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Multimessenger diffuse fluxes from a subdominant source population emitting UHE protons

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Observations of the ultra-high energy cosmic ray (UHECR) composition over the last years have unveiled the trend of a flux that is dominated by protons around the ankle and becomes progressively heavier towards higher energies. However, a subdominant proton contribution at the highest energies cannot be ruled out at present. Compelled by the associated, possibly substantial, flux of cosmogenic neutrinos and gamma rays, and the potential for charged particle astronomy with UHE protons, we investigate this scenario by numerical simulation of two independent populations of extragalactic sources of heavy and purely-proton cosmic rays. A fit of the source parameters to the UHECR spectrum and composition observed by the Pierre Auger Collaboration reveals that a proton contribution of up to 15% is possible at the highest energies. The cosmogenic multimessenger signal of this subdominant proton flux exceeds the signal derived from the heavier cosmic rays for most favoured source configurations if the maximum energy of the additional protons is large. In addition, we anticipate a significant flux of neutrinos with energy above the EeV level as a distinguishing feature of this model.

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1. Introduction

Ultra-high energy cosmic rays (UHECRs) are charged nuclei of astrophysical origin with energies above 10^{18}eV. Their sources have so far escaped identification due to the deflection of cosmic rays by the intervening Galactic and extragalactic magnetic fields. The strength of these deflections is proportional to the particle rigidity $R = Z\,E$ (in natural units), with Z the charge and E the energy. For a given energy, lighter cosmic rays are therefore deflected less than heavy cosmic rays. This opens the possibility that, if the highest energy cosmic rays are protons then "direct" observations of the sources could be possible. Before the advent of the current generation of UHECR observatories (Auger and TA), the leading model predicted precisely such a pure-proton composition up to the highest energies [1] which naturally explains the dip in the cosmic rays spectrum at $10^{18.7}$eV – referred to as the "ankle" – and the flux cutoff beyond $10^{19.7}$eV. However, measurements over the last decade, show that the CR mass increases continuously toward the highest energies – possibly all the way up to iron [2].

The sequence of increasing UHECR mean mass with energy can be explained by the "Peters cycle" [3] model, where the maximum energy of a cosmic ray is proportional to the charge. Protons are not expected to exist at the highest energies if UHECRs are only produced by a single population of approximately identical sources. However, the existence of a subdominant flux of light cosmic rays cannot be excluded at the highest energies due to the lack of reliable composition measurements, and some evidence exists in the form of a flattening of the average CR mass above 30 EeV [4, 5]. Such a secondary UHE proton flux is difficult to reconcile with the one-population model, e.g. via reprocessing of heavier cosmic rays but requires the existence of a second population of sources that accelerates only protons. The existence of UHE protons would aid the discovery of UHECR sources immensely and could pave the way for "UHECR astronomy" where sources and cosmic rays can be associated on an event-by-event basis as opposed to the ensemble-averaged approach currently in use.

Here we present an analysis to constrain the allowed flux of UHE protons by assuming two populations of sources; the primary population which produces the typical mixed proton-to-iron UHECR flux and a secondary population that injects only protons. More details can be found in the companion paper [6].

2. Model Description

We adopt the well-developed, effective source model of [7]. Here we briefly summarise the model for an overview of the procedure. The sources of the mixed-composition UHECRs **(MIX)** are assumed to host an acceleration process universal in particle rigidity that produces a power-law cosmic-ray spectrum with exponential cutoff at some maximum rigidity (cf. "Peters cycle" [3]). We select five representative injection elements, $A \in \{^1\mathrm{H}, ^4\mathrm{He}, ^{14}\mathrm{N}, ^{28}\mathrm{Si}, ^{56}\mathrm{Fe}\}$, that provide an approximately uniform coverage in $\ln(A)$ space relevant for key composition observables. Conventionally, the cosmic ray sources are assumed to be identical in all parameters relevant to the particle acceleration (see e.g. [7]). This assumption is well justified due to the low observed variance of UHECRs [8]. Under this parametrisation, the volumetric emission rate of the MIX source population in erg Mpc^{-3} yr^{-1}, per injected element A, can be expressed as

$$Q_A(E) = Q_A^{E_0} \left(\frac{E}{E_0}\right)^{-\gamma} \exp\left(-\frac{E}{Z\,E_{\rm max}}\right). \tag{1}$$

The maximum (proton) energy $E_{\rm max}$, spectral index γ and local emission rate $Q_A^{E_0}$ at some arbitrary normalisation energy $E_0 \ll E_{\rm max}$ are free parameters that are determined during the fit to data. The flux expected at Earth, for cosmic rays of mass A' and energy E' from all sources is then obtained by integrating over all injection energies and distances

$$\phi(E', A') = \sum_A \int \mathrm{d}E \int \mathrm{d}z \left|\frac{\mathrm{d}t}{\mathrm{d}z}\right| n(z)\, Q_A(E) \cdot \frac{\mathrm{d}N_{A'}}{\mathrm{d}E'\mathrm{d}N_A}(E', E, z)\,, \tag{2}$$

where the last term comprises all propagation effects and is determined numerically for any combination of (A, A', E, E') from simulations with CRPropa [9]. The redshift evolution of the total population emissivity is described by a broken power law, where $n(z) = (1+z)^m$ for $z \leq 1.5$ and $n(z) =$ const. above until $z = 4$ after which we truncate the distribution. High redshift sources at $z \gtrsim 1$ have a negligible impact on the UHECR flux but can produce a sizeable contribution to the cosmogenic flux of neutrinos and low-energy gamma rays produced during propagation of the cosmic rays. In total, the MIX sources are characterised by up to 8 free parameters; the maximum (proton) energy $E_{\rm max}$, spectral index γ, redshift evolution m, and the source emissivity per injection element L_0^A (×5).

The secondary population of UHE proton sources **(PP)** are modelled in the same way but with a set of parameters $E_{\rm max}^{\rm PP}$, $\gamma^{\rm PP}$, $m^{\rm PP}$, and $L_0^{\rm PP}$ independent of the MIX sources[1]. We evaluate the contribution $f^{\rm PP}$ of this proton flux to the observed UHECR flux at $E_{\rm CR} = 20$ EeV.

We include all relevant interaction processes during propagation, i.e. redshift losses, photopion production, photodisintegration, nuclear decay, and Bethe-Heitler pair production, and also track the cosmogenic neutrinos and gamma rays produced by these processes. The attenuation of the gamma rays via electromagnetic cascades is also taken into account. The important target photons fields for these interactions are the cosmic microwave background and the extragalactic background light. For the latter we assume the model by Gilmore et al. [10].

3. Methods

The parameters of both populations are optimised simultaneously by fitting the model predictions to the UHECR energy spectrum and composition observed by Auger above $10^{18.7}$ eV [2, 11]. Due to the extremely low cosmic ray flux at these energies, the composition cannot be measured directly but must be inferred from observables such as the mean $\langle X_{\rm max}\rangle$ and variance $\sigma(X_{\rm max})$ of the air shower maximum. We convert the composition predicted by our model before interactions in the atmosphere to these observables to compare with observations. This requires the use of hadronic interaction models. For the entire analysis, we assume EPOS-LHC [12] as hadronic interaction model.

The goodness-of-fit between our model predictions and the Auger observations is evaluated with a regular χ^2-estimator. Due to the low statistics, we include upper limits of the spectrum at

[1] $E_{\rm max}^{\rm PP}$ is not a free parameter but fixed to specific values for different investigated scenarios.

the highest energies with an additional Poissonian penalty term. Spectral data points below the investigated energy range are only included as one-sided χ^2-penalty terms which only contribute if the predicted flux exceeds the observations.

The constraints from multimessenger data are also used to further constrain the source model. Observed fluxes, e.g. the Fermi-LAT IGRB [13] and IceCube HESE neutrino flux [14] are treated as ones-sided χ^2-penalties analogous to the low-energy cosmic ray spectrum data, while upper-limit points such as the Auger UHE neutrino [15] and gamma-ray limits [16, 17] are considered as Poissonian χ^2 penalty terms similar to the highest energy upper limit points of the UHECR spectrum. Source configurations still allowed by UHECR data are excluded by the multimessenger constraints of the penalty exceeds two sigma, i.e. $\Delta\chi^2_\nu + \Delta\chi^2_\gamma > 4$.

4. Results

We study two qualitatively different scenarios for the proton sources; one model with very high and low maximum energy respectively (2SC-dip/-uhecr). Because the additional flux consists only of protons, interactions during propagation do not alter the composition and the predicted flux at Earth is nearly insensitive to the redshift evolution of the PP sources. While propagation softens the observed spectrum and attenuates the original flux, the effects of more distant sources can always be compensated by harder injection spectra and higher source luminosities.

4.1 Two-Source-Class Dip Model (2SC-dip)

This study was primarily motivated by the possibility of “UHECR astronomy” with low-deflection UHE protons, and the large multimessenger signal expected from such a flux. This requires a high maximum energy of the protons which we choose arbitrarily to be $E^{\rm PP}_{\rm max} = 10^{23}$ eV. We have verified that the precise value only has a small effect on all the messengers provided it is sufficiently above the GZK limit, i.e. $E^{\rm PP}_{\rm max} \gtrsim 10^{20.5}$ eV.

Cosmic Rays In this scenario, the maximum observed proton energy is not limited by the acceleration process but by photopion production on CMB photons. The best fit (Table 1, 2nd column) reproduces the predictions of the classical proton-dip model [1] but with subdominant proton component that contributes approx. 5 – 10% of the observed flux at all energies above the ankle (Fig. 1, left). Notably, the preferred parameters of the dominant MIX source population are compatible with the best-fit values identified for the baseline model without additional proton sources (Table 1, 1st column). A moderately soft spectrum, $\gamma^{\rm PP} \approx 2$, is required for the proton sources. Much softer spectra would result in an over-prediction of the UHECR flux below the ankle, while significantly harder spectra would limit the energy range where the protons can provide an appreciable contribution to the observed flux and therefore the maximum improvement of the fit.

Multimessenger Fluxes As a consequence of the low maximum energy of the mixed-composition cosmic rays the expected gamma-ray signal at ultra-high energies is small. In contrast, the UHE protons from the second source population have the energy required for photopion production with abundant CMB photons. The resulting neutral pions decay typically into a pair of photons with energy approx. 10% of the original cosmic ray. Most of the initial photon energy is reprocessed from the UHE regime to sub-TeV energies through the development of electromagnetic cascades.

The expected signal of cosmogenic gamma rays in the Fermi-LAT energy range produced by the UHE protons is at a similar level to the gamma rays from the mixed-composition cosmic rays. This is a consequence of the overall low admixture of protons within the best-fit realisation. The predictions are compatible with the Fermi-LAT IGRB measurements, even after a conservative rescaling of the limits by a factor of ×0.4 due to expected "hidden" gamma-ray sources. At UHE, where no gamma rays are expected from the heavier cosmic rays due to the low maximum energy, the contribution from the protons dominates. Larger UHE gamma-ray fluxes correspond to harder proton injection spectra. While present limits by Auger are not constraining even under the most favourable conditions, we note that the predicted flux is only a factor of a few below current sensitivities.

The most promising results are found for the flux of cosmogenic neutrinos (Fig. 2, left) which, depending on the redshift evolution of the source emissivity, can be much larger than the flux produced by the MIX cosmic rays. Based on current observations by IceCube [14] and upper limits by Auger [15], we can constrain the PP source parameters to

$$\gamma^{\mathrm{PP}} \gtrsim 1.6\,,\; m^{\mathrm{PP}} \lesssim 4\,,\text{ and } L_0^{\mathrm{PP}} \lesssim 10^{44.5}\,\frac{\mathrm{erg}}{\mathrm{Mpc}^3\,\mathrm{yr}}\,. \tag{3}$$

A notable feature of the 2SC-dip scenario is the large UHE neutrino flux at and above $E_\nu \approx 1\,\mathrm{EeV}$.

4.2 Two-Source-Class Best-Fit Model (2SC-uhecr)

Cosmic Rays A better fit of the observed UHECR spectrum and composition observables is obtained for maximum proton energies below the GZK limit ($E_{\mathrm{max}}^{\mathrm{PP}} = 10\,\mathrm{EeV}$). This requires very hard proton spectra, and the resulting shape is similar to the per-element contributions of the MIX sources but shifted upward in energy. The proton contribution to the observed UHECR flux reaches up to 15% at 20 EeV but is highly peaked and decreases quickly toward higher and lower energies. Separation of the two flux components based on the spectral shape alone will be difficult due to the similar spectral index but the identification of two proton peaks in the spectrum would be a clear sign in support of this scenario.

Multimessenger Fluxes With the maximum energy of the protons below the GZK limit, the predicted flux of gamma rays is safely below existing limits at all energies. At the best fit, the neutrino flux produced by the UHE protons is subdominant compared the neutrinos originating from the mixed-compositions cosmic rays (Fig. 2, right), however, within uncertainties a large, highly peaked flux at $E_\nu \approx 1\,\mathrm{EeV}$ is possible and the source redshift evolution can be constrained as $m^{\mathrm{PP}} \lesssim 4$. We note that, due to the absence of PP protons at lower energies, the cross-section for interactions on the EBL is low and the resulting usual PeV bump in the neutrino spectrum is highly suppressed. This enables the decoupling of the two regimes, and a large UHE neutrino flux is possible for strong redshift evolutions without an associated flux in the IceCube HESE energy interval.

5. Conclusions

We have studied a two-population model for the sources of ultra-high-energy cosmic rays with a primary source population of standard, mixed-composition, cosmic rays with mass up to iron, and

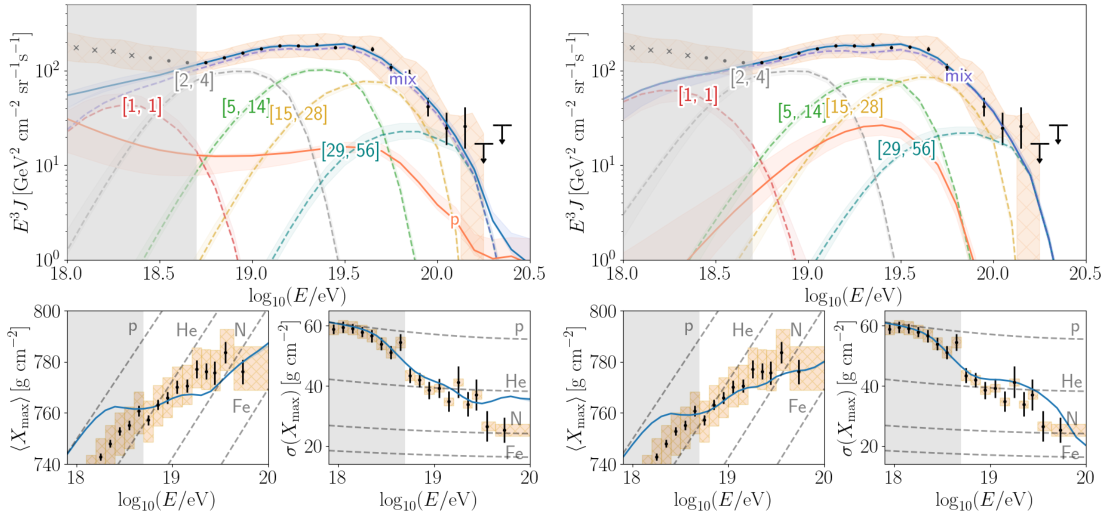

Figure 1: Predicted spectrum and composition at Earth for the two investigated scenarios, with Epos-LHC as hadronic interaction model. Left: "proton-dip" (2SC-dip). Right: "UHECR" best fit (2SC-uhecr). Best-fit parameter values are listed in Table 1. Dashed lines indicate the contributions of the separate mass groups from the mixed-composition sources, with $[A_{\min}, A_{\max}]$. The additional protons from the second population are shown as a solid, orange line. Coloured bands indicate the 68% uncertainties.

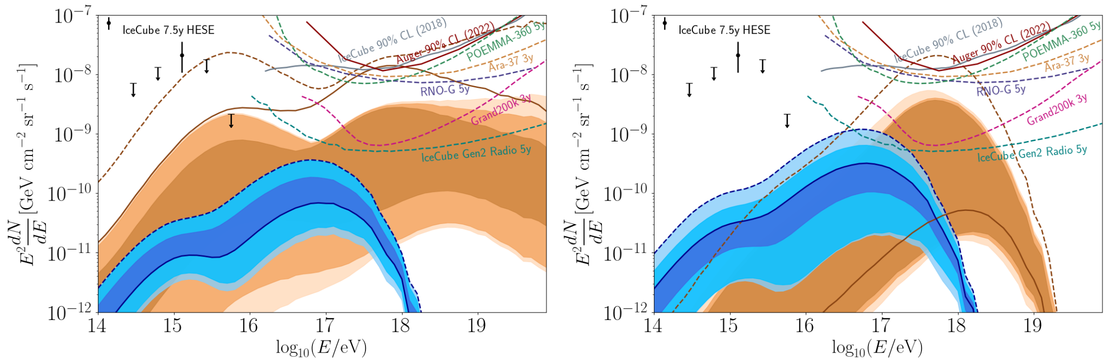

Figure 2: Predicted cosmogenic neutrino flux for the 2SC-dip (left) and 2SC-uhecr model (right). The maximum allowed flux within 3σ of the best CR fit but without including the multimessenger penalty is shown as a dashed line of the respective colour. Solid lines indicate the neutrino flux corresponding to the cosmic-ray best fit without multimessenger constraints. The shaded confidence intervals include the additional χ^2 penalty from the existing neutrino limits.

a secondary population that accelerates only protons to UHE. By comparing our model predictions with observations of the UHECR spectrum and composition by the Pierre Auger Observatory we have constrained the maximum contribution of these additional proton sources to the observed UHECR flux to $f^{\mathrm{PP}} \lesssim 15\%$ at $E_{\mathrm{CR}} = 20\,\mathrm{EeV}$. We were also able to constrain the spectral shape of the injected proton spectrum and the redshift evolution of the underlying source population.

The cosmogenic neutrinos produced during the propagation of the cosmic rays can provide significant constraints on the proton source parameters, in particular the redshift evolution of the source emissivity, while gamma rays do not constrain the sources further.

Table 1: Best-fit parameters for the single- and two-population source models with EPOS-LHC used as the hadronic-interaction model describing air-shower development. The "1SC" scenario is the benchmark model with only a single population of sources injecting mixed-composition cosmic rays. "Population 1" refers to the baseline source class that injects a mixed cosmic-ray flux of protons to iron, and "Population 2" denotes pure-proton sources. We give the best-fit parameters of the UHECR spectrum and composition including the neutrino and gamma-ray constraints. For the 2SC-uhecr model, the cosmic-ray best fit is compatible with existing multimessenger limits. Confidence intervals that extend to the edges of the sampled parameter range are indicated by an asterisk.

Model	1SC	2SC-dip		2SC-uhecr	
		Pop. 1	**Pop. 2**	**Pop. 1**	**Pop. 2**
$R_{\max}$ [EV]	$1.25^{+0.23}_{-0.19}$	$1.5^{+0.5}_{-0.4}$	10^5 (fix)	$1.5^{+0.5}_{-0.4}$	10 (fix)
γ	$-2.5^{+1.0}_{-0}$	$-1.41^{+0.44}_{-0.22}$	$2.5^{+0.3}_{-0.3}$	$-1.41^{+0.22}_{-0.22}$	$-0.25^{+0.50}_{-0.75}$
m	$1.9^{+0.6}_{-4.1}$	-1^{+1}_{-3}	4^{+1}_{-10*}	1^{+1}_{-2}	-3^{+9*}_{-3*}
L_0 [$10^{44}\,\frac{\text{erg}}{\text{Mpc}^3\,\text{yr}}$]	$5.6^{+1.0}_{-3.4}$	$2.5^{+0.6}_{-1.0}$	$1.8^{+0.6}_{-1.4}$	$3.77^{+0.06}_{-1.39}$	$0.12^{+1.88}_{-0.06}$
f^R_{p} [%]	$6.6^{+15.4}_{-6.6}$	$\approx 0^{+8.6}_{-0}$	100	$\approx 0^{+7.2}_{-0}$	100
f^R_{He} [%]	$48.1^{+7.6}_{-2.8}$	$66.9^{+4.6}_{-4.8}$		$70.2^{+4.1}_{-4.4}$	
f^R_{N} [%]	$40.1^{+4.9}_{-16.8}$	$28.0^{+4.5}_{-5.3}$		$23.6^{+3.0}_{-4.8}$	
f^R_{Si} [%]	$4.8^{+0.7}_{-1.5}$	$4.8^{+0.3}_{-0.9}$		$5.8^{+0.6}_{-1.5}$	
f^R_{Fe} [%]	$0.45^{+0.06}_{-0.17}$	$0.33^{+0.10}_{-0.05}$		$0.42^{+0.07}_{-0.08}$	
$f^{\text{PP}}(20\,\text{EeV})$ [%]			$7.0^{+0.8}_{-0.5}$		$14.2^{+1.2}_{-0.5}$
χ^2/dof	101.0/29		74.4/26		58.0/26

Two different scenarios for the maximum proton energy were investigated. If the maximum energy is assumed to be far above the GZK limit then the results are reminiscent of the classical proton-dip model [1] except that the proton component now plays only a subdominant role compared to the mixed-composition CR flux. We report an improvement of the fit over the baseline model without additional proton sources of 2.2σ. The predicted cosmogenic gamma-ray and neutrino flux can constrain part of the parameter space.

In contrast, the 2SC-uhecr model with sub-GZK maximum proton energy provides a larger fit improvement of 3.7σ but requires a hard injection spectrum for the protons and does not predict a large multimessenger signal.

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