THE DIFFUSE GAMMA-RAY FLUX ASSOCIATED WITH SUB-PEV/PEV NEUTRINOS FROM STARBURST GALAXIES

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ABSTRACT

One attractive scenario for the excess of sub-PeV/PeV neutrinos recently reported by IceCube is that they are produced by cosmic rays in starburst galaxies colliding with the dense interstellar medium. These proton–proton (pp) collisions also produce high-energy gamma rays, which finally contribute to the diffuse high-energy gamma-ray background. We calculate the diffuse gamma-ray flux with a semi-analytic approach and consider that the very high energy gamma rays will be absorbed in the galaxies and converted into electron–positron pairs, which then lose almost all of their energy through synchrotron radiation in the strong magnetic fields in the starburst region. Since the synchrotron emission goes into energies below GeV, this synchrotron loss reduces the diffuse high-energy gamma-ray flux by a factor of about two, thus leaving more room for other sources to contribute to the gamma-ray background. For an $E^{-2}$ neutrino spectrum, we find that the diffuse gamma-ray flux contributes about 20% of the observed diffuse gamma-ray background in the 100 GeV range. However, for a steeper neutrino spectrum, this synchrotron loss effect is less important, since the energy fraction in absorbed gamma rays becomes lower.

Key words: cosmic rays – neutrinos

Online-only material: color figures

1. INTRODUCTION

The IceCube Collaboration reported 37 events ranging from 60 TeV to 3 PeV within three years of operation, corresponding to a 5.3σ excess over the background atmospheric neutrinos and muons (Aartsen et al. 2014). The observed events can be fitted by a hard spectra $(E^{-1})$ with $\Gamma = 2$ and a cutoff above 2 PeV, implied by the non-detection of higher energy events, or alternatively by a slightly softer but unbroken power-law spectrum with index $\Gamma \simeq 2.2$–2.3 (Aartsen et al. 2014; Anchordoqui et al. 2014a). The best-fit single-flavor astrophysical flux $(\nu_{\tau})$ is $E^2\Phi_{\nu} = 0.95 \pm 0.3 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$, assuming an $E^{-2}$ spectrum. The sky distribution of the events is consistent with isotropy (Aartsen et al. 2014), implying an extragalactic origin or possibly a Galactic halo origin (Taylor et al. 2014), though a fraction of them could come from Galactic sources (Fox et al. 2013; Ahlers & Murase 2014; Neronov et al. 2014; Razzaque 2013; Lunardini et al. 2013).

However, the source of these IceCube neutrinos is unknown. Jets and/or cores of active galactic nuclei (AGNs), and gamma-ray bursts have been suggested to be possible sources (Stecker et al. 1991; Anchordoqui et al. 2008; Kalashev et al. 2013; Stecker 2013; Waxman & Bahcall 1997; He et al. 2012; Murase & Ioka 2013; Liu & Wang 2013), where the hadronic (e.g., $p\gamma$) reaction is typically the main neutrino generation process (Winter 2013). On the other hand, starburst galaxies and galaxy clusters may also produce PeV neutrinos, mainly via the hadronuclear (e.g., pp) reaction (Liu et al. 2014; He et al. 2013; Murase et al. 2013; Tamborra et al. 2014; Anchordoqui et al. 2014b). In this paper, we investigate the pp process in starburst galaxies, following earlier works in which remnants of supernovae, in general, (Loeb & Waxman 2006) or a special class of supernova–hypernovae (Liu et al. 2014) in starburst galaxies accelerate cosmic rays (CRs), which in turn produce neutrinos by interacting with the dense surrounding medium during propagation in their host galaxies. Here we use starburst galaxies to refer to those galaxies that have much higher specific star formation rates than the “main sequence” of star-forming galaxies. To produce neutrinos with energy, $E_{\nu}$, we require a source located at redshift, $z$, to accelerate protons to energies of $50(1+z)/2 E_{\nu}$ (Kelner et al. 2006). It is suggested that semi-relativistic hypernova remnants in starburst galaxies, by virtue of their fast ejecta, are able to accelerate protons to EeV energies (Wang et al. 2007; Liu & Wang 2012). Alternatively, assuming sufficient amplification of the magnetic fields in the starburst region, normal supernova remnants might also be able to accelerate protons to $10^{17}$ eV and produce PeV neutrinos (Murase et al. 2013).

In pp collisions, charged and neutral pions are both generated. Charged pions decay to neutrinos ($\pi^+ \rightarrow \nu_{\pi}, \bar{\nu}_{\pi}, e^+$, $\pi^- \rightarrow \bar{\nu}_{\pi}, \nu_{\pi}, e^-$), while neutral pions decay to gamma-rays ($\pi^0 \rightarrow \gamma\gamma$). Thus, PeV neutrinos are accompanied by high-energy gamma rays. For an $E^{-2}$ neutrino spectrum with a single-flavor flux of $E^2\Phi_{\nu} \simeq 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ produced by $\pi^\pm$ decay, the flux of gamma rays from $\pi^0$ decay is $2 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$. While low-energy gamma rays may escape freely from the galaxy, very high energy (VHE) gamma rays are absorbed by the soft photons in starbursts, as starburst galaxies are optically thick to VHE gamma rays (Inoue 2011; Lacki & Thompson 2013). The absorbed gamma rays will convert to electron–positron ($e^\pm$) pairs, which then initiate electromagnetic cascades on soft background photons, reprocessing the energy of VHE photons to low-energy emission.
and contributing to the diffuse gamma-ray background. Detailed calculations show that the diffuse gamma-ray emission associated with sub-PeV/PeV neutrinos contribute a fraction \(\gtrsim 30\%\) to the gamma-ray background when the source density follows the star-formation history and contributes a fraction \(\gtrsim 40\%\) for the non-evolving source density case (Murase et al. 2013). Analytical calculations in Liu et al. (2014) show that this fraction is about \(\gtrsim 40\%\). Since other sources, such as AGNs (Stecker & Salamon 1996) or truly diffuse gamma-ray emission from the propagation of ultra-high energy cosmic rays in cosmic microwave and infrared background radiation (Berezinskii & Smirnov 1975; Kalashev et al. 2009; Berezinsky et al. 2011; Wang et al. 2011), also contribute significantly to the diffuse gamma-ray background, a tension between a too high diffuse gamma-ray flux expected from sources and the observed background flux exists. However, the above calculations do not consider the synchrotron cooling of electron–positron \((e^\pm)\) pairs formed during the cascades. As we argue in this paper, this synchrotron loss effect could significantly reduce the flux of cascade gamma-ray emission.

In this paper, we calculate the accumulated diffuse gamma-ray flux by considering the synchrotron loss of \(e^\pm\) produced by the absorbed gamma rays in the magnetic fields of the starburst region. For reasonable assumptions of the strength of the magnetic fields in the starburst region, we find that the synchrotron loss dominates over the IC scattering loss. Since the synchrotron emission goes into energies below GeV, the intensity of the cascade gamma-ray component is significantly reduced in the \(\sim 100\) GeV energy range. In Section 2, we first obtain the normalization of the gamma-ray flux of an individual starburst galaxy with the observed neutrino flux. In Section 3, we calculate the gamma-ray flux after considering the synchrotron loss. Then, in Section 4, we calculate the accumulated gamma-ray flux from the population of starburst galaxies. Finally, we give our conclusions and discussions in Section 5.

2. NORMALIZATION

To calculate the accumulated diffuse gamma-ray flux, we need to know the gamma-ray flux of individual starburst galaxies and then integrate over contributions by all the starburst galaxies in the universe. The gamma-ray flux of an individual galaxy can then be calibrated with the observed neutrino flux, assuming that all the observed neutrinos by IceCube are produced by starburst galaxies.

As the neutrino flux is linearly proportional to the CR proton flux and the efficiency in transferring the proton energy to secondary pions, the single-flavor \((v + \bar{v})\) neutrino luminosity per unit energy from a starburst galaxy is expressed by

\[
L_{\nu_i} = \frac{dN_{\nu_i}}{dt dE_{\nu_i}} \propto f_{\pi} L_p E_{\nu_i}^{-p},
\]

where \(i = (\nu, \mu, \tau)\), \(L_p\) is the CR proton flux at some fixed energy, and \(f_{\pi}\) is the pion production efficiency. \(p\) is the index of the proton spectrum \((dn/dE_p \propto E_p^{-p})\) and we assume \(p = 2\), as expected from Fermi acceleration, unless otherwise specified. Starbursts have very high star-formation rates (SFR) of massive stars. Massive stars produce supernovae or hypernovae, which accelerate CRs in the remnant blast waves, thus we expect that \(L_p \propto SFR\). On the other hand, the radiation of a large population of hot young stars are absorbed by dense dust and reradiated in the infrared band, so \(L_{\text{TIR}} \propto SFR\), where \(L_{\text{TIR}}\) is the total infrared luminosity of the starburst galaxy. Thus, we expect that \(L_p \propto L_{\text{TIR}}\), so

\[
L_{\nu_i} (E_{\nu_i}, L_{\text{TIR}}) = C_1 f_{\pi} L_{\text{TIR}} \frac{E_{\nu_i}}{1\text{GeV}}^{-p},
\]

where \(C_1\) is the normalization factor and \(L_\odot\) is the bolometric luminosity of the Sun. The pionic efficiency is \(f_{\pi} = 1 - \exp(-t_{\text{esc}}/\tau_{\text{loss}})\), where \(\tau_{\text{loss}}\) is the energy-loss time for \(pp\) collisions and \(t_{\text{esc}}\) is the escape time of protons. \(t_{\text{loss}} = (0.5 n \sigma_{\text{PP}} c)^{-1}\), where the factor 0.5 is inelasticity, \(n\) is the particle density of gas, and \(\sigma_{\text{PP}}\) is the inelastic proton collision cross section, which is insensitive to proton energy. Introducing a parameter \(\Sigma_v = m_p R\) as the surface mass density of the gas (where \(R\) is the length scale of the starburst region), the energy loss time is

\[
t_{\text{loss}} = 7 \times 10^4 \text{yr} \frac{R}{500 \text{pc}} \left(\frac{\Sigma_v}{1 \text{ g cm}^{-2}}\right)^{-1}.
\]

We use \(R = 500\) pc as the reference value because neutrinos are predominantly produced by high-redshift starbursts, as implied by the star-formation history, and high-redshift starbursts typically have \(R \sim 500\) pc (Taccioli et al. 2006). There are two ways for CRs to escape from a galaxy. One is the advective escape via a galactic wind and the other is the diffusive escape. The advective escape time is

\[
t_{\text{adv}} = R/v_w = 4.5 \times 10^5 \text{yr} \frac{R}{500 \text{pc}} \left(\frac{v_w}{1000 \text{ km s}^{-1}}\right)^{-1},
\]

where \(v_w\) is the velocity of galactic wind. One can see that protons lose almost all of their energy in dense starburst galaxies with \(\Sigma_v \gtrsim 0.15 (v_w/1000 \text{ km s}^{-1}) \text{ g cm}^{-2}\), if the advective time is shorter than the diffusive escape time. Little is known about the diffusive escape time in starbursts. The diffusive escape time can be estimated as \(t_{\text{diff}} = R^2/2D\), where \(D = D_0 (E/E_0)^{\delta}\) is the diffusion coefficient, \(D_0\) and \(E_0\) are normalization factors, and \(\delta = 0–1\) depending on the spectrum of interstellar magnetic turbulence. As in Liu et al. (2014) and Murase et al. (2013), we assume a lower diffusion coefficient \(D_0 \lesssim 10^{22}\text{ cm}^2\text{s}^{-1}\) at \(E_0 = 3\text{ GeV}\) for starburst galaxies, because the magnetic fields in nearby starburst galaxies such as M82 and NGC 253 are observed to be 100 times stronger than in our Galaxy and the diffusion coefficient is expected to scale with the CR Larmor radius in the case of Bohm diffusion. The fact that no break in the GeV–TeV gamma-ray spectrum up to several TeV from HESS observations also suggests a small diffusion coefficient

\footnote{A simple estimate of the contribution to the gamma-ray background can be given below if the synchrotron loss of \(e^\pm\) pairs formed during the cascades is not taken into account. Assuming a flat cascade gamma-ray spectrum (i.e., \(\Phi_{\gamma} \propto E_{\gamma}^{-\alpha}\) with \(\alpha \approx 2\); Berezinskii & Smirnov 1975; Coppi & Aharonian 1997), the additional contribution to the gamma-ray background flux by the cascade emission can reach as much as \(2 \times 10^{-5}\) GeV cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\). Another component that can contribute to the diffuse gamma-ray emission is \(e^\pm\) pairs produced simultaneously with the neutrinos in the \(\pi^\pm\) decay. The inverse-Compton (IC) scatterings of these pairs with infrared photons will produce VHE photons, which may be absorbed and finally contribute to the cascade gamma-ray component with a flux \(\sim 10^{-8}\) GeV cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\). Noting that the observed gamma-ray flux background observed by Fermi/LAT is \(\sim 10^{-7}\) GeV cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) at \(\sim 100\) GeV (Abdo et al. 2010), the total diffuse gamma-ray flux associated with PeV neutrinos in the \(pp\) scenario would thus contribute \(\sim 50\%\) of the observed diffuse gamma-ray background in the \(\sim 100\) GeV range.}

\footnote{For comparison, we also consider \(R = 200\) pc and \(R = 1\) kpc in the following calculations.}
in starburst galaxies (Abramowski et al. 2012). The diffusive escape time is thus

$$t_{\text{diff}} = 10^5 \, \text{yr} \left( \frac{R}{500 \, \text{pc}} \right)^2 \left( \frac{D_0}{10^{27} \, \text{cm}^2 \, \text{s}^{-1}} \right)^{-1} \left( \frac{E_p}{60 \, \text{PeV}} \right)^{-0.3}$$

for $\delta = 0.3$ (Trotta et al. 2011). Alternatively, Lacki et al. (2011) assume that CRs stream out the starbursts at the average Alfvén speed $v_A = B \sqrt{4\pi \rho m_p n}$, thus

$$t_{\text{diff}} = 2.2 \, \text{Myr} \left( \frac{R}{500 \, \text{pc}} \right)^{1/2} \left( \frac{\Sigma_g}{1 \, \text{g cm}^{-2}} \right)^{1/2} \left( \frac{B}{2 \, \text{mG}} \right)^{-1},$$

where $B$ is the magnetic field in the starburst region. The escape time is the minimum of the advective time and the diffusive time, i.e., $t_{\text{esc}} = \min(t_{\text{adv}}, t_{\text{diff}}).

The accumulated neutrino flux can be estimated by summing up the contribution by all starbursts galaxies throughout the whole universe, i.e.,

$$E^2 \Phi_{\nu_i}^{\text{accu}} = \frac{E^2 \nu_i \Phi_{\nu_i} \int_{z_{\text{min}}}^{z_{\text{max}}} \int_{L_{\text{TIR, min}}}^{L_{\text{TIR, max}}} \frac{\phi(L_{\text{TIR}}, z) L_{\nu_i} [(1 + z) E_{\nu_i} L_{\text{TIR}}]}{H_0 (1 + z)^2 \Omega_M + \Omega_\Lambda} dL_{\text{TIR}} dz,}$$

where $\phi(L_{\text{TIR}}, z)$ represents the luminosity function of starbursts. $H_0 = 71 \, \text{km s}^{-1} \text{Mpc}^{-1}$, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$. Herschel PEP/HerMES has recently provided an estimation of the IR-galaxy luminosity function for separate classes (Gruppioni et al. 2013), which is a modified-Schechter function

$$\phi(L_{\text{TIR}}) = \phi^* \left( \frac{L_{\text{TIR}}}{L_*} \right)^{-1-\alpha} \exp \left[ -\frac{1}{2\sigma^2} \log_{10} \left( 1 + \frac{L_{\text{TIR}}}{L_*} \right) \right].$$

For starburst galaxies, $\alpha = 1.00 \pm 0.20$, $\sigma = 0.35 \pm 0.10$, $\log_{10}(L_*/L_\odot) = 11.17 \pm 0.16$, $\log_{10}(\phi^*/\text{Mpc}^{-3}\text{dex}^{-1}) = -4.46 \pm 0.06$. $L^*$ evolves with redshift as $\propto (1 + z)^{k_L}$ with $k_L = 1.96 \pm 0.13$. For $\phi^*$, it evolves as $\propto (1 + z)^{k_{\rho, p}-1}$ when $z < z_{\rho, p}$, and as $\propto (1 + z)^{k_{\rho, p}-1}$ when $z > z_{\rho, p}$, with $k_{\rho, p} = 3.79 \pm 0.21$. We set $z_{\max} = 4$ and the luminosity ranges from $10^{40} \, L_\odot$ to $10^{42} \, L_\odot$.

We assume that all of the observed neutrinos are produced by starburst galaxies, thus we can normalize the accumulated diffuse neutrino flux in Equation (7) with the observed flux at PeV energy, i.e.,

$$E^2 \Phi_{\nu_i}^{\text{accu}}|_{E_i = 1 \, \text{PeV}} = 0.95 \times 10^{-18} \, \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}.$$

Using the central values of the above parameters in the luminosity function (e.g., $\alpha = 1.00$, $\sigma = 0.35$ and $\log_{10}(L_*/L_\odot) = 11.17$), we get $C_1 = 4.1 \times 10^{22} \text{eV}^{-1}\text{s}^{-1}$ for $p = 2$. Varying the values of these parameters within their error, the value of $C_1$ changes within a factor of a few. However, we note that the result of the accumulated gamma-ray flux, as calculated below in Section 4, remains almost unchanged. We also find that the spectrum of the accumulated neutrino flux, as given by Equation (7), is flat ($\propto E_\nu^{-2}$) for either choice of the diffusive escape times in Equation (5) or (6).

For $pp$ collisions, the energy flux in $\pi^0$-decay gamma rays is $E^2 \gamma \nu_i \propto (1/3) E_p Q_p$, where $Q_p$ represents the differential CR energy flux. Since the neutrino flux is $E^2 \nu_i \propto (1/6) E_p Q_p$, the gamma-ray luminosity per unit energy resulted from the $\pi^0$-decay is related to the neutrino luminosity by

$$E^2 \gamma L_\gamma \approx 2E^2 \nu_i L_{\nu_i}|_{E_i = 0.5E_\gamma}. \quad (10)$$

Thus, the $\pi^0$-decay photon luminosity per unit energy of a single starburst should be

$$L_\gamma = 8.2 \times 10^{21} f_\gamma L_{\text{TIR}} \left( \frac{E_\gamma}{1 \, \text{GeV}} \right)^{-2} \, \text{eV}^{-1}\text{s}^{-1} \quad (11)$$

for $p = 2$.

3. GAMMA-RAY FLUX FROM ONE SINGLE STARBURST GALAXY

The $pp$ process produces neutral pions $\pi^0$ and charged pions $\pi^\pm$. The neutral pion decay produces gamma rays. Besides, $e^\pm$ pairs from the decay of $\pi^\pm$ can also produce gamma rays through IC scattering off the soft photons in the starburst region, mainly the infrared photons (through competition with the synchrotron radiation in the magnetic field). While the low-energy gamma rays can escape and contribute to the diffuse gamma-ray background, the VHE gamma rays will be absorbed due to the dense photon field in the starburst region. The absorbed gamma rays will be converted into $e^\pm$ pairs, which initiate cascades through interactions with the soft photons. As the VHE gamma rays cascade down to enough low energies, they can escape out of the starburst and also contribute to the diffuse gamma-ray background. Below, we consider the separate contributions by the absorbed gamma rays and the unabsorbed ones.

3.1. Absorption of High-energy Gamma Rays in Starbursts

The rapid star formation process makes an intense infrared photon field in the starburst. The VHE gamma-ray photons may be absorbed by background photons and generate $e^\pm$ pairs. The optical depth is $\tau_{\gamma\gamma}(E_\gamma) = \int \sigma_{\gamma\gamma}(\epsilon, E_\gamma) n(\epsilon) R \, d\epsilon$, where $\sigma_{\gamma\gamma}$ is the cross section for pair production (Bonometto & Rees 1971; Schlickeiser et al. 2012) and $n(\epsilon)$ is the number density of the infrared background photons. We adopt the optical–infrared spectral energy models for the nuclei of starburst galaxies developed by Siebenmorgen & Kriigel (2007) and take Arp 220 as a template for starbursts to calculate the absorption optical depth. We use Arp220 as a template because its infrared luminosity is close to the luminosities of those starburst galaxies that dominantly contribute to the diffuse neutrino background (see Section 4). We find that the absorption energy does not change too much if we use M82 as a template instead. For simplicity, we assume all starbursts have the same photon spectra as Arp 220. With such simplifications, the optical depth $\tau_{\gamma\gamma}(E_\gamma)$ in a starburst depends only on its total infrared luminosity, $L_{\text{TIR}}$. Figure 1 shows the corresponding absorption energy, $E_{\text{cut}}$ (where $\tau_{\gamma\gamma} = 1$), as a function of the total infrared luminosity of starburst galaxies for different choices of $R = 200 \, \text{pc}$, $R = 500 \, \text{pc}$ and $R = 1 \, \text{kpc}$. It can be seen that photons with energies above $1$–$10 \, \text{TeV}$ will be absorbed inside the starburst region.

3.2. Absorbed Gamma Rays

The $\pi^0$ decay gamma rays above $E_{\text{cut}}$ will be absorbed in the soft photons in the starbursts and produce pairs, each carrying about half the energy of the initial photons ($\gamma \gamma \rightarrow e^+e^-$). These pairs, together with the pairs that resulted from $\pi^\pm$ decay, will cool through synchrotron and IC emission. The synchrotron
The energy loss fraction of the synchrotron photons in one electron or positron of a particular energy is

\[
\epsilon_b = \frac{2000}{400} \left( \frac{\Sigma_g}{\text{g cm}^{-2}} \right)^{0.7} \left( \frac{B}{\mu G} \right) \left( \frac{E_{\text{e}}}{1 \text{ PeV}} \right)^{0.4},
\]

where \( \Sigma_g \) is the surface density of the soft photons, \( B \) is the magnetic field, and \( E_{\text{e}} \) is the energy of the electron or positron.

As the gas surface density, \( \Sigma_g \), scales with the surface density of the star formation rate as \( \Sigma_g \propto \Sigma_{\text{SFR}} \) and the star formation rate \( (\pi R^2 \Sigma_{\text{SFR}}) \) scales linearly with the total infrared luminosity \( L_{\text{IR}} \), we get the relation (assuming a constant star-formation radius \( R )

\[
\frac{\Sigma_g}{\text{g cm}^{-2}} \approx 3.6 \left( \frac{L_{\text{IR}}}{10^{12} L_\odot} \right)^{0.71}.
\]

The synchrotron energy loss timescale of the synchrotron photons is

\[
\tau_{\text{sync}} = 6\pi m_e c^2 / (c \sigma_T B^2 \gamma_e^2).
\]

where \( U_{\text{ph}} \approx L / (2\pi R^2 c) \) is the energy density of the soft photons, \( \gamma_K \approx 4 \times 10^7 (T/40 \text{K})^{-1} \), \( T \) is the temperature of the graybody radiation field, and \( \gamma_e \) is the Lorentz factor of the electron.

The fraction of the energy loss through synchrotron radiation in the high-energy range, which is

\[
\tau_{\text{sync}} \left( \tau_{\text{sync}} + 1 / \tau_{\text{IC}} \right) \text{ for one electron or positron of a particular energy. Since this fraction is a function of the energy of the electron, we integrate it over a proper energy range to estimate the fraction of the total energy loss of } e^\pm \text{ through synchrotron radiation in the energy range, which is}

\[
\rho \approx \int E_{\text{e,min}}^{E_{\text{e,max}}/2} \left( \frac{E_{\text{e,min}}}{E_{\text{e,max}}/2} \right)^{p+1} dE_e.
\]

where \( E_{\text{e,max}} = 4 \text{ PeV} \) is used for the maximum energy of the electron, corresponding to a maximum neutrino energy of 2 PeV.
The black, red, and blue lines show the cases of $B_1$ the magnetic energy density is larger than the photon energy two factors that lead to such a large synchrotron loss fraction: line of $r$ represent the cases of $R$ radiation in the starburst magnetic field. The solid, dashed, and dotted lines $\propto B L$ respectively, the $B$ for both the $B \propto \Sigma_0$ and $B \propto \Sigma_0^{-4}$ cases. Note that the $B \propto \Sigma_0$ lines overlap with the horizontal line of $r = 1$.

(A color version of this figure is available in the online journal.)

In Figure 2, we show this fraction for starburst galaxies with different $L_{\text{TIR}}$. The black, red, and blue lines represent, respectively, the $B \propto \Sigma_0$, $B \propto \Sigma_0^{-3/2}$, and $B \propto \Sigma_0^{-4}$ cases. It shows that for both the $B \propto \Sigma_0$ and $B \propto \Sigma_0^{-7}$ cases, the synchrotron loss constitute a fraction $\geq 90\%$ of the total energy loss. There are two factors that lead to such a large synchrotron loss fraction: (1) the magnetic energy density is larger than the photon energy density in these cases; (2) the Klein–Nishina effect for $e^\pm$ above $\sim 20(T/40 \text{ K})^{-1} \text{ TeV}$ (Lucki & Thompson 2013) causes the IC energy loss time to increase with $\gamma_e$, while the synchrotron loss time continues to fall as $\gamma_e^{-1}$.

3.2.2. Cascade Gamma Rays

While the synchrotron loss energy goes into low-energy emission and thus does not contribute to the diffuse high-energy gamma-ray background, the IC loss energy will cascade down to the relevant energy range of the diffuse gamma-ray emission. If the cascade develops sufficiently, the spectrum of the cascade emission has a nearly universal form of

$$L_{\text{cas}} \propto \begin{cases} E^{-1.5}_\gamma & (E_\gamma < E_{\gamma, b}) \\ E^{-0.5}_\gamma & (E_{\gamma, b} < E_\gamma < E_{\text{cut}}) \end{cases},$$

(16)

where $E_{\text{cut}}$ is the absorption cutoff energy, $E_{\gamma, b} \approx (4/3)(E_{\text{cut}}/2m_e c^2)^{2/3}$ is the break energy corresponding to $E_{\gamma, b}$, and $\alpha_\gamma \simeq 2$ typically (Berezinskii & Smirnov 1975; Coppi & Aharonian 1997). The spectrum above $E_{\text{cut}}$ decreases rapidly as $e^{-\tau_{\gamma \gamma}}$. The normalization of the cascade emission spectrum is determined by equating the total cascade energy with the total IC energy loss above $E_{\text{cut}}$, i.e.,

$$\int E_\gamma L_{\text{cas}} dE_\gamma \simeq \frac{3}{2} (1 - r) E_{\text{abs}},$$

(17)

where $E_{\text{abs}} = \int_{E_{\text{cut}}/2}^{E_{\text{cut}}/2} E_{\gamma} L_{\gamma} dE_{\gamma}$ is the energy of all $\pi^0$-decay gamma rays above $E_{\text{cut}}$ and the factor $3/2$ represents the sum contributions by the $\pi^0$-decay gamma rays and the gamma rays from the IC scattering of $\pi^\pm$-decay $e^\pm$, the latter of which has a flux of about half that of $\pi^0$-decay gamma rays.

3.3. Unabsorbed Gamma Rays

The gamma rays from $\pi^0$ that decay with energies below $E_{\text{cut}}$ will escape out of the starburst galaxies and contribute directly to the diffuse gamma-ray background. This flux is model-independent and readily obtained from the observed neutrino flux by using Equation (10). For a flat neutrino spectrum, the differential flux of $\pi^0$-decay gamma rays below $E_{\text{cut}}$ is $E_\gamma^2 \Phi_\gamma \simeq 2 \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$.

As we pointed out before, the electrons and positrons accompanying the neutrino production in the $\pi^\pm$ decay also contribute to the diffuse gamma rays through the IC scattering of soft background photons. These $e^\pm$ pairs cool by both synchrotron and IC emission. We denote the flux contributed by the IC process with $L_{\pi^\pm, \text{IC}}$, which is important only when the magnetic energy density in the starburst region is low. Therefore, the flux of the unabsorbed gamma rays is

$$L_{\gamma, \text{un}} = (L_\gamma + L_{\pi^\pm, \text{IC}}) e^{-\tau_{\gamma \gamma}}$$

(18)

Adding the luminosity of the unabsorbed gamma rays and that of the cascade gamma rays, we get the total gamma-ray photon luminosity emitted from one starburst galaxy

$$L_{\text{total}} = L_{\gamma, \text{un}} + L_{\text{cas}}.$$  \hspace{1cm} (19)

4. THE ACCUMULATED DIFFUSE GAMMA-RAY FLUX

Once the gamma rays escape out of the starburst galaxy, they will further interact with the extragalactic infrared and microwave background photons and similar cascades are formed for VHE gamma rays. In this case, however, $E_{\text{cut}}$ is different and dependent on the redshift distribution of starburst galaxies. The cascade emission spectrum has the same form as Equation (16). Taking such cosmic cascades into consideration, the accumulated gamma-ray flux includes two parts; one is from the direct source contribution and the other is from the intergalactic cascades, i.e.,

$$\Phi_\gamma^{\text{accu}} = \Phi_\gamma^{\text{ sour}} + \Phi_\gamma^{\text{ cas}}.$$ \hspace{1cm} (20)

where $\Phi_\gamma^{\text{ sour}}$ represents the direct source contribution by starburst galaxies and $\Phi_\gamma^{\text{ cas}}$ represents the flux from the intergalactic cascades.

The direct source contribution can be obtained by integrating the contributions of all starburst galaxies in the universe over their redshift and luminosity range, i.e.,

$$E_\gamma^2 \Phi_\gamma^{\text{ sour}} = \frac{E_\gamma^2 c}{4 \pi} \int_0^{z_{\text{max}}} \int_0^{L_{\text{TIR, max}}} \frac{\phi(L_{\text{TIR}}, z) L'_{\gamma, \text{total}}[(1 + z)E_{\gamma}]}{H_0 \sqrt{(1+z)^3 \Omega_M + \Omega_\Lambda}} dL_{\text{TIR}} dz,$$ \hspace{1cm} (21)

where $L'_{\gamma, \text{total}}[(1 + z)E_{\gamma}] = L_{\text{total}}[(1 + z)E_{\gamma}] e^{-\tau_{\gamma \gamma}'(E_{\gamma, z})}$ and $\tau_{\gamma \gamma}'$ is the absorption optical depth due to the extragalactic infrared and microwave background photons.

The accumulated diffuse gamma-ray flux is shown in Figures 3–5 for the cases of $R = 500 \text{ pc}$, $R = 200 \text{ pc}$, and $R = 1 \text{ kpc}$, respectively. It can be seen that, the diffuse gamma-ray flux in the case considering the synchrotron loss is less than half of that in the case neglecting the synchrotron loss. This is because the cascade component that resulted from the absorbed gamma rays is strongly suppressed due to the synchrotron
Figure 3. Accumulated diffuse gamma-ray flux of starburst galaxies for different assumptions of the magnetic fields in the starburst region. $R = 500$ pc and $p = 2$ are assumed. The black, red, and blue lines show the cases of $B \propto \Sigma$, $B \propto \Sigma^{0.7}$, and $B \propto \Sigma^{0.4}$, respectively. For illustration, the green line shows the case of $B = 0$. The neutrino flux is obtained using Equation (7). The extragalactic gamma-ray background data from Fermi/LAT are depicted as the black dots. The atmospheric neutrino data and the IceCube data are also shown. (A color version of this figure is available in the online journal.)

Figure 4. Same as Figure 3, but with $R = 200$ pc. (A color version of this figure is available in the online journal.)

Figure 5. Same as Figure 3, but with $R = 1$ kpc. (A color version of this figure is available in the online journal.)

Figure 6. Same as Figure 3, but assuming a steeper proton spectrum with $p = 2.18$. (A color version of this figure is available in the online journal.)

Figure 7. Diffuse gamma-ray flux contributed by starburst galaxies in different luminosity ranges. The grey, red, blue, and orange lines represent the contributions by the starburst galaxies in the luminosity ranges of $10^{10} - 10^{11} L_\odot$, $10^{11} - 10^{12} L_\odot$, $10^{12} - 10^{13} L_\odot$, and $10^{13} - 10^{14} L_\odot$, respectively. The black line represents their sum. $R = 500$ pc, $B \propto \Sigma$ and $p = 2$ are assumed. (A color version of this figure is available in the online journal.)

The accumulated diffuse gamma-ray flux, after considering the synchrotron loss effect, contributes $\sim 20\%$ of the observed diffuse gamma-ray background by Fermi/Large Area Telescope (LAT) at $\sim 100$ GeV for both $B \propto \Sigma$ and $B \propto \Sigma^{0.7}$ cases.

For a steeper neutrino spectrum, since the energy fraction in absorbed gamma rays above $E_{\text{cut}}$ is lower, this effect is expected to be less important. As in Murase et al. (2013), we study the allowed range of the spectral index by the observed gamma-ray background data. We find that the index must be $p \lesssim 2.18$, as shown in Figure 6, in order not to violate the observed gamma-ray background data by Fermi/LAT, which is in agreement with the results in Murase et al. (2013).

We also study how much the starburst galaxies in different luminosity ranges and redshift ranges contribute to the diffuse gamma-ray background. Figure 7 shows the contributions in each luminosity range to the total flux. It can be seen that most flux is contributed by the starbursts in the luminosity range from $10^{11}$ to $10^{13} L_\odot$. For starburst galaxies of such high luminosity range, the contribution is $\sim 20\%$.
luminosity, the pion production efficiency, $f_\pi$, is close to one and these galaxies are proton calorimeters. Figure 8 shows the contributions by starburst galaxies in different redshift ranges to the total flux. As expected, the dominant contribution is by starburst galaxies in the redshift range of $1 < z < 2$.

5. DISCUSSION AND CONCLUSIONS

Starburst galaxies, which have many supernova or hypernova explosions, are proposed as possible sources for the sub-PeV/PeV neutrinos recently detected by IceCube (Murase et al. 2013; Liu et al. 2014; Anchordoqui et al. 2014b). We have shown that the minimum diffuse gamma-ray flux associated with these sub-PeV/PeV neutrinos is about $(2-3) \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$, which is a factor of two lower than the case that does not consider the synchrotron loss of the $e^\pm$ pairs that resulted from the absorption of VHE photons. This minimum diffuse gamma-ray flux constitutes a fraction of $\sim 20\%$ of the observed gamma-ray background flux at $\sim 100$ GeV energies, thus leaving a relatively large amount of room for other sources to contribute to the gamma-ray background.

It was proposed that hypernova remnants in starburst galaxies accelerate protons to $> 10^{17}$ eV (Wang et al. 2007), which then produce PeV neutrinos via $p\bar{p}$ collisions with the dense surrounding medium (Liu et al. 2014). Remnants of normal supernovae may accelerate protons to PeV energies; therefore, they may not contribute to the $\gtrsim 100$ TeV neutrino flux, but they can produce $< 100$ TeV gamma rays, thus contributing to the diffuse gamma-ray background as well. However, as long as the diffuse gamma-ray flux contributed by these normal supernovae does not exceed that contributed by the hypernova remnants too much, the total diffuse flux may still fall below the observed background. It may also be possible that, if the remnants of normal supernovae produce a gamma-ray flux that is three to four times higher, then the total gamma-ray flux from starburst galaxies can reach the level of the observed one. Interestingly, Tamborra et al. (2014) recently showed that star-forming and starburst galaxies can explain the whole diffuse gamma-ray background in the $0.3-30$ GeV range.

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