High Energy Blazar Astronomy
ASP Conference Series, Vol. 299, 2003
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Simulations on the effect of internal structure of shock fronts on particle acceleration

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Abstract. We have studied the effect of internal structure of shock fronts on their efficiency of particle acceleration. We present a simple model of the width of a parallel shock front depending on the spectral index of the ambient magnetic turbulence. Using Monte-Carlo simulations, we determine the spectral index of energy distribution of shock accelerated particles in this model as well as in a case, where the shock width is independent of the ambient turbulence. In both cases, the acceleration capability of a wide shock structure is shown to be much smaller than for a step-like shock front.

1. Introduction

Shock waves in blazar jets are commonly thought to accelerate the ultra-relativistic electron populations that according to the standard picture produce the observed electromagnetic emission covering wavelengths from radio waves to gamma rays. This idea is mainly based on the known ability of a step-like shock front to accelerate test particles to a hard power-law spectral form.

The alternative idea of studying a shock as smooth and continuous (ie. modified) structure has been discarded mainly because of the theoretical difficulties that are related to this approach, but also because the thickness of the shock front is generally thought to be only fractions of the free mean path of the accelerated particles. Such a thin structure could then be approximatively described as a step from pre-shock to post-shock conditions.

The width of the shock structure should be of the order of the mean free path of downstream thermal plasma ions (see, eg. Vainio, this volume). Such a structure would, indeed, be step-like to the accelerated ions, but for electrons and positrons the mean free path may be orders of magnitude shorter and for them, the shock front can be far from a step. The purpose of this paper is to study the structure of a shock front having a thickness of the order of the downstream plasma ions. We present a simple model of the scattering frequency off the magnetic turbulence present in the plasma that leads to a description of the relative shock width as a function of particle energy.

2. Model of scattering and shock structure

We will use the simplest description of particle scattering off the magnetic fluctuations, namely the quasilinear theory of scattering (QLT) (for a short review, see eg. Schlickeiser, 1999). In the magnetostatic approximation, QLT gives the scattering frequency of relativistic ($v \approx c$) charged particles (of species α) off the magnetic irregularities as

$$\nu_\alpha = \frac{\pi}{2} \frac{\Omega_\alpha}{\gamma'} \frac{kI(k)}{B^2} \propto \left(\frac{|q_\alpha|}{m_\alpha \gamma'} \right)^{2-q} \tag{1}$$

where $\Omega_\alpha = |q_\alpha| B_0/(m_\alpha c)$ is particle's gyrofrequency at non-relativistic energies, γ' is the Lorentz factor of the particle in the plasma frame, B_0 is the large scale magnetic field strength, and $k = \Omega_\alpha/(\gamma' c)$ (neglecting directional dependencies) is the resonant wavenumber of the magnetic field fluctuations. The wavenumber spectrum of the magnetic field fluctuations is here assumed to be a power law, $I(k) = I_0(k_0/k)^q \propto k^{-q}$, for wavenumbers greater than some outer-scale wavenumber $k > k_0$.

Now we can describe the width of the shock W using q: W can be estimated to be approximately one mean free path of a proton λ_p of energy $\Gamma m_p c^2$:

$$W \simeq \lambda_p(\Gamma) = \frac{c}{\nu_p(\Gamma)}, \tag{2}$$

where Γ is the Lorentz-factor of the shock. Using the scaling law of the scattering frequency, we obtain

$$W = \frac{c}{(\frac{m_e}{m_p})^{2-q} \nu_e(\Gamma)} = \left(\frac{m_p}{m_e} \right)^{2-q} [l] \;\simeq\; 1836^{2-q}\,[l]. \tag{3}$$

where we have chosen $[l] = c/\nu_e(\Gamma)$ as a length unit.

The shock front itself is characterized using a soft speed profile for the background flow. We used a hyperbolic tangent function, dependent of up- and downstream velocities (u_- and u_+ respectively), width of the shock (W) and position (x), first introduced by Schneider & Kirk (1989):

$$u(x) = u_- + \frac{u_+ - u_-}{2} \Big[1 + \tanh\Big(\frac{x}{W} \Big) \Big]. \tag{4}$$

3. Numerical simulations

We use a Monte Carlo model of particle transport and acceleration similar to that of Vainio et al. (2000). Energetic particles are injected to the simulation box and each particle trajectory is followed under the guiding-center approximation until the particle reaches the downstream escape boundary. Then, the particle can either get absorbed to the downstream (and escape from the shock) or it can return. The fate of the particle is decided utilizing the propability of return of $P_{ret} = [(v' - u_+)/(v' + u_+)]^2$ where v' is the particle speed in the fluid frame (Jones & Ellison 1991). We use particle splitting to increase the statistics at the highest energies.

In order to minimize the time spent in simulations but still allow the particles to undergo sufficient amount of scattering to have enough time to isotropize, we set the escape boundary to depend on particle's energy. This way, high-energy particles can have long downstream (that they need for proper scattering effects) without the disadvantage of having the same long downstream for lower energy particles also, because the latter (with shorter mean free path) need only a fraction of the long donwstream of the most energetic particles.

The scattering process is considered in means of pitch angle diffusion due to inhomogeneities of the magnetic field: charged particle scatter of the small disturbances so that the direction of its momentum, rather than the amount of it, is altered. As long as all computations are made in respective plasma rest frame (upstream or downstream), this will lead to elastic small angle scattering. Energy losses were considered to be solely due to synchrotron emission. All the loss-implementations, as well as other calculations, were performed in the applicable frame, where the description of the process is simplest, ie. movings in shock frame, scatterings and energy losses in plasma frame (where scattering centers are at rest).

4. Results and discussion

In the simulations we had two basically different cases: we either held the magnetic field turbulence constant ($q = \frac{5}{3}$, the Kolmogorov index) and let the width of the shock be a free parameter, or alternatively tied, using eqn. (3), the width of the shock to the turbulence specral index q, which was then varied. While the QLT can not precicely describe the conditions for which the turbulence index s exceeds the value of 2, we will ignore this in our numerical model assuming the filling of the QLT resonance gap by some efficient process, eg. resonance broadening. We let q have values from 1.65 to 2.60, corresponding shock widths $\approx 14 - 0.011$ respectively. Letting q vary, we get shocks of different widths, and determine the resulting particle energy spectral indices for them. The spectral index here corresponds to the region of lowest energies, where the power-law type spectrum starts to form.

Results for the simulations are shown in Figure 1. The acceleration efficiency clearly depends on the width of the shock, as one might expect, so that with thinner shocks ($W \lesssim 1$) the particle spectra hardens, and in all cases, approaches the value of $s \sim 2$, consistent with earlier, step-like tratments of relativistic shock acceleration (eg. Kirk & Duffy 1999). As one can clearly see, the acceleration capability depends heavily on the width of the accelerating shock. There is a difference between cases "q is constant and W changes" and "W is tied to q" (former case producing harder spectra with thinner shock, and latter with shock wider than a few particle mean free paths), but the general behavior

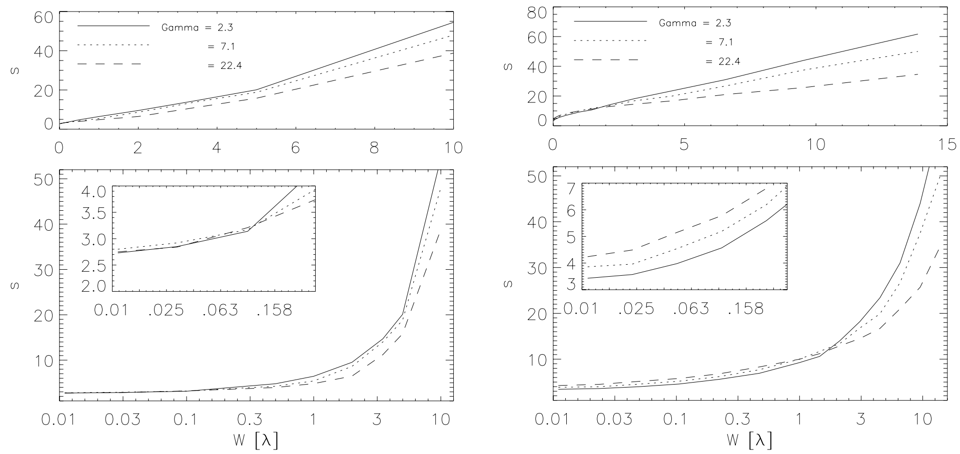

Figure 1. The particle energy spectral index s as a function of the width W (in units of mean free path) of the accelerating shock for velocities 0.9, 0.99 and 0.999 c. On the left-hand panel the spectral index of magnetic field turbulence power-law q is kept constant $q = \frac{5}{3}$ and W varied independently, whereas on the right-hand panel the width was tied to the magnetic field fluctuation spectrum q, using $W = 1836^{2-q}$.

of s is similar in all cases. It also seems, that shocks thicker than only a fraction of a mean free path can not accelerate particles efficiently enough to be able to produce energy spectra comparable to those observed from eg. AGN jets.

The results of our model suggest that relativistic shock waves of parallel geometry are *not* particularly well suited for accelerating electrons; the energy spectrum of the electrons far downstream the shock front was more close to adiabatically compressed plasma than a power law in cases with $W > 1$. The result was obtained for a scattering model with rigidity-dependent scattering frequency, and injection of electrons of rather low energies ($E' = \Gamma m_e c^2$ in the upstream plasma frame). This points towards a need to consider more general transport models and shock geometries to study the ability of modified relativistic shocks to produce the hard electron energy spectra needed in the common blazar radiation models.

Acknowledgments. Academy of Finland is thanked for financial support.

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