Neutrino emission of Fermi supernova remnants

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Abstract

The Fermi $\gamma$-ray space telescope reported the observation of several Galactic supernova remnants recently, with the $\gamma$-ray spectra well described by hadronic $pp$ collisions. The possible neutrino emissions from these Fermi detected supernova remnants are discussed in this work, assuming the hadronic origin of the $\gamma$-ray emission. The muon event rates induced by the neutrinos from these supernova remnants on typical km$^3$ neutrino telescopes, such as the IceCube and the KM3NeT, are calculated. The results show that for most of these supernova remnants the neutrino signals are too weak to be detected by the on-going or up-coming neutrino experiment. Only for the TeV bright sources RX J1713.7-3946 and possibly W28 the neutrino signals can be comparable with the atmospheric background in the TeV region, if the protons can be accelerated to very high energies. The northern hemisphere based neutrino telescope might detect the neutrinos from these two sources.

Keywords: radiation mechanism: non-thermal, supernova remnants, gamma rays, neutrinos

1. Introduction

Supernova remnants (SNR) are usually thought the most possible candidate of the acceleration site of Galactic cosmic rays (CRs). However, there is no firm evidence to verify such a conjecture. High energy $\gamma$-ray observations of the sky, by e.g., the Cherenkov telescope High Energy Stereoscopic System (H.E.S.S.) and the Fermi space telescope, can provide very useful information which enables us to approach the acceleration sources of CRs. One good example is the SNR RX J1713.7-3946. The early observation of the
very high energy (VHE) $\gamma$-ray emission from RX J1713.7-3946 by CANGA-ROO indicated that there might be nuclei acceleration in this SNR [1]. The following detailed observation made by H.E.S.S. favored a hadronic origin of the VHE $\gamma$-ray emission according to the spectral shape [2]. Although there are claims against the hadronic scenario or favoring the leptonic scenario of the emission mechanism of SNR RX J1713.7-3946 (e.g., [3, 4, 5, 6]), it is still one of the most interesting candidates of CR nuclei acceleration sources.

After about one year’s operation, Fermi collaboration reported the observations of over 1400 sources, within which 41 are possible associations of SNRs [7]. However, it is very likely that some of the 41 sources are actually associated with pulsars or pulsar wind nebulae (PWN) rather than the SNRs. According to the morphology analysis, Fermi collaboration identified three sources with firm association with SNRs: W44 [8], W51C [9] and IC443 [10]. Further studies revealed other candidate sources of SNRs, including Cassiopeia A [11], W28 [12], RX J1713.7-3946 [13] and W49B [14]. The spectral studies of most of these sources favor hadronic origin of the $\gamma$-ray emission (see also, [15, 16]), although for several ones the leptonic scenario can also give an acceptable fit to the data.

It is difficult to identify the hadronic sources of CRs using $\gamma$-rays alone. Neutrinos, if detected, can be regarded as a definite diagnostic of the hadronic nature of the $\gamma$-ray sources. Actually after the great progress of the discoveries of many VHE $\gamma$-ray sources by e.g., H.E.S.S., MAGIC and Milagro, many works studied the possible perspective of detecting neutrinos from these sources with ongoing or upcoming neutrino detectors (e.g., [17, 18, 19, 20, 21, 22, 23, 24, 25, 26]). The general result is that given the $\gamma$-rays are produced through hadronic interactions of $pp$ collisions, some bright $\gamma$-ray sources with hard spectra might be able to be detected with km$^3$ level neutrino telescope like IceCube. However, the signals are usually weak.

Since the Fermi observations of the several SNRs, especially for those associated with molecular clouds, show strong hints of nuclei acceleration in the SNRs, these SNRs should be prior targets for the neutrino detection. Furthermore, the combined fit of the Fermi data and VHE data (if available) can help to better determine the underlying CR spectra, and give more precise prediction of the neutrino spectra. In this work we try to explore the detectability of neutrinos from the Fermi detected SNRs, under the assumption that the $\gamma$-rays are produced through $pp$ collision in the sources. The neutrino detector configuration adopts typical km$^3$ projects, such as IceCube and KM3NeT.
It should be noted that, however, generally we should not restrict the search for neutrinos on the sources which are probably of hardronic origin. Any sources with high enough $\gamma$-ray emission deserve to be paid attention to for the neutrino detection, because neutrino emission can independently determine the hadronic or leptonic origin of the sources. See e.g., [19, 20, 21, 24] for the studies of neutrinos from various kinds of TeV $\gamma$-ray sources. There are also other studies of the neutrino emission from Fermi sources such as the blazars [27] and the newly discovered nova [28].

This paper is organized as follows. In Sec. 2 we first derive the proton spectra in these SNRs to reproduce the $\gamma$-ray data measured by Fermi and higher energy experiments. Then the neutrino emissions of these sources are discussed in Sec. 3. We draw the conclusion in Sec. 4.

2. Fitting the gamma-ray spectra with hadronic model

In this section we calculate the $\pi^0$-decay induced $\gamma$-rays due to $pp$ collisions. We employ the parametrization given in [29] to calculate the differential production spectra of secondary particles, including $\gamma$-rays and neutrinos. The proton spectrum at the source is adjusted to reproduce the GeV-TeV data of the SNRs. Following the ways of Fermi collaboration, we generally adopt a broken power-law function to describe the proton spectrum. The high energy cutoff of the proton spectrum is not well constrained by the current TeV data. Therefore we adopt three cases for comparison: without cutoff, exponential cutoff with $E_c = 50$ TeV and $E_c = 10$ TeV respectively. However, there are two exceptions: RX J1713.7-3946 and W28.

- RX J1713.7-3946 — The H.E.S.S. experiment gave very good measurements of the TeV $\gamma$-ray spectrum of this source up to energies exceeding 100 TeV [30]. The measured spectrum shows an evident curvature which disfavors a single power-law with high significance [30]. We find that a power-law distribution of protons with an exponential cutoff can well reproduce the observational GeV-TeV data. By fitting the data we find the power-law index and the cutoff energy of protons are 1.7 and $\sim 70$ TeV respectively [31].

- W28 — In the vicinity of SNR W28, H.E.S.S. observation revealed 4 sources: HESS J1801-233 (W28 North), HESS J1800-240B (W28 South), HESS J1800-240A and HESS J1800-240C [32]. The Fermi observation discovered two sources coinciding with HESS J1801-233 and
Table 1: Coordinates and proton spectral parameters of the SNRs

| Source                        | R.A.   | Dec.    | $\gamma_1$ | $\gamma_2$ | $E_{\text{br}}$ (GeV) | $E_{\text{cut}}$ (TeV) |
|-------------------------------|--------|---------|-------------|-------------|-----------------------|------------------------|
| RX J1713.7-3946 (G347.3-0.5) | 17$^h$14$^m$ | $-$39°45′ | 1.70        | 1.70        | —                     | 68                     |
| W49B (G43.3-0.2)              | 19$^h$11$^m$ | $+$09°06′ | 2.45        | 2.55        | 5                     | —                      |
| IC443 (G189.1+3.0)           | 06$^h$17$^m$ | $+$22°34′ | 2.09        | 2.87        | 69                    | —                      |
| W44 (G34.7-0.4)              | 18$^h$56$^m$ | $+$01°22′ | 2.00        | 3.20        | 10                    | —                      |
| W51C (G49.2-0.7)             | 19$^h$24$^m$ | $+$14°06′ | 2.00        | 2.65        | 15                    | —                      |
| Cassiopeia A (G111.7-2.1)    | 23$^h$23$^m$ | $+$58°48′ | 1.90        | 2.30        | 30                    | —                      |
| W28 North (G6.4-0.1)         | 18$^h$00$^m$ | $-$23°26′ | 2.70        | 2.70        | —                     | —                      |
| W28 South (G6.4-0.1)         | 18$^h$00$^m$ | $-$23°26′ | 2.38        | 2.38        | —                     | —                      |
| HESS J1800-240A (G6.4-0.1)   | 18$^h$00$^m$ | $-$23°26′ | 2.10        | 2.10        | —                     | —                      |
| HESS J1800-240C (G6.4-0.1)   | 18$^h$00$^m$ | $-$23°26′ | 2.40        | 2.40        | —                     | —                      |

For W28 there are 4 sources.
Figure 1: The $\gamma$-ray spectra of seven SNRs revealed by Fermi, together with available measurements at TeV energy range by Cherenkov telescope. As a comparison we also show the flux of muon neutrinos of each source (see Sec. 3). References of the $\gamma$-ray data are: RX J1713.7-3946, Fermi [13], H.E.S.S. [30]; W49B, Fermi [14]; IC 443, Fermi [10], MAGIC [34], VERITAS [35]; W44, Fermi [8], Whipple [36], HEGRA [37]; W51C, Fermi [9], H.E.S.S. [38]; Cassiopeia A, Fermi [11], MAGIC [39], VERITAS [40].
Figure 2: Continuance of Figure 1. The observational data of Fermi are taken from [12], and H.E.S.S. data are taken from [32].
3. Neutrino emissions and muon events

In this section, we discuss the capability of detecting neutrino signals from the SNRs discussed in the previous section. The SNRs can be treated as point sources at the neutrino telescope. The SNRs in the northern hemisphere are possibly detected by the km$^3$ volume detector IceCube located at the South Pole. For the sources in the southern hemisphere we discuss detectability on an imaginary km$^3$ scale detector located in the northern hemisphere of the Earth, such as the proposed KM3NeT.

The initial neutrino flavor ratio is approximately $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ from the decay of $\pi^+$ and $\pi^-$ produced by high energy $pp$ collisions\footnote{Actually we use the parametrization given in \cite{29} to calculate the initial neutrino spectrum.}. Such high energy neutrinos arrive at the neutrino telescope after oscillations. For the vacuum oscillation, we adopt neutrino mixing angles as $\sin^2 \theta_{12} = 0.304$, $\sin^2 \theta_{23} = 0.5$, $\sin^2 \theta_{13} = 0.01$\footnote{Actually we use the parametrization given in \cite{29} to calculate the initial neutrino spectrum.}, and the neutrino flavor conversion probabilities are $P_{\nu_\mu \leftrightarrow \nu_\mu} = 0.22$, $P_{\nu_\mu \leftrightarrow \nu_\tau} = P_{\nu_\tau \leftrightarrow \nu_\tau} = 0.39$\footnote{Actually we use the parametrization given in \cite{29} to calculate the initial neutrino spectrum.}. Then the flux of muon-neutrinos arriving at the Earth is $\Phi_{\nu_\mu} = \sum_i \Phi_{\nu_i} P_{\nu_i \leftrightarrow \nu_\mu} \sim \Phi_{\nu_\mu}/2$. We neglect the matter effect in the Earth because we discuss the high energy neutrinos with $E > 1$ TeV here. In addition, if the neutrino energy is larger than 10 TeV, the absorption effects of the Earth becomes important. Therefore, the detected neutrino flux should be multiplied by a factor $\exp[-\rho_N \sigma_t(E_\nu)]$ to take into account such absorption effects, where $\rho_N$ is the averaged nucleon numbers, $l$ is the distance when neutrino travel through the Earth, and $\sigma_t(E_\nu)$ is the total cross section of neutrino-nucleon scattering. The fluxes of muon neutrinos of these sources are shown in Figs. 1 and 2.

The charged-current interactions between muon-neutrinos and nucleons around/inside the detector will produce high energy muons, which can emit Cherenkov light and then be recorded by the detector. There will be also an additional a few percent contribution, depending on the neutrino spectrum, to the muon events induced by $\nu_\tau$\footnote{Actually we use the parametrization given in \cite{29} to calculate the initial neutrino spectrum.}. In this work we do not include such a contribution. The conversion probability of a muon-neutrino into a muon is

$$P_{\text{CC}} dr dE_{\nu_\mu} = \left[ \frac{d\sigma_{\text{CC}}^p(E_{\nu_\mu}, E_\mu^0)}{dE_\mu^0} \right] \rho_p + (p \rightarrow n) dr dE_{\nu_\mu},$$

where $\rho_p(\rho_n)$ is the number density of protons (neutrons) in the matter. The cross sections of deep inelastic neutrino-nucleon scattering processes are given
by \[44\]

\[
\frac{d\sigma^{\nu(p,n)}(E_\nu, y)}{dy} \simeq \frac{2 m_{p,n} G_F^2}{\pi} E_\nu \left( a^{(p,n)}_{CC} + b^{(p,n)}_{CC} (1 - y)^2 \right),
\]

(2)

where \(y \equiv 1 - E_\ell/E_\nu\), \(a^{(p,n)}_{CC} = 0.15, 0.25\), \(b^{(p,n)}_{CC} = 0.04, 0.06\).

If the scattering between neutrino and nucleon occur inside the detector, then the muon tracks will also start inside the detector. This is the so-called contained event. The differential muon event rate of contained events is given by \[45\]

\[
\left( \frac{d\Phi_\mu}{dE_\mu} \right)_{\text{con}} = L_{\text{det}} \int_{E_\mu}^\infty dE_\nu \frac{d\Phi_\nu}{dE_\nu} P_{CC} + (\nu \to \bar{\nu}),
\]

(3)

where \(L_{\text{det}}\) is the length of the detector, which is adopted to be 1 km.

The neutrino induced muons could also be produced in the medium around the instrument volume. In such cases, some of the muons can propagate into the detector and leave the tails of tracks in the detector. These events are called through-going muons. For the high energy neutrinos, they could produce muons which can travel a long distance, and enhance the final muon event rate. The muons will lose energy due to ionization and radiation when they travel in the medium. To calculate the event rate of through-going muons, the energy losses of muons before they arrive at the detector need to be taken into account. If we consider the average rate of muon energy loss as \(dE_\mu/dx = -\alpha - \beta E_\mu\), the distance that a muon with energy \(E_\mu^0\) can travel in matter when its energy drops to \(E_\mu\) is given by

\[
R(E_\mu^0, E_\mu) = \frac{1}{\rho \beta} \ln \frac{\alpha + \beta E_\mu^0}{\alpha + \beta E_\mu}.
\]

(4)

On the other hand, if the detector observes a muon with energy of \(E_\mu\), the initial muon energy at the place with a distance \(r\) from the detector could be calculated as

\[
E_\mu^0 = e^{\beta r} E_\mu + (e^{\beta r} - 1) \frac{\alpha}{\beta}.
\]

(5)

Therefore, the event rate of through-going muons is given by \[45, 42\]

\[
\left( \frac{d\Phi_\mu}{dE_\mu} \right)_{\text{thr}} = \int_{E_\mu}^{\infty} dE_\nu \int_0^{R(E_\nu, E_\mu)} dr e^{\beta r} \frac{d\Phi_\nu}{dE_\nu} P_{CC} P_{\text{surv}} + (\nu \to \bar{\nu}),
\]

(6)
where the factor \( dE_\mu^0/dE_\mu = e^{\beta \rho r} \) accounts for the energy shift when the muon travel in the medium before arriving at the detector, \( P_{\text{surv}} \) is the surviving probability of the muon before decay, which roughly equals to 1 for high energy neutrino interested here \[45\].

The total muon event number at the detector is

\[
N = \int d\Omega \int dE_\mu \frac{d\Phi_\mu}{dE_\mu} A_{\text{det}} T f(E_\mu), \tag{7}
\]

where \( f(E_\mu) \) is the energy response function with energy resolution width \( \Delta \log_{10} E_\mu = 0.3 \), \( T \) is the operation time, and \( A_{\text{det}} \) is the effective area of the detector. For the contained events, \( A_{\text{det}} \) is assumed to be 1 km\(^2\), and for the through-going events, \( A_{\text{det}} \) is the effective muon detecting area which is a function of muon’s energy and direction. We take the effective muon detecting area of the IceCube from \[46\]. In \[46\] the authors also proved that such an effective muon detection area is equivalent to the simulated effective neutrino detection area as reported in \[43, 47, 48\]. To calculate the final muon event number, we add the contained and through-going muons together.

The main background for high energy neutrino detection is the atmospheric neutrinos. Here we use a parametrizations of atmospheric neutrino flux following \[45\], which describes the calculated results of \[49\]. The high angular resolution of the detector can be used to suppress the atmospheric neutrino background. In this work we utilize an angle resolution of 1° (half angle of a cone).
Figure 4: The total muon number in one year induced by neutrino emissions from the six Fermi SNRs. See the text for details.
Compared to the SNR neutrino signals, the atmospheric neutrino background is large but decrease quickly as \( E^{-3.7} \). Therefore we only pay attention to muon events with energy higher than TeV. In Fig. 3, we show the differential muon rates of the through-going (left) and contained (right) events respectively, induced by neutrino emission from Cassiopeia A. According to the \( \gamma \)-ray emission, we know that Cassiopeia A has a larger initial neutrino flux with \( E_\nu > 1 \) TeV than other sources in the northern hemisphere. Furthermore, the atmospheric neutrino flux from the direction of Cassiopeia A is relatively small due to the large zenith angle. Therefore Cassiopeia A should be the most possible candidate of detecting neutrinos among these SNRs in the northern hemisphere, which can be probed with the on-going IceCube detector. However, we can see that the muon rate with energy of \( O(\text{TeV}) \) from Cassiopeia A is lower by about one order of magnitude compared with the atmospheric background, even for the case without energy cutoff of the proton spectrum. For \( E \geq 10 \) TeV the signal will exceed the background. However, the absolute event rate is too low (\( O(0.1) \)) to be detected. If there is energy cutoff of the accelerated protons at the level of 10 – 100 TeV like SNR RX J1713.7-3946, the detection perspective of neutrinos from Cassiopeia A by IceCube would be poorer.

The total muon event numbers of six of the SNRs compiled in Table 1 in one year exposure are shown in Fig. 4. Note that the four \( \gamma \)-ray sources in the vicinity of W28 are added together to be one neutrino source due to the relatively poor angular resolution of neutrino detector. The result of SNR W44 is not displayed either due to its extremely soft spectrum at high energy range. The contained and through-going muon events are added together. For the four SNRs located in the northern hemisphere, i.e., W49B, IC443, W51C and Cassiopeia A, the total muon event number with \( E > 1 \) TeV is only \( O(0.1) \). Compared with the atmospheric background with the event rate of several, it seems to be very difficult for IceCube to discover the neutrinos from these SNRs.

For the two SNRs located in the southern hemisphere, RX J1713.7-3946 and W28, the situation are better. We study the detectability with a speculated km\(^3\) level neutrino telescope in the northern hemisphere. The actual detectability needs full Monte Carlo simulation based on realistic detector configuration. Here we adopt the same instrumental parameters of this detector as IceCube. We neglect the angular information of the atmospheric neutrinos, but take a directional averaged background. The absorption length of neutrinos when propagating through the Earth is calculated assuming the
detector is located at the North Pole. In fact, the absorption effect is not strong. Thus, different neutrino traveling distances will not change the final results significantly. We also assume the detector only has half of the time to observe the southern sky per year. This is a reasonable approximation if the detector is not located at the North Pole. It is shown that the muon event number with $E > 1$ TeV can reach 3 for RX J1713.7-3946 at such a detector in one year. Our result is in agreement with that derived in previous studies, for example, $N_\mu (> 1 \text{TeV}) \approx 2.8 \text{ yr}^{-1}$ in [19], $\sim 2 \text{ yr}^{-1}$ in [21], $\sim 1.5 \text{ yr}^{-1}$ in [23], $\sim 1.9 \text{ yr}^{-1}$ in [26]. Compared with the background level of $\sim 2 \text{ yr}^{-1}$, it would be hopeful to detect the SNR neutrinos. This result is easy to understand because RX J1713.7-3946 is the brightest source in the $1 - 10$ TeV range among these SNRs. For W28, the number of muon event might reach the order of 1 for the case without cutoff of the accelerated proton spectrum. For larger detectors and/or longer exposure time, we may still have chance to detect such neutrinos. If there is a cutoff of the proton spectrum at energy $\sim 10 - 100$ TeV the number of signal events would decrease significantly.

4. Conclusion

In this work we investigate the possible neutrino emissions of several Fermi detected SNRs. Seven SNRs are compiled in this work according to the Fermi observations, most of which are also detected by high energy observations such as H.E.S.S., MAGIC and VERITAS. The study of the $\gamma$-ray spectra of these sources tend to favor hadronic CRs acceleration at the sources. Therefore the accompanied neutrino emission will be a unique diagnostic of the nature of the radiation of these SNRs. Assuming the $\gamma$-rays are produced through $pp$ collisions, we first determine the proton spectral parameters and intensity normalization using the GeV band data from Fermi and the available TeV band data from MAGIC, VERITAS or H.E.S.S.. The proton spectra are generally adopted as a broken power-law. For RX J1713.7-3946 the TeV data measured by H.E.S.S. are precise enough to determine the cutoff energy of protons. However, for other sources we cannot precisely determine the high energy behaviors using the present data. Therefore we assume $E_{\text{cut}} = \infty$, 50 TeV and 10 TeV for the accelerated proton spectra for comparison. The neutrino signals are then calculated based on $\text{km}^3$ level experiments like IceCube in the south hemisphere and KM3NeT in the north hemisphere.

The results show that for the four SNRs located in the northern sky,
W49B, IC443, W51C and Cassiopeia A, the numbers of TeV muons induced by the muon-neutrinos are only of the order $O(0.1)$ with one year exposure of IceCube, whereas the atmospheric background is larger by one or two orders of magnitude. Compared with the large atmospheric background the detectability seems quite poor. The two sources located in the southern sky, RX J1713.7-3946 and W28, have larger neutrino signals than other sources. We assume an IceCube-like detector located in the northern hemisphere of the Earth to estimate the detectability of such northern sky sources. We find that the number of muon events from RX J1713.7-3946 can reach severer for one year observation. The atmospheric background in $1^{\circ}$ cone is of the same level as the signal. For W28 the signal will be slightly weaker than that of RX J1713.7-3946, if the cutoff energy of accelerated protons is high enough. We expect that for a long time exposure (e.g., $\sim 10$ yr) of a km$^3$ neutrino telescope located in the northern hemisphere, it would be possible to detect the neutrinos from the SNRs like RX J1713.7-3946. If these neutrinos are really detected, it would be the smoking gun of identifying the acceleration sources of the Galactic CRs.

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