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Diffuse CR, neutrino and gamma-ray fluxes from AGNs

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We investigate how the extragalactic proton component derived within the 'escape model' can be explained by astrophysical sources. We find that the complete extragalactic proton spectrum can be explained by a single source population with late time evolution, such as BL Lacs or FR I galaxies. We then calculate the diffuse neutrino and γ-ray fluxes produced by these CR protons interacting with gas inside their sources, their host galaxies and galaxy clusters. For a spectral slope of CRs close to $\alpha = 2.1-2.2$ as suggested by shock acceleration, we find that these UHECR sources contribute to a dominant fraction of both the isotropic γ-ray background and to the extragalactic part of the astrophysical neutrino signal observed by IceCube [1].

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1. Introduction

The Auger collaboration provided in [2] constraints on the fraction of four elemental groups above 6×10^{17} eV, and the KASCADE-Grande experiment covered with composition measurements energies up to 2×10^{17} eV [3]. The proton fraction amounts to $\sim$ 40–60% for $E = 7 \times 10^{17}$–7×10^{18} eV. The iron fraction at $E = 7 \times 10^{17}$–2×10^{19} eV is limited to $\lesssim$ 15–20% and its central value is consistent with zero. Thus the Galactic contribution to the CR spectrum has to die out around 7×10^{17} eV. This conclusion is supported by the limits on the CR dipole anisotropy [4].

Several recent studies showed that both the measured spectrum and the composition above the ankle can be well fitted using models with a mixed composition [5, 6, 7]. The first two predict that the flux below the ankle is strongly dominated by protons, which is in tension with Auger composition data. Another disadvantage is the prediction of a negligible contribution from extragalactic CR sources to the observed IceCube neutrinos. This requires that these neutrinos are produced in 'hidden' sources with a large interaction depth for protons.

In this work, we investigate if the extragalactic proton component derived within the escape model [8, 9] provides a viable model for the measured CR proton flux and can give a significant contribution to the isotropic γ-ray background (IGRB) measured by Fermi-LAT and to the astrophysical neutrino signal observed by IceCube. We find that active galactic nuclei (AGN) with late time evolution can explain the entire extragalactic CR flux. For a spectral slope of CRs close to $\alpha = 2.1 - 2.2$, these UHECR sources can contribute to a major fraction of the IGRB and of the extragalactic part of the IceCube neutrino signal.

2. Method

2.1 Extragalactic CR proton flux

We summarize first how the extragalactic CR proton flux in the escape model was derived in Ref. [9]. In a first step, we derived the Galactic all-particle CR flux summing up all CR groups obtained for the maximal rigidity $\mathscr{R}_{\max} = 1.0 \times 10^{17}$ V and accounting for the Auger iron constraint. Then we obtained the total extragalactic flux by subtracting the predicted total Galactic flux from the measured total CR flux. The extragalactic proton flux observed by Auger followed applying the composition measurement [2] where we chose conservatively the results obtained using the EPOS-LHC simulation. Finally, we deduced the contribution of extragalactic protons to the observed proton flux by KASCADE and KASCADE-Grande, subtracting from the proton fluxes given in Ref. [3] the prediction of the escape model: Since the predicted proton flux lies for energies above $E \gtrsim 3 \times 10^{16}$ eV below the measured one, the difference has to be accounted for by extragalactic protons. Combining the KASCADE, KASCADE-Grande and Auger data suggests that the slope of the energy spectrum of the extragalactic component is flat at low energies, $E \lesssim 10^{18}$ eV, consistent with $\alpha_p \sim 2.2$, and softens to $\alpha_p \sim 3$ at higher energies, $E \gtrsim 10^{18}$ eV.

2.2 CR interactions on gas and photons

We summarize below how we calculate the interactions of CRs with gas and the extragalactic background light (EBL). We split the propagation in two parts: The first includes the propagation in the source, the host galaxy and galaxy cluster where we assume that proton interactions with gas are

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dominant. The spectrum of exiting particles is then used in the second step as an 'effective source spectrum' from which we calculate the resulting diffuse flux taking into account the distribution $\rho(z,L)$ of sources as well as the interaction of protons, electron and photon with the EBL and the CMB. For both steps, we use open source code [10] which solves the corresponding kinetic equations in one dimension.

As input for the first step, we require the energy dependent grammage $X(E)$ and the proton injection spectrum dN_{CR}/dE. Starting from the injection spectrum of protons, we simulate their propagation and their interaction to obtain the spectra of protons and secondary particles leaving the 'effective source'. We neglect all interactions except pp in the 'effective source'. We also assume that all secondaries, except electrons, escape freely; for the latter, we assume that they lose all their energy via synchrotron radiation. The contribution of synchrotron photons to the total photon flux is negligible. For simplicity, we neglect also pair production by photons inside the source, since the following cascade development outside the source leads to an universal spectrum.

The code [10] has been extended implementing pp interactions. The inelastic cross sections $\sigma_{\rm inel}$ of CR nuclei on gas were calculated with QGSJET-II-04 [11]. For the spectrum of secondary photons and neutrinos produced in pp interactions, differential cross sections tabulated from QGSJET-II-04 were used [12]. Secondaries from heavier elements in the CR flux are suppressed; their contributions are included adding a nuclear enhancement factor ε_M. Similarly, the helium component of the interstellar medium was accounted for. Combining both effects we set $\varepsilon_M \sim 2.0$ [13]. In order to take into account properly the energy dependence of the grammage, while still using a 1D kinetic equation framework, we multiply the pp interaction rates $R(E)$ by the ratio of grammage $X(E)/X(\infty)$. For the BL Lac grammage, we used the simple parameterization $X(E) \sim E^{-1/3}$ and normalized grammage to have optical depth $\tau_{pp} = 1$ at specific energy E_{esc}, being the only free model parameter in this case.

3. Extragalactic CRs, diffuse γ-ray and neutrino fluxes from AGNs

We have found that star-forming galaxies only give a sub-dominant contribution to the high-energy CR flux at $E \sim 10^{17-18}$ eV, in the escape model (injection spectrum $\propto E^{-2.2}$ [8, 9]). See Ref. [1] for more details. Both their overall luminosity and their redshift evolution which peaks at $z \sim 2-3$ disfavor this source class as the main source of extragalactic CRs up to the ankle. Even keeping the grammage as a free parameter, it is not possible to explain at the same time a large contribution to the IGRB and to the IceCube neutrinos. In the following, we then consider AGNs.

3.1 Interactions in the sources of UHECRs

To estimate the IGRB and isotropic neutrino background (INB) produced by pp interactions in the UHECR sources, one needs to know the energy-dependent efficiency of pp interactions in the source and cosmological evolution of the source population. In this section we take the BL Lac/Fanaroff-Riley I (FR I) sub-class of the radio-loud AGN population as an example.

We determine the cosmological evolution of BL Lac/FR I sources from the corresponding evolution of the γ-ray luminosity, assuming that the CR and the CR luminosity are proportional: $N_c(z) \propto \int_{L_\gamma^{min}}^{L_\gamma^{max}} \rho(z,L_\gamma) L_\gamma dL_\gamma$. Here, $\rho(z,L_\gamma)$ is the γ-ray luminosity function (LF), i.e. the num-

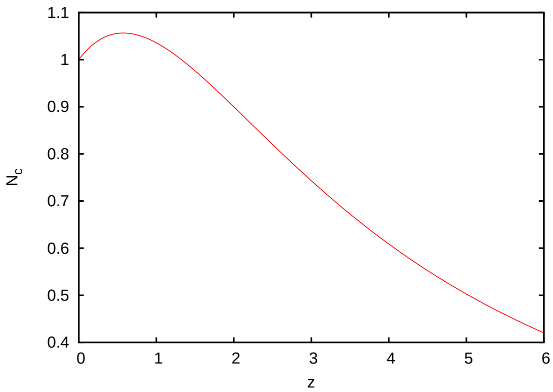

Figure 1: Effective comoving source density $N_c(z)$ as a function of redshift for BL Lacs, normalized to present value $N_c(0) = 1$.

ber of sources per comoving volume and luminosity. For $\rho(z,L_\gamma)$ we adopt the Luminosity-Dependent Density Evolution (LDDE) model of Ref. [14]. Within this model, the LF $\rho(z,L_\gamma)$ can be expressed as $\rho(z,L_\gamma) = \rho(L_\gamma)\,e(z,L_\gamma)$, with $\rho(L_\gamma) = \frac{A}{\log(10)L_\gamma}\left[\left(\frac{L_\gamma}{L_c}\right)^{\gamma_1} + \left(\frac{L_\gamma}{L_c}\right)^{\gamma_2}\right]^{-1}$, and $e(z,L_\gamma) = \left[\left(\frac{1+z}{1+z_c(L_\gamma)}\right)^{p_1} + \left(\frac{1+z}{1+z_c(L_\gamma)}\right)^{p_2}\right]^{-1}$ where $z_c(L_\gamma) = z_c^\star\left(\frac{L_\gamma}{10^{48}\,\mathrm{erg\,s^{-1}}}\right)^{\alpha}$. The numerical values for the parameter were determined from a fit to the statistics of BL Lacs observed by the Fermi/LAT telescope; they are given in Table 3 of [14]. The evolution of the effective source density with the redshift is shown in Fig. 1.

In contrast to the average AGNs, the number density of BL Lacs and FR I galaxies peaks at low redshift, $z \lesssim 1$. Their evolution is similar to that of the clusters. Most FR I sources, which are the parent population of BL Lacs, reside in the centres of the dominant central elliptical galaxies of galaxy clusters (cD galaxies).

For each source, we assume that the injection spectrum of cosmic rays is a power-law with slope α_p and exponential cut-off, $\frac{dN_{CR}}{dE} \propto E^{-\alpha_p}\exp\left(-\frac{E}{E_{\rm cut}}\right)$. We assume that the highest energy cosmic rays are able to escape from the source on the free escape time scale $T_{\rm free} = \frac{R}{c} \simeq 3\times 10^3\ \mathrm{s}\left[\frac{R}{10^{14}\ \mathrm{cm}}\right]$, where R is the source size. For each assumed slope α_p of the spectrum, we adjust the cutoff energy $E_{\rm cut}$ in such a way that the spectrum of the entire source population (integrated over redshift) fits best the observed cosmic ray spectrum in the energy range 10^{17} eV – 10^{20} eV.

Cosmic rays of low energy are not necessarily escaping from the source. First of all, they may be trapped right in the source. For example, if the source is a radio-loud AGN and cosmic rays (including UHECR) are accelerated in one of its structures (central engine, jet or radio lobes), the condition of free escape from the source is that the gyroradius of the accelerated particle is comparable to the source size. This condition reads $E \gtrsim E_{\rm free}$ where $E_{\rm free} \simeq eBR \simeq 10^{20}\left[\frac{B}{10^4\ \mathrm{G}}\right]\left[\frac{R}{10^{14}\ \mathrm{cm}}\right]$ eV, where e is electric charge of the particle and B is the strength of magnetic field. This condition is obviously satisfied only for UHECR. All the lower energy particles are trapped inside the source (be it the AGN central engine, jet or the radio lobes). The trapped lower energy particles could still finally escape from the source, diffusively (on a much longer time scale), scattering off the turbulent magnetic fields expected to be present there. Let us assume in the following that the power spectrum of the turbulence follows a Kolmogorov power-law. The escape time of cosmic rays propagating through the turbulent magnetic field with Kolmogorov power spectrum scales with energy as $T_{\rm esc} = T_{\rm free}\left(\frac{E}{E_{\rm free}}\right)^{-\delta} \simeq 3\times 10^6\left[\frac{E}{10^{11}\ {\rm eV}}\right]^{-\delta}$ s, where we have taken $\delta = 1/3$ and the above values of B and R for the numerical estimate. It takes one hour for UHECR to escape from the central engine of an AGN powered by a black hole of the mass $3\times 10^8 M_\odot$. It takes one month for a 100 GeV cosmic ray to escape from the central engine. In a similar way, UHECR cross the kpc scale jet on the time scale of thousand years, but the 100 GeV cosmic rays would reside for several Myr. Finally, 100 GeV cosmic rays do not leave the Mpc-scale radio lobes even on the longest time scale of the AGN lifetime, $\sim 10^8$ yr. Cosmic rays trapped inside the source loose energy in interactions with the ambient medium present in the source. In the case of accretion flow, its density is moderately low $n \lesssim 10^{10}$ cm^{-3} for the Radiatively inefficient accretion flow (RIAF) powering the FR I/BL Lac sources. Still, the energy loss time of the cosmic ray protons is $t_{pp} = \frac{1}{\kappa\sigma_{pp}n} \simeq 2\times 10^5\left[\frac{n}{10^{10}\ {\rm cm}^{-3}}\right]$ s, where $\sigma_{pp}\sim 3\times 10^{-26}$ is the pp interaction cross-section and $\kappa \simeq 0.6$ is inelasticity of pp collisions. The interaction time could be shorter than the escape time, $T_{\rm esc} \gtrsim t_{pp}$, for cosmic rays with low enough energy $E < E_{\rm esc}$, where $E_{\rm esc} \simeq 10^{14}$ eV for the above values of n, B and R. Cosmic rays with energies below ~ 100 TeV would, in fact, not escape from the central engine of an AGN powered by a $3\times 10^8 M_\odot$ black hole.

In a similar way, cosmic rays residing in a kiloparsec scale jet interact with the interstellar medium of the AGN host galaxy. The energy loss time t_{pp} for the typical ISM density $n \sim 1$ cm^{-3} is about 10^8 yr, which is longer than the escape time even for the GeV energy cosmic rays. This means that the cosmic rays trapped in the kiloparsec scale jet escape into the interstellar medium of the source host galaxy, rather than release their energy inside the jet. The density of the intracluster medium spread over the Megaparsec scale of the radio lobes has still lower density $n \sim 10^{-2}$ cm^{-3}, so that the pp energy loss time is still longer. In fact, it is comparable to the age of the Universe. Thus also the cosmic rays residing in the radio lobes escape into the host galaxy cluster of the source, rather than dissipate their energy in the lobes.

The spectrum of the low-energy cosmic rays trapped in the source is a broken powerlaw with the break at $E_{\rm esc}$

$$\frac{dN}{dE} \propto \begin{cases} E^{-\alpha_p}, & E < E_{\rm esc} \\ E^{-(\alpha_p+\delta)}\exp\left(-E/E_{\rm cut}\right), & E_{\rm esc} < E < E_{\rm free} \\ E^{-\alpha_p}\exp\left(-E/E_{\rm cut}\right), & E > E_{\rm free} \end{cases} \tag{3.1}$$

Below this energy the spectrum just repeats the injection spectrum and has the slope α_p. This is because at each energy the injected cosmic rays are accumulated in the source on the time scale t_{pp} which (almost) does not depend on energy. Above $E_{\rm esc}$ and up to the energy $E_{\rm free}$, the spectrum of cosmic rays residing in the source is determined by the competition of injection and escape processes. Cosmic rays at the energy E are accumulated in the source during the time $T_{\rm esc}$ which decreases with energy. Because of this, the spectrum of the residing cosmic rays is softer than the injection spectrum, $\Gamma = \alpha_p + \delta$. Energy lost by the low-energy cosmic rays trapped in the source is used for generation of γ-ray and neutrino emission, through the production and decay of $\pi^{0,\pm}$.

The spectrum of neutrinos from the trapped cosmic rays could be readily calculated, because the neutrinos freely escape from the source without further interactions. Taking into account that the parent proton spectrum is the broken powerlaw with high-energy cutoff, one expects that the

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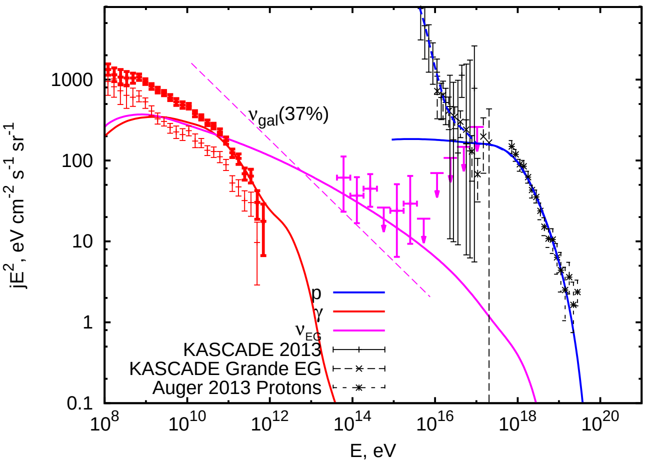

Figure 2: Extragalactic CR protons (blue), diffuse neutrino (magenta) and γ-ray (red) fluxes, compared to observations, see Section 3.1 for details. BL Lac / FR I cosmological evolution of the source population, with $E_{\rm cut} = 10^{19}$ eV, $\alpha_p = 2.10$, and $\tau_{pp} = 1$ at 10^{14} eV. Dashed blue line for Galactic CR protons in the escape model, and dashed magenta line for Galactic neutrinos, see Section 3.2.

spectrum of neutrinos is also a broken cutoff powerlaw with the break / cutoff at the energy ~ 0.05 of the break / cutoff energy of the proton spectrum. The result of numerical calculation of the neutrino flux from an entire population of UHECR sources which follow the BL Lac cosmological evolution is shown in Fig. 2. The break in the neutrino spectrum is rather a rollover, because of the width of the neutrino production cross-section and because of the redshift of the break energy in the spectra of distant sources. A remarkable fact is that the neutrino flux of the reference model (BL Lac / FR I cosmological evolution of the source population, $E_{\rm esc} = 10^{14}$ eV, as expected for the central engine of a source powered by $3 \times 10^8 M_\odot$ black hole) is comparable ($\approx 50\%$) to the flux of astrophysical neutrinos above 10 TeV as measured by IceCube. Moreover, the slope of the neutrino spectrum in the IceCube range is $\alpha_\nu \simeq \alpha_p + \delta \simeq 2.4 - 2.5$, if the injection spectrum of cosmic rays in the UHECR source is $\alpha_p \simeq 2.1 - 2.2$. This slope of the neutrino spectrum is close to the slope measured by IceCube.

γ-rays produced in pp interactions do not escape freely because of the pair production on low energy photons present in the source. The effect of the pair production on the γ-ray spectrum is difficult to calculate because of uncertainty of the detailed shape and spatial distribution of the low energy photon background inside the sources. The effect of the pair production modifies the γ-ray spectrum at the energies $E > 1\,[\varepsilon/1\text{ eV}]^{-1}$ TeV, where ε is the energy of the low-energy photon. The RIAF spectrum in the central engine of FR I galaxies / BL Lacs typically peaks in the infrared, so that γ-rays with energies below ~ 10 TeV still could escape from the source. Even if γ-rays escape from the source, their spectrum is further modified during propagation through the extragalactic background light (EBL). The EBL spectrum peaks in the visible / near infrared and affects the γ-ray spectra of distant sources already in the sub-TeV energy band. Fig. 2 shows the result of calculation of the γ-ray spectra from the pp interactions in UHECR sources produced under assumption that all γ-rays (not only those with energies below 10 TeV) escape from the sources. One could see that, after all, this assumption is not constraining, because the $E > 10$ TeV γ-rays are anyway removed from the source spectrum by the effect of pair production. For an injection spectrum of cosmic rays in the sources with a slope $\alpha_p \simeq 2.0$, we find that the flux of γ-rays from interactions of lower energy cosmic rays in the sources is moderate compared to the overall level of IGRB. If the injection spectrum is softer, there are more low energy cosmic rays. Their interactions produce higher flux. If the injection spectrum is just slightly softer, about $\alpha_p \simeq 2.1 - 2.2$, the γ-ray flux is comparable to the IGRB measurement. In fact, model of the γ-ray flux from pp interactions in UHECR sources provides a fit to the IGRB spectrum. This is a non-trivial fact, because the model parameters were chosen to fit the UHECR, rather than the IGRB spectrum. In any case, the spectrum of cosmic rays generated by the acceleration process operating in UHECR source cannot be softer than 2.2. Otherwise, the flux produced γ-ray emission from the low energy cosmic rays trapped inside the sources would exceed the measured level of IGRB.

3.2 Diffuse neutrino flux and IceCube neutrinos

We have computed in the previous subsection the diffuse flux of secondary neutrinos expected from BL Lacs (or FR I galaxies) in our model. Quite interestingly, this flux corresponds to an important fraction ($\sim 50\%$) of the IceCube flux of high-energy neutrinos, see magenta line in Figure 2. Also, the slope of our neutrino spectrum (≈ 2.5) is the same as the slope of IceCube neutrino flux. This is an important difference with respect to other theoretical models that predict a much harder spectrum, with slopes ≈ 2.0, similar to the slope of the injection spectrum of cosmic rays at the sources. In such models, either the parent cosmic rays escape freely from the sources or lose all their energy in the sources – see first and third lines of Eqn. (3.1). In our model, we allow for cosmic rays to diffuse in the source before escaping, see middle line of Eqn. (3.1). This results in a slope for the diffuse neutrino flux that is softer than that of the injected cosmic rays in the sources.

As for the remaining half of the IceCube flux, References [15] have found a high-energy neutrino flux from our Galaxy at the level of $\sim 50\%$ of the IceCube flux, taking a global Galactic cosmic ray spectrum slope of 2.5, instead of 2.7 (local flux). Therefore, our model can explain the entire astrophysical neutrino signal observed by IceCube, both in terms of flux level (about half Galactic and half extragalactic) and of slope.

4. Conclusions

We have investigated here if the extragalactic proton component derived within the escape model [8, 9] can provide a viable model for the measured CR proton flux and, at the same time, give a significant contribution to the isotropic γ-ray background (IGRB) measured by Fermi-LAT and to the astrophysical neutrino signal observed by IceCube. We have examined which CR source classes can explain the spectral shape and the magnitude of the derived extragalactic proton flux. We consider as possible CR sources normal/starburst galaxies and radio-loud active galactic nuclei (AGN).

We have found that the BL Lac/FR I population as source for extragalactic CRs can explain in a unified way both the observations of primary and secondary fluxes. We have shown that for radio-loud AGNs the complete extragalactic energy spectrum can be explained by a single source population. We have also calculated the diffuse neutrino and γ-ray fluxes produced by these CR protons interacting with gas. These secondary fluxes depend on the grammage CRs cross in their host galaxies and galaxy clusters. For a spectral slope of CRs close to $\alpha = 2.1 - 2.2$, we have found that these UHECR sources can contribute to the dominant fraction of the isotropic γ-ray background (IGRB), and the major contribution to the extragalactic part of the astrophysical neutrino signal observed by IceCube.

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