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Ultra-high energy cosmic rays: gamma-ray bursts messengers ?

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To investigate whether gamma-ray bursts could be the sources of ultra-high energy cosmic-rays (UHECRs), we developed a Monte Carlo code to compute the acceleration of particles at mildly relativistic shocks. This code includes energy losses and handles particle escape according to specific prescriptions. We showed that particle acceleration can indeed be efficient, including for heavy nuclei, which survive photo-dissociation for a large range of gamma-ray bursts luminosities. However, only the models assuming that the prompt emission represent only a very small fraction of the energy dissipated at internal shocks, and that most of this dissipated energy is communicated to accelerated cosmic-rays, are able to reproduce the magnitude of the diffuse UHECR flux expected on Earth. For these models, we showed that the shape of the UHECR spectrum can be well reproduced above the ankle and the evolution of the composition is compatible with the trend suggested by Auger data.

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[†] A footnote may follow.

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1. Introduction

The cosmic-rays consist of energetic nuclei propagating through the interstellar and intergalactic space. They are characterised by a non-thermal spectrum showing remarkable regularity over an unmatched energy range, from sub relativistic energies to literally macroscopic energies larger than 10^{20} eV. This energy spectrum can be described grossly as a power-law, which clearly indicates that they are out of equilibrium and must be related to active (although possibly intermittent) dynamical processes at work in specific astrophysical sources or cosmic environments. These sources, however, are yet to be discovered. The lowest energy particles are known to have a Galactic origin, while the highest energy ones are almost certainly extragalactic. Among the possible sources of the Galactic cosmic rays, the expanding shock waves of isolated supernova remnants are the ones which have been studied in most detail. However, the question of the maximum energy accessible in supernova remnants is the subject of intense research and debate. Other potential sources include, for instance, superbubbles, pulsars, magnetars. At the other end of the spectrum, ultra-high energy cosmic rays (UHECRs), believed to be extragalactic at energies above $\sim 10^{19}$ eV, could be accelerated in very powerful sources such as gamma-ray bursts or active galactic nuclei.

Gamma-ray bursts (GRBs) are among the best candidate sources for UHECRs [1, 2]. Their very luminous prompt and afterglow emissions are thought to be related to the ejection of an ultrarelativistic outflow consecutive to the core collapse of a very massive star (long burst) or the merging of two compact objects (short burst). The leading model for production of prompt emission relies on the presence of short time scale variability of the Lorentz factor within the relativistic plasma outflow emitted by the central engine [5]. Mildly relativistic shocks are expected to form once the fast layers of plasma catch up with the slower parts, and to accelerate electrons whose subsequent cooling triggers the prompt emission. Shortly after this scenario was proposed to account for GRBs prompt emission, internal shocks also appeared as credible potential candidates for the acceleration of UHECRs [6]. In fact internal shocks physical parameters are likely to fulfill the "Hillas criterion" [7] for cosmic-rays acceleration above 10^{20} eV and the GRB emissivity in gamma-rays during the prompt phase was of the same order as the emissivity required for UHECR sources above 10^{18} eV. Although the latter argument has become quite controversial in the past few years [8], the study of protons acceleration at GRB internal shocks has been the purpose of many studies since Waxman's pioneering work [9, 10, 11, 12, 13, 14]. Among them, some were dedicated to the possible contribution of galactic GRBs to cosmic-rays at knee and above energies [15] or more recently to UHECRs [16]. The specific case of ultra-high energy (above 10^{19} eV) nuclei acceleration was considered in fewer studies [17, 24, 19] the latter also considering the possibility of heavy nuclei nucleosynthesis within GRBs relativistic outflows. The important question of nuclei survival during the early phase of GRBs (and its dependence on the physical processes at play during this phase) was recently discussed in [20]. The production of very high energy secondary particles, natural aftermath and possible signature of cosmic-ray acceleration to the highest energies has also been extensively studied. Predictions for very high and ultrahigh energy neutrino fluxes from GRBs can be found for instance in [21, 22, 23, 24, 25, 26, 27, 28] while the possible contribution of accelerated cosmic-ray induced gamma-rays to the prompt emission was estimated in [29, 30, 31, 32].

In a recent study [33], we reconsidered the question of UHECR acceleration at GRBs internal shocks, to investigate different shock model parameters (related to the shock microphysics) as well as the impact of energy losses (photo-interactions, hadronic interactions, pair production, synchrotron emission and adiabatic losses due to the expansion of the shell). Our study is based on a Monte-Carlo calculation of UHECR protons and nuclei acceleration at mildly relativistic shocks *including all the relevant energy loss processes cited above and the associated secondary neutrinos and photons emission*. We calculate cosmic-ray spectra at the source, for different GRB luminosities, as well as secondary particles production. We then use the recent GRB luminosity function and cosmological evolution derived by [34] to estimate the diffuse UHECR and neutrino fluxes expected on Earth, and discuss the physical parameter space (especially the different cases of energy redistribution between electrons, cosmic-rays and the magnetic field) that could allow GRBs internal shocks to be the main source of UHECRs.

2. Modeling a single pulse burst

We model the internal shocks using the approach of [36], where the relativistic outflow emitted by the central engine is represented by a large number of shells that interact with one another, discretizing the propagation of a collisionless shock within the outflow. This treatment allow us to estimate the key physical quantities at work during the internal shock phase and their evolution during the shock propagation. We assume a given initial Lorentz factor distribution of the relativistic wind to obtain a single pulse lasting a few seconds in the lightcurve, with a fast rise and an exponential decay which is typical in long GRBs. We discretize the evolution of the shock and make calculations at 18 different stages regularly distributed during the shock propagation. This simple model allows to calculate the physical parameters of the internal shocks, such as the magnetic field strength, the electron density and characteristic energy, and gives values relatively close to more sophisticated hydrodynamic models. Using our own radiative code for synchrotron emission and inverse Compton scattering (in this case synchrotron self-Compton) we calculate the internal shock prompt emission. Those photons will serve as targets for the accelerated cosmic-rays.

To investigate the impact of the model parameters related to the shock microphysics, we consider three different models consisting in different combinations of the parameters ε_e, ε_{CR} and ε_B, which represent the fraction of the energy released in the internal shocks which is given to the electrons, the cosmic-rays and the magnetic field, respectively. The first model (model A) assumed equipartition of the dissipated energy ($\varepsilon_e = \varepsilon_{CR} = \varepsilon_B = 0.33$) leading to an efficiency of the prompt emission of the order of 5%, independent of the burst luminosity L_γ. For models B and C, we make a different assumption: we use much lower values of ε_e, which implies that most of the dissipated energy is communicated to the accelerated cosmic-rays and the magnetic field. We consider $\varepsilon_{CR} \approx 0.9$ (resp. 0.66) and $\varepsilon_B \approx 0.1$ (resp. 0.33) for model B (resp. model C). Therefore, the prompt emission efficiency is lower than in the case of model A, and goes from approximately 0.01% for low values of L_γ to 1% for the highest prompt emission luminosities. It implies larger assumed values of the wind luminosity $L_{\rm wind}$ for a given prompt emission luminosity L_γ. Practically, to reproduce prompt emission luminosities L_γ between $5\,10^{49}$ and $5\,10^{53}$ erg.s^{-1} as in the case of model A, we assume wind luminosities between $3\,10^{53}$ and $3\,10^{55}$ erg.s^{-1}. We use then the following relation between the wind luminosities of the three different models:

$$L_{\rm wind}^{\rm B/C} = 3 \times \left(\frac{L_{\rm wind}^{\rm eq}}{10^{55}\,{\rm erg\,s^{-1}}} \right)^{-1/2} \times L_{\rm wind}^{\rm eq}, \tag{2.1}$$

where $L_{\rm wind}^{\rm B/C}$ refers to the wind luminosity for models B and C and $L_{\rm wind}^{\rm eq}$ to the corresponding wind luminosity for model A. This assumption may seem somewhat extreme from the energetics point of view. However, this does not increase the maximum power usually assumed for the GRBs by unreasonable factors. The highest luminosity GRBs ($L_\gamma > 5\,10^{53}$ erg.s^{-1}) require a wind power of only a factor of 3 for models B and C larger than for model A, while the difference in the power needed increases for lower luminosity GRBs, to reach a factor of 300 at the lowest luminosity. Consequently, the spread in the assumed intrinsic power of GBRs is smaller in the case of models B and C than in the case of model A (see [33] fore more details).

3. Particle acceleration including energy losses

We performed numerical simulations of cosmic-ray acceleration at mildly relativistic shocks, using a Monte Carlo code inspired by [37]. We considered mildly relativistic shocks with Lorentz factors between 1 and 2, which is the typical range expected at GRB internal shocks. We tested various magnetic field configurations in the vicinity of the shock, assuming different turbulence power spectra, turbulence levels or regular field obliquities. We calculated the spectra of particles escaping downstream and upstream as well as the energy evolution of the acceleration time for different magnetic field configurations. Most of the spectra of particles advected downstream deviated significantly from single power laws, as already pointed out by [37]. In the cases of purely turbulent fields (assuming a Kolmogorov power spectrum), we found relatively hard spectra with a sizeable fraction of the available energy communicated to high energies. In the case of quasi parallel shocks with low turbulence level, the hardest spectra (well harder than $\propto E^{-2}$) were found, while quasi-perpendicular "superluminal" shocks resulted in much softer spectra with sharp cutoffs below $E_{\rm max}$ (the energy at which the Larmor radius equals the largest turbulence length scale).

Concerning the energy evolution of the acceleration time, our finding significantly differ from the usually assumed Bohm scaling. In particular, for purely turbulent magnetic fields the acceleration times at $E_{\rm max}$ where between ~ 10 and ~ 80 times larger (depending of the shock Lorentz factor) than the Larmor time of the particles.

In a preliminary attempt, we compared the acceleration timescales with all the relevant energy loss timescales (including interactions with the calculated prompt emission photons) to estimate the maximum energy that a cosmic ray can reach in the shock wave. We investigated different shock configurations and found that it is possible to accelerate heavy nuclei at energies larger than 10^{20} eV in some cases. An example is shown in Fig. 1, where the case of a GRB with wind luminosity $L_{\rm wind} = 10^{53}$ erg s^{-1}, the estimate is performed for Fe nuclei at a given stage of the shock propagation at a distance $r_{\rm sh} \simeq 6.9 \times 10^{14}$ cm from the central source. The mean value of the acceleration time $t_{\rm acc}$ is displayed (as well as the 90% intervals of the distribution and the comparison to the Bohm scaling), and compared to the different loss timescales. One sees that in this case the acceleration is expected to be limited by photodisintegration losses at an energy of the order of $\sim 2 \times 10^{17}$ eV in the shock frame ($\sim 6\,10^{19}$ eV in the central source frame). It indicates

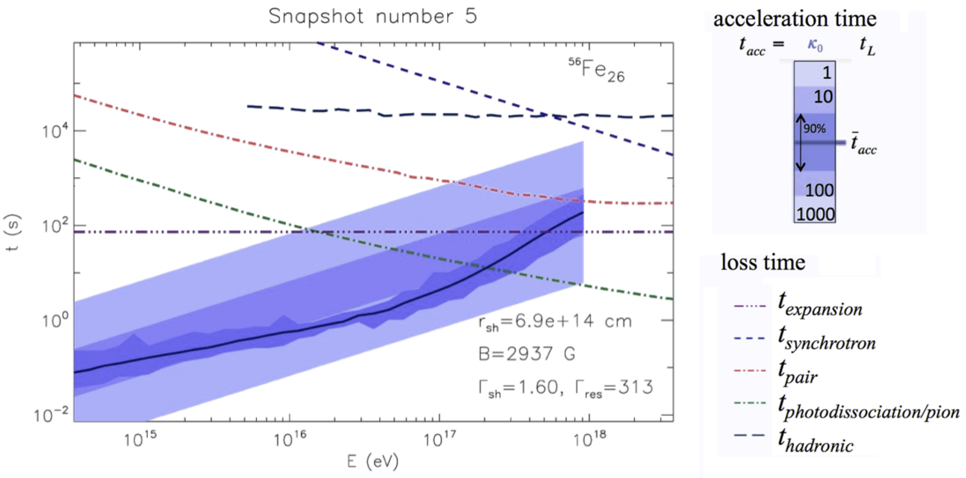

Figure 1: Comparison of the acceleration typical timescales with the energy loss timescales for Fe nuclei for a GRB with physical parameters : $L_{\rm wind} = 10^{53}$ erg s^{-1}, $t_{\rm wind}$ = 2s, model B, at a given stage of the shock propagation (the distance of the shock from the central source $r_{\rm sh}$, the shock Lorentz factor $\Gamma_{\rm sh}$, the magnetic field of the shocked fluid B and the bulk Lorentz factor of the flow $\Gamma_{\rm res}$ are indicated). The energy scale refers the energy in the shock frame. The figure is taken from [33].

that the acceleration of Fe nuclei (and in general of nuclei heavier than protons) will be limited by photodisintegration processes at the beginning of the shock propagation. Then the medium will become more and more transparent and the acceleration will be limited by adiabatic losses due to the expansion of the shell (see [33]).

We then included the energy loss mechanisms into the Monte-Carlo calculation of cosmic-ray acceleration at mildly relativistic shocks. We performed simulations reproducing the physical conditions (magnetic fields, baryon and photon densities, shock Lorentz factors) at different stages of the shock propagation. This treatment allowed us to estimate the cosmic-ray and secondary neutrino emission, for GRBs with various luminosities, taking into account their time dependance during the shock propagation. Moreover, we considered the three models A, B and C corresponding to the different combinations of the parameters ε_{CR}, ε_e and ε_B, presented in Sect. 2. Examples of cosmic-ray outputs for models A and B are shown in Fig. 2. For these cases and in the following, a composition with a metallicity ten times larger than that of Galactic cosmic-ray sources is injected at the beginning of the acceleration processes.

Overall, according to our modeling of mildly relativistic acceleration at GRBs internal shocks, relatively heavy nuclei (say, Si and above) can reach energies above 10^{20} eV in most cases, except for the lowest values of $L^{\rm eq}_{\rm wind}$ for model A. Intermediate nuclei such as CNO can reach energies above $10^{19.5}$ eV and approach 10^{20} eV for most values of $L^{\rm eq}_{\rm wind}$ for models B and C, while protons can only approach at most $10^{19.5}$ eV for the highest values of $L^{\rm eq}_{\rm wind}$ and remain below 10^{19} eV in most cases. As discussed in detail in [33], these low maximum energies for the proton component can only be increased, in principle, by invoking a faster acceleration mechanism, a magnetic field configuration allowing acceleration rates close to the so-called Bohm rate or larger magnetic fields than those implied by our hypotheses.

Fig. 2 shows the shape of the spectrum of cosmic-rays of different nuclear species escaping

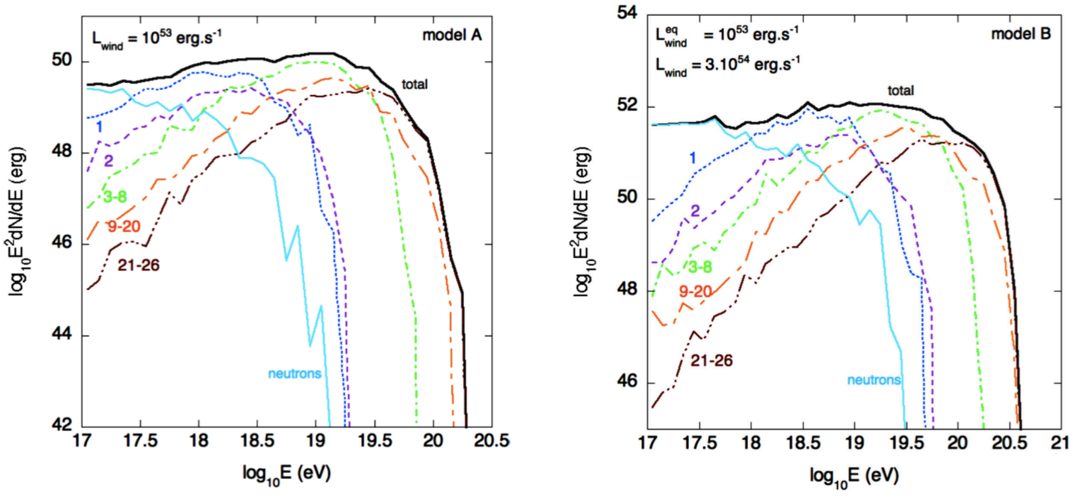

Figure 2: Cosmic-ray spectra, multiplied by E^2, emitted by GRBs, in the central source frame, assuming $L_{\rm wind} = 10^{53}$ erg s^{-1} , $t_{\rm wind}$ = 2s, , in the cases of model A (left panel) and B (right panel) . The contribution of different groups of nuclear species is shown (the labels refer to the nuclei atomic number Z). The normalization is obtained by integrating over the whole shock propagation. Figures are taken from [33].

from the GRB environment. One sees that the different species exhibit very hard spectra due fact that only high rigidity particles, which are in the week scattering regime, manage to escape from the magnetized region in the vicinity of the shock. The escape mechanism thus behave like a high-pass filter and the spectra of the different species escaping from the GRB is well harder that the spectra of the shock accelerated nuclei. The latter is not true for the neutrons which are mostly produced by the partial photodisintegration of shock accelerated nuclei. These neutrons, once produced, can freely escape from the GRB environment and as a result their spectrum is significantly softer than that of the other nuclear species, at least for intermediate and high luminosity for which the photodisintegration of accelerated nuclei is significant. These neutrons escaping from the source environment are obviously expected to decay rapidly to protons when propagating through the intergalactic medium.

4. Calculation of the diffuse UHECR fluxes expected on Earth

Finally, we calculated the expected UHECR and neutrino diffuse fluxes on Earth, by convoluting the cosmic-ray and neutrino release obtained for given GRB luminosities, taking into account their luminosity function and cosmological evolution as recently derived by [34]. In the case of model A, we obtained an integrated cosmic-ray luminosity density, above 10^{18} eV, of the order of 6 10^{42} erg Mpc^{-3} yr^{-1}, almost two orders of magnitude below that required to reproduce the observed UHECR flux. This means that GRBs are very strongly disfavored as the dominant source of UHECRs, if the dissipated energy is equally shared between accelerated electrons and cosmic-rays, as already concluded by several authors (e.g. [35]). For models B and C, we found UHECR luminosity densities of 3.9 10^{44} and 3.2 10^{44} erg Mpc^{-3} yr^{-1}, respectively, of the same order as those required. We then simulated the extragalactic propagation of UHECR from GRB sources, considering (i) different assumptions on the extragalactic magnetic field (EGMF) variance, (ii) the

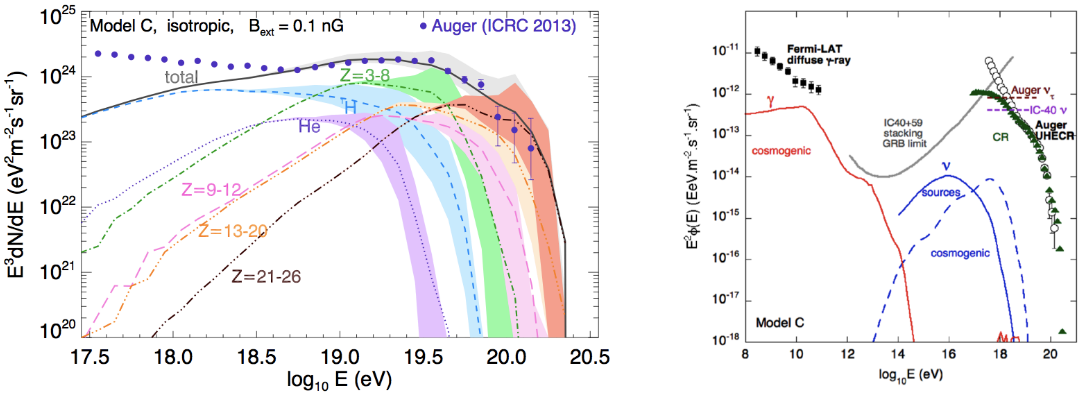

Figure 3: Left: Diffuse cosmique ray flux spectrum, expected on Earth, assuming an EGMF variance of 0.1 nG, in the case of model C. The contributions of different groups of nuclei are shown, the lines (plain lines for the total spectrum) represent the mean value calculated over 300 realizations of GRB history in the universe, the shaded areas represent the 90% intervals. Right: UHECR spectrum, cosmogenic neutrinos and photons spectra and diffuse neutrino spectrum from GRB sources predicted for model C, compared to various experimental limits or measurements. Figures are taken from [33].

cases of isotropic or beamed GRBs, (iii) a large number of realizations of the history of GRB explosions in the universe. We found that the magnitude of the observed UHECR flux is well reproduced by models B and C, providing very moderate renormalizations of the predicted fluxes by 5% downward and 25% upward, respectively. The shape of the observed UHECR spectrum is also well reproduced above the ankle by both models, particularly by model C (see left panel of Fig. 3). Concerning the evolution of the composition, we found a good qualitative agreement with the trend suggested by the Auger data: a light composition at the ankle becoming gradually heavier with increasing energy. Because of the slightly higher maximum energies predicted, model C differs from model B by a slight shift in energy of the decrease of the proton component.

Moreover, for all the different models, the spectrum of protons is found to be much softer than those of the other species due to the contribution of the soft neutron component produced in intermediate and high luminosity GRBs. As a result the predicted diffuse extragalactic cosmic-ray spectrum shows a low energy tail mostly made of protons which can provide a significant fraction of the total cosmic-ray flux down to $\sim 10^{17}$ eV. The presence of this soft proton component at low energy potentially has strong implications for the phenomenology of the transition for Galactic to extragalactic cosmic-rays as discussed in detail in [33, 38]. Overall, the evolution of the composition between $\sim 10^{17}$ eV and the highest energies appears fully compatible the recent finding of the Auger and KASCADE-Grande collaborations.

We finally calculated diffuse neutrino fluxes from GRB sources as well as cosmogenic neutrinos and photons fluxes, and found that those fluxes were currently not constrained by any experimental measurement or limit (see right panel of Fig. 3).

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