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Production of high-energy neutrinos in binary-neutron-star merger events

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Abstract. High-energy neutral astrophysical messengers, such as neutrinos and photons, can be produced by the interaction of ultra-high-energy cosmic rays (UHECRs) with radiation fields, either during extragalactic propagation or within source environments. Neutrinos and gamma-rays can play a crucial role in the study of acceleration mechanisms of cosmic rays. In particular, after being produced, neutrinos leave the source environment and propagate to the Earth without further interactions. They are only subject to energy redshift and flavour oscillation, which makes them bearers of otherwise inaccessible information about their sources. We study high-energy environments of the type that are likely to be the end states of a binary-neutron-star (BNS) merger, and we model their local photon field as a black body at a given temperature. Using a modified version of the Monte Carlo code *SimProp* v2r4 we simulate the propagation and interaction of UHECRs through these environments. We consider several combinations for the spectral index and high-energy cutoff of the UHECR protons, in order to obtain the escaped neutrino flux. We propagate these fluxes to the Earth and compare to the astrophysical IceCube neutrino flux to obtain constraints on the BNS merger spectra properties, emissivity and density rate.

1 Introduction

Ultra-high-energy cosmic rays (UHECRs) are ionized nuclei with energy $E \gtrsim 10^{17}$ eV and represent the most energetic class of particles ever observed. Acceleration mechanisms and source classes which enable them to reach these extreme energies are still an open issue in modern astroparticle physics. Magnetic deflection due to galactic and extragalactic magnetic fields and interactions with background photon fields of cosmic origin make it difficult to use UHECRs as astrophysical probes to reveal their sources. On the other hand, neutral and stable particles could represent an important class of new astrophysical messengers: in particular neutrinos propagate almost undisturbed through the Universe being electrically neutral and only weakly interacting particles.

In the last few years, the IceCube Neutrino Observatory reported the evidence of a diffusive neutrino flux in the TeV - PeV energy range consistent with an astrophysical origin [1]. Extremely energetic astrophysical environments (e.g. SNRs, AGNs and GRBs) might be able to accelerate cosmic rays to the production of high-energy neutrinos. However, the coincidence analysis between neutrino events and plausible source catalogues did not lead to a definitive answer on the origin of the observed neutrino events [2, 3].

In this work we consider as a neutrino source class the final state of binary-neutron-star (BNS) mergers. As suggested in [4], we assume the presence of some acceleration mechanisms focusing on the study of photo-hadronic interactions of confined UHECRs with the local photon fields generated by the surrounding material ejected by the merger (more details can be found in [4]). From these interactions charged pions can be produced, and subsequently neutrinos show up in their decay chains. Due to the low cross-section, neutrinos can easily leave the source environment providing information not accessible through charged particles and photons.

After interactions within the source environment, cosmic rays (CRs) and neutrinos propagation to the Earth is considered. Due to the very efficient relativistic boost of the energy of cosmic photons in the CR rest frame, photo-hadronic interactions with the CMB and the EBL (i.e. the Cosmic Microwave Background and the Extragalactic Background Light) are possible [5, 6]. Therefore photo-hadronic interactions like electron-positron pair production, photo-pion production and photo-disintegration and adiabatic energy loss due to the expansion of the universe ($-1/E{\cdot}dE/dt = H_0$, where H_0 is the Hubble constant at the present time) have been taken into consideration in order to predict the observed neutrinos flux from BNS mergers.

2 UHECR interactions

Monte Carlo simulation codes are essential tools to produce statistically significant ensembles of data to unveil possible characteristics of UHECR and neutrino sources. In order to take into account all the relevant processes

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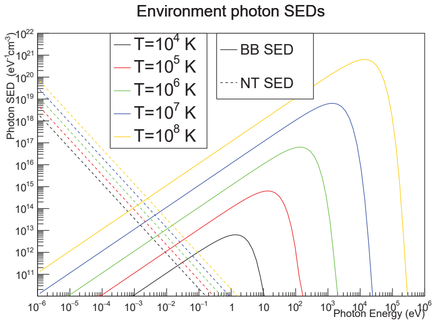

Figure 1. Thermal (continuous lines) and non-thermal (dashed lines) photon SEDs considered in this work at different black body temperatures (from yellow 10^8 K to black 10^4 K).

during the propagation of UHECRs over extragalactic distances, the Monte Carlo code *SimProp* v2r4 [7] has been used in this work. The energy loss mechanisms mentioned above and the decay of unstable particles are implemented in *SimProp* v2r4. A generic run of *SimProp* consists of N nucl injected into extragalactic space at a given redshift $z_{\rm inj}$ with specific energy $E_{\rm inj}$ and mass composition $(A_{\rm inj}, Z_{\rm inj})$. After the injection, the nucleus and its interaction products are followed step by step to the Earth at $z = 0$ representing the end-condition of the simulation.

The interaction rate τ_{ij}^{-1} for the process i due to the interaction between the nucleus and the photon field j is computed as

$$\frac{1}{\tau_{ij}} = \frac{c}{2\Gamma^2} \int_{\epsilon_{\rm th}}^{\infty} d\epsilon\, \sigma_i\,(\epsilon)\, \epsilon \int_{\epsilon/2\Gamma}^{\infty} dx\, n_j\,(x)\, x^{-2}, \qquad (1)$$

where x is the photon energy in the laboratory rest frame, $n_j\,(x)$ is the photon spectral energy density (SED, i.e. the number of photons per unit of volume and unit of energy) in the laboratory rest frame, $\sigma_i\,(\epsilon)$ is the total cross-section expressed as a function of photon energy in the cosmic-ray rest frame and $\epsilon_{\rm th}$ is the photon energy threshold in the same frame. Since the interaction rate in (1) is linear in both the cross-section and the photon field, the total interaction rate of a series of different stochastic processes is given by

$$\tau_{\rm tot}^{-1} = \sum_{i,j} \tau_{ij}^{-1}, \qquad (2)$$

and the corresponding interaction probability is $p_{ij} = \tau_{ij}^{-1}/\tau_{\rm tot}^{-1}$. With regards to leptons produced in photo-hadronic interactions, the propagation of electromagnetic particles is not implemented in *SimProp* v2r4, and neutrinos produced at the redshift $z_{\nu,\rm prod}$ with energy $E_{\nu,\rm prod}$ are immediately propagated to $z = 0$ with energy

$$E_{\nu,\rm Earth} = \frac{E_{\nu,\rm prod}}{1 + z_{\nu,\rm prod}}. \qquad (3)$$

2.1 Simulations within the source environment

In this work the original code *SimProp* v2r4 has been modified in order to study the interactions between confined UHECRs and local photon fields present in the source environment. Particles escaping from the interaction region will represent the injection configuration for the extragalactic propagation that is computed by the original *SimProp* code.

The first modification to *SimProp* v2r4 concerns the target photon fields for UHECR interactions. Cosmic photon fields (CMB and EBL) have been replaced by local photon fields within the source environment. We report the SEDs of these photon fields in Figure 1 in which continuous lines correspond to the black body (BB) SEDs, while the dashed lines correspond to the non-thermal (NT) SEDs obtained from [8]. After the merger, the ejected material induces the synthesis of heavy nuclei, responsible for the thermal photon field powered by the nuclear decay of heavy elements. This thermal emission subsequently decreases until the non-thermal domination phase. At this point the source environment is mostly characterised by synchrotron emission.

As shown in [8], the non-thermal emission can be modeled by the flux density function $\phi(\epsilon) \propto \epsilon^{-\beta}$, where ϵ is the photon energy. The spectral index β is given by observations and its values is ~ 0.6; time evolution of $\phi(\epsilon)$ can then be included in the normalization factor. Starting from the flux density in [8], we obtain the non-thermal photon SED evolution shown in Figure 1.

The black body temperature evolution has been obtained from the so called "Optimistic" scenario reported in [4] (this scenario has been designed to optimise the production of high-energy neutrinos within the source environment). Following the approach in [4], the source temperature can be semi-analytically computed obtaining the time evolution

$$\log\left(\frac{t}{1\,\rm s}\right) \simeq -\frac{1}{2}\log\left(\frac{T}{1\,\rm K}\right) + 6. \qquad (4)$$

Different temperatures are shown with different colors in Figure 1.

In order to reproduce the propagation within the source, we define a new end-condition for our simulations to introduce the escape from the interaction region. We define the typical radius of the source as

$$\lambda_{\rm esc}(t) = \beta_{\rm ej} c t, \qquad (5)$$

where $\beta_{\rm ej}$ represents the speed of the ejected material in units of speed of light by the merger (hereinafter this parameter is fixed to $\beta_{\rm ej} = 0.3$, as done in [4]). The escape condition is obtained assuming the leaky box model, parametrised by the escape rate $\tau_{\rm esc}^{-1} = c\,\lambda_{\rm esc}(t)^{-1}$, that can be compared to the other interaction rates τ_{ij}^{-1}. We want to remind that, in this simple scheme, the confinement of a charged particle is only given by the dimension of the source itself and does not depend on the particle rigidity.

We evaluate the efficiency of the photo-hadronic interactions in these environments by defining the total opacity of the source η_j with respect to a specific photon field j as the ratio between the typical escape length and the total interaction length of a nucleus with the photon field $n_j(\epsilon)$:

$$\eta_j = \frac{\lambda_{\rm esc}}{\lambda_j} = \frac{\sum_i \tau_{ij}^{-1}}{\tau_{\rm esc}^{-1}}. \qquad (6)$$

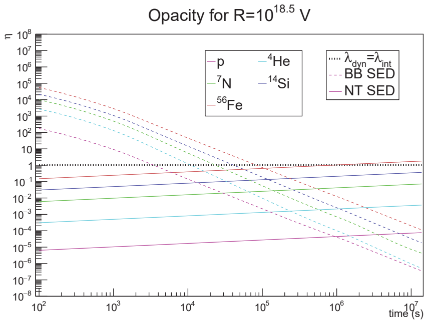

Figure 2. Source opacity for several nuclei with rigidity $R = 10^{18.5}$ V obtained with the photon SEDs in Figure 1. The escape condition is given by the black dashed line.

The opacity is thus a time-dependent quantity; we can see that for $\eta_j > 1$ ($\eta_j < 1$) interactions are more (less) efficient than escape and thus the source environment is opaque (transparent) for a given nucleus. In Figure 2 we show the opacity for several nuclei with rigidity $10^{18.5}$ V where all the interactions are considered. Interactions of UHECRs with the thermal photon field are very efficient right after the merger, but this contribution decreases rapidly with the cooling down of the source. The non-thermal contribution increases very slowly and it is negligible almost in every time. Similar results were obtained in [9].

In this work we considered an injection scenario of protons only. Based on our previous results, we simulate a source environment only with the thermal photon field. Therefore, the maximum relevant time after the merger for neutrino production is $\sim 10^4$ s (or the minimal relevant temperature $\sim 10^4$ K). We would like to point out that a non-thermal contribution would become relevant in the case of a heavy composition confined within the source environment for times $t \gtrsim 10$ days after the merger.

3 Results

3.1 Source escape

The modified version of the simulation code *SimProp* v2r4 has been used to perform in-source simulations as described in Section 2.1. We consider the five temperatures reported in Figure 1 and an injected UHECR spectrum of the form

$$J_{\rm inj}(E, Z) \propto E^{-\gamma} \exp\left(-\frac{E/Z}{R_{\rm max}}\right), \tag{7}$$

where E and Z are the energy and the charge number of the injected nucleus, γ is the spectral index and $R_{\rm max}$ is the high-rigidity cutoff. In this work we only consider protons at the injection ($Z = 1$).The choice of different values for γ and $R_{\rm max}$ allows the study of the contribution of different energies at the injection.

We simulate the propagation of a pure proton flux with energy uniformly distributed in $\log E$ between 10^{14} eV and 10^{20} eV. As mentioned above, the non-thermal contribution is negligible for all nuclei and therefore we only considered the black body photon field in this study.

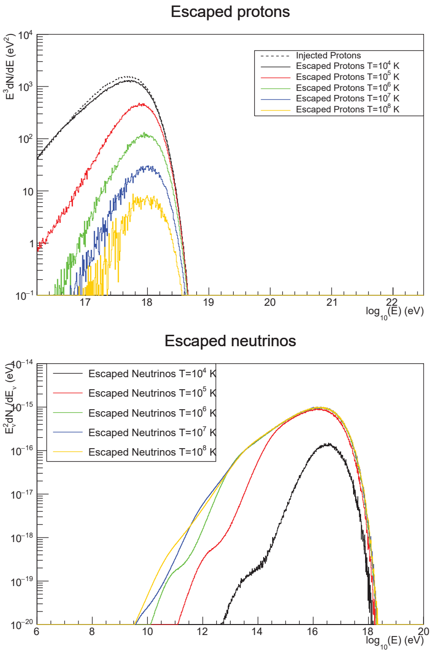

Figure 3. CR (top) and neutrino (bottom) spectra escaped from the source environment; CR fluxes are multiplied by E^3 while the neutrino ones by E^2. The parameters at injection are $\gamma = 1.5$ and $R_{\rm max} = 10^{17.5}$ V and the mass composition is pure protons.

In Figure 3 we show the escaped UHECR (top) and neutrino (bottom) spectra form the source environment for the following injection parameters: $\gamma = 1.5$ and $R_{\rm max} = 10^{17.5}$ V. The color scheme is the same of Figure 1 and the black dotted line in the top panel represent the injected spectrum. In the top panel of Figure 3 we can see that the UHECR emission is larger for low temperatures (black line) than for high temperatures (yellow line) of the thermal black body. The interpretation of this result is that as the temperature decreases, the source gradually becomes larger, but with the condition $\eta_{\rm BB} > 1$. The latter condition implies that the radius of the source $\lambda_{\rm esc}$ increases slower than the photo-pion interaction length. On the other hand, the production of neutrinos (Figure 3, bottom panel) is maximal right after the merger, when the temperature is the highest possible and it decreases with time. We obtain that all these considerations are independent of the injection CR parameters, which only affect the slope and the maximum energy of the escape spectra.

3.2 Extragalactic propagation

UHECR and neutrino spectra obtained above have been used as inputs for the simulations of the extragalactic propagation. This second phase requires further assumptions about the source distribution and cosmological evolution. A uniform distribution of identical sources is assumed. Since in-source simulations do not take into account the source evolution, we can introduce the redshift dependence with the following factorisation

$$J_{\rm inj}(E, Z, z) = (1 + z)^m J_{\rm inj}(E, Z), \tag{8}$$

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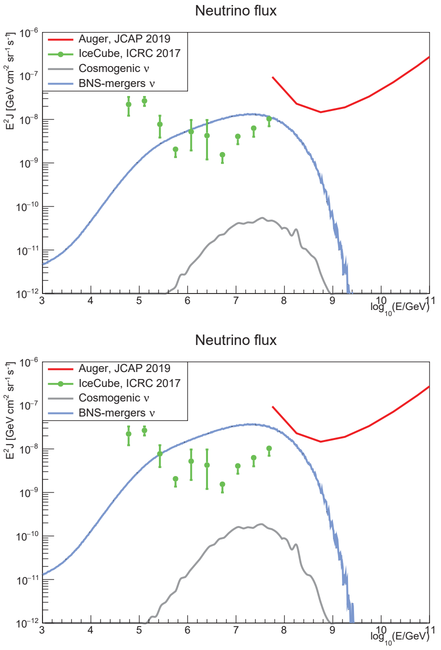

Figure 4. Expected BNS mergers and cosmogenic neutrino fluxes, with the measured flux by IceCube [12] and the limit for cosmogenic neutrinos by the Pierre Auger Observatory [13]. The expected neutrino fluxes refer to the following parameters of a pure-proton spectrum at injection and for a GW-like source class: $\gamma = 1.5$, $R_{\max} = 10^{18}$ V and $m = 0$ (top panel); $\gamma = 1.5$, $R_{\max} = 10^{18}$ V and $m = 3.4$ (bottom panel).

where z is the redshift and the parameter m defines the cosmological evolution of the source class. In this work different cosmological evolutions are taken into account for the distribution of sources, such as the case of non-evolution ($m = 0$) and the one following the star-forming rate (SFR). The diffuse fluxes of CRs and neutrinos at Earth were computed using *SimProp* v2r4 for the propagation in the extragalactic space.

Since the injection of particles within the source environment occurs over time after the merger, it is reasonable to expect that the production of high-energy neutrinos is a time dependent quantity. Then the total injected spectrum will be given by the integral over time since the merger event. We take into account the time evolution of the merger by fixing the initial black body temperature and summing the lower temperature simulation results. Then we defined two classes of sources: the GW-like class in which the initial temperature is 10^6 K and the Optimistic class for 10^8 K (as inspired by [4]). We report only the results for the GW-like class since the Optimistic class gives rise to neutrino fluxes far above the experimental limits.

In order to compare our results with experimental results we chose to normalize the propagated cosmic ray spectrum to the observed flux by the Pierre Auger Observatory below the ankle [11]. This therefore also fixes the normalization for the corresponding neutrino fluxes, that include both the neutrinos produced in the source environment and the ones produced in the extragalactic propagation (the so called cosmogenic neutrinos).

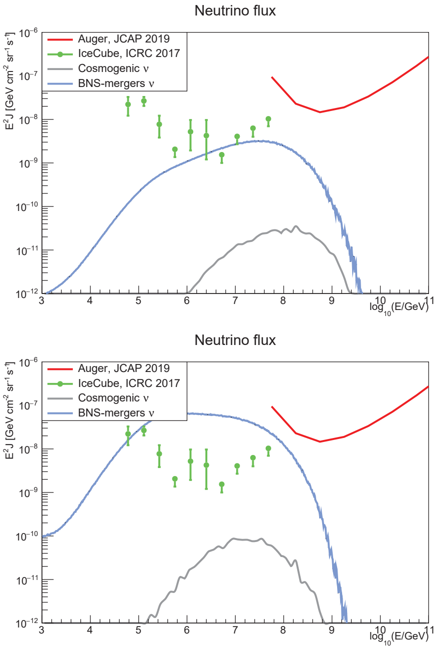

Figure 5. The same of Figure 4, but for the following parameters: $\gamma = 1.5$, $R_{\max} = 10^{18.5}$ V and $m = 0$ (top panel); $\gamma = 2.1$, $R_{\max} = 10^{18}$ V and $m = 0$ (bottom panel).

In Figures 4 and 5 we show the neutrinos fluxes for several choices of injection and propagation parameters (details in figure captions). In Figure 4 we can see the effect of different cosmological evolution. When a SFR evolution is assumed ($m = 3.4$) the expected neutrino flux is increased with respect to the non-evolution case due to the larger contribution of high redshift sources. This is visible both for the source neutrinos (blue lines) and for the cosmogenic ones (gray lines). In Figure 5 the effect of different injection scenarios is shown: in the top panel a higher value for the maximum rigidity is used, while in the bottom panel the spectral index is changed. When increasing the maximum rigidity the fluxes can reach higher cutoff energies, but the source neutrinos result in a slightly smaller flux, mainly due to the normalization of the corresponding cosmic ray flux. The effect of a softer spectral index for the injected protons is given by an observed neutrinos flux which is increased in the low energy range.

4 Conclusions

We have studied the production of high-energy neutrinos within the environment produced by BNS mergers with a modified version of the Monte Carlo code *SimProp* v2r4. We assumed a pure proton composition and an energy range of the UHECR spectrum, given in (7), injected into the source environment leaving the other parameters free in order to investigate the source phase space of BNS mergers, that could explain the observed astrophysical neutrino flux.

The first result, valid in all the configuration studied in this work, is that cosmogenic neutrinos produced during the extragalactic propagation cannot be responsible of the observed diffuse neutrino flux. For any source configuration we found that the cosmogenic neutrino flux is a subdominant component.

The neutrino flux produced in the sources is strongly connected to the time after the merger, being this linked to the temperature of the black-body photon field and to the dimension of the source. In this scenario, colder sources seem to be the most favoured since scenarios where $T \gtrsim 10^7$ K give rise to neutrino fluxes far above the experimental limits. Different spectral parameters also affected the expected flux; we obtained that a hard spectral index and a large maximum rigidity of the protons at the source could better reproduce the experimental results. Moreover, source classes that evolve weakly with redshift seems to be favoured.

The normalization procedure assumed in this work allows us to compute the emissivity at the escape from the source environment. Considering the parameter configuration shown in Figure 5 top panel, we obtain $\mathcal{E}_{\rm esc} \simeq 2.5 \cdot 10^{45}\,{\rm erg\,Mpc^{-3}\,yr^{-1}}$. With this quantity we can estimate the BNS merger density rate ṅ considering the relation $\mathcal{E}_{\rm esc} = \mathcal{L}_{\rm esc} \cdot n = E_{\rm esc} \cdot \dot{n}$, where n is the BNS merger density, $\mathcal{L}_{\rm esc}$ is the luminosity at the escape and $E_{\rm esc}$ is the total energy at the escape. We compute the energy at the escape by considering the fallback luminosity reported in [4]. The corresponding BNS merger density rate obtained for the above configuration corresponds to $\dot{n} \simeq 5 \cdot 10^5\,{\rm Gpc^{-3}\,yr^{-1}}$. The experimentally estimated BNS merger rate (reported in [4]) is $\dot{n} \sim 600\,{\rm Gpc^{-3}\,yr^{-1}}$; we can see that our choice of normalization lead us to a merger rate greater than the experimental range.

Future outcomes of this work will take into account heavier nuclear species injected into the source region: this new scenario will require the study of the propagation through both the thermal and the non-thermal SEDs. It will be also relevant to extrapolate the required efficiency for powering the cosmic-ray flux below the ankle, taking into account the luminosity of the SED in a BNS merger, given the current estimates of the rate of BNS mergers.

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