29th International Cosmic Ray Conference Pune (2005) **3**, 229–232

On the cosmic rays acceleration at super-luminal shocks

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The particle shock acceleration at super-luminal shocks is discussed and evaluated by performing Monte Carlo calculations. Different upstream flow Lorentz gamma factors are used ranging from 10 up to 1000. These could be relevant to models of relativistic astrophysical environments like Active Galactic Nuclei hot spots and Gamma Ray Burst sites. The behavior of the particles spectral shape irregularities is emphasized, in connection with the upstream Lorentz gamma flow, the magnetic field inclinations and different scattering models, which help to understand the limitations of the first order Fermi acceleration, the contribution to the cosmic ray spectrum and the consequent ν fluxes.

1. Introduction

It is well accepted by now that shocks are a source of cosmic ray acceleration. The work of the late 70s by a number of authors [1, 2, 3, 4, 5] established the basic mechanism of particle 'diffusive' acceleration (in non-relativistic shocks). Relativistic beaming in many relativistic astrophysical sources suggest the appearance of super-luminal shocks. The range of magnetic field orientations for which a shock is super-luminal increases as the upstream plasma flow speed increases. In order to study the sub-luminal case, it is possible to find a relativistic transformation to the frame of reference (de Hoffmann-Teller frame [6]), in which the shock front is stationary and the electric field is zero (**E**=0) in both upstream and downstream regions. However, super-luminal shock fronts do not admit a transformation to such a frame, the particle 'diffusive' approximation cannot be applied and the particles are more likely to gain energy as their gyrocenter makes a single crossing of the shock front from upstream to downstream or else as doing 'drifts' parallel or antiparallel to the present electric field. In this work we have established a numerical Monte Carlo method to study the cosmic ray acceleration properties (spectral shapes, energy gain, scattering model dependence, magnetic field dependence, etc) in highly relativistic super-luminal shocks by following the helix-trajectory of the particle in the region of a shock front.

2. Monte Carlo simulations - Results

Our aim is to examine which is the role that different scattering models (large angle scattering or pitch angle diffusion) can play in reference to the spectral shape at very high gamma plasma flows, by we consider super-luminal shock configurations. Let us note that the flow into and out of the shock discontinuity is not along the shock normal, but a transformation is possible into the normal shock frame to render the flows along the normal [7] and for simplicity we assume such a transformation has already been made. For these simulation runs a Monte Carlo technique is applied by considering the motion of a particle of momentum p in a magnetic field **B**. As mentioned, in super-luminal conditions it is not possible to transform into a frame where **E**=0 (de Hoffmann-Teller frame) a condition that is only possible for the sub-luminal case where $V \leq V_{sh} \tan\psi$. Thus, the frames to be used in this simulation will be the fluid frames, where still the electric field is zero **E**=0, and the shock frame, which it will be used only as a 'check frame' to test whether upstream or downstream conditions apply. Initially the particles are injected at 50λ, where λ is the particles' mean free path, from the shock and their guiding center is followed upstream, at the upstream frame until the particle reaches the shock at $x_{sh} = 0$

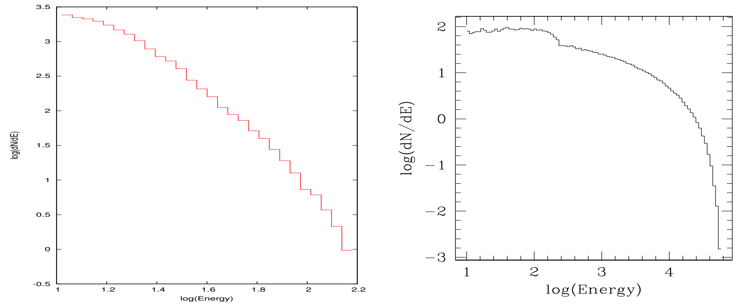

Figure 1. Spectrum for the super-luminal pitch angle diffusion case, in the shock frame at the downstream side for Γ=10 and ψ=89°. As an indication a gamma of 10^5 corresponds to $\sim$ 100 GeV for protons. *Right*: We note here that the steep cut-off may suggest a connection to the spectra of relativistic electrons originating from observed hot spots (super-luminal shocks) in extragalactic radio sources.

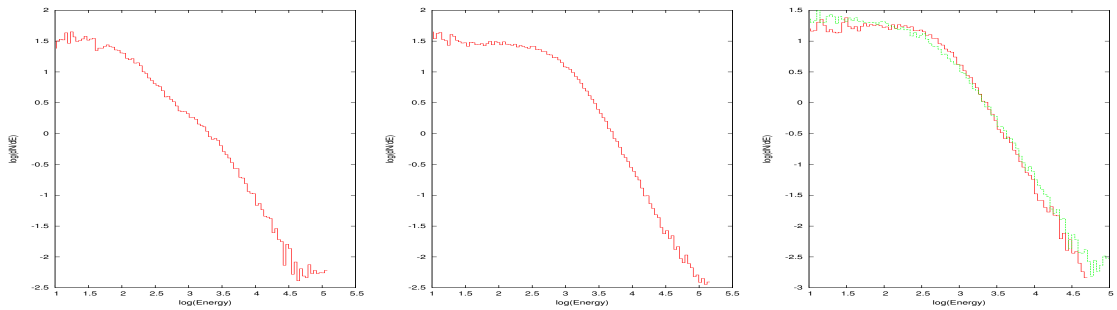

Figure 2. Spectral shapes for Γ=500 (right), 1000 (middle) for 76 degrees. *Right*: Two spectra for Γ=50 and an inclination of 50 and 89 degrees respectively. We see no dependence of the spectrum with the angle of the magnetic field at the shock normal. This is tested for all gamma and different shock angles. The behavior is the same.

followed by an appropriate transformation to the shock frame. At injection the speed of the plasma upstream is highly relativistic and we keep values between Γ = 10 and 1000.

For the pitch angle scattering we follow a standard Monte Carlo random walk approach to simulate the energetic particle propagation by using a small angle scattering procedure with steps sampled from an exponential distribution with mean free path $L = \delta\theta^2\lambda$ and keeping the angle $\delta\theta$ less than $0.1/\Gamma$ [8] while following the diffusion approximation of the scattering during and immediately before the particle reaches the shock front. Since there is no easy approximation at this juncture to determine the probability of shock crossing or reflection, we change the model following the helical trajectory of the particle, in the fluid frames upstream ('1') or downstream ('2') (**E**=0) respectively, where the velocity coordinates of the particle are calculated in a *three-dimensional* space. We assume that the tip of a particle's momentum vector undergoes randomly a small change θ_1 in its direction on the surface of a sphere and within a small range of polar angle (after a small increment of time). If the particle had an initial pitch angle θ_o, we calculate its new pitch angle θ' by a trigonometric formula [9]. We follow the trajectory in time, using $\phi_1 = \phi_\circ + \omega t$, and t is the time from first detecting the shock presence at x_{sh}, y_{sh}, z_{sh} and assuming that $\delta t = r_g/Hc$, where r_g is the Larmor radius, $H \geq 100$. After the suitable calculations we check whether the particle meets the shock again by transforming to the shock frame. If the particle meets the shock then the suitable transformations to the upstream frame are made again and we follow the particle's trajectory as described above. If the particle never meets the shock its guiding center is followed, the same way as mentioned earlier for the upstream side after the injection and it is left to leave the system if it reaches a well defined E_{max} momentum boundary or a spatial boundary of 100λ. From figures 1-3 one may understand that for pitch angle diffusion, the spectral shape of the accelerated particles follows a rather smooth power-law shape in comparison to the large angle scattering where the spectral shape gives a steep sudden cut-off. For both cases the simulations show that most of the particles are 'swept' downstream the shock after only a cycle. This condition limits the particle's ability to gain very high energies, contrary to the simulation findings of [11] and [12] for highly relativistic sub-luminal shocks, where plateau structured spectral shapes are seen, however.

3. Application: A diffuse signal from sources with super-luminal shock fronts

In the previous sections, energy spectra of sources with different boost factors have been presented. These source spectra can be translated into an expected diffuse signal from certain astrophysical sources by folding the spectrum with the spatial distribution of the sources. In this ansatz, we use Active Galactic Nuclei (AGN) and Gamma Ray Bursts (GRBs) as potential sources, since these are the sources with the highest observed boost factors. We assume that both source types follow Star Formation Rate (SFR) with a redshift behavior as suggested in [14]. For AGN, $\Gamma = 10$ is assumed. For GRBs, the Γ dependence is considered by taking into account a range of boost factors of $100 < \Gamma < 1000$ with a maximum in the distribution at $\Gamma = 300$ [13]. As a simple model, it is assumed that 10% of all GRBs have $\Gamma = 100$ and further 10% are as powerful as $\Gamma = 1000$. For the remaining 80%, the average expected boost factor of $\Gamma = 300$ is assumed. The normalization of the expected signal is done using the most restrictive upper limit on the neutrino signal from extraterrestrial sources given by the AMANDA experiment (see [15]),

$$E_\nu^2 \frac{dN_\nu}{dE_\nu} < 2.6 \cdot 10^{-7} \frac{\text{GeV}}{\text{s sr cm}^2}$$

With an E^{-2} spectrum for both neutrinos and protons, the spectra are connected by assuming that the expected neutrino energy fluence is a fraction x of the proton spectrum,

$$\int \frac{dN_\nu}{dE_\nu} E_\nu \, dE_\nu = x \cdot \int \frac{dN_p}{dE_p} E_p \, dE_p$$

with $x = 1/40$, since only 20% of the proton flux goes into pion production via the Delta resonance, $1/2$ of the remaining flux goes into the charged pion component of which $1/4$ goes into neutrinos. The resulting spectrum is shown in Fig. 3. It can be seen that the only possible contribution to the cosmic ray spectrum from the super-luminal shock sources as predicted in this paper is around the knee of the measured cosmic ray spectrum. It is expected however, that the effective flux is actually even lower, since the normalization is based upon the assumption that the contribution cannot be more than the current neutrino flux limits omit.

4. Conclusions

These simulations are relevant to models of highly relativistic particle shock acceleration in sources as AGN jets and GRBs. We can conclude that: (1) Large angle scattering is unrealistic -as expected- (our test spectra gave a steep sudden cut off) in such high plasma velocities and the pitch angle diffusion scheme resembling the high turbulence upstream the shock was simulated, keeping the scattering cone angle within $0.1/\Gamma$ at crossing the shock front [8]. (2) There is no decrease observed in the acceleration rate, comparing to results of

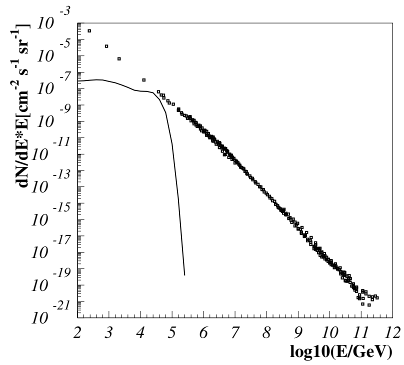

Figure 3. The maximum predicted diffuse flux from GRBs and AGN with super-luminal shock fronts. The normalization is based on current neutrino flux limits, see [15]. The flux is compared to the measured Cosmic Ray Spectrum [16].

diffusive relativistic shock acceleration (e.g. [10, 11, 12]). (3) In order to keep a power-law spectra the angular distribution at crossing the shock is highly anisotropic and 'beamed'. (4) The energy gain of the cosmic rays in super-luminal shocks seems limited -comparing to highly relativistic shocks. (5) The possible contribution to the cosmic ray spectrum from super-luminal shock sources is predicted around to the knee of the measured cosmic ray spectrum.

5. Acknowledgements

The authors would like to thank Todor Stanev for providing Cosmic Ray data. This work has been supported by the DFG (BE 3714/1-1).

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