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The role of hidden jets from GRBs as potential candidates for the astrophysical neutrino signal measured by IceCube experiment

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Summary. — During the last years the IceCube Collaboration has detected the largest astrophysical neutrino sample ever obtained up to few PeV energies. The origin of these events encourage the astroparticle community and several hypotheses are now under debate. Taking into consideration the lack of temporal and spatial correlations with γ-ray sources, we explore the hidden jets from the gamma-ray bursts progenitor stars as possible extragalactic sources to explain the observed astrophysical neutrino events.

1. – Introduction

The IceCube Collaboration has reported very large evidence for extragalactic neutrinos. This Collaboration announced in total 54 events after analysing four years of data (from 2010 to 2014)(1). Arrival directions of these astrophysical events are compatible with an isotropic distribution and no neutrino track-like has been associated with the location of known sources.

Long gamma-ray bursts (lGRBs) are usually linked to core collapse of massive stars leading to supernovae (CCSNe). Taking into consideration the photon luminosities and durations, successful lGRBs are classified in low-luminosity (ll), ultra-long and high-luminosity (hl) GRBs. Other relevant population associated with CCSNe is failed GRBs (without an electromagnetic counterpart) which might be much more numerous than successful bursts. Simulations have revealed that the previous population might have high-luminosities, mildly relativistic jets and durations from some to ten seconds [1]. Recently, Murase and Ioka proposed that high-energy neutrinos reported by IceCube might have their origin inside the stars [2]. They argued that ll GRBs represent potential

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(1) http://icecube.wisc.edu/science/data/HE-nu-2010-2014

candidates to explain these high-energy neutrinos. Recently, Fraija showed that not only ll GRB but also hlGRBs with $L \simeq 10^{50}\,$erg/s could produce the high-energy neutrinos reported by IceCube [3].

2. – Internal shocks and neutrino production

The Fireball model is one of the most successful models in describing the prompt emission [4]. The emission from the prompt phase is usually interpreted by internal shell collisions. These shocks occur at a radius of $r_j = 2\Gamma^2\, t_\nu$, where t_v is the variability time scale of the central object and Γ is the bulk Lorentz factor of the propagating shock. The middle relativistic jet inside star is collimated by the cocoon pressure [5] and internal shocks are constrained by $r_j < R_*$ where R_* is the progenitor's stellar radius.

In the shocks, the energy density $U = 1/(8\,\pi\, m_p)\,\Gamma^{-4}\, L\, t_\nu^{-2}$ is given both to accelerate particles $\epsilon_i = U_i/U$, with i the i-th kind of particle and to increase the magnetic field $B' = \epsilon_B^{1/2}\,\Gamma^{-2}\, L^{1/2}\, t_\nu^{-1}$ with m_p the proton mass, L the luminosity, ϵ_e and ϵ_B the microphysical parameters. Accelerated charged particles are cooled down by synchrotron processes. The synchrotron photons radiated by relativistic electrons can generate a large opacity $\tau'_{th} = \frac{\sigma_T}{4\pi\, m_p}\Gamma^{-3}\, L\, t_\nu^{-1}$ and then be thermalized in a black body peak-energy temperature $T'_\gamma \simeq \frac{1.2}{\pi}\,\epsilon_e^{1/4}\, L^{1/4}\,\Gamma^{-1}\, t_v^{-1/2}$ with σ_T the Thompson cross section. Relativistic protons are cooled down by hadronic proton-photon (p-γ) and proton-hadron (p-h) processes. High-energy neutrinos are created in the charged pion and kaon decays $K^+/\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$ and $K^-/\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$. Henceforward, primed (unprimed) quantities are used for a comoving (observer) frame, $Q_x \equiv Q/10^x$ in c.g.s. and $k = \hbar = c = 1$ in natural units.

2·1. *P-γ interactions.* – The number density of synchrotron photons can be written as $n'_\gamma = \frac{3.2\,\zeta(3)}{\pi^5}\,\epsilon_e^{3/4} L^{3/4}\,\Gamma^{-3} t_v^{-3/2}$. From the resonance $p + \gamma \rightarrow \Delta^+$ in the rest frame, the neutrino energy can be written as

$$E_{\nu,\pi} \simeq 10^{-1.67}\,\pi\,(m_\Delta^2 - m_p^2)\,\epsilon_e^{-1/4}\, L^{-1/4}\,\Gamma^2\, t_v^{1/2}, \tag{1}$$

where m_Δ is the resonance mass.

2·2. *P-h interactions.* – Protons co-accelerated in the internal shocks have a comoving number density [6] $n'_p = 1/(8\,\pi\, m_p)\,\Gamma^{-4}\, L\, t_\nu^{-2}$ with energy density $n'_p m_p$. The optical depth for p-h interactions is $\tau'_{pp} \simeq \frac{\sigma_{pp}}{4\,\pi\, m_p}\, L\,\Gamma^{-3}\, t_v^{-1}$, where $\sigma_{pp} = 34.3 + 1.88\,\mathrm{S} + 0.25\,\mathrm{S}^2$ mb is the cross section for these interactions with $\mathrm{S} = \log(E_p/\,\mathrm{TeV})$ [7]. Pions ($\pi^\pm$) and kaons ($K^\pm$) can be produced as products of p-h interactions ($p + h \rightarrow X + \pi^\pm/K^\pm$).

2·2.1. Pion component. Taking into consideration the cooling synchrotron radiation, the lifetime of pions and the hadronic time scale, the neutrino break energies are

$$E_{\nu,\pi^+ syn} = 1.2\frac{m_{\pi^+}^4\,\sigma_{pp}}{m_p\,\sigma_T\, m_e^2}\epsilon_B^{-1}\,\Gamma \quad \text{and} \quad E_{\nu,\pi^+ lt} = 2.5\frac{\pi\, m_p\, m_{\pi^+}}{\sigma_{pp}}\,\tau_{\pi^+}^{-1}\, L^{-1}\,\Gamma^5\, t_v^2. \tag{2}$$

Here m_{π^+} is the charged pion mass and τ_{π^+} is the lifetime of the charged pion.

2·2.2. Kaon component. Considering the cooling synchrotron radiation, the lifetime of pions and the hadronic time scale, the neutrino break energies are

$$E_{\nu,k^+syn} = 0.3 \times \frac{m_{k^+}^4\,\sigma_{pp}}{m_p\,\sigma_T\,m_e^2}\epsilon_B^{-1}\Gamma \quad \text{and} \quad E_{\nu,k^+lt} = 2.5\frac{\pi\,m_p\,m_{k^+}}{\sigma_{pp}}\,\tau_{k^+}^{-1}\,L^{-1}\,\Gamma^5\,t_v^2. \tag{3}$$

Here m_{k^+} is the charged pion mass and τ_{k^+} is the lifetime of the charged kaon.

3. – Particle acceleration processes

The characteristic radius to which the shocked jet becomes cylindrical and the position of the non-relativistic head are given at [5]

$$r_c = \left[\frac{3\varepsilon_c^2}{16\pi^{3/2}\eta_c\chi_c}\right]^{1/5} t^{2/5}\,L_j^{3/10}\,\theta_0^{4/5}\,\rho_a^{-3/10} \quad , \quad r_h = \left[\frac{16\eta_h\zeta_h^2}{3\pi}\right]^{1/5} t^{3/5}\,L_j^{1/5}\,\theta_0^{-4/5}\,\rho_a^{-1/5}, \tag{4}$$

where θ_0 is the initial opening angle, $\varepsilon_c = \frac{5}{3+\alpha_\delta}$, $\eta_c = \frac{3}{3-\alpha_\delta}$ and $\chi_c = \frac{5}{7-\alpha_\delta}$, $\eta_h = \frac{3}{3-\alpha_\delta}$, $\zeta_h = \frac{5-\alpha_\delta}{3}$ and $L_j = \theta_0^2\,\frac{L}{4}$ is the absolute jet luminosity defined through the total luminosity L. The term ρ_a is the ambient density of the Wolf-Rayet (WR) and blue super giant stars (BSG) defined in [3]. Using the density profiles, the cylindrical and head radii for a WR are

$$\begin{aligned} r_c &= \left[\frac{3\varepsilon_c^2}{16(3-\alpha_\delta)^{3/2}\eta_c\chi_c}\right]^{\frac{2}{10-3\alpha_\delta}} t^{\frac{4}{10-3\alpha_\delta}}\,L^{\frac{3}{10-3\alpha_\delta}}\,\theta_0^{\frac{14}{10-3\alpha_\delta}}\,M_\star^{\frac{3}{3\alpha_\delta-10}}\,R_\star^{\frac{9-3\alpha_\delta}{10-3\alpha_\delta}}, \\ r_h &= \left[\frac{16\eta_h\zeta_h^2}{3(3-\alpha_\delta)}\right]^{\frac{1}{5-\alpha_\delta}} t^{\frac{3}{5-\alpha_\delta}}\,L^{\frac{1}{5-\alpha_\delta}}\,\theta_0^{-\frac{2}{5-\alpha_\delta}}\,M_\star^{\frac{1}{\alpha_\delta-5}}\,R_\star^{\frac{3-\alpha_\delta}{5-\alpha_\delta}}, \end{aligned} \tag{5}$$

and for a BSG are

$$\begin{aligned} r_c &= \left[\frac{3\varepsilon_c^2}{2^7\pi^{3/2}\eta_c\chi_c}\right]^{1/5} t^{2/5}\,L^{3/10}\,\theta_0^{7/5}\,\rho_0^{-3/10}\,K^{-3/10}, \\ r_h &= \left[\frac{2^3\eta_h\zeta_h^2}{3\pi}\right]^{1/5} t^{3/5}\,L^{1/5}\,\theta_0^{-2/5}\,\rho_0^{-1/5}\,K^{-1/5}. \end{aligned} \tag{6}$$

Protons within the stars cannot be efficiently accelerated due to radiation mediated shocks. Protons in the upstream flow are decelerated by photons generated in the downstream and also are diffused into the upstream zone [8]. It occurs when the width of the deceleration size $l_{dec} \simeq (n_p\,\sigma_T y_\pm)^{-1}$ is less than the comoving size (l_ν) of the upstream flow [2]. Protons accelerated up to very high-energies are expected near the photosphere (see, *e.g.*, the dissipative scenario [9]). In this case the optical depth becomes $\tau \sim$ (1–10) [10] and $l_\nu \ll l_{dec}$. Therefore, a required condition is $\tau = n_p\,\sigma_T\,r \leq \min[\Gamma_{rel}^2, 0.1\left(1+2\ln\Gamma_{rel}^2\right)^{-1}\Gamma_{rel}^3]$ [2], where $\Gamma_{rel} \approx \frac{\Gamma}{2}(\Gamma_f/\Gamma^2 + 1/\Gamma_f)$ is the relative Lorentz factor between the faster and merged shells.

The neutrino energy limited by the maximum proton (*e.g.*, see [11]) is given by $E_{p,max} = (\frac{3\,q_e\,m_p^4}{\sigma_T\,\xi\,m_e^2})^{1/2}\,\epsilon_B^{-1/4}\,L^{-1/4}\,\Gamma^2\,t_v^{1/2}$, where q_e is the electric charge, m_e is the electron mass and $\xi \simeq 1$.

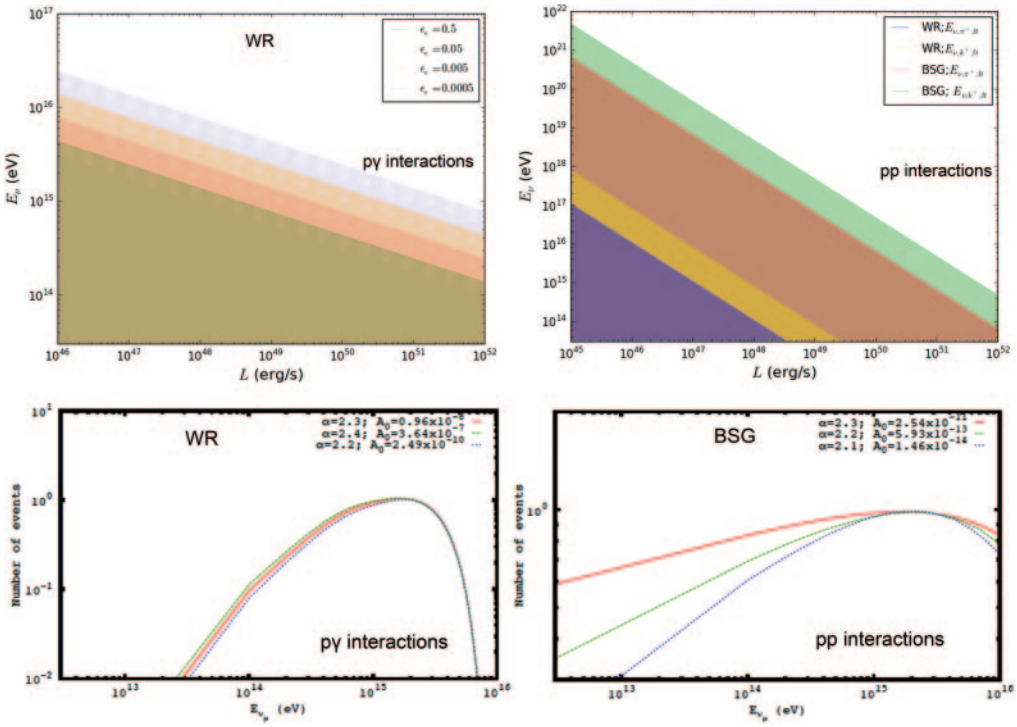

Fig. 1. – Above: neutrino energy as a function of luminosity generated by p-γ and p-h interactions. Below: number of events as a function of neutrino energy expected in the IceCube experiment from the p-γ and p-h interactions.

4. – Neutrino expectation

The expected number of reconstructed neutrino events in the IceCube experiment can be computed as

$$N_{ev} = T\, N_A \int_{E_\nu^{th}} \sigma_{\nu N}\, M_{\mathit{eff}}\, \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\, \mathrm{d}E_\nu, \tag{7}$$

where $T \simeq 4$ years is the observation time, $N_A = 6.022 \times 10^{23}\,\mathrm{g}^{-1}$ is the Avogadro number, $\sigma_{\nu N} = 6.78 \times 10^{-35}\mathrm{cm}^2 (E_\nu/\,\mathrm{TeV})^{0.363}$ is the neutrino-nucleon cross section [12] and M_{eff} is the effective target mass of the IceCube experiment [3, 13]. The neutrino spectrum $\mathrm{d}N_\nu/\mathrm{d}E_\nu$ is computed from p-γ and p-h interactions as follows.

4·1. *P-γ interactions.* – The spectrum of muon neutrino generated by p-γ interactions is [14] $\left(\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\right)_{p\gamma} eqnarray = \frac{V}{4\pi \mathrm{d}_z^2} \int_{E_p} \int_{\epsilon} \frac{\mathrm{d}N_p}{\mathrm{d}E_p} \frac{\mathrm{d}N_\epsilon}{\mathrm{d}\epsilon} F_{\nu_\mu}^{p\gamma}(\eta, x) \frac{\mathrm{d}E_p}{E_p}\, \mathrm{d}\epsilon$, where $V = \frac{4}{3}\pi r_j^3$, d_z is the luminosity distance from the source and the proton distribution is $\frac{\mathrm{d}N_p}{\mathrm{d}E_p} \simeq A_p\, E_p^{-\alpha}$ with $A_p \simeq n_p/\,\mathrm{GeV}$. The distribution of target photons $\mathrm{d}N_\epsilon/\mathrm{d}\epsilon$ corresponds to the thermalized synchrotron radiation and the function $F_{\nu_\mu}^{p\gamma}(\eta, x)$ is explicitly given in [3].

4·2. *P-h interactions.* – The spectrum of muon neutrino generated by *p-h* interactions is [7] $\left(\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\right)_{ph} = \frac{V\, n_p}{4\pi \mathrm{d}_z^2} \int_{E_p}^{\infty} \sigma_{pp} \frac{\mathrm{d}N_p}{\mathrm{d}E_p} F^{pp}_{\nu_\mu}(E_p, x) \frac{\mathrm{d}E_p}{E_p}$, where the function F_{ν_μ} is explicitly given in [3].

5. – Results and conclusions

In the context of CCSNe-GRB connection, WR and BSG stars with formation of jets leading to internal shocks have been considered. Particles are expected to be accelerated in internal shocks and cooled down mainly by synchrotron radiation and hadronic processes (p-γ and p-h interactions). A detailed description of time scales for all processes and neutrino oscillations is given in [11, 15]. Figure 1 (above) shows neutrino energy created by hadronic interactions at internal shocks inside a WR and BSG for a luminosity in the range of $10^{46} \leq L \leq 10^{52}$ erg/s. These panels show that neutrinos in the range of 30 TeV and a few PeV can be created in these shocks when $10^{-3}\,\mathrm{s} \leq t_\nu \leq 1$ s and $\Gamma \leq 40$ (220) for a WR (BSG) [3]. For instance, left panel (pγ interactions) displays that for a typical value $\epsilon_e = 0.1$, PeV neutrinos are expected only when $L \leq 10^{49}$ erg/s. Panels below exhibits the number of events as a function of neutrino energy expected in the IceCube experiment. We have explored the values allowed of the bulk Lorentz factor, luminosity, variability and microphysical parameters given in the hadronic interactions of the internal shocks that could explain the high-energy neutrinos reported by IceCube. We have found that, depending on the parameter values, PeV neutrinos could be generated inside the progenitors, either WR and BSG. Although ll GRBs and big stars like BSG are more favorable so that these neutrinos are generated, classical hlGRBs and progenitors like WR also have potential to generate them. The number of sources with internal shocks inside the stars may be much larger than the number of those exhibiting one. Within 10 Mpc, the rate of core-collapse supernovae would be $\sim$1–3 yr^{-1}, with a substantial contribution of galaxies around a few Mpc [16].

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