Probing the Extragalactic Cosmic-Ray Origin with Gamma-Ray and Neutrino Backgrounds

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Abstract

GeV–TeV gamma-rays and PeV–EeV neutrino backgrounds provide a unique window on the nature of the ultra-high-energy cosmic rays (UHECRs). We discuss the implications of the recent Fermi-LAT data regarding the extragalactic gamma-ray background and related estimates of the contribution of point sources as well as IceCube neutrino data on the origin of the UHECRs. We calculate the diffuse flux of cosmogenic γ-rays and neutrinos produced by the UHECRs and derive constraints on the possible cosmological evolution of UHECR sources. In particular, we show that the mixed-composition scenario considered in Globus et al., which is in agreement with both (i) Auger measurements of the energy spectrum and composition up to the highest energies and (ii) the ankle-like feature in the light component detected by KASCADE-Grande, is compatible with both the Fermi-LAT measurements and with current IceCube limits. We also discuss the possibility for future experiments to detect associated cosmogenic neutrinos and further constrain the UHECR models, including possible subdominant UHECR proton sources.

Key words: cosmic rays

1. Motivation

The interaction of UHECRs with the photon backgrounds during their propagation in intergalactic space produces cosmogenic γ-ray photons (Stecker 1973; Strong & Wolfendale 1973) through electromagnetic cascades that contribute to the extragalactic gamma-ray background (EGB) at GeV–TeV energies, and cosmogenic neutrinos (νs, Berezinsky & Zatsepin 1969) mostly from PeV to multi-EeV energies. The flux of these secondary messengers is highly sensitive to the spectral shape, maximal energy, composition, and cosmological evolution of the UHECR sources. Therefore, one can derive important constraints on the UHECR origin from a multi-messenger approach that takes these into account (Protheroe & Johnson 1996; Coppi & Aharonian 1997; Ahlers & Salvado 2011; Decerprit & Allard 2011; Berezinsky et al. 2016; Gavish & Eichler 2016; Supanitsky 2016 for γ-rays; e.g., Stecker 1979; Engel et al. 2001; Seckel & Stanev 2005; Allard et al. 2006; Anchordoqui et al. 2007; Ahlers et al. 2009; Kotera et al. 2010, for νs).

Source models implying a cosmological evolution much stronger than the star formation rate (SFR) have already been ruled out as the main UHECR contributors by the first Fermi-LAT estimates of the purely diffuse component of the EGB (Abdo et al. 2010), independently of the maximum energy of UHECRs (E_max), in particular for steep (soft) cosmic-ray injection spectra (e.g., Ahlers et al. 2010; Berezinsky et al. 2010; Decerprit & Allard 2011). These strong evolutions have also been ruled out by the IceCube limits on νs in the case of source spectra with large values of the maximum energy-per-nucleon (E_max/A ≳ 10^{20} eV, see Aartsen et al. 2016).

Moreover, the recent Fermi-LAT data (Ackermann et al. 2015) together with statistics of the photon counts in the sky map pixels (e.g., Malysh & Hogg 2011, and references therein) have enabled different authors (Ackermann et al. 2016; Zechlin et al. 2016, hereafter A16 and Z16, respectively) to estimate the flux contributed by point sources (PS) well below the Fermi-LAT detection limits. These studies show that resolved and unresolved PS account for the majority of the EGB. Because a γ-ray background due to extragalactic cosmic rays (EGCRs) is unavoidable, it is crucial to verify that the proposed UHECR source models do not violate the existing constraints.

Recent measurements by the Pierre Auger Observatory (Auger) indicate that the composition of UHECRs is mixed (predominantly light) at the ankle of the cosmic-ray spectrum, and it gets progressively heavier as the energy increases (Aab et al. 2014). This composition trend can be interpreted as the signature of a low maximal energy-per-unit-charge (E_max/Z ≲ 10^{19} eV) of the nuclei accelerated at the dominant sources of UHECRs. Below 10^{18} eV, the KASCADE-Grande experiment reported an ankle-like feature in the energy spectrum of light (proton-helium) elements with a break at ≈10^{17} eV (Apel et al. 2013; Bertain et al. 2015). This “light ankle” can be naturally understood as the emergence of a light EGCR component, taking over the steeper Galactic cosmic-ray (GCR) component.

In this letter, we investigate constraints that can be set on mixed-composition EGCR models, taking into account the most recent Fermi-LAT estimates of the EGB and its unresolved component. We discuss the viability of a class of mixed-composition models in which the KASCADE-Grande and Auger data are understood in terms of a transition between a GCR component and a single EGCR component with a soft proton spectrum and low E_max. This soft proton component would be responsible for the light ankle and would be the dominant contributor to the cosmogenic γ-ray flux. This model was shown to be compatible with the spectrum and composition data at all energies (Globus et al. 2015b, hereafter G15b), and is consistent with the anisotropy constraints on galactic protons (Tinyakov et al. 2016).

2. Source Model

Any phenomenological EGCR model that accounts for the data needs a very hard spectrum at the sources to reproduce the
evolution of the composition above the ankle observed by Auger and a soft proton component to account for the light ankle seen by KASCADE-Grande. As an example, we consider the EGCR source model for UHECR acceleration at gamma-ray bursts (GRBs) internal shocks (Globus et al. 2015a, hereafter G15a), whose basic features result from the presence of a dense, broadband photon field in the acceleration environment, and should thus also be expected in other types of powerful high-energy sources. Those features are:

1. A very hard source spectrum for the composed nuclei (harder than \(\sim E^{-1}\) below \(E_{\text{max}}(Z)\)) with a rigidity-dependent cutoff due to the selection of high-rigidity particles by the escape process.

2. A much softer source spectrum for the nucleons due to the free escape of neutrons produced by the photo-disintegration of nuclei.

Both features would arise in any model based on electromagnetic acceleration, including a significant dissociation of the nuclei at the source.

The exact shape of the source spectrum of the escaping nucleons and composed nuclei depends on various physical parameters, such as the shock geometry and its time evolution, the local magnetic turbulence, and the competition between energy losses and escape (G15a). Moreover, the distribution of source luminosities influences the shape of the effective UHECR spectrum (obtained after convoluting the individual source spectra by the source luminosity function). The effective spectrum from the GRB model (G15a) is displayed in the upper panel of Figure 1.

Because the extragalactic protons around \(10^{17}\) eV contribute significantly to the expected cosmogenic \(\gamma\)-ray flux in the Fermi energy range, we explore, for the sake of generality, (i) different slopes for the proton component (as could result from different physical parameters describing the sources) while keeping the same maximal rigidity and spectral shape for heavier nuclei and (ii) different cosmological evolutions, assuming an average source power proportional to \((1+z)^a\) up to a redshift \(z_{\text{max}}\).

The soft proton component of the effective UHECR spectrum (upper panel of Figure 1) is well fitted by a power law with a Gaussian cutoff, \(dN/dE \propto E^{-\beta} \exp[-E^2/(2E_{\text{max}}^2)]\), with \(\beta = 2.0\) and \(E_{\text{max}} \approx 1.7 \times 10^{19}\) eV. In the following, we allow for a modification of the original proton spectrum and consider a range of spectral indices \(2.0 \leq \beta \leq 2.5\). The two proton spectra obtained with the extreme values of \(\beta\) are represented by thick dashed and dotted blue lines, respectively. The implied range of UHECR emissivities above \(10^{17}\) eV is \(L_{\text{CR}}^{\gamma} \sim [5.7-14] \cdot 10^{47}\) erg Mpc\(^{-3}\) yr\(^{-1}\). When considering different cosmological evolutions, we need to further rescale the propagated spectrum by a factor between \(\sim 0.8\) and \(\sim 1.5\) to match the Auger data at high energy. The Monte-Carlo procedure used to calculate the cosmic-ray, \(\nu\), and \(\gamma\)-ray spectra is presented in Decerprit & Allard (2011).

3. Propagated Cosmic-Ray Spectra

The lower panel of Figure 1 depicts the propagated UHECR spectra for \(2.0 \leq \beta \leq 2.5\), for EGCR sources evolving as GRBs (Wanderman & Piran 2010, blue lines) and for non-evolving sources (violet shaded area). Varying the cosmological evolution of UHECR sources does not affect the high-energy part of the propagated spectrum because the sources contributing at these energies are located at low redshifts; (due to the GZK horizon effect). However, a stronger source evolution implies a larger contribution of the more distant sources and thus a larger UHECR flux at lower energies. As a result, a suitable combination of the soft proton source spectrum and a strong cosmological evolution can reproduce the light (supposedly proton-helium) cosmic-ray component estimated from KASCADE-Grande data.

In the case of a GRB-like cosmological evolution (or SFR-like (Yüksekm et al. 2008) that gives very similar results), proton spectral indices \(\beta = 2.4-2.5\) provide a good fit to the KASCADE-Grande data when summing the light EGCR component with the GCR light component obtained in G15b (dashed line in Figure 1). The resulting proton abundance increases over the \(10^{17-10^{18}}\) eV energy range before slowly dropping above the ankle, reproducing the observed composition trend in the GCR-to-EGCR transition and above.

In a non-evolving scenario, softer proton indices (\(\beta \sim 2.7\), and thus larger injection power density) are required to obtain such a large contribution of the EGCR component at low energy. Conversely, a stronger source evolution than that of GRBs would require harder proton indices.

4. The Gamma-Ray Background

The interactions of the propagating EGCRs leads to the production of cosmogenic \(\gamma\)-rays in the GeV–TeV range, through the development of electromagnetic cascades. The resulting spectra are shown in Figure 2 for a mixed-composition model with proton spectral indices \(2.0 \leq \beta \leq 2.5\), for sources with no cosmological evolution (violet lines) and with a GRB-like evolution (in blue). For a given source evolution, softer proton injection spectra result in larger \(\gamma\)-ray fluxes, due to the larger amount of low-energy protons that efficiently fuel the electromagnetic cascades via the pair production process. These \(\gamma\)-ray fluxes represent only a small contribution to the total EGB, which is reproduced from Ackermann et al. (2015) for two different models of the Galactic \(\gamma\)-ray foreground, referred to as model A and model B by the authors, according to whom neither is preferred over the other. These two models roughly differ by \(\sim 20\% - 30\%\), which can be seen as a rough estimate of their systematics in the subtraction process.

To determine whether a given EGCR source model is compatible with the \(\gamma\)-ray data, we need to take into account other known contributions to the EGB. Recently, A16 and Z16 showed that the EGB is dominated by \(\text{(resolved and unresolved)}\) PS, notably above \(\sim 50\) GeV, and estimated their contributions in six different energy bands, from 1 GeV to 2 TeV. These contributions are given in Table 1 in terms of flux as well as percentage of the EGB for both models A and B. While this PS flux is thought to be dominated by blazars, source populations with much smaller fluxes (thus, mostly unresolved) may not be included in these estimates (see discussions in A16, Z16, and Lisanti et al. 2016). We thus consider in addition a possibly important contribution of star-forming galaxies (SFG) and misaligned active galactic nuclei (misAGN), based on the models by Inoue (2011) and Ackermann et al. (2012). Table 1 gives their integrated fluxes and relative contributions to the EGB in the six energy bands considered by A16 and Z16. The SFG and misAGN \(\gamma\)-ray spectra are shown in Figure 2 (omitting the uncertainty bands for clarity). Also shown is the \(\gamma\)-ray spectrum arising from
blazars, adapted from Ajello et al. (2015). This spectrum appears in good agreement with the PS contribution estimated by A16 and Z16 over the whole energy range.

Turning now to include the contribution of the EGCRs to the γ-ray background we find that for the GRB or non-evolving scenarios, the sum of all components (UHECR, misAGN, SFG, and blazars) never exceeds the total EGB, in the case of model B. In the case of model A, the sum is above the EGB. However, it falls below it if one adopts the 1σ lower bound on the misAGN+SFG+blazars contribution.

Table 2 gives more details on the integrated γ-ray fluxes ($F_{\text{UHECR}}$) contributed by the extragalactic UHECRs in the same six energy bands for which A16 and Z16 have estimated the PS contribution. We compare those contributions with the total EGB (Models A and B). The percentages of these γ-ray fluxes from UHECRs to the EGB ($F_{\text{UHECR}}/F_{\text{EGB}} \times 100$), are shown for three different source evolutions (GRB, SFR, and non-evolving), and two different spectral index of the proton component with spectral index $b = 2.0$ and $b = 2.5$. We also give the percentage of the sum of PS, UHECR, misAGNs, and SFGs to the EGB. The sum of all components never exceeds the Fermi-LAT limits in the case of Model B, as already hinted by Figure 2.

The case of model A is less clear. The sum of the PS and γ-rays from UHECRs without adding the more uncertain misAGNs and SFGs (part of which may already be included in the PS contribution estimated by A16 and Z16 anyway) respects the observational constraints for all our models, as can be seen in the last three lines of Table 2. However, should model A and the contribution of all the various PS (including misAGNs and SFGs) be confirmed, our calculations show a tension in the γ-ray and UHECR data even in the case of the non-evolving scenario.

Figure 3 shows the allowed parameter space of different evolutionary scenarios. This estimate is based on the summed contribution of all components in the 10.4–50 GeV band, where the contribution from UHECRs is the largest. Only very strong evolutions are excluded by the current observations.

5. Neutrino Counterpart

Figure 4 shows the resulting ν spectra for different EGCR models together with the sensitivity of current and planned experiments. The mixed-composition models predict ν fluxes too low to be detected by IceCube (Aartsen et al. 2016) or ARIANNA (Hallgren 2016), even in the case of a GRB-like cosmological evolution. They would require a sensitivity such as that expected for the GRAND observatory (Martineau-Huynh et al. 2015) or CHANT satellite concept (Neronov et al. 2017). For this reason, it is often considered that a possible future detection of cosmogenic νs by IceCube or ARIANNA would be a very strong argument against the
mixed-composition UHECR models. Pure proton scenarios can indeed be seen on Figure 4 to yield detectable fluxes, while still being allowed by the current IceCube limits and Fermi-LAT data. For these calculations, we assumed a pure proton $E^{-2}$ spectrum with an exponential cutoff at $E_{\text{max}} = 60$ EeV (which is known to reproduce reasonably well the Auger spectrum above the ankle).

However, it is interesting to note that when the $\nu$ flux is concerned there is a trade off between the strength of the protonic UHECR sources and its cosmic evolution. Hence a $\nu$ detection would not necessarily sign a pure proton scenario. An albeit hypothetical at present, subdominant (less than $\sim 5\%$ to $10\%$ of the UHECR flux) proton component with $E_{\text{max}} \sim 10^{20}$ eV and a strong cosmological evolution, would contribute a detectable $\nu$ flux around $10^{18}$ eV (see Figure 4), while the bulk of the UHECRs would still be provided by sources with a mixed-composition and low proton fraction. The corresponding relative contributions to the total EGB is also given as a percentage, assuming galactic foreground models A or B (Ackermann et al. 2015).

Note. The corresponding relative contributions to the total EGB is also given as a percentage, assuming galactic foreground models A or B (Ackermann et al. 2015).

Table 1

| Energy Bands (in GeV) | Energy Bands (5 = 2.0) | Energy Bands (5 = 2.5) |
|----------------------|------------------------|------------------------|
| 1.04–1.99           | 1999                   | 1999                   |
| 5.0–10.4            | 10.4–50               | 50–171                |
| 0.4–50              | 50–2000               | 50–2000               |

Table 2

| Components and Source Evolution | Energy Bands ($5 = 2.0$) | Energy Bands ($5 = 2.5$) |
|--------------------------------|------------------------|------------------------|
| F$_{UHECR} (X \times 10^{-9}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$) | GRB 170 120 44 32 2.5 2.7 | GRB 260 190 70 52 4.7 5.1 |
|                                  | SFR 200 140 51 38 3.6 3.9 | SFR 270 190 70 52 4.7 5.1 |
|                                  | Non-evol 42 30 11 8.6 1.1 1.3 | Non-evol 58 41 15 11 1.4 1.6 |
| $F_{UHECR} / F_{EGB}$           | GRB 4.6 6.2 8.5 12 9.6 9.4 | GRB 7.0 9.5 13 17 13 13 |
|                                  | SFR 5.3 7.1 9.8 14 14 13 | SFR 7.3 9.9 14 19 18 17 |
|                                  | Non-evol 1.1 1.6 2.2 3.1 4.2 4.4 | Non-evol 1.6 2.1 2.9 4.1 5.3 5.4 |

Note. The corresponding percentage of the total EGB is given, for models A and B, as well as (in bold) the percentage contributed by the sum of UHECR+misAGN +SFG+PS components (using central values). In the case of model A, the total UHECR+PS is also shown separately.
show the percentages of the sum of all components (UHECR + PS + misAGN + SFG) to the EGB (Models A and B) in the 10.4–50 GeV energy band in the $(\alpha, z_{\text{max}})$ parameter space, where $z_{\text{max}}$ is the maximum redshift up to which sources experience a cosmological evolution in $\left(1 + z\right)^{\alpha}$. Some possible EGCR sources (see e.g., Gavish & Eichler 2016 for the references to the cosmological evolutions) are shown. GRB: gamma-ray bursts. SFR: star formation rate. MLLAGN: medium-low-luminosity AGNs. MHLAGN: medium-high-luminosity AGNs. HLAGN: high-luminosity AGNs.

6. Summary

The UHECR model considered in G15b gives a coherent picture of the GCR-to-EGCR transition, and appears to be compatible with the Fermi-LAT measurements and the estimates of the PS contributions by A16 and Z16. It is compatible, with even more room for UHECRs, with the estimates of Lisanti et al. (2016) for the PS contributions (~54% and 68% of the EGB Model A around 2 GeV and above 50 GeV, respectively). Only very strong evolutions are excluded by the current observations. The mixed-composition model appear to be less constrained by the Fermi-LAT than the electron-positron dip (pure proton) scenario (Berezinsky et al. 2016; Gavish & Eichler 2016; Supanitsky 2016) that rules out SFR-like and stronger cosmological evolutions (see also Heinze et al. 2016) for more radical conclusions on the dip model.

Our interpretation$^3$ differs from Liu et al. (2016). Considering only model A and a pure proton composition at $10^{18}$ eV, these authors found a $\sim 1\sigma$ excess and therefore suggested the existence of a local overdensity of $10^{18}$ eV proton sources. We find that these local proton sources are unnecessary. Our UHECR model is consistent, within the current uncertainties of PS and Galactic foreground, with the EGB data.

For the evolutionary models allowed by Fermi, the $\nu$s fluxes above $10^{17}$ eV associated with the mixed-composition scenario are well below the current IceCube limits. These fluxes are within the reach only of the most sensitive plane $\nu$ observatories. These fluxes could be outshined by the $\nu$s produced by hypothetical

$^3$ We checked that the different interpretation did not originate from numerical discrepancies between the two studies.
puzzling features in the observed $\gamma$-ray Galactic signal. These models have a smaller halo extension and would probably result in a lower Galactic foreground, leaving more room for EGCR contributions.

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