Cosmic Rays and Neutrinos from Gamma Ray Bursts

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Abstract. We review the hypothesis that the acceleration of protons at internal shocks in Gamma Ray Bursts (GRB) could be the origin of the ultra-high energy cosmic rays (UHECR) observed at earth, $E_{\max} \gtrsim 10^{19}$ eV. We find that, even though protons may be accelerated to such energies, their ejection into the interstellar/intergalactic medium is problematic because it is likely to be accompanied by considerable adiabatic losses in the expanding shell. The problem is circumvented by neutrons produced in photohadronic interactions, which are not magnetically bound and thus effectively ejected in the moment of their production. They can be both produced in sufficient number and be able to leave the emission region if the optical depth of the emission region to photohadronic interactions is of order 1. We show that this requirement can be fulfilled under the same conditions which allow acceleration of protons to the highest energies. The production of neutrinos in this process correlates the fluxes of cosmic rays and neutrinos, and makes the hypothesis of UHECR origin in GRBs testable.

ACCELERATION OF PROTONS IN GRBS

The hypothesis that Gamma Ray Bursts (GRB) might be responsible for the origin of ultra high energy cosmic rays (UHECR) has been proposed by Waxman [1], who assumed cosmic ray acceleration by momentum diffusion (2nd order Fermi acceleration), or at internal shock waves (1st order Fermi acceleration) within the expanding wind. We investigate here in some more detail the problems and consequences of this idea, in particular under reference to the internal shock scenario [2], where the observed variability in GRBs is explained by the presence of shocks in an unsteady outflow which occur when expanding subshells of different velocity catch up and merge.

The energy of protons accelerated at internal shocks in GRBs is essentially constrained by two conditions: (1) confinement in the acceleration region, $r'_{\rm g} = E'_p/eB' < R' \sim cT_{\rm var}\Gamma$; (2) balance of acceleration and synchrotron cooling, $t'_{\rm acc} \sim 2\pi r'_{\rm g}/c < t'_{\rm syn}$. Here, $T_{\rm var}$ is the observed variability time scale, and Γ is the bulk Lorentz factor of the wind; primed quantities refer to the comoving frame. It can be shown that energy losses due to photohadronic interactions and other cooling processes are less relevant [3]. Expressing the magnetic field relative to its equipartition value with the radiation, $U'_B = \xi_{B\gamma} U'_\gamma$, the maximum proton energy has to satisfy the conditions

$$E_{p,20} \lesssim 3(L_{51}\xi_{B\gamma})^{1/2}\Gamma_2^{-1} \tag{1a}$$

$$E_{p,20} \lesssim \tfrac{1}{3}(L_{51}\xi_{B\gamma})^{-1/4}T_{-1}^{1/2}\Gamma_2^{5/2} \tag{1b}$$

Quantities are expressed in canonical units: $E_{p,20} = E_p/10^{20}\,\mathrm{eV}$, $L_{51} = L/10^{51}\,\mathrm{erg\,s^{-1}}$, $T_{-1} = T/0.1\,\mathrm{s}$, and $\Gamma_2 = \Gamma/100$. These equations can be rewritten to express the minimum requirements on the physical conditions in the GRB wind in order to produce the highest energy cosmic rays:

$$\Gamma_2 \gtrsim E_{p,20}^{3/4}T_{-1}^{-1/4} \tag{2a}$$

$$\xi_{B\gamma} \gtrsim 0.2\,E_{p,20}^{7/2}T_{-1}^{-1/2}L_{51}^{-1} \tag{2b}$$

Since the highest energy cosmic rays are observed with energies up to $3{\times}10^{20}\,\mathrm{eV}$ [4], GRB winds must have bulk Lorentz factors $\Gamma \gtrsim 100$ and require $U'_B \gtrsim U'_\gamma$. The first condition is remarkably close to the canonical value assumed for GRBs in the internal shock scenario [2]. The latter condition is reasonable if the cosmic ray energy density dominates about that of relativistic electrons, $U'_p \gtrsim U'_e \sim U'_\gamma$, because the magnetic field could still be in equipartition with the total energy density in relativistic particles, $U'_B \sim U'_p + U'_e$.

THE EJECTION PROBLEM FOR UHE PROTONS

For cosmic ray acceleration at internal shocks, the acceleration site is placed within a relativistically expanding wind. The acceleration takes place typically at radii $r_i \sim 10^{14}$ cm, while the expansion continues until the wind hits the decelerated material behind the external shock at radii $r_e \sim 10^{16}$ cm. In a pointing dominated flux, the magnetic field decreases as $B' \propto r^{-1}$ and is largely transversal, because the longitudinal component decays with r^{-2}. Magnetic reconnection can, however, maintain isotropy of the magnetic field, leading to $B' \propto r^{-2}$ [5], consistent with the generic approach of a matter dominated flow where some mechanism keeps the magnetic field in equipartition with the thermal gas. In a decreasing magnetic field, charged particles suffer adiabatic energy loss due to the constancy of the adiabatic invariant $B' r'^2_{\mathrm{g}}$, which leads to an energy evolution of the nonthermal particle component with $E' \propto B'^{1/2}$. The condition for adiabaticity is that the time scale of particle gyration is much shorter than the expansion time scale, $r'_{\mathrm{g}}/c \ll r/c\Gamma$, which is equivalent to the confinement condition during acceleration for protons sufficiently below the maximum energy defined by $r'_{\mathrm{g}} \sim R' = r/\Gamma$. During expansion,

$r'_{\rm g}/R' \propto r^{-1/2}$ if $B \propto r^{-1}$, and confinement during acceleration implies that even the most energetic protons remain confined in the expanding shell and cool adiabatically. For $B' \propto r^{-2}$, $r'_{\rm g}/R'$ remains constant and adiabaticity applies only for protons with $E'_p \ll E'_{p,\rm max}$, but some cooling should be also expected for $E'_p \sim E'_{p,\rm max}$ (this requires further calculations).

When the material hits the outer shell at $r = r_e$, its bulk Lorentz factor, Γ, drops as a power law to values close to unity [6]. In this deceleration phase, the magnetic field confinement may break up and the energetic particles can be released. Their energy in the comoving field is then $E'_{\rm ej} \lesssim (r_i/r_e)^{\alpha/2} E'_{\rm acc}$, if $B' \propto r^{-\alpha}$, and $\Gamma_{\rm ej} \ll \Gamma_{\rm acc}$ would additionally reduce the energy in the observers frame. Hence, we expect a reduction of the energy of most protons *at ejection* by some orders of magnitude compared to their observer frame energy immediately after acceleration. This would essentially rule out a dominant contribution of GRBs to the UHECR spectrum above 10^{19} eV.

NEUTRON AND NEUTRINO PRODUCTION

The problem of adiabatic losses can be circumvented if the ejection of neutral particles is considered, because they are not coupled to the magnetic field. The obvious candidates are here neutrons, which are produced by protons in charged current photomeson-production, e.g. $p\gamma \to n\pi^+$. This is the same process which is also responsible for the production of neutrinos as a result of the pion decay, $\pi^+ \to \mu^+\bar{\nu}_\mu$, $\mu^+ \to e^+\nu_\mu\bar{\nu}_e$. Neutrinos are produced with an energy $E_\nu \lesssim 0.05 E_n$; the neutrino energy can be considerably below this limit, if energy losses of pions and muons are relevant, which is the case in GRBs [3]. The neutrino flux produced by this mechanism was recently proposed to reach observable levels above 100 TeV [7]. One can show that the conditions for the acceleration of protons to $\gtrsim 10^{20}$ eV implies that neutrinos up to 10^{16} eV must be produced [3].

The neutrons are left with about 80% of the proton energy and carry therefore cosmic ray energy efficiently. The production spectrum of neutrons depends on the both the proton spectrum and the spectrum of background photons. The relevant photon energies for the reaction are $\epsilon' \gtrsim 150\,{\rm MeV}\,\gamma'^{-1}_p$; for $\gamma'_p \gtrsim 10^5$ this is below the break energy of GRB spectra, so that the integrated number of photons above the reaction threshold rises only slowly with Lorentz factor. The neutron spectrum would than be expected to follow the proton spectrum, which is canonically assumed as $N'_p \propto E'^{-2}_p$; the same is the case for the accompanying neutrino spectrum (for details see Ref. [3]).

In order to escape from the GRB shell, neutrons must fulfill two conditions: Their decay time in the lab frame, $\tau_n\gamma_n$, must be considerably larger than the total time of the burst, and the probability of reabsorption by a $n\gamma \to p\pi^-$ reaction must be small. It is easy to see that the first condition is satisfied in GRBs, since $c\tau_n\gamma_n > r_e$ for $\gamma_n > 10^3$; for $\gamma_n \gtrsim 10^{10}$, it may even leave

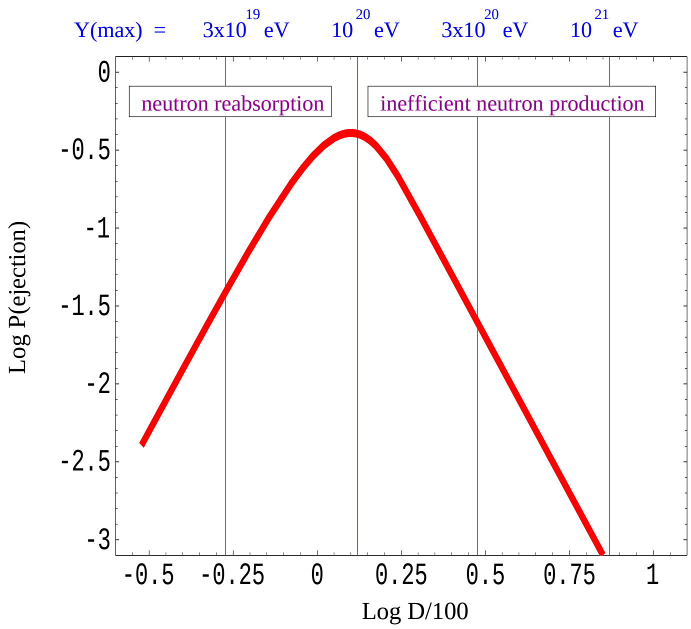

FIGURE 1. The ejection probability of neutrons from GRBs vs. $D = \Gamma T_{-1}^{1/4} L_{51}^{-1/4}$, and the correlated maximum proton energy scaled with luminosity, $Y_{\rm max} = E_{p,{\rm max}} L_{51}^{-1/3}$.

any possible stronger magnetized environment of the GRB before undergoing β-decay. Less trivial is the second condition: The probability of a neutron to leave the GRB shell, which has a thickness $R' = r/\Gamma$, is

$$P_{\rm esc} \sim \frac{c}{R'} \int_0^{R'/c} \exp\left(-\frac{t'}{t'_{p\gamma\to n}}\right)\, dt' \tag{3}$$

where the integral covers the range of distances of the point of the production of the neutron to the border of the shell. This probability is directly related to the probability of the neutron to be produced, $P_{\rm prod} \approx 1 - \exp(-t'_{\rm ad}/t'_{p\gamma\to n})$, where $t_{\rm ad}$ is the time scale for adiabatic cooling of the protons. In the relativistically expanding GRB shell we have $t'_{\rm ad} \approx R'/c$. Consequently we can write the probability $P_{\rm ej}$ for a UHECR proton to be ejected from the GRB as a neutron as

$$P_{\rm ej} \sim \frac{ct'_{p\gamma\to n}}{R'} \left[1 - \exp\left(-\frac{R'}{ct'_{p\gamma\to n}}\right)\right]^2 \quad . \tag{4}$$

The characteristic ratio involved in this expression can be expressed by canonical GRB parameters, $R'/ct'_{p\gamma\to n} \sim \frac{1}{2}\Gamma_2^4 T_{-1} L_{51}^{-1}$. The probability $P_{\rm ej}$ as a function of $D \equiv \Gamma_2 T_{-1}^{1/4} L_{51}^{-1/4}$ is shown in Fig. 1, together with the lower limits on D to produce UHECR protons. We see that the same conditions which make GRBs perfect proton accelerators, makes them also to almost perfect “neutron bombs” with ejection efficiencies of order 1–30%.

CONSEQUENCES

Under the assumption that GRBs produce protons with an energy density comparable to the radiation, and that each proton produces about 1 pion during its lifetime, i.e. transferring about 20% of the cosmic ray energy to neutrinos, Waxman and Bahcall [7] have shown that GRBs can produce a diffuse background flux of neutrinos above 100 TeV, which would lead to about 10 to 100 GRB correlated events per year in a km^3 underground neutrino detector. This flux should be easily detectable above the background due to the possibility of a correlation in both direction and time with the GRB. The same conditions would suffice to contribute a large fraction of the observed UHECR flux [1], but the connection of cosmic ray and neutrino ejection efficiencies depends in the GRB parameters.

Here, we have argued that energetic protons cannot be emitted directly from a GRB without losing most of their energy in adiabatic expansion, but that neutrons produced in charged current photohadronic interactions can escape the GRB and contribute to the cosmic ray proton spectrum after β-decay, provided that every proton produces on average one pion or less. This "one-pion-requirement" constrains the physical parameters of GRBs, but allows the acceleration of $\sim 10^{20}\,\mathrm{eV}$ protons, however, with a strongly decreasing ejection efficiency for larger energies. One conclusion might be that only the most luminous GRBs can produce cosmic rays of the highest energies, $E \gtrsim 3\times 10^{20}\,\mathrm{eV}$. The neutrino flux is then one-to-one correlated to the emitted cosmic ray flux, thus VHE neutrino observations could test the hypothesis of UHECR origin from GRBs; non-observation of a GRB correlated neutrino flux at the level predicted by Waxman and Bahcall [7] would rule out this hypothesis for standard assumptions of UHECR propagation.

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