Ultra High Energy Neutrinos from Supernova Remnants

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In this paper we discuss possible ultra high energy (≥ TeV) neutrino emission from Supernova Remnants (SNRs), specifically the hadronic gamma ray production models. Recent very high energy (VHE) γ ray observation from SNRs is the main motivation behind this study.

I. INTRODUCTION

The supernova remnants (SNRs) could be the principal source of galactic cosmic rays up to energies of ∼ 10^{15} eV [1]. A fraction of the accelerated particles interact within the supernova remnants and its adjacent neighborhood, and produce γ rays. If the nuclear component of cosmic rays is strongly enhanced inside SNRs, then through nuclear collisions leading to pion production and subsequent decay, γ rays and νs are produced. Therefore, simultaneous high energy γ ray and ν observations from SNR sources would suggest accelerated hadrons in SNR.

Recent observations above 100 MeV by the EGRET instrument have found γ ray emission from the direction of several SNRs (e.g. IC 443, γ cygni, etc.). However, the production mechanisms of these high energy gamma-rays has not been unambiguously identified. The emission may be due to the interaction of protons, accelerated by the SNR blast wave, with adjacent molecular clouds [2], bremsstrahlung or inverse Compton from accelerated electrons [3], or due to pulsars residing within the SNRs. Evidence for electron acceleration in SNR comes from the ASCA satellite detection of non-thermal X-ray emission from SN 1006 [4] and IC 443 [5]. Ground based telescopes have detected TeV emission from SN 1006 [6] and the Crab Nebula [7]. For recent reviews see [1]. Our objective in this paper is to look closely at SNRs as sources of ultra high energy (UHE) neutrinos and we investigate different possibilities in the sections II and III below. Section IV gives a brief overview and conclusions.

II. NEUTRINOS FROM SUPERNOVA REMNANTS ASSUMING P-P INTERACTIONS

There are two schools of thought describing the high and very high energy gamma-ray emission from SNRs. In one, TeV γ rays are suggested to be leptonic in origin [8] where TeV photons are produced in inverse Compton scattering off the microwave radiation and other ambient photon fields by relativistic electrons. In the second, the decay of neutral pions produced in proton nucleon collisions produce gamma-rays. TeV neutrino emission from SNRs is possible only if hadronic models are taken into consideration.

Non-linear particle acceleration concepts have been used in [2] to provide SNR gamma-ray fluxes. Following [2] the gamma-ray flux above 1 TeV from a SNR at a distance, d, and considering a differential energy spectrum of
accelerated protons inside the remnant of the form $E^{2-\alpha}$, would be

$$F_\gamma(>1 \text{ TeV}) \sim 8.4 \times 10^6 \theta q_\gamma(\alpha) \left( \frac{E}{1 \text{ TeV}} \right)^{3-\alpha} \left( \frac{E_{sn}}{10^{51} \text{ erg}} \right) \left( \frac{n}{1 \text{ cm}^{-3}} \right) \left( \frac{d}{1 \text{kpc}} \right)^{-2} \text{ cm}^{-2} \text{s}^{-1}$$

(1)

where $n$ is the number density of the gas and $q_\gamma$ is the production rate of photons. These results correspond to the SNR in the Sedov (adiabatic) phase where the luminosity is roughly constant.

UHE neutrinos can be predicted to be produced as a significant byproduct of the decay of charged pions. To find the neutrino flux ($F_{\nu_\mu + \bar{\nu}_\mu}$) for different spectral indices we resort to the calculated ratios $\frac{F_{\nu_\mu + \bar{\nu}_\mu}}{F_\gamma}$ [2,9] as given in Table 1. $q_\gamma(\alpha)$ values for different $\alpha$ are also included. The contribution of nuclei other than H in both the target matter and cosmic rays is assumed to be the same as in the ISM [10]. The units of $q_\gamma$ are s$^{-1}$ erg$^{-1}$ cm$^3$ (H$^{-1}$. A comprehensive discussion of the spectrum weighted moments for secondary hadrons, based on the accelerator beams with fixed targets at beam energies $\leq 1$ TeV, has been presented by Gaisser [9]. This has been shown to also characterize correctly the energy region beyond 1 TeV [2]. A direct ratio estimate was calculated in [2] to give results very close to that in [9]. For harder spectra the ratio is found to approach unity.

| $\alpha$ | 4.2 | 4.4 | 4.6 | 4.8 |
|---------|-----|-----|-----|-----|
| $\frac{F_{\nu_\mu + \bar{\nu}_\mu}}{F_\gamma}$ [Gaisser (1990) [9]] | 0.80 | 0.67 | 0.56 | 0.46 |
| $\frac{F_{\nu_\mu + \bar{\nu}_\mu}}{F_\gamma}$ [Drury et.al. (1993) [2]] | 0.86 | 0.77 | 0.66 | 0.58 |
| $q_\gamma(\alpha)$ [2] | $4.9 \times 10^{-18}$ | $8.1 \times 10^{-19}$ | $1.9 \times 10^{-19}$ | $3.7 \times 10^{-20}$ |

TABLE I. Values of expected UHE neutrino and gamma ray ratio
We have taken the average of the two ratios as given in Table 1 to calculate the corresponding neutrino flux from equation (1) for each spectral index. The expression for the $\nu_\mu$ flux for $\alpha \sim 4.2$ is

$$F_{\nu_\mu}(>1 \text{ TeV}) \sim 3.4 \times 10^{-11} \theta \left( \frac{E}{1 \text{ TeV}} \right)^{-1.2} \left( \frac{E_{\text{sn}}}{10^{51} \text{ erg}} \right) \left( \frac{n}{1 \text{ cm}^{-3}} \right) \left( \frac{d}{1 \text{kpc}} \right)^{-2} \text{cm}^{-2} \text{s}^{-1}$$  (2)

This is twice the corresponding $\nu_e$ flux.

Recent data from the CANGAROO detector [7] indicate that the energy spectrum of $\gamma$ rays from the Crab pulsar/nebula may extend up to at least 50 TeV. The CANGAROO detector has also observed VHE $\gamma$ rays upto 10 TeV from SN1006 [6]. These emissions could be explained on the basis of electron inverse Compton processes. However, as the energy increases, Compton process produces steeper spectra because of synchrotron energy loss of electrons in magnetic fields. Hence, leptonic models have difficulty in explaining the observed hard spectrum that extends to beyond 10 TeV as is observed from the Crab. If we consider hadronic models to be viable at such energies, we should expect corresponding UHE neutrino emission from SNRs.

The hadronic mechanism for production of $\pi^0$ and hence $\gamma$ rays as described above has been used in [11] to explain the UHE emission from the Crab. Nuclear p-p interactions are considered to occur among protons accelerated in the nebula. However, the energy balance between the magnetic field and relativistic particles in the nebula show that nucleon contribution is dominant only at energies above 10 TeV. The derived gamma-ray spectrum in this model closely matches the SN1006 spectrum obtained by the CANGAROO instrument.

An approximate expression for the gamma ray spectrum from equation (1) could be written for spectral index $\alpha$ varying between 4.0-4.5 as [11],

$$F_{\gamma}(>1 \text{TeV}) \sim 4.0 \times 10^{-3\alpha} \left( \frac{W_p}{10^{48} \text{ erg}} \right) \left( \frac{n}{100 \text{ cm}^{-3}} \right) \left( \frac{d}{2 \text{kpc}} \right)^{-2} \left( \frac{E}{7 \text{ TeV}} \right)^{3-\alpha} \text{cm}^{-2} \text{s}^{-1}$$  (3)

where $d$ is the distance to the source (distance to Crab is 2 kpc), $W_p$ is the kinetic energy of the accelerated protons.
(reasonable value is $\sim 10^{48}$ erg) and $n$ is the effective number density (100 cm$^{-3}$). The corresponding UHE neutrino flux can be calculated directly using values from Table 1. For reasonable parameters as an example for $\alpha \sim 4.2$ the neutrino flux from the Crab would be,

$$F_\nu(>1\text{TeV}) \sim 8.3 \times 10^{-13} \left(\frac{E}{\text{TeV}}\right)^{-1.2} \text{cm}^{-2}\text{s}^{-1}$$

(4)

In the shell type supernova remnant, SN1006, at a distance of $\sim 1.8$ Kpc [8], the total estimated kinetic energy of the accelerated protons would be $\sim 10^{49}$ ergs (10% of the supernova explosion energy of $\sim 10^{50}$ ergs [12]) and the matter density is 0.4 cm$^{-3}$ [13] (The matter density is low since SN1006 is located above the galactic plane). The observed $\gamma$ ray flux cannot be accounted for by the hadronic acceleration mechanism alone due to this low matter density. However, there could be corresponding UHE neutrino emission.

We show in Figure 1 the expected neutrino flux from the Crab Nebula and SN1006 for different spectral indices as calculated above for typical parametric constants. The expected neutrino flux for SN1006 is found to be several orders of magnitude lower than the Crab for the same neutrino energies.

### III. UHE NEUTRINO EMISSION FROM SNR AND PULSARS DUE TO NUCLEAR INTERACTIONS

There is another model which predicts UHE neutrinos from SNR [14,15]. In this model, very young SNRs are considered in which ions are accelerated in the slot gap of the highly magnetized rapidly spinning pulsar. Nuclei, probably mainly Fe nuclei, extracted from the neutron star surface and accelerated to high Lorentz factors can be photodisintegrated by interaction with neutron star’s radiation field and hot polar caps. Photodisintegration can also occur in the presence of extremely strong magnetic fields typical of neutron star environments ($\sim 10^{12}$ G). For acceleration to sufficiently high energies we need a short initial pulsar period ($\sim 5$ ms). The energetic neutrons produced as a result of photodisintegration interact with target nuclei (matter in the shell) as they travel out of the SNR, producing gamma ray and neutrino signals; those neutrons passing through the shell decay into relativistic protons contributing to the pool of galactic cosmic rays. For a beaming solid angle to the Earth of $\Omega_b$, the neutrino flux in this model can be calculated from,

$$F_\nu(E_\nu) \sim \frac{\dot{N}_{\text{Fe}}}{\Omega_b d^2} \left[1 - \exp\left(-\tau_{pp}\right)\right] \int N_n(E_n) P_{n\nu}^M(E_\nu, E_n) dE_n$$

(5)

where $\dot{N}_{\text{Fe}}$ is the total rate of Fe nuclei injected, $d$ is the distance to the SNR, $P_{n\nu}^M(E_\nu, E_n) dE_n$ is the number of neutrinos produced with energies in the range $E_\nu$ to $(E_\nu + dE_\nu)$ (via pion production and subsequent decay), and $N_n(E_n)$ is the spectrum of neutrons extracted from a single Fe nucleus. $\tau_{pp}$ is the optical depth of the shell to nuclear collisions (assuming shell type SNR) which is a function of the mass ejected into the shell during the supernova explosion and of the time after explosion. We show in Figure 2 the $\nu_\mu + \bar{\nu}_\mu$ spectra obtained from this model at a
distance of 10 kpc; the time after explosion is 0.1 year. Signals from nuclei, which are not completely fragmented, are ignored. These particles are charged and would be trapped in the central region of the SNR which has a relatively low matter density and therefore would not make any significant contribution to neutrino fluxes.

FIG. 2. Plot of expected neutrino $\nu_\mu + \bar{\nu}_\mu$ spectrum from SNR produced by collisions of neutrons with matter in a supernova shell for $B = 10^{12}$ G and initial pulsar period 5 ms using the maximim polar cap heating model (very young SNR); Here F is in cm$^{-2}$ s$^{-1}$ and neutrino energy E is in GeV.

IV. OVERVIEW AND CONCLUSIONS

UHE neutrinos can be detected by observing muons, electrons and tau leptons produced in charged-current neutrino nucleon interactions [16,17]. To minimize the effects of atmospheric muon and neutrino background, usually the upward going muons (to identify muon neutrinos) are observed. To observe $\nu_e$, one looks at the contained event rates for resonant formation of $W^-$ in the $\bar{\nu}_e$ interactions at $E_\nu = 6.3$ PeV for downward moving $\nu_e$. The key signature for the detection of $\nu_\tau$ is the charged current $\nu_\tau$ interaction, which produces a double cascade on either end of a minimum ionizing track [17]. The threshold energy for detecting these neutrinos is near 1 PeV. At this energy cascades are separated by roughly 100m which should be resolvable in the planned neutrino telescopes. However, the evidence for $\nu_\tau$ would indicate neutrino oscillations since they are not expected from the hadronic models. Neutrinos produced by cosmic ray interactions in the atmosphere are considerably larger than individual source fluxes at 1 TeV but falls rapidly with energy. The “conventional” atmospheric neutrino flux is derived from the decay of charged pions and kaons produced by cosmic ray interactions in the atmosphere. The angle averaged atmospheric flux in the neutrino energy range $1 \, \text{TeV} < E_\nu < 10^3 \, \text{TeV}$, can be parametrized [16] by the equation

$$F_\nu = 7.8 \times 10^{-8} \left( \frac{E_\nu}{1 \, \text{TeV}} \right)^{-2.6} \, \text{cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1}$$

An additional “prompt” contribution of neutrinos to the atmospheric flux arises from charm production and decay. The vertical prompt neutrino flux has been recently reexamined using the Lund model for particle production [18] and has been shown to be slightly larger than the conventional atmospheric neutrino flux at higher energies $\geq 100$. 

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TeV. We compare equations (3) and (5) to find that the neutrino flux from the Crab would be significantly above the atmospheric background beyond a few TeV. For energies of a TeV or more the neutrino direction can be reconstructed to better than 1 degree, and less than one event per year in a one degree bin is expected from the combined atmospheric and AGN backgrounds [19,20]. For a muon neutrino of energy \( \sim 1 \) TeV the rate of upward muons in a detector with effective area of 1 km\(^2\) from the Crab will be \( \sim 1 – 30 \) per year, depending on the model chosen. This neutrino flux should be detectable by large neutrino telescopes with good angular resolution of about 1 degree. However, neutrino flux from SN1006 will be negligible even in such large area detectors.

We must also account for the shadow factor which represents the attenuation of the neutrinos traversing the earth. This effect is prominent at energies \( \geq 100 \) TeV. In that case, it is necessary to restrict our attention to downward moving neutrinos. The expected rates would be larger, but the effects of atmospheric muons have to be eliminated by restricting the solid angle to include only large column depths [16].

The question of the importance of hadronic interactions in the Crab Nebula and other SNRs can therefore be settled by the detection of neutrinos which is likely in the next generation UHE kilometer scale detectors in ice/water.

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