NEUTRINO CONSTRAINTS TO THE DIFFUSE GAMMA-RAY EMISSION FROM ACCRETION SHOCKS

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ABSTRACT

Accretion of gas during the large-scale structure formation has been thought to give rise to shocks that can accelerate cosmic rays. This process then results in an isotropic extragalactic gamma-ray emission contributing to the extragalactic gamma-ray background (EGRB) observed by Fermi-LAT. Unfortunately, this emission has been difficult to constrain and thus presents an uncertain foreground to any attempts to extract a potential dark matter signal. Recently, IceCube has detected high-energy isotropic neutrino flux that could be of an extragalactic origin. In general, neutrinos can be linked to gamma rays since cosmic-ray interactions produce neutral and charged pions where neutral pions decay into gamma rays, while charged pions decay to give neutrinos. By assuming that isotropic high-energy IceCube neutrinos are entirely produced by cosmic rays accelerated in accretion shocks during the process of structure formation, we obtain the strongest constraint to the gamma-ray emission from large-scale structure formation (strong) shocks and find that they can make at best ∼20% of the EGRB, corresponding to neutrino flux with spectral index $\alpha_v = 2$, or ∼10% for spectral index $\alpha_v = 2.46$. Since typical objects where cosmic rays are accelerated in accretion shocks are galaxy clusters, observed high-energy neutrino fluxes can then be used to determine the gamma-ray emission of a dominant cluster type and constrain acceleration efficiency, and thus probe the process of large-scale structure formation.

Key words: cosmic rays – diffuse radiation – gamma rays: diffuse background – gamma rays: galaxies: clusters – large-scale structure of universe – neutrinos

1. INTRODUCTION

Interactions of cosmic rays accelerated in various astrophysical environments result in production of both charged and neutral pions through $pp$ collisions. Although charged pions decay producing neutrinos $\pi^+ \rightarrow \nu_\mu \pi^- \nu_e e^+$, $\pi^- \rightarrow \bar{\nu}_\mu \pi^+ \nu_e e^-$ (Margolis et al. 1978; Stecker 1979; Michalak et al. 1990), while neutral pions decay into gamma rays $\pi^0 \rightarrow \gamma \gamma$ (Stecker 1970, 1971), both originate from the same cosmic-ray source, and thus observations of resulting neutrinos and gamma rays can be linked to give us a more detailed picture of the source of cosmic rays. Neutrinos are especially important tracers of acceleration processes, since they travel long distances without absorption or magnetic deflection. Recent high-energy neutrino detection reported by the IceCube collaboration includes 37 events with energies ranging from 60 TeV to 3 PeV (Aartsen et al. 2014b). These high-energy events are best fitted by hard spectra $E^{-2}$, and the best-fit single-flavor $(\nu_i + \bar{\nu}_i)$ neutrino flux (where $i = e, \mu, \tau$) in this energy range is $E_i^2 I_i(E_i) = 0.95 \pm 0.3 \times 10^{-9}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ (Aartsen et al. 2014b). These high-energy neutrino events were detected isotropically, which suggests that their origin is from either common isotropically distributed sources or diffuse sources (Aartsen et al. 2014b). Sources of these neutrinos are still unknown, but many have already been proposed, such as jets and cores of active galactic nuclei (Stecker et al. 1991; Anchordoqui et al. 2008), gamma-ray bursts (Waxman & Bahcall 1997; Anchordoqui et al. 2008; Murase & Ioka 2013), starburst galaxies (He et al. 2013; Murase et al. 2013; Chang & Wang 2014; Liu et al. 2014), and galaxy clusters (Zandanel et al. 2015).

Most recent all-sky gamma-ray observations have been performed by Fermi-LAT, which has observed the diffuse gamma-ray sky in the energy range 0.1–820 GeV (Ackermann et al. 2015). Besides the Galactic gamma-ray emission, a diffuse extragalactic gamma-ray background (EGRB) emission was also detected by Fermi (Ackermann et al. 2015). Objects such as unresolved blazars (Stecker & Salamon 1996; Dermer 2007; Narumoto & Totani 2007; Inoue & Totani 2009; Singal et al. 2012), high-latitude contamination by pulsar radiation (Faucher-Giguère & Loeb 2010), dark matter annihilation (Scott et al. 2010; Abdo et al. 2010b), secondary gamma-ray cascades (Inoue & Ioka 2012; Murase et al. 2012), and unresolved star-forming galaxies (Strong et al. 1976; Pavlidou & Fields 2002; Prodanović & Fields 2006; Makiya et al. 2011) were considered, and although some combinations of these components could explain the observed EGRB, large uncertainties are still present, and thus the presence of additional component(s) has not yet been ruled out.

Here we investigate the case of cosmic rays expected to be accelerated in accretion shocks during the large-scale structure formation—structure formation cosmic rays (SFCRRs; Loeb & Waxman 2000; Miniati et al. 2000; Furlanetto & Loeb 2004). Though still hypothetical, this cosmic-ray population is expected to be present at accretion and merger shocks, especially in connection with accretion shocks around clusters. This should result in gamma-ray emission from hadronic (Kushnir & Waxman 2009; Pinzke & Pfrommer 2010) processes that dominate and subdominant primary and secondary inverse Compton leptonic emission (Loeb & Waxman 2000; Furlanetto & Loeb 2004; Pinzke & Pfrommer 2010), as well as radio emission dominated by its leptonic component (Ensslin et al. 1998; Kushnir et al. 2009). In this work we focus on the hadronic emission component. The collective emission from all unresolved clusters would also contribute to the extragalactic emission background, but as the evolution of the sources is unknown and no sources have been detected, the
limits are weak (Miniati 2003; Prodanović & Fields 2004, 2005; Kuo et al. 2005). Signatures of SFCRs were expected to be detected by the Fermi-LAT observations of galaxy clusters; however, only flux upper limits have been placed so far (Ackermann et al. 2010, 2014). In order to constrain their contribution to the EGRB, in Dobardžić & Prodanović (2014) we have constructed a model of gamma-ray emission from large-scale accretion shocks around clusters, implementing for the first time a source evolution and normalizing using Fermi-LAT cluster observation limits. Due to large uncertainty in normalization of our models, the resulting limits were very weak and dependent on the choice of a typical source, i.e., a typical cluster size that dominates emission. On the other hand, if a strong limit to SFCR contribution to the EGRB could be placed, our model could be very constraining for the typical cluster-class that dominates the SFCR emission and also serve to probe different models of accretion shock evolution.

A significant flux of isotropic high-energy neutrinos has recently been detected by IceCube. The observed IceCube neutrinos cover an energy range 60 TeV–3 PeV (Aartsen et al. 2014b), and detected flux is best fitted with the high spectrum $E_{\nu}^{-2}$. Since cosmic-ray interactions also result in neutrino production through charged pions, any extragalactic cosmic-ray population would produce the extragalactic neutrino background, as well as the diffuse gamma-ray background component. In the case of detected neutrino flux with spectral index $\alpha_\nu = 2$, corresponding to cosmic rays accelerated in strong shocks, Chang & Wang (2014) calculated that these sub-GeV and PeV neutrinos should be accompanied by gamma-ray flux of $E_{\gamma}^2 I_\gamma(E_{\gamma}) = 2 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. Such a hard spectrum is consistent with emission expected from galactic cosmic rays in starburst galaxies. This possibility was explored in Tamborra et al. (2014), and though it can provide an explanation to the observed neutrino flux consistent with the observed EGRB, there remain issues regarding acceleration of protons to such high energies and their confinement. On the other hand, accretion shocks that arise during the growth of structures cover a distribution of strengths (Miniati et al. 2000), and an SFCR population accelerated in them would also be consistent with such a hard spectral index as follows from neutrino observations. Moreover, due to their large scale, accretion shocks would be more likely sites to accelerate and confine such energetic cosmic rays (Norman et al. 1995).

The possibility of clusters as a source of observed high-energy neutrino flux has been also explored in different several works. For example, Murase et al. (2013) have considered the contribution of clusters, active galactic nuclei, and star-forming galaxies in galaxy clusters as sources contributing to the neutrino background observed by IceCube. Without including source evolution, they found that contributing galaxy clusters should have spectra with hard spectral index $\alpha \lesssim 2.1–2.2$ contributing $\geq 30\%–40\%$ to the EGRB. Zandanel et al. (2015) have modeled gamma-ray and neutrino backgrounds for a range of radio-loud galaxy cluster types. In their work Zandanel et al. (2015) have used an evolving, numerically modeled cluster mass function from Tinker et al. (2008), with cluster gamma-ray luminosity determined from (a) a phenomenological mass–gamma-ray luminosity relation that was calibrated by radio observations of clusters with gamma-ray luminosity scaled of radio luminosity; and (b) a more sophisticated intracluster medium and cosmic-ray distributions. Zandanel et al. (2015) have found that for the case of strong shock with $\alpha = 2$, if all clusters are radio-loud, they can account for at least 20% of the observed neutrino background, or 10% if only 30% are radio-loud, corresponding to only a few percent of the gamma-ray background. For softer spectra these numbers are even lower. In a more sophisticated model with percentage of radio-loud clusters ranging from 10% to 40% where gamma-ray fluxes of radio-quiet ones were taken to be an order of magnitude lower than the fluxes of radio-loud ones, Zandanel et al. (2015) have found that SFCRs contribute <1% to neutrino and gamma-ray backgrounds.

Since an SFCR population is yet to be detected and large uncertainties remain, in this work we will place constraints on the SFCR contribution to the gamma-ray background in a more model-independent way. We use high-energy neutrinos recently detected by IceCube as an upper limit to SFCR-made neutrino background flux, from which we derive the corresponding gamma-ray background emission using the approach analyzed in Dobardžić & Prodanović (2014). In Dobardžić & Prodanović (2014) we have constructed a model of gamma-ray background expected from cosmic rays accelerated in accretion shocks with evolution of the sources based on the Pavlidou & Fields (2006) model of accretion shocks, where evolution of the power processed by a distribution of accretion shocks was analyzed. Furthermore, a gamma-ray background limit obtained this way can then be used to learn about the accretion shock emission and types of objects that it originates from.

2. FORMALISM AND RESULTS

Hadronic interactions of cosmic-ray protons with ambient gas (pp interactions) produce neutral and charged pions, which decay and produce gamma-rays and neutrinos $\pi^0 \rightarrow \gamma \gamma$, $\pi^- \rightarrow \nu_\mu \bar{\nu}_\mu \pi^0$, $\pi^- \rightarrow \nu_e \bar{\nu}_e \pi^0$. In these reactions each gamma ray takes half of the pion energy, while each of the three neutrinos from charged pion decay carries about one-quarter of the pion’s energy (hence $E_\nu = 2E_{\pi_0}$). The relative flux of neutrinos and gamma rays depends on the relative number of produced charged and neutral pions, which is in the case of the $pp$ interactions $N_{\pi^0}/N_{\pi^+} \approx 2$ (Kamae et al. 2006; Kelner et al. 2006). After oscillations, the relative flavor ratio of neutrinos, as well as anti-neutrinos, is $\nu_\mu^0: \nu_\mu: \nu_\tau = 1:1:1$ (Kamae et al. 2006; Kelner et al. 2006). At a given energy $E$ this result lies in a simple connection (Ahlers & Murase 2014; Chang & Wang 2014; Tamborra et al. 2014) between differential fluxes of all neutrino flavors and gamma rays $E^2 I_\gamma(E) \simeq \frac{3}{2} \frac{E^{2\alpha}}{\Gamma^{2\alpha}}$ (Ahlers & Murase 2014), which in the case of strong shocks $\alpha = 2$ becomes

$$E^2 I_\gamma(E) \simeq 2E^2 I_\nu(E) = \frac{2}{3} E^2 I_\nu(E),$$

where $I_\nu$, $I_\mu$, and $I_\tau$ are differential fluxes $I(E) \propto E^{-\alpha}$ of single-flavor neutrinos, all-flavor neutrinos, and gamma rays, respectively. So, if we include all neutrino flavors and neglect any absorption of gamma rays and neutrinos during their propagation, we expect the differential gamma-ray flux to be around twice as high as that of single-flavor neutrinos for the case of strong shocks with spectral index $\alpha = 2$, and for the case of weaker shocks even slightly higher.

Using the best-fit single-flavor high-energy neutrino flux and spectrum as measured by IceCube (Aartsen et al. 2014b), we
can use relation (1), which links gamma-ray flux and all-flavor neutrino flux, to find the corresponding gamma-ray flux. In the case of cosmic rays accelerated in strong shocks with spectral index $\alpha = 2$, we get that the gamma-ray flux at some energy that corresponds to combined flux of all neutrino flavors at that same energy is $E^2 I(E) = 1.9 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. Assuming that the cosmic rays in question are in fact SFCRs, i.e., that all of the high-energy IceCube neutrinos came from interactions of cosmological cosmic rays, we use the corresponding gamma-ray flux at TeV energies to determine the gamma-ray background emission resulting from SFCRs. This directly fixes the normalization of our model of SFCR gamma-ray emission from accretion shocks derived in Dobardžić & Prodanović (2014). Models of SFCR gamma-ray emission from accretion shocks presented in Dobardžić & Prodanović (2014) depend on the choice of the normalizing cluster. This should be a typical cluster with respect to its SFCR gamma-ray emission, i.e., a cluster class that processes most of the accretion shock power (when averaged over the cosmic history) and is thus composed of dominant sources of SFCRs. Therefore, when neutrino emission is used to fix the normalization, the resulting gamma-ray flux also fixes the SFCR gamma-ray flux from a typical cluster of galaxies.

If large-scale structure-formation shocks that process most of the gas are weak shocks, rather than strong as we have assumed so far, then the spectral index of the SFCRs will be larger than that of observed high-energy neutrinos $\alpha > 2$. Even then we can use detected neutrino flux as the uppermost limit that must not be overshot, and constrain maximal allowed SFCR-made neutrino and gamma-ray flux for any given weak shock spectrum. In that case, however, cosmic rays accelerated in such shocks would not be able to account for observed neutrino flux entirely due to the difference in spectral indices, and additional sources would be needed. Nevertheless, we find that in the case of weak shocks, even though all of the SFCR neutrino fluxes were adopted to be consistent with the IceCube data, for spectral indices $\alpha \gtrsim 2.3$ all of the accompanying gamma-ray background fluxes violate the Fermi data. Thus, for the case of SFCRs accelerated in weak shocks with $\alpha \gtrsim 2.3$, Fermi gamma-ray observations are more constraining than the detected IceCube neutrino flux. In the case of sources with spectral index $\alpha \approx 2.3$ both gamma-ray and neutrino background fluxes can be used in concert to place the strongest constraint on such SFCR contribution. For any other spectral index either gamma-ray or neutrino background will be more constraining. However, if more than one source besides standard known sources is considered, then again both gamma-ray and neutrino backgrounds can be used together to limit their joint contribution on different ends—gamma rays to constrain sources with steep spectral indices, and neutrinos to constrain sources with hard spectral indices.

Very recently an update to the diffuse neutrino flux detected by IceCube collaboration was reported for the energy range 5–250 TeV. 4 PeV (Aartsen et al. 2015), with the best-fit single-flavor neutrino spectral index of $\alpha_\nu = 2.46$ and flux $I_{\nu}(E_\nu) = 2.6^{+0.4}_{-0.3} \times 10^{-19} (E_\nu/10^3 \text{GeV})^{-2.46 \pm 0.12}$ GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$. We complete our analysis for both reported neutrino fluxes in parallel.

Assuming that some or the entire detected high-energy neutrino flux originates from cosmic rays accelerated in structure-formation accretion shocks, we find the corresponding gamma-ray flux and determine its contribution to the EGRB for different assumed cosmic-ray spectra and plot these results in Figure 1. Panels on the left show SFCR curves after normalization to the $\alpha_\nu = 2$ neutrino spectrum from Aartsen et al. (2014b), and panels on the right use normalization to the latest $\alpha_\nu = 2.46$ neutrino spectrum from Aartsen et al. (2015). Top panels represent SFCR curves (dot-dashed line) derived for the case of strong shocks, i.e., for cosmic-ray spectral index $\alpha = 2.0$, which matches that of neutrinos from Aartsen et al. (2014b). Normalization to the $\alpha_\nu = 2.0$ neutrino spectrum from Aartsen et al. (2014b) yields an upper limit to the SFCR contribution of $\approx 46\%$ of the EGRB observed by Fermi, which is around the contribution of some of the major components, such as unresolved star-forming galaxies contributing $\lesssim 50\%$ (Fields et al. 2010; dashed line), or blazars contributing $\approx 16\%$ (Abdo et al. 2010a; dotted line). If, for this same SFCR model, the attenuation of highest-energy gamma-ray photons by extragalactic background light (EBL; Gilmore et al. 2012) is included (thin red solid line), we find that this reduces the SFCR contribution to $\lesssim 18\%$ of the observed EGRB. The sum of all components is shown with a thick blue solid line. Using the latest neutrino spectrum with $\alpha_\nu = 2.46$ (Aartsen et al. 2015) as the upper limit constraint, we find that for SFCRs accelerated in strong shocks, i.e., with spectral index $\alpha = 2.0$, their contribution to the EGRB can be $\approx 29\%$, or $\lesssim 12\%$ after the EBL attenuation was included. However, SFCRs with such a spectrum cannot explain the entire detected high-energy neutrino flux, and additional sources would be needed. If, on the other hand, SFCRs are assumed to have softer spectra with indices $\alpha > 2.0$, their resulting fluxes would quickly violate the Fermi EGRB observations. The middle panels of Figure 1 show SFCR gamma-ray fluxes for source spectra $\alpha = 2.3$, while the bottom panels correspond to $\alpha = 2.6$. Here we point out that using the latest neutrino fluxes with spectrum $\alpha_\nu = 2.46$ (Aartsen et al. 2015) is more constraining in the sense that it does not allow for this entire neutrino flux to be of the SFCR origin because the accompanying gamma-ray flux quickly violates the observed EGRB, as we can see in the bottom two panels on the right side of Figure 1. Such a soft neutrino spectrum, together with gamma-ray observations from Fermi, allows for only a small fraction of its flux to be made by SFCRs with high spectral index $\alpha \lesssim 2.2$.

Zandanel et al. (2015) analyzed the contribution of galaxy clusters to the gamma-ray and neutrino background in a more model-dependent way and found that at best 10% of the neutrino background can originate from SFCR interactions if all clusters are radio-loud with cosmic-ray spectrum $\alpha = 2$, corresponding to gamma-ray flux at the level of only a few percent of the observed EGRB. Of course, given that our model is based on using detected neutrino flux as an upper limit to SFCR-made neutrinos, our results are consistent with Zandanel et al. (2015). It should also be noted that the difference between the results of Zandanel et al. (2015) and the results of the work presented in this paper is also in part due to the difference between a typical cluster with respect to its SFCR contribution, which is what our model gives, and the analysis based on the radio-loud clusters from Zandanel et al. (2015), which do not necessarily have to be dominant sites for cosmic-ray acceleration at structure-formation shocks. Compared to Murase et al. (2013), who did not include source evolution and have found that clusters can contribute $\gtrsim 30\%–40\%$ to the
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Figure 1. SFCR contribution to the EGRB (Ackermann et al. 2015) calculated using models derived in Dobardžić & Prodanović (2014), with spectral indices $\alpha = 2.0$ (top panels), $\alpha = 2.3$ (middle panels), and $\alpha = 2.6$ (bottom panels). Our SFCR curves are all normalized to gamma-ray flux that corresponds to maximal neutrino flux allowed by the IceCube neutrino measurement for a given spectral index. Plots in the left column show normalization to the $\alpha = 2$ IceCube spectrum (Aartsen et al. 2014b), and plots in the right column show SFCR curves normalized to the latest $\alpha = 2.46$ IceCube neutrino spectrum (Aartsen et al. 2015). The dot–dashed line represents SFCR gamma-ray emission without the EBL attenuation effects, while the thin red solid line includes the EBL attenuation (Gilmore et al. 2012). We also plot the blazar contribution (Abdo et al. 2010a; dotted line) and normal star-forming galaxies based on the luminosity evolution model given in Fields et al. (2010; dashed line). The summarized contribution of these three components—SFCR with EBL attenuation, blazars, and normal galaxies—is plotted with the thick blue solid line. On our plot EBL attenuation is not included in blazar and normal galaxy spectra.

The SFCR contribution to the EGRB can further constrain the underlying assumption that this cluster is representative of strong shocks. Since this is typical of most high-redshift clusters, we can use the well-known SFR–redshift correlation to estimate the SFR at that redshift. For example, starting from detected IceCube neutrino flux (Aartsen et al. 2014b), assuming that it originates from interactions of SFCRs with spectral index representative of strong shocks $\alpha = 2$, we directly find the accompanying gamma-ray background emission. We can now estimate the expected flux of a typical cluster type that dominates this background emission. For example, let us assume that this typical cluster type is similar in size and mass to galaxy cluster NGC 1550, with total mass $M = 0.68 \times 10^{14} M_{\odot}$, virial radius $r = 0.77$ Mpc, and redshift $z = 0.0123$ (Chen et al. 2007), which should be close to the cosmic average. Gamma-ray emission of this cluster is not expected to be dark matter dominated. Starting with neutrino background emission, we can then estimate the gamma-ray flux of this cluster to be

$$F_\gamma = (0.2–3.6) \times 10^{-12} \text{photons cm}^{-2} \text{s}^{-1} \text{in the Fermi energy range 0.1–820 GeV.}$$

For comparison, Ackermann et al. (2014) calculated flux upper limits for 50 galaxy clusters based on joint likelihood analysis of 4 yr of Fermi-LAT data and using the assumption of the universal cosmic-ray model proposed by Pinzke & Pfrommer (2010). NGC 1550 is one of the smallest clusters in their sample, and for this cluster they estimate the flux above 500 MeV to be $F_\gamma = 4.9 \times 10^{-11}$ photons cm$^{-2}$ s$^{-1}$.

In the same energy range we derive an NGC 1550 flux of $F_\gamma = (0.09–1.4) \times 10^{-12}$ photons cm$^{-2}$ s$^{-1}$. On the other hand, Griffin et al. (2014) give latest estimates for cluster flux upper limits in the energy range 0.8–100 GeV of $2.3 \times 10^{-11}$ photons cm$^{-2}$ s$^{-1}$, which were based on stacking analysis of Fermi-LAT photon count maps for the 78 nearby rich clusters from the Two Micron All Sky Survey catalog. In this energy range we find the flux of our example cluster to be $F_\gamma = (0.6–9.9) \times 10^{-13}$ photons cm$^{-2}$ s$^{-1}$, which is at best over an order of magnitude below the estimate of Griffin et al. (2014).

Similarly, we can estimate gamma-ray fluxes of other clusters, for example, the Coma cluster, but again with the underlying assumption that this cluster is representative of typical-type clusters that dominated the gamma-ray background. Thus, in the case of Coma, using $z_{\text{Coma}} = 0.0232$, $M_{\text{Coma}} = 9.95 \times 10^{14} M_{\odot}$, and $r_{\text{Coma}} = 1.86$ Mpc (Chen et al. 2007) as values for redshift, total mass, and virial radius, respectively, we estimate the gamma-ray flux of this rich cluster to be around $F_\gamma = (0.09–1.5) \times 10^{-11}$ photons cm$^{-2}$ s$^{-1}$ in the 0.8–100 GeV energy range, which comes close (but not
quite) to the Griffin et al. (2014) upper limits. Though Coma is a rich cluster with mass about an order of magnitude larger than the average cluster mass and thus may not be a typical representative in terms of a dominant SFCR gamma-ray emission source, it is an example of a cluster where gamma-ray emission would be expected to be dominated by SFCR interactions rather than by dark matter, which makes it suitable when we want to compare its modeled emission with detection limits.

We can even further extend this analysis and constrain cosmic-ray acceleration efficiency. Using accretion shock models like Pavlidou & Fields (2006), we can estimate particle acceleration energy efficiency by comparing the kinetic power of accreted gas that follows from the model, with the power that goes into SFCR particles that is constrained by the detected neutrino and gamma-ray fluxes. For example, if we assume that SFCRs are dominantly accelerated in shocks that produce gamma-ray and neutrino spectra with index \( \alpha = 2.2 \) (corresponding to Mach number ~5; Bell 1978; Schlickeiser 2010), then from using the latest observed neutrino flux (with index \( \alpha_{\nu} = 2.46 \)) as the upper limit, it follows that the energy efficiency of accelerating cosmic rays at these structures in the energy range 1 GeV–1 TeV is \( \sim 40\% \), that is, we find that \( \sim 40\% \) of energy that goes into shocks gets converted into accelerated particles. This is a slightly higher efficiency compared to results from numerical models of nonlinear diffusive shock acceleration of, for example, Kang & Ryu (2013), who found that shocks of similar strength result in \( \geq 10\% \) acceleration energy efficiency. If, on the other hand, we consider spectral index \( \alpha = 2 \) to represent the SFCR spectra (corresponding to Mach number ~10) and use that to find the upper limit of SFCR flux as maximally allowed by the observed EGBR and neutrino flux with index \( \alpha_{\nu} = 2 \), we find that in this case cosmic-ray acceleration energy efficiency is \( < 1\% \). This efficiency is about an order of magnitude lower compared to results from the numerical model of Kang & Ryu (2013), who found that shocks of similar strength result in an efficiency of \( \sim 20\% \). Such extreme changes in efficiency that follow from our analysis are, of course, due to the fact that our constraint comes from the high-energy end that is fixed by observed neutrino fluxes, while most energy in cosmic rays comes from the low-energy end due to the power-law spectra.

3. DISCUSSION AND CONCLUSION

Gamma-ray observations have revealed the existence of an EGRB, which is still not completely explained. Formation of large-scale structures results in accretion shocks that can accelerate cosmic rays, which should in turn leave an imprint on the EGRB. Interactions of these cosmic rays also produce charged pions, which then decay and produce neutrinos. This common source directly links neutrino and gamma-ray astrophysics. Here we use the analytical models of gamma-ray emission of cosmic rays accelerated in accretion shocks around virialized structures over a range of redshifts derived in Dobardžić & Prodanović (2014), and we normalize them to match the gamma-ray flux that would correspond to the observed high-energy IceCube neutrino flux (Aartsen et al. 2014b, 2015) if they are assumed to come from SFCR interactions. This places an uppermost limit on the SFCR gamma-ray contribution to the EGRB observed by Fermi: \( \lesssim 18\% \) for neutrino flux reported by Aartsen et al. (2014b), and \( \lesssim 12\% \) for neutrino flux reported by Aartsen et al. (2015), assuming that SFCRs were accelerated in strong shocks (\( \alpha = 2.0 \)). This is the strongest model-independent observational limit to this still unobserved cosmological cosmic-ray population. Moreover, a solid limit to SFCR gamma-ray emission background in turn constrains the emission of typical objects that are the dominant source of SFCRs. The gamma-ray flux of the typical cluster estimated from our obtained limit was found to be around an order of magnitude lower than the expected cluster emission from Griffin et al. (2014). We note, however, that this estimate is sensitive to the assumed spectral index of SFCRs, which, if adopted to match the high-energy IceCube neutrino flux of Aartsen et al. (2014b), should be characteristic of strong shocks i.e., \( \alpha = 2 \). For softer spectra up to \( \alpha < 2.3 \), gamma-ray fluxes expected from SFCR interactions would be even higher; however, in that case the high-energy neutrino flux would not be completely explained by an SFCR population but would need at least one more source. Furthermore, if a typical cluster has mass and radius like the Coma cluster, radio observations of the Coma cluster constrain its cosmic-ray spectral index to be closer to \( \alpha = 2.6 \) (Brunetti et al. 2012), and the limits that can be derived from IceCube neutrino flux for such weak shocks become less constraining since the derived gamma-ray flux overshoots the EGRB data measured by Fermi-LAT. One of the major problems is actually identifying which type of clusters dominate accretion shock processing and are dominant sources of SFCR radiation, because no clear detection of clusters has been made yet. However, using now new IceCube point-source limits from 4 yr of data (Aartsen et al. 2014a), together with known Fermi-LAT (Ackermann et al. 2014) cluster limits, and observations of radio halos might prove to be sufficient to find strong predictions for SFCR emission of some clusters, and that is the topic of our upcoming analysis.

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