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A minimal model for extragalactic high-energy particles

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We explain in a unified way the experimental data on ultrahigh energy cosmic rays (UHECR) and neutrinos, using a single source class and obeying limits on the extragalactic diffuse gamma-ray background (EGRB). If UHECRs only interact hadronically with gas around their sources, the resulting diffuse CR flux can be matched well to the observed one, providing at the same time large neutrino fluxes. Since the required fraction of heavy nuclei is, however, rather large, air showers in the Earth's atmosphere induced by UHECRs with energies $E \gtrsim 3 \times 10^{18}$ eV would reach in such a case their maxima too high. Therefore additional photo-hadronic interactions of UHECRs close to the accelerator have to be present, in order to modify the nuclear composition of CRs in a relatively narrow energy interval. We include thus both photon and gas backgrounds, and combine the resulting CR spectra with the high-energy part of the Galactic CR fluxes predicted by the escape model. As result, we find a good description of experimental data on the total CR flux, the mean shower maximum depth $X_{\max}$ and its width $\mathrm{RMS}(X_{\max})$ in the whole energy range above $E \simeq 10^{17}$ eV. The predicted high-energy neutrino flux matches IceCube measurements, while the contribution to the EGRB is of order 30%.

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1. Introduction

A major motivation for the construction of km^3 neutrino telescopes has been the goal to identify the sources of ultrahigh energy cosmic rays (UHECR): While deflections of charged CRs in magnetic fields have prevented so far a successful correlation of their arrival directions with potential sources even at the highest energies, photons and neutrinos point back to their sources. These neutral secondaries are produced by UHECRs interacting with gas or photons in their sources, and with cosmic microwave and other background photons during propagation. Any process involving hadronization leads mainly to the production of pions, and isospin symmetry fixes then the ratio of charged to neutral pions produced. The production of neutrinos is thus intimately tied to the one of photons, and both depend in turn on the flux of primary cosmic rays.

In Ref. [1], we addressed the question if a single source class can explain *i*) the extragalactic CR flux, *ii*) its nuclear composition and *iii*) the observed neutrino flux in IceCube. Moreover, we required that *iv*) the accompanying photon flux is only a subdominant contribution to the extragalactic gamma-ray background (EGRB) measured by Fermi-LAT [2]. Finally, *v*) the model should be consistent with an early galactic to extragalactic transition. No model has been developed yet which satisfies all five requirements. Since the neutrino flux measured by IceCube is high [3], i.e. close to the cascade limit [4], combining *iii*) and *iv*) is challenging for many source classes. Moreover, existing models aiming to reproduce the observed nuclear composition of UHECRs fail to produce sizable neutrino fluxes, see e.g. [5]. In contrast, models leading to large neutrino fluxes in the 0.1–1 PeV energy range use typically proton primaries with 10–100 PeV energies, without a direct connection to measurements of UHECR composition [6].

2. Constraints

Let us explain these conditions in more detail. Additionally to the all-particle CR spectrum, data on the primary composition have become available in the last years: The Auger collaboration derived the fraction of four different elemental groups above 6×10^{17} eV [7], while the KASCADE-Grande experiment measured the composition up to 2×10^{17} eV [8]. These measurements can be summarized as follows: First, the proton fraction amounts to $\sim$ 40–60% in the energy range between 7×10^{17} eV and 7×10^{18} eV and decreases afterwards, while the fraction of intermediate nuclei increases. Second, the iron fraction in the energy range between 7×10^{17} eV and 2×10^{19} eV is limited by $\lesssim$ 15–20%. Despite both theoretical and experimental uncertainties, the following conclusions can be drawn: First, the Galactic contribution to the observed CR spectrum has to die out around 7×10^{17} eV. This inference is supported by limits on the CR dipole anisotropy which require a transition below $\sim 10^{18}$ eV in case of a light composition [9]. Consequently, we demanded an early Galactic-extragalactic transition and had to explain therefore the ankle as a feature in the extragalactic CR spectrum. Second, the composition measurements are inconsistent with a strong dominance of either protons or iron nuclei. We assumed therefore that a mixture of nuclei is injected in the source, with a rigidity dependent maximal energy.

The main part of the EGRB is attributed to unresolved blazars [10, 11]. This makes blazars and in particular BL Lacs attractive neutrino sources, since their contribution to the EGRB is much larger than the one from other sources. An attempt to connect the observed UHECR proton flux with neutrino and gamma-ray data was performed in Ref. [12]. However, correlation studies of arrival directions of muon neutrinos with Fermi blazars showed that blazars cannot be the main source of IceCube neutrinos [13]. Thus leptonic models are favored to explain the main part of the photon flux from blazars. As a result, neutrino sources should give a subdominant contribution to the EGRB.

3. Source model

We assumed in Ref. [1] that UHECRs are accelerated by (a subclass of) active galactic nuclei (AGN). We neglected the details of the acceleration process, and assumed that the energy spectra of nuclei follow a power-law with a rigidity dependent cutoff $j_{\rm inj}(E) \propto E^{-\alpha} \exp[-E/(ZE_{\rm max})]$. Subsequently, the CR nuclei diffuse first through a zone dominated by photo-hadronic interactions, before they escape into a second zone dominated by hadronic interactions with gas. The propagation in both zones is modeled as a one-dimensional process, determined by the ratio τ of the interaction rate $R_{\rm int}$ to the escape rate $R_{\rm esc}$.

The spectra of AGN show a characteristic blue bump produced by UV photons from the accretion disc and, at lower energies, thermal emission from dust surrounding the SMBH. We assumed that these IR photons provide the main interaction target. Interactions on these IR photons will result in a suppression of the heavier nuclei fluxes at the desired energy range. We parametrised the interaction depth τ as $\tau_0^{p\gamma} = R_{\rm int}/R_{\rm esc}$, using protons with energy $E_0 = 10\,{\rm EeV}$ as reference. We assumed that the accelerated CR nuclei escape from the region filled with thermal photons in a diffusive way, so that their escape rate $R_{\rm esc}$ is proportional to $(E/Z)^{\delta_{p\gamma}}$. For the numerical simulations, we used the open source code [14] which is based on kinetic equations in one dimension. Diffusion of charged particles was taken into account by multiplying the interaction rates by the escape times; neutrons escape freely. In the 2nd zone, we modeled both interactions with the gas and the escape of CRs as a Monte Carlo process, using QGSJET-II-04 [15] to describe nucleus-proton collisions. We assumed that charged CRs diffuse in an extended halo and modeled escape and interactions in the leaky-box picture. The produced neutrons escape again freely. The source is then fully described specifying the interaction depth $\tau_0^{pp} = R_{\rm int}/R_{\rm esc}$ of protons at the reference energy $E_0 = 10\,{\rm EeV}$ and the energy dependence of the escape rate, $R_{\rm esc} = R_0[E/(ZE_0)]^{\delta_{pp}}$. The spectrum of particles exiting the source is then used in the third step as an "effective injection spectrum", from which we calculate the resulting diffuse flux, taking into account the distribution of sources as well as the interaction of protons, electrons and photons with the EBL and the CMB.

For the cosmological evolution of AGNs we use the parameterization obtained in Ref. [16], choosing the ones derived in Ref. [16] for $\log(L_X/{\rm erg}) = 43.5$. As second option, we use the parameterization for BL Lac/FR1 evolution presented in [11]. We use the numerical values given in Table 3 of Ref. [11] for the free parameters of this model. The evolution of the effective source density as function of redshift shown in Fig. 3 of Ref. [17] illustrates that, in contrast to average AGNs, the number density of BL Lac and FR I galaxies peaks at low redshift, $z \lesssim 1$. Thus their evolution is similar to that of galaxy clusters. In fact, most of the 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). Thus these two models serve as templates for an evolution peaking early or late, respectively. We performed steps 1–3 injecting pure p, He, N, Si or Fe primaries in the initial step and obtained then results for a mixed injection spectrum performing a linear combination of the final spectra.

4. Results

Having calculated for a specific set of source parameters the diffuse flux of UHECR nuclei and their secondaries, we combine them with the high-energy part of the Galactic CR fluxes predicted in the escape model [18]. We aim to reproduce the total CR flux, the average maximum depth $X_{\max}$ of observed CR-induced air showers and the width of the $X_{\max}$ distributions [7]. Since the experimental and theoretical systematic uncertainties in both the $X_{\max}$ and the RMS($X_{\max}$) measurements are difficult to quantify, we do not perform a standard χ^2 analysis. Instead, we determine first the nuclear composition of extragalactic CRs which fits best the observed total CR flux, since this is the most reliable quantity. After that we check if the composition is allowed by the EGRB constraint and results in a sufficiently large neutrino flux.

We consider first the case that photo-hadronic interactions are negligible. Requiring both a small contribution to the EGRB and a large contribution to the neutrino signal observed by IceCube restricts the allowed range of slopes α strongly, $\alpha \lesssim 2.1$. We choose $\delta_{Ap} = 0.5$ as the energy-dependence of the escape rate $R_{\rm esc} = R_0[E/(ZE_0)]^{1/2}$, corresponding to Kraichnan turbulence. The interaction and escape rates have been normalized such that $\tau_0^{pp} = 0.035$ for proton primaries at $E_0 = 10\,$EeV. Since the interaction depth decreases with increasing energies due to the faster CR escape, the UHECR flux is dominated by primary nuclei. In order to reproduce the light component in the KASKADE-Grande data, the extragalactic CR flux has to remain light up to 10^{18} eV. Insisting to reproduce the ankle requires a relatively low cutoff energy, $E_{\max} = 3\times 10^{18}$ eV, and a small contribution of intermediate nuclei. This drives the composition towards a two-component model, consisting mainly of protons and iron. In this scenario the spectra of intermediate CNO nuclei are cut off around the ankle energy, and hence their contribution is insignificant, unless the proton flux is strongly reduced. A reduction of the proton flux would in turn reduce the neutrino flux and the model will fall short of explaining the IceCube data. The upper left panel of Fig. 1 shows the resulting diffuse fluxes of CR nuclei and their secondaries. Both the ankle, which corresponds in this scenario to the transition between the proton and iron dominated components in the extragalactic CR flux, and the proton (light) component observed by KASCADE-Grande are reproduced well. The contribution to the diffuse EGRB is low except in the TeV range, while the neutrino flux is somewhat below the level indicated by IceCube observations. The two lower left panels of Fig. 1 show the predicted shower maximum $X_{\max}$ and the corresponding distribution width RMS($X_{\max}$), respectively. Since the composition above the ankle is heavy, the predicted $X_{\max}$ coincides with the one of Fe, in contradiction to observations. Also the predicted width RMS($X_{\max}$) is smaller than the observed one.

In our second scenario, we added photo-hadronic interactions close to the source. In contrast to hadronic interactions, nuclear scattering on IR photons can give rise to relatively large interaction depths, leading to the dominance of secondary nuclei in the ankle region. The parameter space of this case, however without including hadronic interactions on gas, was extensively studied in Ref. [5]. We employ therefore simply their base case, using $T = 850\,$K, $\tau^{p\gamma} = 0.29$ and $\delta_{p\gamma} = 0.77$ for diffusion close to the source. In contrast to Ref. [5], we assume however a compact acceleration

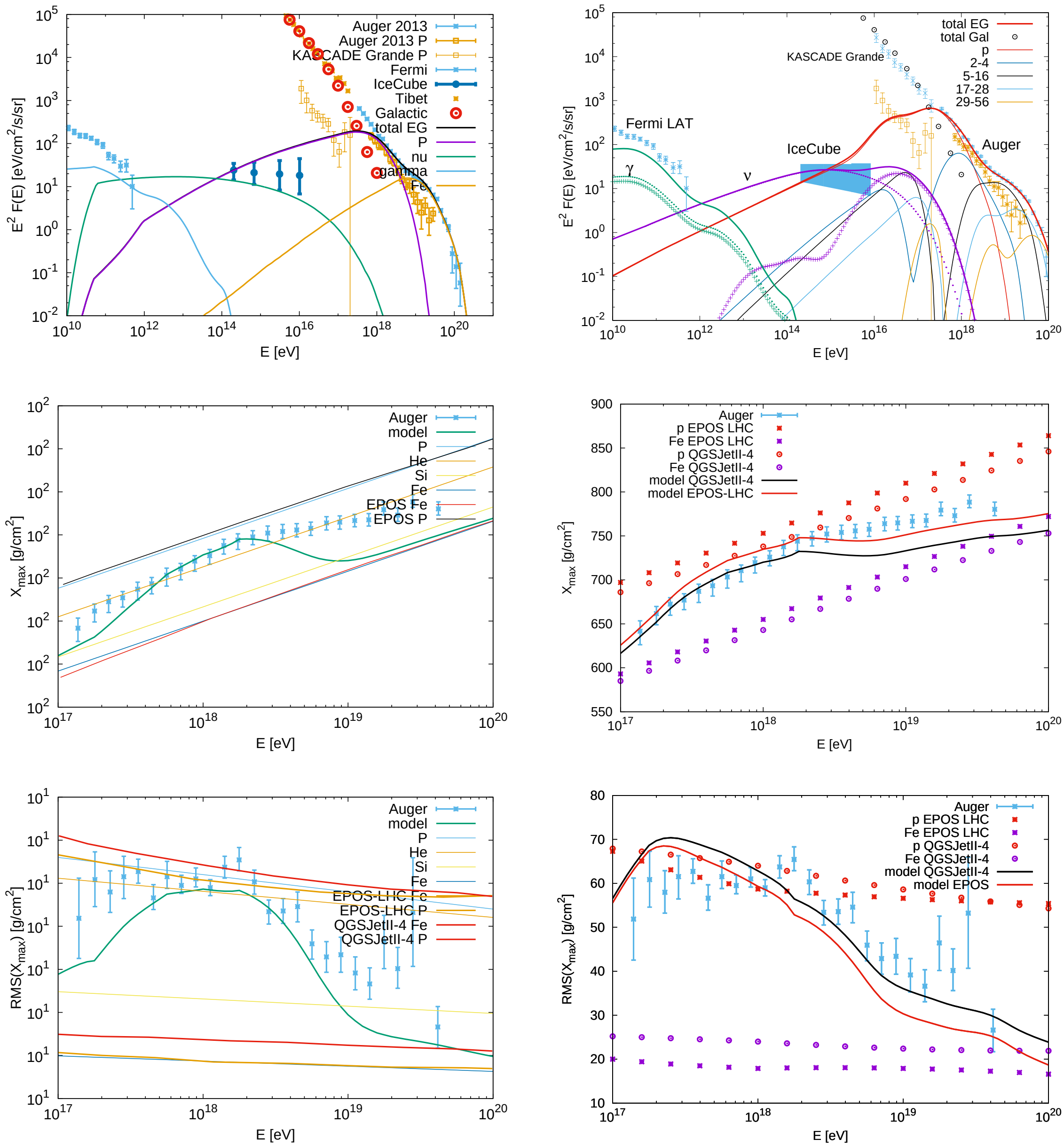

Figure 1: Predictions for the diffuse flux (top) of five elemental groups together with the proton (orange errorbars) and total flux from KASCADE, KASCADE-Grande (light-blue errorbars) [8] and Auger (dark-blue errorbars) [7], the EGRB from Fermi-LAT (light-blue errorbars) [2], and the high-energy neutrino flux from IceCube (light-blue shaded area) [3]. Crosses and dotted lines denote neutrinos and photons from $A\gamma$ and Ap interaction, respectively. The middle and lower panels compare predictions for $X_{\rm max}$ and RMS($X_{\rm max}$) using the EPOS-LHC [19] and QGSJET-II-04 [15] models to data from Auger [7]. Left panels for only hadronic interactions with $\alpha = 1.8$, $E_{\rm max} = 3\times10^{18}$ eV and BL Lac evolution. Right panels for both $A\gamma$ and Ap interactions with $\alpha = 1.5$, $E_{\rm max} = 6\times10^{18}$ eV, $\tau^{p\gamma} = 0.29$ and AGN evolution. The hadronic interaction depth is normalised as $\tau_0^{pp} = 0.035$.

region and use therefore an exponential attenuation. Moreover, we choose as injection slope $\alpha = 1.5$ and $E_{\rm max} = 6\times 10^{18}$ eV. The interaction depth for hadronic interactions is kept as before, i.e. normalised as $\tau_0^{pp} = 0.035$. The resulting diffuse fluxes of CR nuclei and their secondaries are shown in the upper right panel of Fig. 1. The spectra of intermediate nuclei show a narrow dip: The low-energy end of this dip is determined by the threshold energy for photo-dissociation, which is at higher energies partly filled by secondary nuclei generated by heavier primary nuclei. The resulting neutrino flux matches now IceCube data, while the contribution to the diffuse EGRB is of order 30%. While neutrinos from interactions on gas dominate at $\lesssim 10^{16}$ eV, $A\gamma$ interactions become important at higher energies. The two lower right panels of Fig. 1 show the predicted shower maximum $X_{\rm max}$ and the corresponding distribution width RMS($X_{\rm max}$), respectively. Accounting for the systematic uncertainties of the experimental data and of the hadronic interaction models, the two distributions are well reproduced. Note that the peak in RMS($X_{\rm max}$) could be shifted to lower energies, reducing the extragalactic proton flux somewhat. This may indicate that not all neutrons escape freely from their sources.

In which astrophysical environments could the considered UHECR interactions be realized? Interaction depths of order one for proton-gamma interaction arise naturally from scattering on IR photons [20]. These photons may be either emitted by the dust torus of few parsecs extension or, as considered here, from a more compact source region [21]. Similarly, the dust and gas in the accretion disc surrounding the SMBH provides a target for hadronic interactions of UHECRs. In both cases, UHECRs have to be accelerated close to the SMBH, excluding e.g. acceleration sites as radio lobes of AGN jets. The composition of injected CRs has to be strongly enhanced towards intermediate nuclei compared to the solar composition. This may indicate a connection to the tidal ignition of white dwarf stars close the the SMBH. Next we comment on the implication of our results for the EGRB. Since the AGN evolution peaks early, the spectral shape of the photon flux is close to the “universal shape” obtained after many cascade generations [22], which in turn reproduces well the observed shape of the EGRB. Moreover, reproducing the large neutrino flux observed by IceCube requires that in our model unresolved AGN contribute around 30% to the EGRB. For a discussion of the dependence of our results on the used experimental data and the hadronic interaction model see Ref. [1].

5. Conclusions

We studied in Ref. [1] if a single source class can explain both the flux and the composition of extragalactic CRs including the sub-ankle region and the high-energy neutrinos observed by IceCube. Using only hadronic interactions of UHECRs with gas around their sources, we obtained a good fit to the CR energy spectrum, however, only if intermediate nuclei are sub-dominant. Therefore the predicted maximum $X_{\rm max}$ of CR-induced air showers lies higher in the atmosphere than observed. Adding photo-nuclear interactions, with a relatively large interaction depth, we were able to reduce significantly the fraction of heavy nuclei in the primary fluxes and, consequently, to fit satisfactorily both the spectrum and the composition data on UHECRs. At the same time, the high-energy neutrino flux obtained matches IceCube measurements, while the contribution of unresolved UHECR sources to the EGRB is of order 30%. The large interaction depth for photo-nuclear interactions suggests that UHECRs are accelerated close to SMBHs.

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