Energetic particle acceleration in shear layers

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Abstract. A plasma velocity shear layer and/or a tangential flow discontinuity provide conditions allowing for energetic particle acceleration. We review such acceleration processes acting both in non-relativistic and in relativistic flows. In heliospheric conditions shear layers can provide particles with energies compatible with the observed values (from several keV up to MeV), while in relativistic extragalactic jets proton energies even in excess of $10^{19}$ eV can be obtained. Application of the discussed theory to particular astrophysical objects is severely limited by inadequate knowledge of local physical conditions.

1 Introduction

The first order Fermi acceleration in shock waves and the second order acceleration in turbulent MHD media are widely considered as main sources of cosmic ray particles in astrophysical conditions. In the present paper we consider an alternative mechanism involving particle acceleration at velocity shear layers formed in non-uniform plasma flows, e.g. in a magnetosheath enveloping the Earth magnetosphere or at the interface between the relativistic jet and its ambient medium. Till now the considered complicated physical phenomenon was only occasionally discussed in the literature. The process was introduced into consideration by Berezhko and collaborators in a series of papers in early eighties (cf. Berezhko 1981, 1982a,b; Berezhko & Krymsky 1983; Bezrodnykh et al. 1984a,b, 1987; summarised in a review by Berezhko 1990). Much later an independent discussion of such processes acting in non-relativistic shear layers was presented by Earl et al. (1988), Jokipii et al. (1989) and Jokipii & Morfill (1990), and for relativistic tangential flow discontinuities by Ostrowski (1990; cf. also Berezhko 1990). A discussion of possible cosmic ray acceleration in mildly relativistic jets up to ultra-high energies and consequences of acting such acceleration processes in ultra-relativistic (‘mili-arc-second’) jets were considered in recent papers by Ostrowski (1998a,b; 1999). Below, we will shortly discuss the main results obtained by the above authors.
2 Particle acceleration in a shear layer

A high energy particle scattered after crossing a shear flow layer can gain or lose energy. It is due to a respective velocity difference of the final scattering centre rest frame with respect to the particle starting point,

$$\Delta \vec{U} = \frac{d\vec{U}}{dx} \Delta x,$$  \hspace{1cm} (1)

where we consider a 1-D situation with the flow velocity $\vec{U}$ directed along the $z$-axis, and the velocity gradient along the $x$-axis of the reference frame. In absence of magnetic field $\Delta x = v_x \Delta t$ is a free path along the $x$-axis ($\vec{v} = [v_x, v_y, v_z]$ is the particle velocity). Let us assume for a while the scattering centres to be static with respect to the local plasma rest frame. Then, in the scattering centre rest frame the particle momentum changes with respect to the one in the starting point plasma rest frame at

$$\Delta p = \frac{\Delta \vec{U} \cdot \vec{v}}{v}.$$  \hspace{1cm} (2)

For a mean $\Delta U \ll v$ the full process can be described as the momentum diffusion with the diffusion coefficient

$$D = \frac{1}{2} \left\langle \frac{(\Delta p)^2}{\Delta t} \right\rangle = \frac{p^2}{15} \left( \frac{\partial U}{\partial x} \right)^2 \tau,$$  \hspace{1cm} (3)

where the second equality comes from averaging over an isotropic particle distribution, $\tau \equiv \left\langle \Delta t \right\rangle$ is the mean scattering time and the term $\left( \partial U/\partial x \right)^2$ is the shear scalar in the considered simple flow pattern.

In the presence of magnetic field the mean particle shift in the $x$ direction can be much smaller than $v \Delta t$. Then the introduced $\tau$ parameter equals the ratio of the particle mean free path (shift) along the $x$-axis, $\lambda_x$, to the respective mean particle velocity $\langle v_x \rangle$, $\tau = \lambda_x / \langle v_x \rangle$. More exactly the particle energy change and the $\tau$ parameter in Eq. 3 has to be derived by averaging over actual particle trajectories.

If the parameter $\tau$ scales with the particle momentum as $\tau \propto p^\eta$, then the acceleration process acting within the shear layer produces the high energy asymptotic phase-space distribution (Berezhko 1982)

$$f(p) \propto p^{-(3+\eta)}.$$  \hspace{1cm} (4)

One should note that the considered acceleration process in a shear layer plays a substantial role if the mean plasma velocity difference at successive scatterings (Eq. 1) is larger than the turbulent velocities leading to the ordinary second-order Fermi acceleration (cf. Eq. 10 below).

3 Cosmic ray viscous acceleration in the Heliosphere

Because of insufficient information about the turbulent shear flow patterns within the astrophysical shear layers it is not possible to give a firm evaluation of the viscous
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acceleration rates. However numerous measurements show enhancements of energetic particle populations in the Heliosphere, where the Solar Wind forms shear flows. In these cases one can estimate the highest energies for accelerated particles by the viscous mechanism and compare its to the measured ones. Within the Heliosphere such estimates were provided for the observed shear flow sites (cf. Berezhko 1990, Jokipii & Morfill 1990), including the Earth and the Jupiter sheared magnetosheath, interplanetary magnetic field sector boundaries, boundaries of the high speed Solar Wind streams. In general the evaluated energies are within the observed ranges.

4 Particle acceleration at relativistic shear layers

The relativistic shear layers occur in a number of objects in space, including galactic and extragalactic relativistic jets and accretion discs near black holes. Below we consider the jet side boundary layer as an example of the relativistic shear flow.

For particles with sufficiently high energies the transition layer between the jet and the ambient medium can be approximated as a surface of a discontinuous velocity change, a tangential discontinuity (‘td’). It becomes an efficient cosmic ray acceleration site provided the considered velocity difference $U$ is relativistic and the sufficient amount of turbulence is present in the medium. The situation with highly relativistic jet ($\Gamma \equiv (1 - U^2)^{-1/2} \gg 1$) was not quantitatively discussed till now and, thus, our present discussion is mostly based on the results derived for mildly relativistic flows by Ostrowski (1990, 1998a).

4.1 Energy gains

Any high energy particle crossing the jet boundary changes its energy, $E$, according to the respective Lorentz transformation. It can gain or loose energy. In the case of uniform magnetic field the successive transformation at the next boundary crossing changes the particle energy back to its original value. However, in the presence of perturbations there is a positive mean energy change:

$$\langle \Delta E \rangle = \eta_E (\Gamma - 1) E.$$  \hspace{1cm} (5)

The numerical factor $\eta_E$ increases with the growing magnetic field perturbations and slowly decreases for increasing $\Gamma$. For mildly relativistic flows, in the strong scattering limit particle simulations give values of $\eta_E$ as substantial fractions of unity (Ostrowski 1990). For large $\Gamma$ we assume the following scaling

$$\eta_E = \eta_0 \frac{2}{\Gamma},$$  \hspace{1cm} (6)

where $\eta_0 = \eta(\Gamma = 2)$. In general $\eta_0$ depends also on particle energy. During the acceleration process, particle scattering is accompanied with the jet’s momentum transfer into the medium surrounding it. On average, a single particle with the momentum $p$ transports across the jet’s boundary the following amount of momentum:

$$\langle \Delta p \rangle = \langle \Delta p_z \rangle = \eta_p (\Gamma - 1) U p,$$  \hspace{1cm} (7)
where the $z$-axis of the reference frame is chosen along the flow velocity. The numerical factor $\eta_p \approx \eta_E$ and there acts a drag force per unit surface of the jet boundary and the opposite force at the medium along the jet, of the magnitude order of the accelerated particles’ energy density. Independent of the exact value of $\eta_E$, the acceleration process can proceed very fast due to the fact that average particle is not able to diffuse – between the successive energizations – far from the accelerating interface. One should remember that in the case of shear layer or tangential discontinuity acceleration and, contrary to the shock waves, there is no particle advection off the ‘accelerating layer’. Of course, particles are carried along the jet with the mean velocity of order $U/2$ and, for efficient acceleration, the distance travelled this way must be shorter than the jet breaking length.

The simulations (Ostrowski 1990) show that the discussed acceleration process can be quite rapid, with the time scale given in the ambient medium rest frame as

$$\tau_{td} = \alpha \frac{r_g}{c},$$

where $r_g$ is a characteristic value of the particle gyroradius. For efficient scattering the numerical factor $\alpha$ can be as small as $\sim 10$ (Ostrowski 1990). One may note that the applied diffusion model involves particles with infinite diffusive trajectories between the successive interactions with the discontinuity. However, quite flat spectra, nearly coincident with the stationary spectrum (cf. Fig. 1), are generated in short time scales given by Eq. 8 and these distributions are considered in the present discussion. For the mean magnetic field $B_g$ given in the Gauss units and the particle (proton) energy $E_{\text{EeV}}$ given in EeV ($1 \text{ EeV} \equiv 10^{18} \text{ eV}$) the time scale (8) reads as

$$\tau_{td} \sim 10^5 \alpha E_{\text{EeV}} B^{-1}_G \text{ [s].}$$

For low energy cosmic ray particles the velocity transition zone at the boundary is a finite-width turbulent shear layer. We do not know of any attempt in the literature to describe the internal structure of such layer on the microscopic level (cf. Aloy et al. 1999, Henriksen, at this meeting). Therefore, we limit the discussion of the acceleration process within such a layer to quantitative considerations only. From rather weak radiation and the observed effective collimation of jets in the powerful FR II radio sources one can conclude, that interaction of a presumable relativistic jet with the ambient medium is relatively weak. Thus the turbulent boundary layer must be relatively thin, with thickness denoted with $D$. Within it two acceleration processes energise low energy – the ones with the mean radial free path $\lambda \ll D$ – particles. The first one, discussed in section 2 above, is connected with the velocity shear and is called ‘cosmic ray viscosity’. The second one is the ordinary Fermi process in the turbulent medium. The acceleration time scales can not be evaluated with accuracy for these processes, but – for particles residing within the considered layer – we can give an acceleration time scale estimate

$$\tau_{II} = \frac{2\pi r_g}{c} \frac{c^2}{V^2 + \left(\frac{U \lambda}{D}\right)^2},$$

(10)
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Fig. 1. Spectra $N(t, p, x = 0) \equiv d n/d \log p$ of accelerated particles at the jet boundary in a sequence of times $t_1 < t_2 < \ldots < t_7$ (each $t_i = 10t_{i-1}$), for continuous particle injection at small momentum $p_0 \ll p_c$. In the upper plot the spectra generated in the turbulent shear layer are given, while, in the two lower ones, the tangential discontinuity generated spectra are presented: the results for the particle mean free path $\lambda \propto p$ are given in the upper panel, and for $\lambda = \text{const}$ in the lower one.
where $V$ is the turbulence velocity. One expects that the first term in the denominator can dominate at low particle energies, while the second one for larger energies, with $\tau_{II}$ approaching the value given in Eq. 8 for $\lambda \sim D$. If the second-order Fermi acceleration dominates, $\lambda < D(V/U)$, the time scale (10) reads as $\tau_{II} \sim 10^8 E_{\mathrm{TeV}} B^{-1}_G V_3^{-2} \text{[s]}$, where $V_3$ is the turbulence velocity in units of 3000 km/s. Depending on the choice of parameters this scale can be comparable or longer than the expansion and internal evolution scales for relativistic jets. In order to efficiently create high energy particles for the further acceleration by the viscous process and the tangential discontinuity acceleration one have to assume that the turbulent layer includes high velocity turbulence, with $V_3$ reaching values substantially larger than 1, or other high energy particles sources are present. For the following discussion we will assume that such effective pre-acceleration takes place, but the validity of this assumption can be estimated only a posteriori from comparison of our conclusions with the observational data.

4.2 Energy losses

To estimate the upper energy limit for accelerated particles, at first one should compare the time scale for energy losses due to radiation and inelastic collisions to the acceleration time scale. The discussion of possible loss processes is presented by Rachen & Biermann (1993). The derived loss time scale for ultra-high energy protons can be written in the form

$$T_{\text{loss}} \simeq 5 \cdot 10^9 B^{-2}_G (1 + Xa)^{-1} E^{-1}_{\text{eV}} \text{[s]},$$

where $a$ is the ratio of the energy density of the ambient photon field relative to that of the magnetic field and $X$ is a quantity for the relative strength of $p\gamma$ interactions compared to synchrotron radiation. For cosmic ray protons the acceleration dominates over the losses (Eqs. 9, 11) up to the maximum energy $E_{\text{eV}} \approx 2 \cdot 10^2 a^{-1} [B_G (1 + Xa)]^{-1/2}$.

4.3 Spectra of accelerated particles

The acceleration process acting at the tangential discontinuity of the velocity field leads to the flat energy spectrum and the spatial distribution expected to increase their extension with particle energy. Below, for illustration, we propose two simple acceleration and diffusion models describing these features.

A turbulent shear layer

At first we consider ‘low energy’ particles wandering in an extended turbulent shear layer, with the particle mean free path $\lambda \propto p$. With the assumed conditions the mean time required for increasing particle energy on a small constant fraction is proportional to the energy itself, and the mean rate of particle energy gain is constant, $\langle \dot{E} \rangle_{\text{gain}} = \text{const}$. Let us take a simple expression for the synchrotron energy loss, $\langle \dot{E} \rangle_{\text{loss}} \propto p^2$, to represent any real process acting near the discontinuity. One may
note that the jet radius and the escape boundary distance provide energy scales to the process. Another scale for particle momentum, $p_c$, is provided as the one for equal losses and gains, $\langle \dot{E} \rangle_{\text{gain}} = \langle \dot{E} \rangle_{\text{loss}}$. As a result, a divergence from the power-law and a cut-off have to occur at high energies in the spectrum.

We use a simple Monte Carlo simulations to model the acceleration process for a continuous particle injection, uniform within the considered layer. The diffusion coefficient $\kappa_\perp$ is taken to be proportional to particle momentum, but independent of the spatial position $x$. We neglected particle escape through the shear layer side boundaries and we assumed $\frac{\partial f}{\partial x} = 0$. For the escape term we simply assume a characteristic escape momentum $p_{\text{max}}$. In Fig. 1 we use $p_c$ as the unit for particle momentum, so it defines also a cut-off for $p_c < p_{\text{max}}$. At small momenta the spectrum has a power-law form – in our model the averaged over angles $f(t,p) \propto p^{-4}$ (cf. Eq. 4) – with a cut-off momentum growing with time. However, in long time scales, when particles reach momenta close to $p_c$, losses lead to spectrum flattening and pilling up particles at $p$ close to $p_c$. Then, a low energy part of the spectrum does not change any more and only a narrow spike at $p \approx p_c$ grows with time. Let us also note that in the case of efficient particle escape, i.e. when $p_{\text{max}} < p_c$, the resulting spectrum would be similar to the presented by Ostrowski (1998a) short time spectrum with a cut-off at $\approx p_{\text{max}}$.

**Tangential discontinuity acceleration**

An illustration of the acceleration process at the tangential discontinuity have to take into account a spatially discrete nature of the acceleration process. Here, particles are assumed to wander subject to radiative losses outside the discontinuity, with the mean free path $\propto p$ and the loss rate $\propto p^2$. At each crossing of the discontinuity a particle is assumed to gain a constant fraction $\Delta$ of momentum (cf. Eqs. 5, 6), $p' = (1 + \Delta)p$, and, due to losses, during each free time $\Delta t$ its momentum decreases from $p_m$ to $p$ according to

$$\frac{1}{p} - \frac{1}{p_m} = \text{const} \cdot \Delta t. \quad (12)$$

The time dependent energy spectra obtained within this model are presented in lower panel in Fig. 1, where we choose units in a way to put the constant in Eq. 12 equal to one and the particle mean free paths are equal in two considered models at $p = p_c$. Comparison of the results in two models allows to evaluate the modification of the acceleration process by changing the momentum dependence of the particle diffusion coefficient. For slowly varying diffusion coefficient (the ‘$\lambda = \text{const}$’ model) high energy particles which diffuse far away off the discontinuity and loose there much of their energy still have a chance to diffuse back to be accelerated at the discontinuity. In the model with $\kappa$ quickly growing with particle energy (the ‘$\lambda = C \cdot p$’ model) such distant particles will decrease their mobility in a degree sufficient to break, or at least to limit their further acceleration. One should note that in both models the spectrum inclination at low energies is the same (here the particle density $n(p) \propto p^{-2}$).
5 Final remarks

Shear layers occurring in astrophysical plasma flows are able to accelerate cosmic ray particles in the so called \textit{viscous acceleration process}. Depending on conditions the process can be described as the particle momentum diffusion or the tangential discontinuity acceleration. The last one can be very efficient in relativistic flows. In particular, in jets in active galactic nuclei the cosmic ray protons can reach energies in excess of $10^{18}$ eV.

The generated cosmic ray populations can influence the shear layer flow through viscous and/or dynamical forces (cf. Arav & Begelman 1992, Ostrowski 1999). In relativistic jets the so called \textit{cosmic ray cocoon} can be formed leading to a number of observational effects. The essential problem with application and verification of the presented theory is insufficient information about the local parameters of the considered shear layers. One may note several recent observational papers showing effects which could be ascribed to, or are at least compatible with the acceleration process acting at jet boundary layer (Attridge \textit{et al.} 1999, Scarpa \textit{et al.} 1999, Perlman \textit{et al.} 1999).

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