IMPLICATION OF THE NON-DETECTION OF GZK NEUTRINOS

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ABSTRACT

The IceCube telescope has detected diffuse neutrino emission up to a deposited energy of 2.6 PeV. Neutrinos with higher energies are expected from the Greisen Zszipin Kuzmin (GZK) effect, namely the interaction of ultrahigh-energy cosmic rays (UHECRs) with the cosmic microwave background (CMB) and the extragalactic background light (EBL), but have not yet been detected. Models for GZK neutrinos vary greatly due to different assumptions on the UHECR elemental composition, as well as on the cosmological evolution of their sources and of the EBL. We show that the high ratio of EeV to PeV neutrinos in essentially all GZK models excludes the currently detected PeV neutrinos from being due to the GZK effect, because many additional higher-energy neutrinos should have been detected but were not. The non-detection of GZK neutrinos, despite more than essentially 1800 observing days, already rules out at 95% confidence all of the models that predict rates of 0.6 neutrinos yr\textsuperscript{-1} or more. The non-detection is further used here to quantify the confidence at which classes of GZK models can be ruled out, and to compute the additional IceCube observing time required in order to rule them out with 95% confidence, if no detection is made. Finally, the number of GZK neutrinos expected from various classes of models in the future neutrino telescopes ARA and KM3NeT is estimated.

Key words: cosmic background radiation – cosmic rays – methods: data analysis – neutrinos

1. INTRODUCTION

For the past five years, IceCube the km\textsuperscript{3} neutrino detector in the south pole has been detecting atmospheric neutrinos. New results for the 2013–2014 season recently updated (Aartsen et al. 2015) the total neutrino count to 34 diffuse neutrinos above 60 TeV. The 2010–2014 neutrino spectrum in the interval of 60 TeV \( \sim E < 3 \) PeV was fitted by a single power-law with a slope of 2.58 \( \pm 0.25 \), and a normalization of \( 2.2 \times 10^{−8} \) GeV cm\textsuperscript{−2} s\textsuperscript{−1} sr\textsuperscript{−1} at 100 TeV (Aartsen et al. 2015). Soon after the end of the season, IceCube announced the highest detected neutrino energy so far, with a deposited energy of 2.6 \( \pm 0.3 \) PeV (Schoenen & Raedel 2015).

The effective area of IceCube has a sharp peak around the Glashow Resonance at 6.3 PeV (Glashow 1960). This makes IceCube particularly sensitive above the highest-detected neutrino energy. Moreover, the extremely high energy (EHE) neutrino search method performed by the IceCube collaboration (Abbasi et al. 2010, 2011; Aartsen et al. 2013, 2015) indicates overall increase of effective area with energy. Nevertheless those searches have not yet found any neutrino above 3 PeV.

Theory predicts ultrahigh-energy neutrinos, especially due to the Greisen Zszipin Kuzmin effect (GZK, Greisen 1966; Zatsepin & Kuz'min 1966). The GZK effect is the photo-hadron interaction between the ultrahigh-energy cosmic-ray (UHECR) protons and the extragalactic background light (EBL) photons. This interaction with the cosmic microwave background (CMB, the low frequency end of the EBL) produces a cutoff in the UHECR spectrum at \( \sim 5 \times 10^{19} \) eV that has been observed with high significance (Abbasi et al. 2008; Abraham et al. 2008; Tinyakov 2014).

The main channel for the photo-hadron interaction is the \( \Delta^- \) resonance:

\[
p + \gamma \rightarrow \Delta^- \rightarrow \begin{cases} n + \pi^+ \\ p + \pi^0. \end{cases}
\]  

In the case of protons in heavier nuclei, the efficiency of the interaction is reduced. Hence, the crucial dependence on the UHECR elemental composition. The neutrino emission is due to pion decay

\[
\pi^+ \rightarrow e^+ + \nu_e + \nu_\mu + \nu_\tau.
\]  

The resonance sets a requirement on \( E_p, E_\gamma = 0.2 \) GeV\textsuperscript{2}, so the proton energy required for the interaction decreases with the redshift, at which the pions are produced. The CMB photons interact with high energy protons producing a peak in the neutrino flux at \( E \approx 5% E_p \approx 10^9 \) GeV, while shorter wavelength photons of the EBL interact with (more abundant) lower energy protons to produce neutrinos around \( E \approx 10^6 \) GeV. An additional minor contribution to the \( \bar{\nu}_e \) flux at \( 10^6-10^7 \) GeV comes from the neutron beta decay.

An analysis of signals from EHE (\( E > 10 \) PeV) neutrinos, including those produced outside of the detector, significantly increases the sensitivity of IceCube to these EHE neutrinos (Abbasi et al. 2010, 2011; Aartsen et al. 2013, 2015). Since the ultrahigh-energy neutrinos are a natural outcome of the observed UHECRs, as they escape from the interaction zone, and since IceCube is particularly sensitive at 10\textsuperscript{9} GeV, they should be detectable. The expected flux of the GZK neutrinos, however, strongly depends on the cosmic-ray composition and the cosmological evolution of the sources, which is why different models differ greatly in their neutrino flux prediction.
The origin of the PeV neutrinos detected by IceCube is unclear, but whether they pertain to the power-law diffuse emission at lower energies or not, the PeV neutrinos are likely not due to the GZK interaction (see, e.g., Roulet et al. 2013, and the discussion below in Section 4.1). Hence, GZK neutrinos have undisputedly not yet been detected. Here, we exploit the non-detection also during previous IceCube seasons prior to the complete 86 string configuration (IC86). In Table 1, we show the five IceCube seasons, which add up to 1788 IC86-equivalent observing days. Despite this tremendous effort, no neutrino has been detected above 3 PeV.

While the IceCube non-detection of GZK neutrinos so far has already constrained many theoretical models (Aartsen et al. 2013), future neutrino observatories, such as the Askaryan Radio Array (ARA) and KM3NeT are being built with the main goal of detecting these high-energy neutrinos. In the present work, we aim to quantify the confidence at which GZK model classes can be rejected, to calculate the observing time without detection that would rule out the models with high confidence, and to anticipate the ARA and KM3NeT neutrino detection rates.

2. METHOD

In order to test different GZK models from the literature we extract the model fluxes. The neutrino number flux density per solid angle can be defined as

\[ \Phi = \frac{dN}{dEdtd\Omega}. \]

We multiply each model \( \Phi \) by the neutrino observatory effective area \( A^{eff} \), which is averaged over the field of view \( \Omega \). We integrate over energy and multiply by the exposure time \( \Delta t \) and by \( \Omega \) to obtain the model neutrino counts \( N \):

\[ N = \Omega \Delta t \int \Phi A^{eff} dE. \]

The integration over energy in Equation (4) is carried out from \( E = 3 \) PeV to \( \sim 20 \) EeV (\( 2 \times 10^{19} \) eV).

No \( \tau \) neutrinos are expected from the GZK effect. However, the neutrinos oscillate between flavors to produce an equal flux density for each of the three flavors \( \Phi_\ell \):

\[ \Phi_\ell = \frac{1}{3} (\Phi_e + \Phi_\nu + \Phi_\mu) \]

where \( \Phi_e \) and \( \Phi_\mu \) are the model electron and muon neutrino flux densities, respectively. Because of the Glashow resonance for \( \nu_\ell \) in the detectors, we compute the model fluxes separately for neutrinos and anti-neutrinos. Hence, Equation (5) holds separately for anti-neutrinos as well. Since the expected flux density is the same for all flavors, the effective areas can be summed

\[ A^{eff} = \sum_{i=e,\mu,\tau} A_i^{eff} \]

and the same for anti-neutrinos. Finally, the prediction for the total number of neutrinos \( N_e + N_\nu \) is obtained by adding the results of Equation (4) for neutrinos and anti-neutrinos.

3. GZK NEUTRINO MODELS

GZK models have been constrained based on IceCube data above 100 PeV (Aartsen et al. 2013). We use the non-detection of neutrinos above 3 PeV, and focus on those models that are still marginally viable. The model families we consider here are Engel et al. (2001), Ahlers et al. (2010), Kotera et al. (2010), and Takami et al. (2009). These models span more than three orders of magnitude in neutrino flux, which covers the predictions of many other models (e.g., Protheroe & Johnson 1996; Kalashev et al. 2002; Ave et al. 2005; Aloisio et al. 2015) as well. For the most part, the models differ by their assumptions on the cosmic-ray composition mostly the Fe content, on the spectrum, and on the cosmological (redshift) evolution of the EBL and UHECR sources. The neutrino flux predictions in terms of \( E^2 \Phi \) of the model families are presented in Figure 1. A range of values is plotted for each family. The figure also shows for reference the IceCube best-fitted diffuse spectrum with the slope of 2.58 (Aartsen et al. 2015). It can be seen that up to 3 PeV all of the models lie below the diffuse spectrum power law, but all of them also predict flux that is significantly above the diffuse spectrum for \( E > 100 \) PeV.

The models of Engel et al. (2001) assume only protons and employ the SOPHIA Monte Carlo code to simulate the full particle physics interactions between UHECR and the CMB, including multi-particle products, and not only the \( \Delta \) resonance. They also consider different cosmic-ray source evolutions. In Figure 1 we plot the model with the mildest evolution with redshift (their Figure 4), which yields the least number of neutrinos. The fact that they include only the CMB and not shorter wavelength background results in the low
prediction of neutrinos around $10^{6.7}$ GeV. Their other models yield many more neutrinos above 3 PeV, which have not been detected. We use their distinction between $\nu$ and $\bar{\nu}$ when considering the detection numbers for IceCube.

The models of Ahlers et al. (2010) assume a pure proton cosmic-ray composition. An important parameter of this model is the energy at which the extragalactic cosmic rays dominate over the galactic component. It is the extragalactic component that produces neutrinos, and the transition energy (denoted there by $E_{\text{min}}$) determines the minimum proton energy for the interaction. In Figure 1 we plot the predictions of Ahlers et al. (2010) from their Figure 4 using the full range of $10^{17.5} - 10^{19}$ eV for this parameter.

The models of Kotera et al. (2010) explore different cosmic-ray chemical compositions, different interacting proton energy ranges and spectra, and different cosmic-ray redshift evolution scenarios, including various transition energies between galactic and extragalactic cosmic-ray components. In Figure 1 we plot the plausible flux range of Kotera et al. (2010, Figure 9 therein), with parameters they consider reasonable.

Takami et al. (2009) assume only proton cosmic rays. Here we use only their scenario in which the cosmic-ray ankle at $10^{19}$ eV is the extragalactic spectrum (dubbed there “proton dip”) scenario. In Figure 1 we plot the flux range of Takami et al. (2009) from their Figure 4 (left-hand side) that includes minimal proton energies of $10^{2} - 10^{9}$ GeV. As expected, and indeed seen in Figure 1, the models of Kotera et al. (2010) and Takami et al. (2009) that include the IR and UV backgrounds produce a higher energy flux of neutrinos in the low-energy peak around $10^{9}$ GeV.

4. DISCUSSION

4.1. Origin of PeV Neutrinos

Since the GZK models have a significant peak at a few PeV (Figure 1) that results from the EBL interaction with the UHECRs, one may wonder whether the four neutrinos detected by IceCube between 1 and 2.6 PeV are actually GZK neutrinos, and not part of the diffuse power-law spectrum. Each model has its normalization and shape. The shape predicts the ratio of the number of neutrinos up to a few PeV and that beyond a few PeV, which can be confronted with IceCube results independent of the normalization. In Figure 2 we show the distribution of IceCube neutrinos counts per logarithm of energy, as predicted by each type of GZK model. All curves are normalized to the logarithm of the energy, i.e., $\Phi_{E_{\text{eff}}} \frac{d}{d(\log(E))}$ is plotted. For Kotera et al. (2010) we use the SFR1 model from Figure 1 therein.

Evidently, in all models, the number of neutrinos predicted to be detected up to 3 PeV is only a small fraction of the total predicted detections. The model that predicts the highest fraction of GZK neutrinos at a few PeV is Takami et al. (2009); even this model predicts IceCube would detect only $\sim$37% of the GZK neutrinos up to 3 PeV, and $\sim$63% above 3 PeV. If the four PeV neutrinos were due to the GZK effect, it would imply that about eight more neutrinos should have been observed at higher energies, but none was detected. If only one of the PeV neutrinos is due to the GZK effect, at least (Takami et al. 2009) two more would be expected above 3 PeV. The non-detection implies with $\sim$90% confidence level (CL, see Section 4.2) that not one of the PeV neutrinos is due to the GZK effect.

If we allow for the actual neutrino energy (rather than deposited energy) of the four PeV neutrinos to be up to 10 PeV —well above the $(E < 3$ PeV) energy deposited in IceCube, the probability distribution function shows that more than 3 neutrinos are expected above 10 PeV in all models, and which are not observed. Thus, the GZK interpretation is inconsistent with the models with more than 95% CL, which strongly suggests that the observed PeV neutrinos are not due to the GZK effect.

One can reach the same conclusion since the model GZK neutrino fluxes are lower than the observed flux at PeV energies, as seen in Figure 1. We strengthen this argument by demonstrating that the generic spectrum of GZK neutrinos, in which the flux of CMB-produced neutrinos (EeV) is higher than that produced (at PeV energies) by longer wavelength EBL, along with the increased detection efficiency of IceCube with energy, preclude the PeV neutrinos from being due to the GZK effect, regardless of the absolute neutrino flux at PeV energies of any specific model.

4.2. Constraints on GZK Neutrino Models

We test the detectability of GZK neutrinos by calculating the number of detections expected from IceCube, ARA, and KM3NeT. In order to cover the energy range above $\sim$3 PeV, we use the effective area for detecting contained neutrinos up to 10 PeV interacting inside the detector (Aartsen et al. 2014), and higher energy (EHE) neutrinos, whose interactions start outside the detector (Aartsen et al. 2013). It was noted by Karle (2010) that both effective area curves match at $\sim$30 PeV. The resulting effective area multiplied by $4\pi$ (i.e., grasp = $A_{\text{eff}} \Omega$) is plotted in Figure 3. The $A_{\text{eff}} \Omega$ curve for ARA and KM3NeT are also plotted. The ARA grasp is taken from Hong & Connolly (2012), where it is zero below 10 PeV, and thus does not benefit from the Glashow resonance, which is clearly seen in the IceCube and KM3NeT curves. The effective area of KM3NeT was calculated by Stransky et al. (2015), multiplied by a field of view of $\Omega = 0.7 \times 2\pi$, and extrapolated here beyond 100 PeV according to the 1–100 PeV slope (dashed line in Figure 3). Interestingly, the difference in $A_{\text{eff}} \Omega$ between the ARA, KM3NeT, and IceCube telescopes is less than an order of magnitude, even at the highest energies.
models at 95% CL, given that no GZK neutrinos are detected. Beginning of operations for ARA and KM3NeT, that it would take to reject the note.

| Class | Model | IceCube | ARA-37 | KM3NeT |
|-------|-------|---------|--------|--------|
| Kotera | 0.9–3.8 | 60–97 | 12–0 | 8.7–3 | 5.4–0.8 |
| Ahlers | 2.3–4.2 | 90–98 | 1.5–0 | 3.1–5 | 1.7–2.4 |
| Engel | 1.33 | 74 | 6.6 | 2.2 | 3.2 |
| Takami | 0.5–1 | 40–62 | 25–11 | 14–12 | 11–3 |

Table 2: GZK Neutrino Detection Numbers Predicted by the Models, and the Respective Confidence Levels for their Rejection

Note. Last three columns give the time, after 2014 for IceCube, and from beginning of operations for ARA and KM3NeT, that it would take to reject the models at 95% CL, given that no GZK neutrinos are detected.

The results are listed in Table 2. The first column gives the number of IceCube neutrinos predicted by the various models from the actual observation time of IceCube to date. It can be seen that the models predict $N_{\text{model}} \approx 0.4$ detections, which allows to constrain their viability. In the second column, we show the CL at which the models can be rejected given that no events were detected. The background free CL is approximately $\text{CL}(\%) = 1 - \exp(-N_{\text{model}})$ (Astone & Pizzella 2000). We also compute the number of years that it would take the three telescopes to reject the various models at 95% CL. This assumes no neutrinos are detected, and 340 operational days a year. The third column shows the additional observation time for IceCube while the fourth and fifth columns list the time from the beginning of their operation for ARA and KM3NeT. Due to the high uncertainty of the extrapolated KM3NeT effective area, we have also tested a constant-area extrapolation beyond 100 PeV. This reduces the KM3NeT neutrino counts for the selected GZK models by $\sim 35\%$ on average.

The longer IceCube goes without detecting GZK neutrinos, the higher the statistical significance at which GZK models can be ruled out. Since IceCube has been observing for about 7 years (effectively), any model that predicts $3/5 = 0.6$ neutrinos per year is already ruled out with 95% CL. As can be seen from Table 2, the IceCube time required to seriously challenge most models is only a few years. There are still several years before neutrino detectors will be able to exclude the full range of models, but it is already possible to constrain the parameters inside each class of models. The first to be ruled out are models that include only protons and those that assume strong cosmological evolution, i.e., many high-$z$ UHECR sources (see also Aartsen et al. 2013), which predict the highest neutrino fluxes.

The latest Pierre Auger Observatory results suggest a UHECR chemical composition with intermediate mass nuclei (Aab et al. 2014). As expected, such a composition results in a much weaker GZK neutrino flux (Taylor et al. 2009) than any of the models discussed above. We folded the models of (Taylor et al. 2009) through the detector responses, and find that even the model with the highest neutrino flux there requires 77 IceCube years, 66 for ARA, or 16 for KM3NeT to detect 3 neutrinos.

5. CONCLUSIONS

We use the PeV to EeV ratio of several GZK models to show that the detected PeV neutrinos are unlikely due to the GZK effect, even if the real energy is ten times the deposited energy in IceCube. We use the lack of neutrino detection above 3 PeV to constrain and even reject several model families that have been suggested for neutrino fluxes expected from the GZK effect. As more data are being collected, neutrino telescopes like IceCube and later ARA and KM3NeT will continue to improve the constraints on the GZK models. These observational constraints will be useful to better understand the origin of the UHECRs, the cosmological evolution of the sources, their spectrum, and chemical composition.

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