays a significant role. In the model the upstream energetic charged particles with the approximately isotropic distribution interact with the shock, increasing on average their energies by a factor of $\sim \Gamma$ and later are isotropized due to interactions with MHD perturbations. If the probability of these particle interactions leading to neutral secondaries (carrying a substantial fraction of the original particle energy) is substantial downstream of the shock, some appearing neutral particles can move to the upstream region gaining another factor-Γ increase of energy.[2] There – at a successive scattering (or a particle decay) – it can transmit a substantial fraction of its energy into the newly formed charged particle. This particle, being formed far upstream of the shock, can be isotropised and later energized at following transmission through the shock. The described loop can be repeated several times, each successive loop providing a new population of energetic particles with energies $\sim \Gamma^2$ larger than the original one. It is not clear for the present author if the conditions for such repeating energizations can be satisfied in the considered ultrarelativistic shocks. However, it is worth to note, that enabling even 2 such loops with reasonable efficiency would provide a substantial number of UHE particles if, say, $\Gamma = 10^3$.

2.2. Acceleration at relativistic tangential discontinuities

An interesting possibility of UHE cosmic ray acceleration is provided by regions with strong velocity shears, which can be considered tangential discontinuities for highest energy particles ([21]; for a review of early work see [22]). Particles being scattered and at least partly isotropised in regions of different mean flow velocity gain on average energy, on expense of the flow energy, in the process of the so called 'cosmic ray viscosity'. At high energies, particles increase their normal mean free paths respectively, to possibly allow for direct transmissions across and scattering at both sides of the shear layer. Then it can be treated as a discontinuity, and the resulting mean energy gain

$$\langle \Delta E \rangle = \eta_E (\Gamma - 1) E, \tag{6}$$

where – again for highly turbulent medium near the discontinuity – the proportionality factor η_E can be ~ 1 in the mildly relativistic flows, and it possibly decreases like $1/\Gamma$ for the ultrarelativistic ones. Here, the minimum acceleration time scale can be again a few times r_g/c, similar to the shocks with the same velocity.

One may note that in principle ultrarelativistic tangential discontinuities allow for more efficient particle reflections with the $\sim \Gamma^2$ energy gains than the analogous shocks. This is due to the fact, that energetic particles near the discontinuity are advected with the magnetized plasma along it, contrary to advection off the shock.

2.3. Acceleration by MHD turbulence

As discussed by Ostrowski and Schlickeiser [23] for non-relativistic shock waves the second order Fermi acceleration processes due to MHD waves propagating near the shock can substantially influence the resulting particle spectrum when the shock velocity is not larger than 5–10 times the mean wave velocity. In relativistic shocks the sound velocity of the downstream plasma is relativistic. The downstream magnetic fields are often postulated to grow close to pressure equipartition with the plasma allowing for propagation of relativistic MHD wave modes. In such conditions the second order process is expected to be a very efficient accelerator if only the turbulence spectrum includes long waves enabling the resonant scattering of high energy particles. From general considerations of particle scattering at scattering centres moving with relativistic velocities one can evaluate the minimum acceleration time scale to be as short as in the relativistic shocks, comparable to the particle gyroperiod. Unfortunately, both issues of relativistic turbulence formation and particle interaction with such waves are hardly discussed in the literature until now (cf. attempts by Dermer [24], Medvedev and Loeb [25]).

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[2] As measured with respect to the local plasma rest frame.

3. UHE cosmic ray acceleration at astrophysical shocks and shear layers

There are a number of astrophysical acceleration processes postulated in the literature to generate cosmic ray particles with energies in excess of 10^{19} eV. Let us comment on such possibilities in the flow discontinuities discussed above. In the discussion below we do not attempt to cover all studies discussing acceleration processes at astrophysical flow non-uniformities, in particular shocks, but rather to shortly review the subject by considering in some details the main or characteristic papers for each process. To start, let us consider non-relativistic shocks in large supergalactic scale accretion flows.

3.1. Supergalactic scale accretion shocks

Hydrodynamic modelling of cosmological structure formation yields extended flat or cylindrical-like supergalactic structures of compressed matter, including galaxy clusters as its sub-components. Diffuse plasma accreted with velocities $u \sim 10^2$–10^3 km/s at such structures extending over several Mpc can form large scale shocks. UHE proton energization at such shocks in the process of Fermi diffusive acceleration (e.g., [5]) meets, however, serious obstacles. In the considered acceleration region with ~ 0.1 μG magnetic fields a 10^{20} eV proton has a gyroradius $r_g \sim 1$ Mpc. Thus (cf. [1]), the particle mean free path $\lambda > r_g$ leads to the unreasonably large diffusive region required for acceleration, with the size $L_{\rm diff} > \frac{c}{u}\lambda \sim 300$ Mpc (!), and the acceleration time comparable to the age of the universe. As the considered mean free path is the one normal to the shock surface, λ_n, the above authors considered the so called 'Jokipii diffusion' regime at highly oblique or perpendicular shocks (i.e., where the shock normal is nearly perpendicular to the mean magnetic field), with $\lambda_n \ll r_g$. Such models formally allow for larger energies of accelerated particles, but can increase the upper energy limit – in comparison to the parallel shocks – at most by a factor of a few, if at all. This is due to the fact that the Jokipii diffusion requires medium amplitude perturbations of the magnetic field, and thus large mean free paths along the magnetic field, $\lambda_\parallel \gg r_g$, or drifts *along* the considered shock structure. The role of this factor limiting cosmic ray acceleration at oblique shocks was discussed by Ostrowski and Siemieniec-Ozięblo [26], who provide upper energy limits for accelerated particles in terms of the shock extension, L, and the gyroradius of the highest energy particle, $r_{g,\max} \equiv r_g(E = E_{\max})$, as

$$r_{g,\max} \leqslant \frac{L}{2}\frac{u}{c}. \tag{7}$$

The upper energy limit due to condition (7) can be sometimes a few orders of magnitude below the limit arising from the acceleration time scales (3) or (4).

In some way, an analogous (super)galactic scale shock can be formed and accelerate particles in the observed cases of colliding galaxies [27]. However, in analogy to the above discussed constraints, the evaluation of the upper particle energy limit presented by these authors seems to be overly optimistic.

3.2. Large scale extragalactic jets and their hot spots

Relativistic jets occurring in FRII radio galaxies carry large amounts of energy up to the radio 'hot spots' situated far (~ 100 kpc) from the central source. These hot spots are believed to harbour strong, mildly relativistic shocks dissipating the jet bulk kinetic energy into heating plasma, generating magnetic fields and efficiently accelerating energetic particles. Because of relatively slow radiative losses for protons (see below) such shocks are prospective cosmic ray accelerators. Additionally, a velocity shear layer at the relativistic jet side boundary can play an active role in accelerating UHE cosmic rays.

A model of UHE cosmic ray acceleration at the relativistic jet terminal shock was presented by, e.g., Rachen and Biermann [28]. They considered a shock wave with parameters derived from observations of hot spots in the considered sources and the evaluated jet velocities in the mildly-relativistic range $u_j \approx 0.2$–0.5 c. In order to derive the upper limit for the accelerated proton energy, $E_{\max}$, one can compare the shock acceleration time scale given by Rachen and Biermann for a parallel '$\parallel$' shock,

$$T_{\rm acc} = \frac{20\kappa_\parallel}{u_j^2}, \tag{8}$$

where $\kappa_\parallel$ is the cosmic ray diffusion coefficient parallel to the mean magnetic field, with the time for radiative losses scaled to the one for the synchrotron radiation

$$T_{\rm loss} = \frac{C}{B^2(1+X)\gamma}, \tag{9}$$

where C ($\approx 5 \cdot 10^{24}$ s for B given in mG) is a constant, X represents (in some conditions a large, varying with the local conditions and particle energy) correction to $T_{\rm loss}$ due to inverse-Compton ('IC') scattering and inelastic collisions, and γ is the proton Lorentz factor. Near the shock, Rachen and Biermann considered the non-linear Kolmogorov turbulence extended up to the scales comparable to the hot spot size. In the long wave range, important for scattering of highest energy particles, the diffusion was the Bohm diffusion, $\kappa_\| \approx r_g c/3$, leading to the most rapid acceleration in the considered parallel shock. Thus, for 'typical' hot-spot parameters $B = 0.5$ mG, $u_j = 0.3$ c, geometric factors[3] $R > H \approx 1$ kpc, $X < 1$, the conditions $T_{\rm acc} < T_{\rm loss}$ and $r_g < H$ can be satisfied up to energies of a few 10^{20} eV.

However, some of the above assumptions or evaluations are only rough estimates, which make the derived $E_{\max}$ somewhat uncertain. For example, the required diffusive size for $\sim 10^{20}$ eV particles seems to be at least (and in fact more than) $(c/u_j)r_g$, otherwise the particle spectrum cuts off due to enhanced particle escape. Also, the turbulence structure downstream of the shock can substantially deviate from the assumed Kolmogorov form, with the maximum power at long waves.

3.3. *Acceleration at the jet shear boundary layer*

Ostrowski [21] discussed the process of particle acceleration up to ultra high energies at tangential velocity transitions at side boundaries of relativistic jets. An UHE particle can cross such a boundary to the inside or the outside of the jet, then be scattered back to cross the jet boundary again. If the process repeats, each boundary crossing increases the particle energy by, on average, $\Delta E/E \sim 1$, see Eq. (6). The exact value of the mean ΔE depends on the particle anisotropy at the boundary and, thus, on the character of MHD turbulence responsible for particle scattering. As far as the radiation losses are negligible, high energy particles near the jet boundary can be accelerated forming a power-law spectrum up to some cut-off energy, E_c, appearing when the respective particle gyroradius $r_g(E_c)$ becomes comparable to the jet radius, R_j. The performed simulations show that $E_{\max}$ $(= E_c)$ obtained in this acceleration process is comparable to, or even slightly higher than the maximum particle energy obtained at the terminal shock discussed above. E_c grows with increasing u_j, but always $r_g(E_c) < R_j$: in the simulations for mildly relativistic jets usually $r_g(E_c) < 0.1R_j$. An additional interesting feature of this acceleration process is the fact, that particles *escaping* diffusively from the jet vicinity can posses an extremely hard spectrum, with the power concentrated in particles near E_c.

The analogous acceleration processes can act at ultrarelativistic jets in blazars. However, due to expected decrease of acceleration efficiency with particle anisotropy, $\eta_E \propto \gamma^{-1}$, the highest energies are still limited by the geometric condition $r_g(E_c) < R_j$. For characteristic physical conditions derived for such jets, $B \sim 1$ G and $R_j \sim 10^{16}$ cm, particles with energies above 10^{19} eV can be obtained. When considered as the source of UHE cosmic rays escaping into the intergalactic space such processes can be further degraded by particle interactions with the strong ambient photon field and/or the diffuse medium near the active galactic nucleus in the parent galaxy. Until now these possibilities were not discussed in detail.

3.4. *Large Γ shock waves*

The gamma ray bursts (GRB) observed approximately once or twice a day are believed to originate from ultrarelativistic shocks, with the Lorentz Γ factors reaching values $\sim 10^3$. Basing on an oversimplified acceleration model Vietri [29] and Waxman [30] suggested that such shocks could provide UHE cosmic rays also. Later discussions (cf. Section 2.1.3) show that due to extreme particle anisotropy (upstream of the shock the energetic particle distribution has an opening angle $\sim \Gamma^{-1}$) the acceleration process is gradual, with $\Delta E/E \sim 1$. Gallant and Achterberg [15] analysed an acceleration process acting at the GRB fireball expanding into the interstellar medium to show that gradual acceleration did not allow for accelerating protons to the ultra high energy range, $E > 5 \cdot 10^{18}$ eV. The situation could be more promising if the shock propagates in a region of strong magnetic field, like the pulsar wind zone. However, no one attempted to model such an acceleration process including the pulsar wind velocity field with a possible large Lorentz factor and the sector-like magnetic field structure. The process of particle reflection from the shock, leading in principle to fast acceleration with $\Delta E/E \sim \Gamma^2$, is much less efficient than thought previously. Also, Stecker [31] pointed out that GRBs, possibly following the star formation rate, are much less frequent in the local universe than in the young galaxies at redshifts above 1. He evaluates that particles from such local *unattenuated* sources can explain only a small part of the observed particle flux at highest energies.

4. Conclusions

With the evaluated parameters of the considered plasma flows a variety of the presented acceleration models exhibit difficulty to achieve cosmic ray energies above 10^{19} eV. In the cases where such high energies are claimed to appear, authors quite often over-estimate the acceleration efficiency by assuming the most favourable acceleration conditions and parameters of the considered flows. The shock acceleration mechanisms are generally considered to be the dominant processes providing cosmic

[3] R, H are the radius and the height of the considered cylindrical shocked plasma volume.

rays from low, up to highest observed energies. In the present review of such processes we attempted to clarify the status of the present day acceleration theory at relativistic shocks, which – in our opinion – is insufficient yet to model particle acceleration in real astrophysical sources.

These pessimistic conclusions can be modified to some degree if we look for comparison with the low energy ($E < 10^6$ GeV) acceleration models. There exist a generally accepted opinion that supernova remnant shock waves are responsible for cosmic ray acceleration in this energy range. However, *simple* acceleration models limit the highest energies achievable in these processes at one or two orders of magnitude below 10^6 GeV [6]. In our opinion this proves that nature is able to choose in some cases not the simplest models, but prefers the ones allowing for higher expansion of the phase space of the considered acceleration processes. Perhaps an analogous phenomenon can happen in relativistic shocks and flows.

We do not expect fast progress in the shock acceleration theory, which could change the described situation. Most simple questions are answered now (but note the paper of Derishev et al. [19]) and the studies bringing new information require either elaborate numerical simulations, or careful analysis of new observational data. As computing power of present day computers is by far insufficient for the full scale shock acceleration modelling, the latter factor seems to be more important in mediating progress in acceleration theory. It is even more true for the highest energy cosmic ray particles considered in this volume.

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