TeV emission from Gamma Ray Bursts, checking the hadronic model

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Abstract. Gamma-Ray Bursts (GRBs) are the most luminous explosions in the Universe. Their luminous prompt emission makes them detectable from cosmological distances. Most GRBs have been detected below a few MeV, however at least a hundred GRBs have been detected at high (0.1 GeV) energies and observed up to tens of GeV with the *Fermi* Large Area Telescope (LAT). Some GRBs have been observed at (0.1–1) TeV by ground-based imaging atmospheric Cherenkov telescopes. To date, the high energy emission mechanism is not understood. In this paper we review the possible leptonic and hadronic mechanisms capable of producing the ~ TeV emission detected in GRBs. In paricular we concentrate on the hadronic origin of this radiation component and discuss in detail the numerical simulation elaborated to reproduce the observed sub-TeV observations of GRB 190114C.

1 Introduction

The detection of GRBs in sub-TeV gamma rays has disclosed a new window of the electromagnetic spectrum for studying mildly relativistic transient outflows at the highest energies. GRB 190114C is the first long-duration GRB reported in the TeV band by the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescopes. High-energy gamma rays (0.2–1 TeV) were detected by the instrument with high significance [1], during both the prompt and afterglow phases of the GRB emission. The sub-TeV radiation component has a power comparable to that of the sub-GeV one, attributed to the synchrotron process. Therefore, sub-TeV emission has been interpreted as due to leptonic processes [2], usually considered responsible for gamma ray production in GRBs. However, a purely leptonic scenario consisting of synchrotron self-Compton radiation produced at external shocks has been shown to not match the broadband emission observed in GRB 190114C [2]. In addition, the large number of parameters involved in the model highly limits its prediction power. Although firm conclusions on the production mechanisms of GeV-TeV emission have been reached so far [3–9], the hypothesis that part of this emission might be caused by the presence of a hadronic component cannot be excluded. Several authors [4, 6, 7] have hence explored the possibility that processes involving photo-meson interactions might play a relevant role in the formation of the gamma-ray spectrum of GRB 190114C up to TeV energies. Since the

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dissipation mechanism responsible for the acceleration of electrons could be invoked for the acceleration of protons, high-energy neutrinos are also expected [10, 12–14]. In this review we provide a concise summary of the radiation mechanisms that may explain the spectral and temporal properties of the $\sim TeV$ emission in GRBs. In particular we test a scenario in which the very high energy (VHE) emission of GRB 190114C is due to photo-hadronic interactions occurring in the GRB jet during the so-called prompt phase. To this extent, we consider the standard fireball model in which, within the relativistic outflow of the jet, energy dissipation occurs at shocks internally to the jet or through interactions with ambient matter [10, 12]. Thus, a substantial part of the bulk kinetic energy is converted into internal energy, which is then distributed between electrons, protons, and the magnetic field. The internally accelerated electrons are presumably responsible for the keV–GeV photons observed in the GRB, which are emitted through synchrotron or inverse Compton processes. Accelerated protons may interact with these photons (~ MeV) and produce both neutral and charged pions, which in turn decay, originating respectively high-energy photons and neutrinos. The review is structured as follows: In Sec. 2 we discuss several high energy radiation mechanisms. In Sec. 3 we introduce the spectral and temporal properties of GRB 190114C. In Sec. 4 we present our hadronic model. In Sec. 5 we compare the photon flux resulting from our simulation to the Extragalactic Background Light (EBL) deconvolved MAGIC data, obtaining a set of best fit values of the model parameters. From the same simulation we predict a flux of high energy neutrinos and we evaluate the expected number of events in present and future experiments. A discussion of the results is provided in Sec. 6, where conclusions are ultimately derived.

2 Mechanism models for the high energy emission

In this section we consider different high energy mechanism that can explain the ~ TeV emission observed. This emission may be due to a completely leptonic process like the synchrotron emission by electrons accelerated in the shock region. However several authors (i.e. [6, 11]) have shown that the maximum energy that can be reached with this mechanism is ~ 10 GeV. Another leptonic model is the synchrotron self-compton emission by the same electron population that produced the seed synchrotron radiation. A distribution of relativistic electrons can inverse-Compton scatter some of the same synchrotron photons that it produced, leading to a synchrotron self-Compton emission. With this model it is hard to explain both the low and the high energy GRB emission. Another mechanism may be the External inverse-Compton emission that arises when the seed photons are inverse Compton scattered to high energies by relativistic electrons in a location different than where the seed photons were produced. This seems to be the best leptonic model to fit the data to date [6]. Alternatively, hadronic models may reproduce the high high energy emission. One of these models is the synchrotron emission produced by high-energy protons that are accelerated at shocks (like the electrons). However, the emitted power per particle is much smaller with respect to that for electrons and therefore this process seems to be unlikely. Another possible model is the photo-hadronic model where the high energy photons come fro neutral pion decay. We discuss this model in detail in the following sections.

3 GRB 190114C: spectral and temporal properties

GRB 190114C was the first GRB detected at sub-TeV energies, among the few observed so far. The combination of a rapid follow-up by MAGIC [15] with the rather contained distance of the source (confirmed from its optical counterpart to be at redshift $z = 0.4245$ [16, 17]), in terms of extra-galactic scales, has allowed to unveil the presence of an extremely energetic radiation component in GRBs, long before theorised [18]. A wealth of observations has allowed for the precise characterisation of the temporal and spectral features of this source. In the gamma-ray band, starting from the triggering instrument Swift [19], further observations have followed by GBM [20] and LAT [21] onboard of the *Fermi* satellite (up to 22.9 GeV), AGILE/MCAL [22], Integral/SPI-ACS [23] and Konus-Wind [24].

The prompt phase of GRB 190114C, as observed by Fermi-GBM, appears as a multi-peak emission lasting $T_{90} \simeq 116$ s (50-300 keV), being T_{90} the duration where 90% of the gamma-ray fluence was detected. The time-averaged spectrum in the first ~ 40 s can be described by a Band function with low and high-energy slopes equal to $\alpha = 1.058$ and $\beta = 3.18$, respectively, ans a break energy value of $E_{\rm b} \simeq 1.1$ MeV in the observed frame [20], and a gamma-ray fluence of $F_\gamma = 3.99 \times 10^{-4}$ erg cm^{-2} (10-1000 keV). As such, the isotropic energy release in the source frame amounts to $E_{\rm iso} \simeq 3 \times 10^{53}$ erg, indicating a fairly energetic (though not the most extreme) GRB. In turn, MAGIC reported a first detection starting from 68 s after the Fermi-GBM trigger with a significance above 50σ: VHE emission lasted for ~ 40 minutes, with the highest photon energy observed amounting to $E_{\rm max} = 0.852$ TeV [1]. Within this extended temporal window, time-dependent analysis of VHE data was also performed, showing a systematical decrease in flux normalization as well as a steepening trend over time. The earliest high-energy photon spectrum reported by MAGIC refers to the time interval 68-110 s, that entirely overlaps with the T_{90} estimated by Fermi-GBM for the prompt emission. During this time interval, the intrinsic burst spectrum in the 0.2-1 TeV band is characterised by a pure power-law ($\propto E^{-\xi}$) with $\xi = 2.16^{+0.29}_{-0.31}$ [2]. The photon spectral slope at the source has been derived taking into account the severe attenuation of the gamma-ray flux due to its propagation to the Earth within the EBL [2], according to the Dominguez et al. model [25]. We hence consider such an intrinsic spectrum and we compare it with the prediction of the gamma-ray flux emerging from our simulation of the IS region. Additionally, we have investigated the effects of adopting a different EBL model, e.g. that from Franceschini et al. [26, 27], finding results consistent with the Dominguez et al. model within the statistical uncertainty of the MAGIC measurements.

The temporal overlap between the MAGIC observations and T_{90} is not sufficient to definitely attribute the high-energy photons measured by MAGIC to the prompt or to the afterglow phase of the GRB emission. In this work, we consider a scenario where the observed TeV emission can be ascribed to the prompt phase, in particular to radiation emerging from hadronic interactions occurring at the IS region between accelerated protons and the Band-like target radiation field. The two main features of a hadronic scenario are the bulk Lorentz factor Γ, and the amount of energy channeled into relativistic protons $E_{\rm iso,p}$. The latter can be expressed with the baryon loading f_p defined as $f_{\rm p} = E_{\rm iso,p}/E_{\rm iso}$. Both the values of Γ and $f_{\rm p}$ can be constrained in order to reproduce the VHE spectrum in terms of hadronic gamma rays. Concerning the value of Γ, we estimate the minimum Lorentz factor required by a $E_\gamma \simeq 1$ MeV photon to be revealed at Earth, as observed by Fermi-GBM. This can be constrained by requiring that the optical thickness τ for pair production $\gamma\gamma \longrightarrow e^+e^-$ has to be $\tau \leq 1$. Following Eq. (5) of [28], we computed the total number of photons emitted during the first ~ 40, s, with energy greater than $E_{\rm max,pair} = (2\Gamma m_e c^2)^2/E_\gamma$, for different variability times $t_{\rm var} = 6, 3, 1$ ms [29], obtaining minimum Lorentz factor values $\Gamma_{\rm min} \simeq 60, 70, 90$ respectively.

4 The hadronic model: numerical simulations

We consider a model where high-energy protons, accelerated in the shock region, interact with photons, producing charged and neutral pions [13]. The pion decay products include leptons and photons:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu \,, \tag{1}$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu \,, \tag{2}$$

$$\pi^0 \rightarrow \gamma + \gamma \,. \tag{3}$$

Modelling the physical processes occurring inside the IS region of the expanding GRB fireball requires the characterisation of the site where particles propagation and interactions take place. The emitted flux depends strongly on the GRB lorentz factor, Γ and to the variability time $t_{\rm var}$. In our simulation, we assume for the variability timescale values ranging from 1 to 6 ms, the latter being suggested by observations performed during the prompt phase of GRB 190114C [29]. In turn, the Γ factor is treated as a free parameter of the model, whose most likely value will be fixed as the one that best reproduces MAGIC data.
All the details of the MC calculation are reported in [30]. The kinematics of $p\gamma$ interactions follows the methods outlined in [31]. The energy particle distribution for interacting protons, charged pions, muons, and neutrinos is shown in Fig.1 of [30].

Concerning the neutral pion production and decay, we consider the possibility that each originated gamma ray might further interact within the IS shell with low energy ambient photons, via $e^\pm$ pair production. For the purposes of our simulation, the Band spectrum of target photons is assumed to extend outside of the Fermi-GBM observed energy range, by about three decades, as to allow the pair production to occur with the gamma ray originated from π^0-decay. As a result of our computation, we find the fraction of absorbed high energy photons amounts to $\simeq 60\%$ for 10 GeV gamma rays in the IS frame ($\Gamma = 100$ and $t_{\rm var} = 1$ ms). This fraction increases for more energetic gamma rays. We observe that, at fixed gamma-ray energy, the effect of $\gamma\gamma$ absorption results larger for lower values of Γ, since the target photon density increases lowering the bulk Lorentz factor.
The gamma rays surviving the $e^\pm$ production process in the IS shell will emerge from this region and would eventually be observed in the laboratory frame with energy $E_{\rm obs} = \Gamma E_{\rm IS}/(1+z)$. Such photons can be directly compared with the intrinsic Spectral Energy Density (SED) derived by MAGIC.

5 Results: gamma rays and neutrinos from photo-hadronic interactions

We perform MC simulation for different values of $t_{\rm var}$ and Γ, obtaining spectra of high-energy gamma rays and neutrinos emerging from the interaction region. We then convert these spectra into expected fluxes on Earth by taking into account the cosmological nature of GRBs. For the particle energy flux $E^2\phi(E)$, either photons or neutrinos, we rescaled the IS energy spectrum through: i) the comoving distance $d_{\rm c} = d_{\rm L}/(1+z)$, where $d_{\rm L}$ represents the luminosity distance, ii) the first time interval of MAGIC observations $\Delta t = 42$ s, and iii) the energy conversion factor from the IS to the observed frame, as:

$$E^2\phi(E) = f_{\rm p}\Gamma \frac{(1+z)}{4\pi d_{\rm L}^2 \Delta t} \left(E^2 \frac{dN}{dE} \right)_{\rm IS} \,. \tag{4}$$

For each simulated Γ and $t_{\rm var}$ set of values, the baryon loading $f_{\rm p}$ has been varied in the interval $0.1 - 5.0$ in uniform steps of width $\Delta f_{\rm p} = 0.1$, in order to derive the best agreement between the EBL-deconvolved MAGIC data in the 68-110 s time interval [2] and the simulated fluxes, through a χ^2 statistical test. Considering the minimum bulk Lorentz factor values dictated by the opacity argument and derived in Sec. 3, we obtain the following set of best-fit parameters: for the case $t_{\rm var} = 6$ ms, we find $\Gamma = 70$ and $f_{\rm p} = 0.95$; in turn, for $t_{\rm var} = 3$ ms, we obtain $\Gamma = 80$ and $f_{\rm p} = 0.93$; finally, for $t_{\rm var} = 1$ ms, we derive $\Gamma = 100$ and $f_{\rm p} = 1.1$. Remarkably, despite the broad variation in the values of bulk Lorentz factor that characterize the models possibly reproducing sub-TeV data, an almost constant $f_{\rm p}$ is obtained, suggesting a comparable amount of energy being channeled in the hadronic and leptonic jet components. By fixing Γ to the best-fit value, we evaluated the statistical uncertainty on flux normalisation. This result is shown in Figure 1, where the modellings that best reproduce the EBL-deconvolved MAGIC data are reported on top of it, the shaded area representing the 1σ statistical uncertainty evaluated over $f_{\rm p}$.

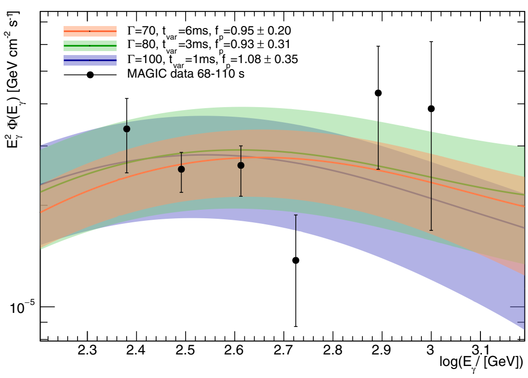

Figure 1. Comparison between the EBL-deconvolved flux of GRB 190114C, as measured by MAGIC in the temporal interval 68-110 s [2], and the simulated photon flux arising from the π^0-decay, after accounting for internal gamma-ray absorption. Different parameter values of the model are tested, as indicated in the legend.

A direct proof of the hadronic origin of the observed TeV radiation might come from coincident neutrino observations. Because of the transient nature of GRBs, the detection of a single neutrino event would allow to identify these sources as extreme hadronic accelerators. Despite the experimental efforts, no clear signal has emerged so far in data from the ANTARES and IceCube telescopes [34] [35], when searching for spatial and temporal coincidences with the prompt emission of GRBs. This leads to a constraint on the possible contribution of standard GRBs to less than 10% of the diffuse cosmic neutrino flux [36–39]. Additionally, it is still unclear whether TeV-emitting GRBs behave as the standard GRB population: consequently, it appears of paramount importance to investigate neutrino emissions from this newly discovered class of sources. Both the ANTARES and IceCube Collaborations have searched for coincident neutrino-induced signals from the direction of GRB 190114C. No events were observed in extended time windows, covering both the prompt and the afterglow phase of the GRB, leading to upper limits on the expected neutrino fluence. In the case of ANTARES, the 90% confidence level integrated limit amounts to 1.6 GeV/cm^2, while for IceCube it amounts to 0.44 GeV/cm^2 [40, 41]. In both cases, the constraints are limited to the muon neutrino component reaching Earth. In fact, because angular precision is a crucial feature to reduce the atmospheric background entering the search cone angle, muon neutrino charged-current interactions constitute the better astronomical channel, as muons emerge from these, which can be identified in large volume neutrino telescopes as long tracks. Neutrino fluxes arriving on Earth differ from those produced at source due to the effect of lep-

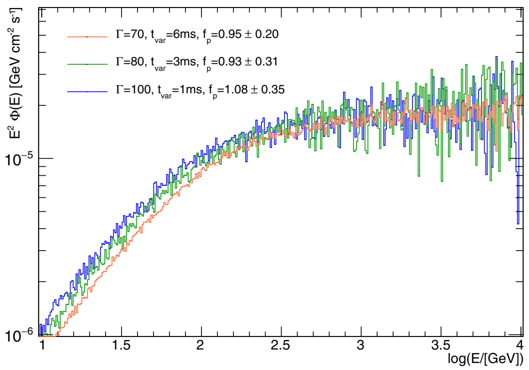

Figure 2. Muon neutrino and antineutrino fluxes expected on Earth from GRB 190114C, obtained from the simulations in the time interval 68-110 s for different model parameter values, as indicated in the legend.

tonic flavor mixing: hence, in order to have a direct comparison between the experimental upper limits and the predictions from the hadronic modelling here developed, neutrino oscillations have to be accounted for. By considering the normal ordering case in the standard three-flavour scenario [42], we obtain the neutrino energy flux on Earth, which is shown for muon neutrinos and antineutrinos in Fig. 2. Current neutrino detectors ANTARES and IceCube have investigated their data looking for possible spatially coincident neutrino signals, however the resulting upper limits are a few order of magnitudes above the model predictions here presented, indicating that the non-detection of current instruments is compatible with the hadronic model expectations for the values of $f_{\rm p}$ and Γ that better reproduce the sub-TeV gamma-ray MAGIC data. To understand whether future neutrino detectors, as the full configuration of KM3NeT, might be able to uncover a level of signal comparable to that expected from GRB 190114C, we first obtain the muon neutrino (and antineutrino) fluence $dN_{\nu_\mu}/(dE_{\nu_\mu}dS)$, and then compute the expected number of track-like events as

$$N_{\rm events}(\delta) = \int A_{\rm eff}^{\nu_\mu}(E_\nu,\delta)\left(\frac{dN_{\nu_\mu}}{dE_{\nu_\mu}dS}\right)_{\rm Earth} dE_{\nu_\mu}\,, \tag{5}$$

where the neutrino telescope effective area $A_{\rm eff}^{\nu_\mu}$ is a function of the neutrino energy and of the source declination δ. For the purpose of the computation, the public effective areas of ANTARES, IceCube and KM3NeT are adopted, averaged over neutrinos and antineutrinos. In the case of ANTARES, we consider the declination band $-45^o < \delta < 0^o$ [34] including the position of GRB 190114C, in the case of IceCube instead the effective area refers to the band $-30^o < \delta < 0^o$ [35], while for KM3NeT we adopt mean values of the high-energy detector ARCA (averaged over the entire sky) [43]. It is also worth to note that, while the ANTARES and IceCube have been released at the analysis level for point source studies, the KM3NeT/ARCA one is at trigger level. We provide in the following the expected number of neutrino-induced events in the three large-volume detectors, as reported in Table 1 relatively to the simulation with $t_{\rm var}$ = 1 ms, Γ = 100 and $f_{\rm p}$ = 1.1. Even though the coincident background rate due to atmospheric neutrinos is by orders of magnitude lower than the signal rate expected from a source like GRB 190114C, a detection from a single GRB appears to be very difficult. This result suggests that stacking several GRBs of the same kind could be the only viable solution for a significant detection.

Detector	Declination band	N_{events}
ANTARES	$-45^o < \delta < 0^o$	1×10^{-3}
IceCube	$-30^o < \delta < 0^o$	2×10^{-2}
KM3NeT/ARCA	Average	1×10^{-1}

Table 1. Signal events expected in different neutrino telescopes, as induced by ν_μ interactions during the [68;100] s time interval of the prompt emission of GRB 190114C, for the model with $t_{\text{var}} = 1$ ms, $\Gamma = 100$ and $f_{\text{p}} = 1.1$. The computations refer to instrument effective areas in the declination band including the source location (ANTARES [34], IceCube [35], and KM3NeT [43]).

6 Discussion and Conclusions

The successful observation of radiation from GRBs extending up to the TeV domain has provided further evidence of the extreme nature of these sources. However, there is still poor understanding of the processes that characterize the observed TeV emission emerging from GRB 190114C (and the few other GRBs detected at TeV energies). The newly discovered radiation component might witness the presence of effective hadronic acceleration in the jet of the burst, possibly already during the prompt phase of the emission. This occurrence would establish the connection between GRBs and Ultra-High-Energy Cosmic Rays (UHECRs), which remains a long-standing paradigm still to be proven. To test the hypothesis of the hadronic origin of TeV radiation, we developed a MC simulation of photo-meson interactions between high-energy protons and target photons distributed according to a Band-like spectrum, as indicated by Fermi-GBM observations. After computing the spectra of secondary particles emerging from these interactions, we additionally simulated the electromagnetic absorption that gamma rays undergo in the IS shell. The spectrum of escaping photons thus obtained has been compared to the intrinsic source spectrum derived by deconvolving MAGIC observations of GRB 190114C in the EBL. The free parameters of the hadronic model have thus been constrained by means of a residual minimisation procedure, indicating that the source channelled a comparable amount of energy into photons and hadrons. Extended studies about the entire sample of observed TeV GRBs are required to understand the physical mechanisms responsible for the TeV emission. In particular, it appears to crucial to have a better characterization of the very-high-energy photon spectrum in the early stages of the GRB emission, which seems to be currently limited by the prompt response of imaging atmospheric Cherenkov telescopes in pointing. Confirmation of the hadronic origin of sub-TeV radiation might, in principle, arise from neutrino observations. In the context of the parameters that better reproduce MAGIC data, however, such a detection from GRB 190114C appears extremely unrealistic, as confirmed by the lack of spatial correlations in data from both the ANTARES and IceCube neutrino telescopes. We may conclude that

1. Both leptonic and hadronic interpretations of the TeV data cannot be excluded.

2. Extended studies about the entire sample of observed TeV GRBs are required to understand the physical mechanisms responsible for the TeV emission.

3. In order to have a complete understanding on the mechanism responsible of the high energy emission, it is crucial to have a better characterization of the very-high-energy photon spectrum in the early stages of the GRB emission. This seems to be currently limited by the prompt response of imaging atmospheric Cherenkov telescopes in pointing but it will be improved in the next future

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