On the flavor composition of neutrinos from choked jets of gamma-ray bursts

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Resumen / Gamma-ray bursts *ahogados* (CGRBs, por sus siglas en inglés) se producen cuando un jet generado en el centro de una estrella masiva en colapso no puede emerger del envoltorio estelar, y por lo tanto los rayos gamma que puedan ser producidos en tales jets son absorbidos. Neutrinos, sin embargo, pueden escapar libremente y por lo tanto estas fuentes han sido propuestas como capaces de generar el flujo difuso de neutrinos observado por IceCube. En el presente trabajo, intentamos obtener el flujo de neutrinos de diferentes familias producidos en CGRBs usando valores típicos para parametros físicos de la región de emisión. Consideramos la inyección tanto de protones como de electrones que suponemos que son acelerados por choques internos en el jet, y que presentan una dependencia con la energía del tipo ley de potencia, con un índice $\alpha = 1.8 - 2.2$. Resolviendo una ecuación de transporte en el estado estacionario, obtenemos las distribuciones de estas partículas y además de piones y muones, dado que estas últimas se generan por copiosas interacciones protón-fotón ($p\gamma$) en el contexto asumido. Considerando que los CGRBs se pueden relacionar con supernovas de colapso gravitacional, suponemos que la tasa de generación de estas fuentes es proporcional a la tasa de formación estelar y podemos integrar sobre el redshift para obtener el flujo difuso total de neutrinos de cada familia. La composición de las tres familias a ser observada en la Tierra vemos que depende de la energía de los neutrinos como consecuencia de las pérdidas de energía que sufren los piones y muones. Este comportamiento podrá ser probado con instrumentos de nueva generación como IceCube-gen2.

Abstract / Choked gamma-ray bursts (CGRBs) are produced when the jet generated in the center of a massive collapsing star fails to emerge from the stellar envelope, and hence the gamma rays produced in such a jet get absorbed. Neutrinos, however, escape freely, and therefore these sources have been proposed as capable of generating the diffuse flux observed by IceCube. In the present work, we aim to obtain the neutrino fluxes of the different flavors corresponding to CGRBs adopting typical values for the physical parameters of the emission region. We then consider the injection of both protons and electrons, which are assumed to be accelerated by internal shocks in the jet and present power-law dependence on the energy with an index $\alpha = 1.8 - 2.2$. By solving a steady-state transport equation, we obtain the particle distributions, including also pions and muons, since these particles are generated after copious proton-photon ($p\gamma$) interactions in the present context. Considering that CGRBs can be related to core collapse supernovae, we assume that the generation rate of these sources is proportional to the star formation rate, and we integrate on the redshift to obtain a total diffuse neutrino flux of each flavor. The flavor composition to be observed at the Earth is found to depend on the neutrino energy as a consequence of the losses suffered mainly by pions and muons. This will be probed with next generation neutrino instruments such as IceCube-gen2.

Keywords / radiation mechanisms: non-thermal — neutrinos — gamma-ray burst: general

1. Introduction

The neutrino observatory IceCube has accumulated events since 2014 allowing to stablish a flux of neutrinos of astrophysical origin, i.e., not produced by cosmic rays in the atmosphere, but it has not been possible to identify the specific sources. This mainly is due to a lack of correlation with known gamma-ray emitters. One possible type of sources are the so-called choked gamma-ray bursts (CGRBs) which cosnsist of a jet being launched inside a collapsing massive star that *fails* to emerge from the stellar mantle, implying that the gamma rays produced get totally absorbed. It is expected that this scenario can be realized in some core-collapse supernovae (SNe), such as those of the types II (MacFadyen et al., 2001) and Ib/c. Although it is currently uncertain what fraction of such systems can harbour these choked jets (Piran et al., 2019), the connection is envisaged similarly to the case of the one confirmed between several type Ib/c SNe and long GRBs with flat spectrum (Hjorth & Bloom, 2011).

The proposed scenarios of neutrino production in GRB jets (e.g., Waxman & Bahcall, 1997), have guided the study of CGRBs as hidden neutrino sources under different assumptions and approximations (Murase & Ioka, 2013; Senno et al., 2016; He et al., 2018; Fasano et al., 2021). In our recent work (Reynoso & Deus, 2023, RD2023), we have addressed in detail the process of neu-

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Tabla 1. Parameters of the CGRB model

input parameter	description	values
L_0[erg s^{-1}]	isotropic power	$(10^{49}; 10^{50})$
α	power-law index of injection	$(1.8; 2; 2.2)$
t_j[s]	duration of typical CGRB	$10^3; 10^4$
$\epsilon_{\rm rel}$	fraction of power in relativistic particles	0.1
a_{pe}	proton-to-electron ratio	100
Γ	Lorentz factor of internal shock region	100
δt[s]	variability timescale	0.01
ϵ_B	magnetic-to-kinetic energy ratio	$(0.01; 0.1; 1)$

trino production in CGRBs by applying a steady-state transport equation to obtain the particle distributions of primary protons (p), electrons (e) and also secondary pions (π), kaons, and muons (μ), which are mainly produced after $p\gamma$ interactions. In particular, we accounted for the possibility that pions and muons can interact with the same soft photon target as the parent proton, as this aspect has not been previously considered. In the present work, we focus on additional possibilities: a lower average jet luminosity and different values the injection index of the accelerated primary particles, α. We present the corresponding results for the diffuse neutrino (ν) flux and flavor ratios.

2. Basics of the model

Here we briefly describe the basics of the model, while the reader can refer to RD2023 for more details. We assume that the jet of a CGRB has a Lorentz factor $\Gamma \sim 100$, a half-opening angle $\theta_{\rm op} \approx 0.2$rad, and its power is $L_{\rm j}$, which corresponds to an isotropic equivalent power

$$L_0 = 2L_{\rm j}/(1-\cos\theta) = 10^{49-50}\text{erg s}^{-1}. \quad (1)$$

For a variability timescale δt, the distance from the central source to the position of the internal shocks in the jet is

$$r_{\rm is} = 2\Gamma^2 c\delta t \simeq 6\times10^{12}\text{cm}\ \delta t_{-2}\Gamma_2, \quad (2)$$

where $\Gamma_2 = \Gamma/100$ and $\delta t_{-2} = \delta t/(0.01\text{s})$. In that region, the comoving number density of cold protons is

$$n'_{\rm j} = \frac{L_0}{4\pi\Gamma^2 r_{\rm is}^2 m_p c^3} \simeq 4.9\times10^{12}\text{cm}^{-3} L_{0,51}\Gamma_2^{-6}\delta t_{-2}^{-2} \quad (3)$$

The flow is magnetized, and the magnetic energy density is usually taken to be a fraction $\epsilon_B \approx 0.1$ of the kinetic energy density $m_p c^2 n'_{\rm j}$, i.e.

$$B' = \sqrt{\frac{2\,\epsilon_B L_0}{\Gamma^2 r_{\rm is}^2 c}} = 1.36\times10^5\text{G}\ \epsilon_{B,-1}^{1/2} L_{0,51}^{1/2}\Gamma_2^{-2}\delta t_{-2}^{-1} \quad (4)$$

We assume that both protons and electrons are accelerated by internal shocks with an acceleration rate

$$t_{\rm acc}^{-1}(E'_i) = \eta\,\frac{e\,B'\,c}{E'_i}, \quad (5)$$

where the efficiency factor is $\eta = 0.1$. The main cooling processes for electrons are synchrotron and inverse Compton (IC) scattering, while $p\gamma$ is dominant for high energy protons. The detailed expressions for these and other processes involved can be found in RD2023, and they are plotted in Fig. 1 for protons. The energy where the acceleration rate is balanced by the total losses is taken as the maximum particle energy $E'_{i,\rm max}$, with $i = \{e, p\}$ for primary electrons and protons. Then, we take the injection of these particles as

$$Q'_i(E'_i) = \frac{d\mathcal{N}_i}{dE'_i d\Omega'\, dV' dt'} = K_i E_i'^{-\alpha}\exp\left(-\frac{E'_i}{E'_{i,\rm max}}\right), \quad (6)$$

where K_i is a normalizing constant which is fixed by considering that the total power injected in electrons and protons in the central source (CS) rest frame is

$$\Delta V \int_{4\pi} d\Omega \int_{2\,m_i c^2}^{\infty} dE_i E_i Q_i(E_i) = L_i, \quad (7)$$

where $\Delta V = 4\pi r_{\rm is}^2(c\,\delta t)$. The relevant target photons for $p\gamma$ interacctions here is the usually adopted one in these scenarios: the thermalized synchrotron and IC emissions produced by electrons accelerated at the shocked jet head, where the jet is actually stopped by the stellar mantle. A fraction of these photons escape into the region with internal shocks. In principle, also the synchrotron emission of electrons accelerated at the internal shocks could provide additional target photons, but these are relevant only if $a_{pe} = L_p/L_e \sim 1$, as obtained in RD2023, while in the present work we assume $a_{pe} = 100$, a similar value as the derived from cosmic ray observations. For particles in the region with internal shocks, the equilibrium distributions are obtained by solving the steady-state transport equation,

$$\frac{d\left[b'_{i,\rm loss}(E'_i)N'_i(E'_i)\right]}{dE'_i} + \frac{N'_i(E'_i)}{T_{i,\rm esc}} = Q'_i(E'_i), \quad (8)$$

where the $b'_{i,\rm loss} = -E'_i\sum_j t'^{-1}_{i,j}(E'_i)$ is the total energy loss for particles of the type i, and $t'^{-1}_{i,j}$ are the cooling rates corresponding to each process j. In turn, $T_{i,\rm esc}$ is the escape timescale, which is typically longer than the dominant cooling rates. In the case of pions and muons, we replace $T_{i,\rm esc} \to T_{i,\rm dec}$ to obtain the particle distributions.

3. Results and discussion

Following the method of calculation described in RD2023 and assuming the sets of parameters shown in Table 1, we obtain the relevant cooling rates and particle distributions. In Fig. 1, we show the cooling rates for protons in the cases of $L_0 = 10^{49}$erg s^{-1} and $L_0 = 10^{50}$erg s^{-1}, where it can be seen that the maximum proton energy is higher in the latter case. This can be seen also in corresponding the proton distributions appearing in Fig. 2. Due to the page limitation,

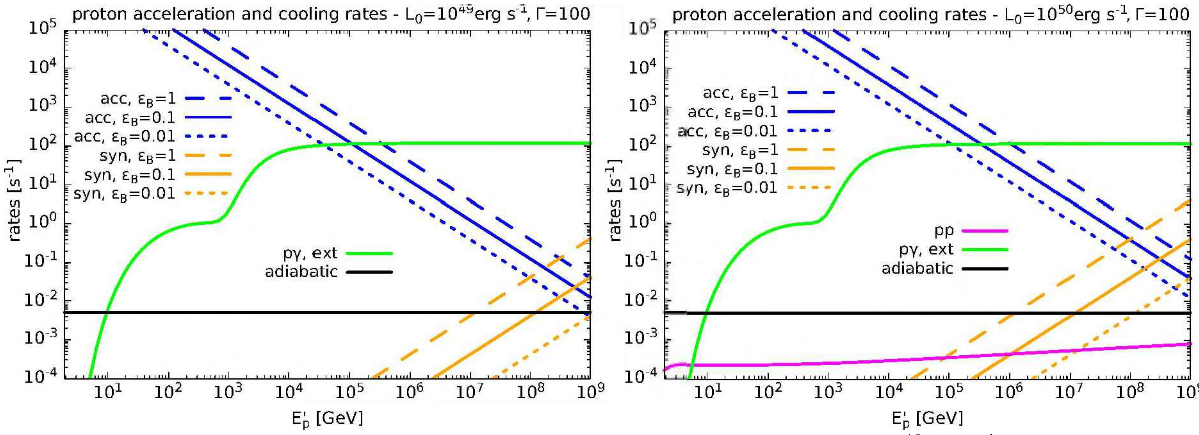

Fig. 1. *Left panel:* Acceleration and cooling rates for protons in CGRBs with $L_0 = 10^{49} \mathrm{erg\,s^{-1}}$. *Right panel:* The same as in left panel, but for $L_0 = 10^{50} \mathrm{erg\,s^{-1}}$.

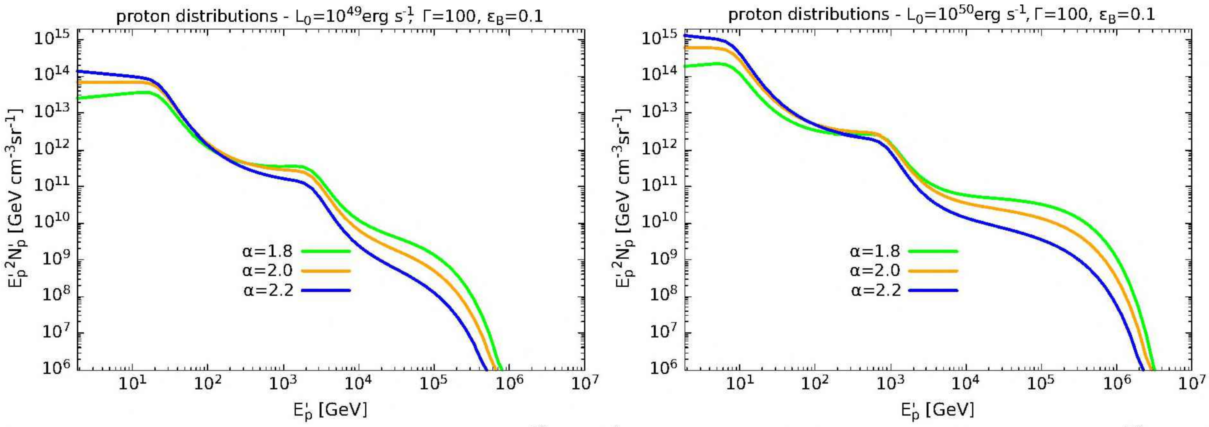

Fig. 2. *Left panel:* Proton distributions for $L_0 = 10^{49} \mathrm{erg\,s^{-1}}$. *Right panel:* Proton distributions for $L_0 = 10^{50} \mathrm{erg\,s^{-1}}$

we omitted the plots of the pion cooling and decay rates, which were similar in both cases of L_0 values, with the losses dominated by the $\pi\gamma$ process. In the case of muons, there is a slight difference in the IC cooling rate as can be seen in Fig. 3, and this is due to the fact that the target photon distribution is somewhat different in each case: for $L_0 = 10^{49}$erg s^{-1} the temperature of the thermalized emission of electrons at the jet head is less than for $L_0 = 10^{50}$erg s^{-1}, and this implies that the Klein-Nishina regime is reached for higher energies in the former case as compared to the latter case.

Having obtained the pion and muon distributions, using the formulae of Lipari et al. (2007), as in RD2023, we can obtain the neutrino injections Q_{ν_e} and Q_{ν_μ} in the CS frame. These are used to obtain the typical neutrino spectrum for a single CGRB as $\frac{dN_{\nu,z}(E_{\nu,z})}{dE_{\nu,z}} = \Delta\Omega\, Q_{\nu,z}(E_{\nu,z}) \Delta V\, t_{\mathrm{j}} \left(\frac{\Delta\Omega}{4\pi}\right)$. Assuming that the rate of generation of CGRBs is proportional to the star formation rate (Madau & Dickinson, 2014), $R_{\mathrm{CGRB}}(z) = A_{\mathrm{CGRB}}\rho_*(z)$ as described in RD2023, it follows that the diffuse flux of flavor α on Earth is

$$\varphi_{\nu_\alpha}(E_\nu) = \frac{c}{4\pi\, H_0} \int_0^{z_{\max}} \frac{dz\, R_{\mathrm{CGRB}}(z)}{\sqrt{\Omega_\Lambda + \Omega_{\mathrm{m}}(1+z)^3}} \left[\frac{dN_{\nu_e,z}(E_\nu(1+z))}{dE_{\nu,z}} P_{e\alpha} + \frac{dN_{\nu_\mu,z}(E_\nu(1+z))}{dE_{\nu,z}} P_{\mu\alpha}\right]. \quad (9)$$

Here, $P_{e\alpha}$ and $P_{\mu\alpha}$ are the probabilities of oscillations $\nu_e \to \nu_\alpha$ and $\nu_\mu \to \nu_\alpha$, respectively, which depend on the neutrino mixing matrix. The latter is determined by three mixing angles and a phase, and their values are extracted from global fits to neutrino experiments (Esteban et al., 2020). The resulting muon neutrino fluxes are shown in Fig. 4 fixing $A_{\mathrm{CGRB}} = 8 \times 10^{-7} M_\odot^{-1}$, consistent with a local rate of choked jet events $R_{\mathrm{CGRB}}(z = 0) \approx 12\,\mathrm{yr^{-1}Gpc^{-3}}$, which is within the range of plausible values (e.g. He et al., 2018). The flavor ratios as a function of the observed neutrino energy are shown in the left panel of Fig. 5, and these are found to be independent of the injection index α. It can be seen that a slight variation is obtained between the two cases of L_0 considered, and this is due to the higher IC cooling of high energy muons for $L_0 = 10^{49}$erg s^{-1} as compared to the case of $L_0 = 10^{50}$erg s^{-1}. Finally, this effect is also present in flavor ratios obtained with the fluxes integrated over a minimum neutrino energy $E_{\nu,\mathrm{min}}$, as can be seen in the right panel of Fig.5. Forthcoming work will allow us to explore other possibilities with different combination of the physical parameters of these choked jets.

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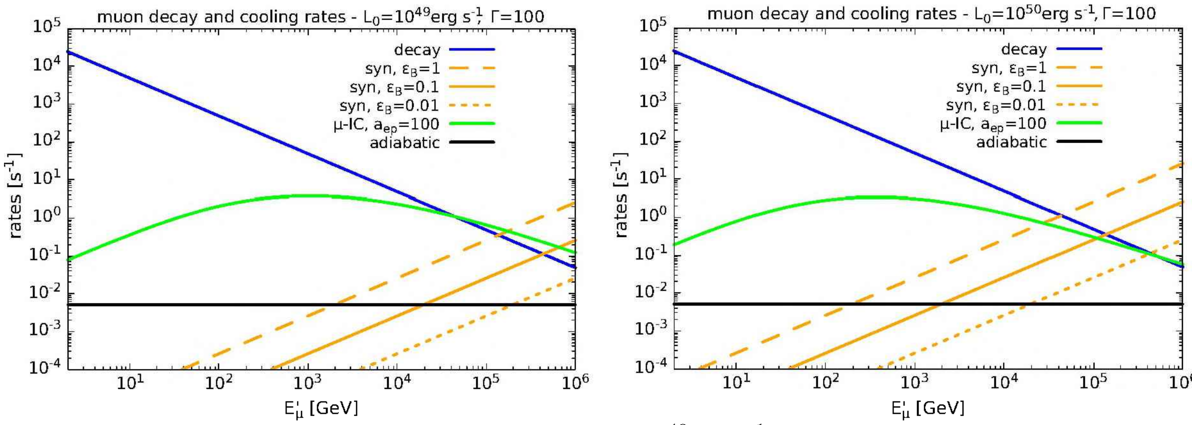

Fig. 3. *Left panel:* Decay and cooling rates for muons for $L_0 = 10^{49}$erg s^{-1}. *Right panel:* The same as in left panel, but for $L_0 = 10^{50}$erg s^{-1}.

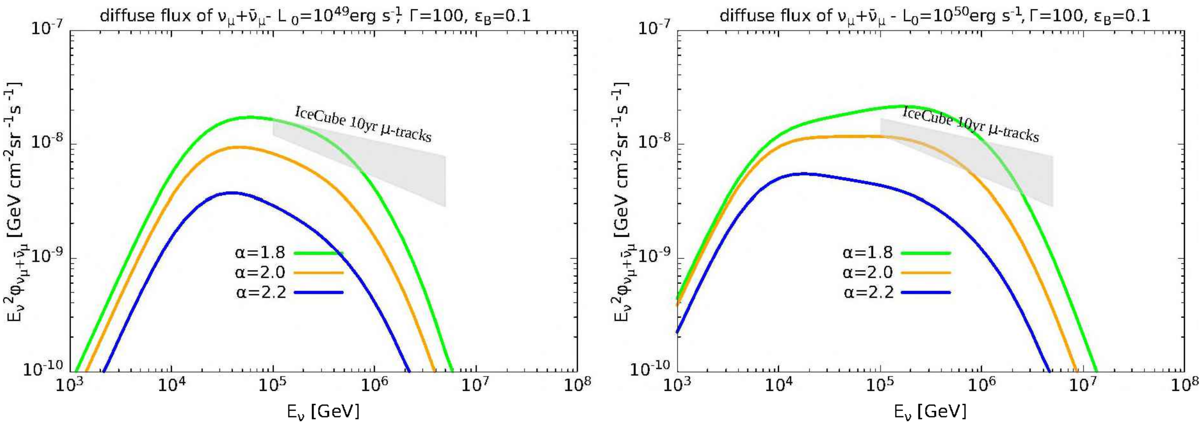

Fig. 4. *Left panel:* Diffuse flux of muon neutrinos for different values of the proton injection index α, setting $L_0 = 10^{49}$erg s^{-1}. *Right panel:* The same as in left panel, but for $L_0 = 10^{50}$erg s^{-1}.

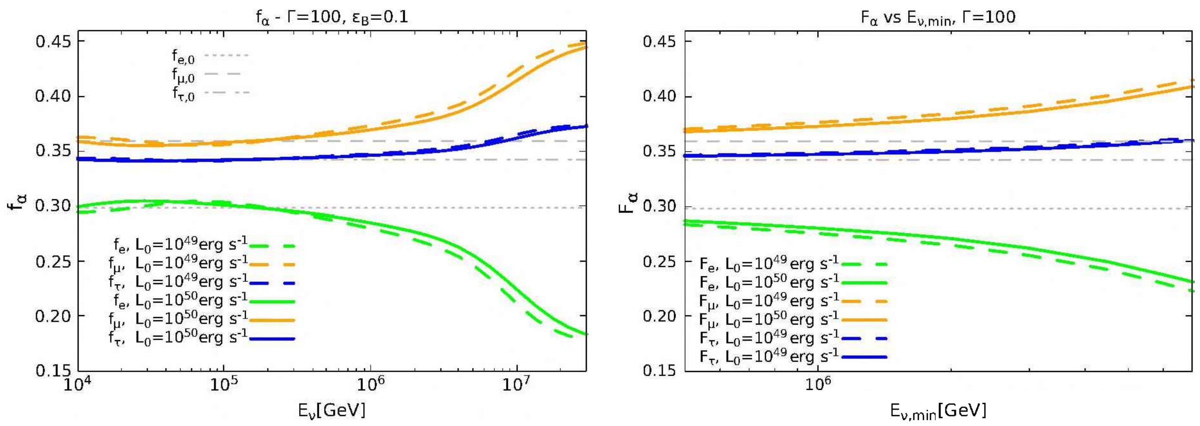

Fig. 5. *Left panel:* Flavor ratios for neutrinos from CGRBs as a function of the neutrino energy. *Right panel:* Flavor ratios of the integrated neutrino fluxes as a function of the minimum neutrino energy. In both panels, dashed curves correspond to $L_0 = 10^{49}$erg s^{-1} and solid ones to $L_0 = 10^{50}$erg s^{-1}.

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