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COSMIC RAYS AND NEUTRINOS FROM GRBS

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Abstract. We have studied the Fermi acceleration of protons in GRBs as part of internal subrelativistic shock model and investigated the possibilities of generation of UHECRs and its associated neutrinos emission. In this purpose, we have compared three variants of the Fermi process: the one based on the usual Bohm assumption, the second based on the Kolmogorov turbulence scaling and the third based on scattering on multiple relativistic fronts. It turns out that the predictions of the three scenarii are very different and only the third one could achieve the goal of UHECRs production.

1 Introduction

The Gamma Ray Bursts (GRBs) have been considered (Vietri 1995, Waxman 1995) as a possible sources of Ultra High Energy Cosmic Rays (UHECRs). In the section 2, we briefly summarize the main dynamical and radiative characteristics concerning the fireball expansion (Mészáros et al. 1993). The problem of the standard UHECRs Fermi acceleration is tackled in the section 3 where we predict a possible double neutrino emission. At last, we propose another ultrarelativistic Fermi acceleration scenario, in the section 4, which suggests a good efficiency concerning the UHECRs generation.

2 The fireball model: dynamic and radiative evolution

The wind flow is considered to be a set of discrete shells which are successively emitted by a central object of size r_0 ($\sim 10^7$ cm) with an energy $E_s = E/N_s$, where N_s is the total number of shells and E the total energy, during the flow duration, namely t_w. In a first stage, the ejecta undergo a purely adiabatic expansion in the surrounding medium and their internal energy is converted into kinetic energy. Thus, the shell Lorentz factor increases until a maximum value of the order of the ratio $\eta = E/M_b c^2 \sim 10^2 - 10^3$, where M_b is the total baryonic mass ejected. This maximum value is achieved at the saturation radius, r_s, which is defined

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by $r_s = \eta\, r_0$. In the observer frame, the shell thickness, Δr, is supposed to remain constant and equal to r_0 until the broadening radius, r_b, which is such that $r_b \simeq \eta^2\, r_0 \sim 10^{12}$ cm. This radius is about the distance where the first collisions between different shells take place and constitute the beginning of the internal shock phase which expands until the deceleration radius, r_d, typically 10^{15}-10^{16} cm. We calculated (Gialis & Pelletier 2003) the radius, $r_\star$, where a shell becomes optically thin with respect to the Compton scattering and we defined a critical value, $\eta_\star$, for η such that the photospheric radius is located at r_b. We obtained;

$$\eta_\star \simeq 570 \times \left(\frac{E}{10^{51} erg}\right)^{1/5} \left(\frac{t_w}{1s}\right)^{-1/5} \left(\frac{\Omega/4\pi}{2\times 10^{-3}}\right)^{-1/5}, \qquad (2.1)$$

where Ω is the opening angle of the shell emission and $r_\star = r_b\ (\eta_\star/\eta)^5$ for $\eta \leq \eta_\star$ or $r_\star = r_b\ (\eta_\star/\eta)^{5/2}$ for $\eta \geq \eta_\star$. In this last case, the internal shocks generate only a non-thermal spectrum just after r_b, whereas, for $\eta < \eta_\star$, the internal shocks start accelerating particles in an optically thick plasma. Considering pp-collisions, any relativistic protons can collide with other protons (or neutrons) producing pions and thus neutrinos. The sheets become thin to pp-collisions always before the photosphere since $\tau_{pp} = n_p\, \sigma_{pp}\, \Delta R = 1$ (where $\sigma_{pp} = 2.7 \times 10^{-26}$ cm^2) at r_{pp} such that $r_{pp} = r_\star\sqrt{\sigma_{pp}/\sigma_T} < r_\star$ for $r_{pp} < r_b$ and $r_{pp} = r_\star \sigma_{pp}/\sigma_T < r_\star$ for $r_{pp} > r_b$. In this latter case, $r_{pp} \simeq 0.04\, r_\star$; which occurs when $\eta \leq \eta_\star/2$.

3 Usual particle acceleration processes in GRBs

3.1 External shock

The UHECR generation by Fermi acceleration at the external ultrarelativistic shock proposed by Vietri (1995) cannot happen in an usual interstellar medium because of a too weak μG magnetic field and a too short acceleration time (Gallant & Achterberg 1999). But, the possibility of a different external medium, as a pulsar wind bubble, gives a new hope for this acceleration process (Vietri et al. 2003).

3.2 Internal shocks

The Fermi acceleration in the internal shock model is usually considered (Waxman 1995) as midly or sub-relativistic with a characteristic time proportional to the Larmor radius (Bohm scaling). However, we have shown (Gialis & Pelletier 2003) that this assumption is not realistic regarding the magnetic energy depletion time. Moreover, the Fermi acceleration time depends on the mean free path, $\bar{\ell}$, of the particle in an irregular magnetic field. This length depends on the Larmor radius, r_L, and the correlation length, ℓ_c: for a turbulence spectrum of magnetic perturbations in a power law of index β, the following law, which is known in weak turbulence theory, has been extended in the regime of strong turbulence and large rigidities such that $r_L < \ell_c$ (Casse et al.): $\bar{\ell} = (r_L/\eta)\ (r_L/\ell_c)^{1-\beta}$ where

$\eta = \frac{<\delta B^2>}{<B^2>}$. The Bohm scaling $\bar{\ell} \sim r_L$, which holds for electrostatic turbulence, does not apply with purely magnetic irregularities on large scale; no theory nor numerical simulation has confirmed Bohm's conjecture. The Bohm estimate corresponds only to the specific case where the magnetic field is totally disorganised and the Larmor radius as large as the correlation length which is not the case in GRBs. We have shown (Gialis & Pelletier 2003) with a Kolmogorov scaling ($\beta = 5/3$) that GRBs are unable to produce UHECRs with this acceleration process because of a strong expansion limitation in energy (in the comoving frame)

$$\epsilon_{exp} \simeq 10^4 \left(\frac{\kappa_0}{10}\right)^{-3} \left(\frac{\eta}{300}\right) \left(\frac{\bar{B}(r_b)}{10^6 G}\right) \left(\frac{r}{r_b}\right)^{1-\alpha} GeV\,, \tag{3.1}$$

where $\alpha \simeq 3/2$, which is more severe than the synchrotron one.

3.3 A double neutrino emission

A double neutrino emission could be expected (Gialis & Pelletier 2003) with a cosmic ray generation by standard Fermi acceleration; the first one, in the high energy range, comes from the $p\gamma$-process and the second one is a significant lower energy emission (5 - 150 GeV) resulting from pp-collisions only for GRBs having $\eta < \eta_\star/2$. Both are not very sensitive to an improved acceleration process.

4 How to generate UHECRs in GRBs ?

4.1 Another scenario for a relativistic acceleration Fermi process

We propose a relativistic interpretation for the Fermi acceleration process that was suggested by Pelletier & Marcowith (1998) and Pelletier (1999). It consists in an interaction between particles and MHD disturbances in the relativistic expanding plasma of the fireball (Gialis & Pelletier 2003b). Each ejected layer can be interpreted as a magnetic sheet of a thickness $\delta \simeq r/\gamma^2$ where γ is the Lorentz factor of the layer. Particles are reflected if and only if their Larmor radius is smaller than δ and their energy gain can be as high as $\gamma^2\,\epsilon$ at each scattering. Particles having an energy larger than $Z\,e\,\gamma\,B\,\delta$, where B is the average magnetic field in the sheet, cross the front with a negligible interaction. In our scenario, we adopted the following scheme: one assume a prescribed value of B for each sheet at r_b and the field decreases with r like $r^{-\alpha}$ with $\alpha \in [1, 2]$.

4.2 A realistic Monte-Carlo simulation

We consider a conical box representing the flow around the broadening radius r_b in which we randomly put a set of identical layers (about several tens) with an uniform Lorentz factor distribution between 10^2 and 10^3 as often considered (Daigne & Mochkovitch 1998, Piran 2000). The isotropic suprathermal proton population is initially injected in each layer with an energy spectrum in the comoving frame $\propto \epsilon_c^{-2}$ between 1 GeV and a cut off energy $E_c = 10^4\ \left(\bar{B}(r_b)/10^6\,G\right)$

GeV according to the strong expansion limitation in energy.
The temporal evolution is the following one: the Lorentz factor distribution leads to collisions of different sheets during the numerical process. Collisions between sheets is taken into account and the total sheet number decreases with time. The proton energy limitation for an MHD-interaction is given by the confinement limit in each layer. We assume that all interactions instantaneously change proton energy because the scattering time in the magnetic interaction can be neglected. We also have neglected the synchrotron losses for protons because the synchrotron limitation in the comoving frame is over 10^5 GeV at r_b and next, increases like $r^{11/8}$ for $B \propto r^{-3/2}$ (Gialis & Pelletier 2003).
The numerical results clearly show that a sizeable part of UHECRs, which is larger than 10^{-5}, is generated whatever the magnetic field (over 10^4 G at r_b) and the flow duration (0.1 to 10 s). Moreover, this generation happens at the very beginning of the internal shock phase and the energy converted in UHECRs is high enough to be a sizeable fraction of the total magnetic energy. A possible detection of a γ-ray emission produced by pp-process via π^0 decay would constitute an interesting diagnosis of UHECRs in GRBs (see Gialis & Pelletier 2003b).

5 Conclusion

The usual Fermi processes seem to be unable to produce UHECRs in GRBs. The acceleration via the ultrarelativistic external shock with a standard interstellar medium is not efficient enough to achieve the goal of the UHECRs and the standard Fermi acceleration in the internal shock model uses the irrelevant Bohm's scaling which makes the goal impossible. However, another scenario is possible, considering an ultrarelativistic Fermi acceleration through multi-scattering off magnetized fronts, and it turns out to be much more efficient (Gialis & Pelletier 2003b) giving a new chance to GRBs as sources of UHECRs.

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