Particle acceleration in relativistic subluminal shock environments

A. Meli[1,2], J. Becker[2], J. Quenby[3] and J. Lünemann[2]

1: Section of Astronomy, Astrophysics and Mechanics, Department of Physics, University of Athens, Greece
2: Institute of Physics, University of Dortmund, Germany
3: Astrophysics Group, Blackett Laboratory, Imperial College London, England

contact email: ameli@phys.uoa.gr

Abstract

The understanding of the particle spectra resulting from acceleration in relativistic shocks as they occur in extragalactic sources is essential for the interpretation of the Cosmic Ray spectrum above the ankle ($E_p > 3 \cdot 10^{18}$ eV). It is believed that extragalactic sources like Active Galactic Nuclei and Gamma Ray Bursts can produce particle spectra up to $E_p \sim 10^{21}$ eV. In this contribution, subluminal shocks are investigated with respect to different shock boost factors Γ and the inclination angle between the shock normal and the magnetic field ψ. A correlation between the boost factor and the spectral behavior of the emitted particles is found. The results are compared to Active Galactic Nuclei and Gamma Ray Burst observations and the Cosmic Ray spectrum at the highest energies.

Introduction

The observations of electron synchrotron radiation in the radio regime and the X-ray variations from astrophysical environments such as Active Galactic Nuclei (AGN) and Gamma Ray Bursts (GRBs) indicate that there is a mechanism with which primary particles (protons or electrons) gain large amounts of energy via acceleration. Connected to this implied mechanism it is accepted that shocks are the source of these Cosmic Rays. The work of the late 70s established the basic mechanism of particle diffusive acceleration in non-relativistic shocks. Later on studies on relativistic shocks appeared (e.g. Peacock '81 , Ellison et al '90) and questioned the nature and limits of the relativistic diffusive acceleration versus the non-relativistic shock mechanism. In this work, we present results of simulations on relativistic particle shock acceleration as an application to relativistic source models (i.e. AGN, GRBs). These involve subluminal shocks with plasma shock velocities ranging from $\Gamma = 10 \rightarrow 1000$ Lorentz factor and both pitch angle and magnetic scattering.

Monte Carlo simulations - Results

The Monte Carlo codes simulate relativistic oblique shocks with application to relativistic environments of AGN and GRBs. Initially the particles are considered relativistic, isotropically injected upstream of the shock and are left to move towards the shock and along the way they collide with the magnetic scattering centers. Consequently, as they keep scattering and crossing the upstream and downstream regions of the shock (its width is much smaller than the particle's gyroradius), they gain a considerable amount of energy. During our simulations a relativistic transformation is performed from the local plasma frames to the shock frame to check for shock crossings. The de Hofmann-Teller frame is used appropriately while the adiabatic invariant is conserved. The calculations have been performed for different parameter settings. Three different shock obliquities have been simulated, i. e. $\psi = 23°$, $33°$ and $43°$, where ψ is the angle between shock normal and magnetic field. For each of the angles, nine different boost factors have been used, $\Gamma = 10, 20, 30, 100, 300, 500, 700, 900$ and 1000. Each single spectrum is then fit by a single power-law approximation, $dN/dE \propto E^{-\alpha_p}$, in order to get an estimate of the spectral index α_p. Since AGN and GRBs are likely to accelerate particles up to $\sim 10^{21}$ eV, this value is used as the maximum energy. This way, each shock boost factor Γ is associated with a spectral index $\alpha_p(\Gamma)$. A linear correlation between α_p and Γ is found as it is displayed in Fig. 1. Indicatively the figure shows the results for $\psi = 43°$. The results for $\psi = 23°$ and $\psi = 33°$ are comparable. A linear fit is applied with a numerical result which is comparable for all three angles:

$$\alpha_p(\psi = 23°) = 2.1 - 0.7 \cdot 10^{-3} \cdot \Gamma$$
$$\alpha_p(\psi = 33°) = 2.0 - 0.9 \cdot 10^{-3} \cdot \Gamma$$
$$\alpha_p(\psi = 43°) = 2.2 - 0.9 \cdot 10^{-3} \cdot \Gamma$$

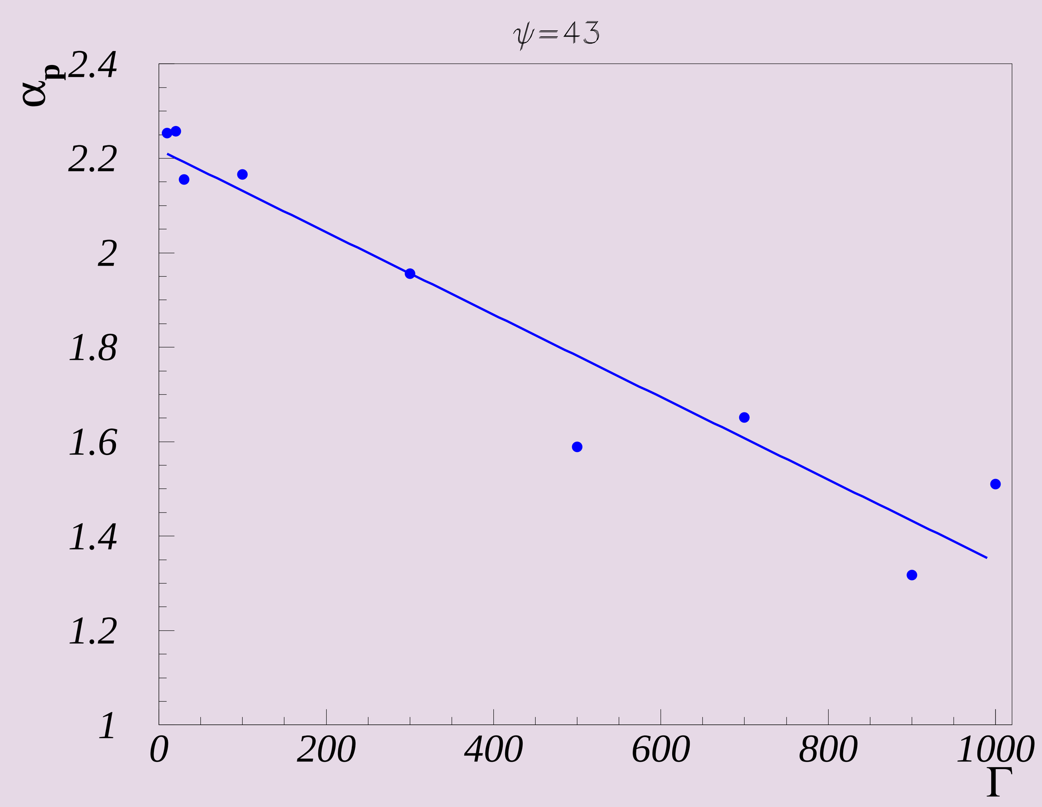

Figure 1. ***Correlation between the Γ shock boost factor of the source and the spectral index of the calculated spectrum after a power-law fit approximation, here for the case of an inclination of $\psi = 43°$. The correlation between α_p and Γ seems to be linear.***

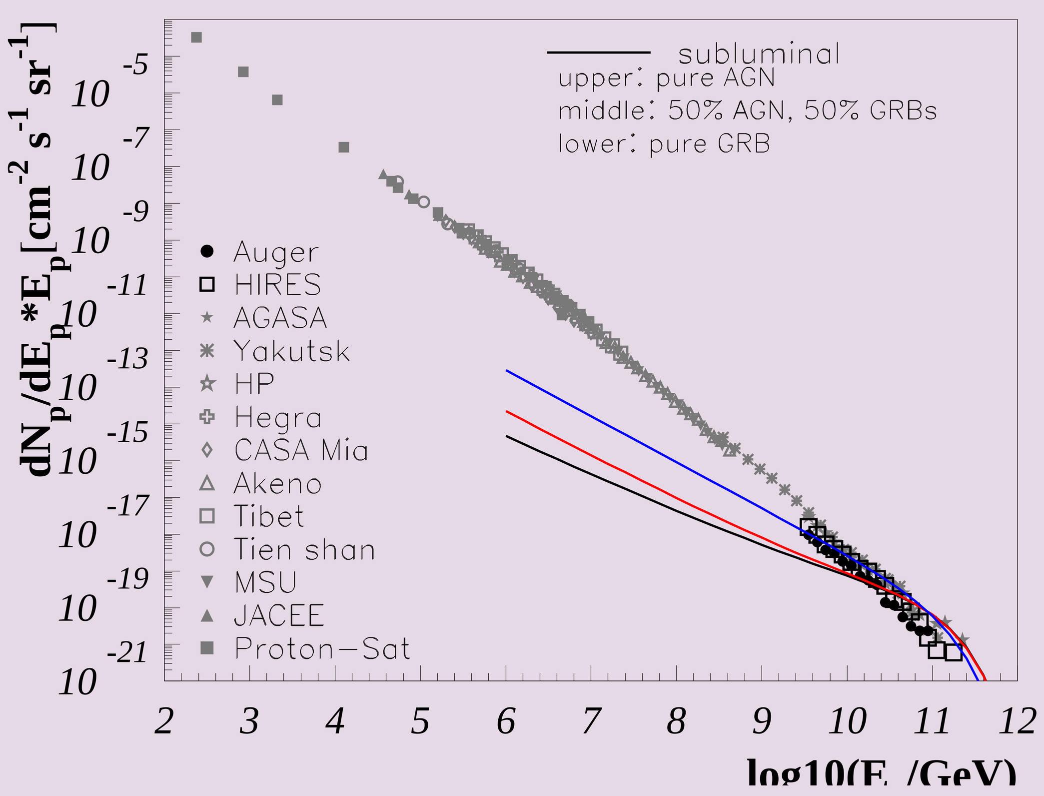

Figure 2. ***The diffuse energy spectrum of relativistic, subluminal sources, compared to the total diffuse cosmic ray spectrum.***

This implies three main characteristics for relativistic, subluminal (for superluminal shocks see Meli et al. '05) shocks:

1. The result is basically independent of the inclination angle between shock normal and magnetic field, as long as the shocks are oblique.

2. Mildly-relativistic shocks have spectral indices of around $\alpha_p \sim 2.0 - 2.4$.

3. The more relativistic the shock, the flatter the spectrum. Highly-relativistic shocks with $\Gamma \sim 1000$ can produce spectra as flat as $\alpha_p \sim 1.5$.

These findings seem to support many observational evidences regarding irregular and flat spectra of many GRBs.

As the spectra of different boost factors are actually associated to different sources, we calculate the possible contribution to the diffuse spectrum of charged Cosmic Rays. It is assumed that the Cosmic Ray spectrum above the ankle, $E > 10^{18.5}$ eV, is produced by protons from AGN and GRBs. For AGN, a boost factor of $\Gamma = 10$ is used. In the case of GRBs, it is assumed that 10% of all GRBs have $\Gamma = 100$, 80% have $\Gamma = 300$ and the remaining 10% have $\Gamma = 1000$. It is further assumed that the observed spectrum of charged Cosmic Rays is produced by a linear combination of AGN, dN_{AGN}/dE, and GRBs, dN_{GRB}/dE,

$$\frac{dN_{CR}}{dE} = \alpha \cdot \frac{dN_{AGN}}{dE} + (1-\alpha) \cdot \frac{dN_{GRB}}{dE}$$

with $0 \leq \alpha \leq 1$. Source evolution has been taken into account by using the source density given by the observation of X-ray AGN (Hasinger '05). This source evolution is also used in the case of GRBs, assuming that GRBs also follow the Star Formation Rate. The energy density of the observed Comic Ray spectrum j_E is then used to normalize the calculated Monte Carlo spectra

$$j_E = \int_{E_{\min}=10^{18.5}\ eV} \frac{dN}{dE} E\, dE \approx 10^{-7}\ GeV\ cm^{-2}\ s^{-1}\ sr^{-1}.$$

The final result is shown in Fig. 2. The upper line represents a pure AGN spectrum, $\alpha = 1$, the middle line represents a mixture of 50% AGN and 50% GRBs ($\alpha = 0.5$) and the lower line is a pure GRB spectrum, $\alpha = 0$. Since the Cosmic Ray spectrum above $E = 10^{18.5}$ eV needs to be explained by extragalactic sources, the best fit results from a pure AGN spectrum. With a significant contribution, the spectrum becomes too flat.

Conclusions

Monte Carlo studies on the acceleration of test particles in relativistic, subluminal shock environments are presented. Source candidates are Active Galactic Nuclei and Gamma Ray Bursts. The resulting particle spectra from those shocks have been investigated in the context of varying Γ shock boost factor and shock obliquity. A linear behavior between the spectral index α_p and Γ was found, leading to spectra of around $\alpha_p \sim 2.2$ for mildly-relativistic shocks ($\Gamma \sim 10$), producing much harder spectra for highly-relativistic ones. Since the very high relativistic shocks produce flatter spectra, it is found that the pure AGN spectrum fits the observed spectrum well.

Bibliography

1. D. C. Ellison, F. C. Jones, S. P. Reynolds, 1990 ApJ 360, 702
2. G. Hasinger, T. Miyaji and M. Schmidt, 2005 APh 441, 417
3. A. Meli, J. Becker, J. Quenby, 2007 to be submitted in A&A.
4. A. Meli and J. J. Quenby, J. Becker, 2005 ICRC 3, 229
5. A. Meli and J. J. Quenby, 2003b APh 19, 649
6. J. A. Peacock, 1981 MNRAS 196, 135