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Implications of supernova remnant origin model of galactic cosmic rays on gamma rays from young supernova remnants

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It is widely believed that Galactic cosmic rays are originated in supernova remnants (SNRs), where they are accelerated by a diffusive shock acceleration (DSA) process in supernova blast waves driven by expanding SNRs. In recent theoretical developments of the DSA theory in SNRs, protons are expected to accelerate in SNRs at least up to the knee energy. If SNRs are the true generators of cosmic rays, they should accelerate not only protons but also heavier nuclei with the right proportions, and the maximum energy of the heavier nuclei should be the atomic number (Z) times the mass of the proton. In this work, we investigate the implications of the acceleration of heavier nuclei in SNRs on energetic gamma rays produced in the hadronic interaction of cosmic rays with ambient matter. Our findings suggest that the energy conversion efficiency has to be nearly double for the mixed cosmic ray composition compared to that of pure protons to explain observations. In addition, the gamma-ray flux above a few tens of TeV would be significantly higher if cosmic ray particles could attain energies Z times the knee energy in lieu of 200 TeV, as suggested earlier for nonamplified magnetic fields. The two stated maximum energy paradigms will be discriminated in the future by upcoming gamma-ray experiments like the Cherenkov telescope array (CTA).

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I. INTRODUCTION

Even after more than a hundred years since their discovery, the origin of cosmic rays is not convincingly known. Among the observed features of cosmic rays, the energy spectrum provides significant clues about their origin. The observed energy spectrum of cosmic rays extends from the MeV range to about 300 EeV and is well described by a universal (falling) power law. However, the slope of the energy spectrum changes at least at two points: one around 3 PeV, where the spectral index steepens from −2.7 to −3.1 (the so-called knee of the spectrum), and another around 3 EeV, where the spectrum again flattens to the pre-knee slope (the so-called the ankle of the spectrum) [1]. Recent observations also claim evidence for a second knee around 80 PeV [2]. Any viable model of origin of cosmic rays has to explain all these spectral features of the energy spectrum.

It is widely believed that the bulk of the cosmic rays observed from the Earth—particularly those with energies below the ankle (or below the second knee)—are of Galactic origin [3]. Among the Galactic sources, supernova remnants (SNRs) are considered the most viable sources of Galactic cosmic rays [3,4]. Such a proposition has two strong bases: First, the energy released in supernova explosions satisfies the energy requirement to maintain cosmic ray energy density considering an overall efficiency of the conversion of explosion energy into cosmic ray particles (hereafter termed "conversion efficiency" throughout the article) of the order of 10% [3]. Second, the diffusive shock acceleration (DSA) operating in SNRs can provide the necessary power-law spectral shape of accelerated particles with a spectral index of −2.0 (or slightly less than that) [5] that subsequently steepens to −2.7, as observed, due to energy-dependent diffusive propagation effects [3].

Some experimental evidence, though circumstantial, has been reported in recent years in favor of the SNR origin of cosmic rays, arising mainly from astronomical studies of SNRs in the gamma-ray regime. If SNRs are the true generators of cosmic rays, TeV gamma rays can be expected to arise from cosmic ray interactions with the ambient matter and the radiation field in the SNRs [6]. Over the last fifteen years or so, GeV to TeV gamma rays from a few SNRs have been detected by the modern gamma-ray observatories with fluxes consistent with the standard scenario of a supernova origin of cosmic rays [7]. Here, note that high-energy gamma-ray fluxes from supernovae also can be explained by the so-called leptonic scenario, in which TeV gamma rays are produced by inverse Compton scattering of accelerated electrons with diffuse radiation fields. A clear signature of gamma rays originating from pion decay ($\pi^o \rightarrow 2\gamma$) should be a gamma-ray emission spectrum that peaks at 67.5 MeV, and evidence for a cutoff below several hundreds of MeV from some SNRs has already been found by AGILE and Fermi [8]. The observation of TeV neutrinos from SNRs will be another clean signature for the hadronic acceleration in supernovae.

A few issues of the SNR origin model are, however, not yet established, including the efficiency of conversion of supernova explosion energy to cosmic rays and the

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maximum energy that can be attained by a cosmic ray particle in a SNR. Though there is no firm upper limit of conversion efficiency, a high conversion efficiency is difficult to achieve. The other key unsettled issue is the maximum attainable energy. The maximum energy that can be attained by a cosmic ray particle in an ordinary SNR when the remnant is passing through a medium of density N_H cm^{-3} is [9]

$$E_{\max} \simeq 4\times 10^5 Z\left(\frac{E_{SN}}{10^{51}\ \mathrm{erg}}\right)^{1/2}\left(\frac{M_{ej}}{10\ M_{\odot}}\right)^{-1/6} \times\left(\frac{N_H}{3\times 10^{-3}\ \mathrm{cm}^{-3}}\right)^{-1/3}\left(\frac{B_o}{3\mu G}\right)\ \mathrm{GeV}, \quad (1)$$

which for a proton primary is falling short even of the knee of the cosmic ray energy spectrum by about 1 order of magnitude. The problem is, however, somewhat alleviated by the fact that the effective magnetic field strength at the shock can be amplified due to the growth of magnetic waves induced by accelerated cosmic rays. With the amplified field, the maximum energy achieved in a SNR can possibly reach the knee for protons, while for Fe nuclei it can reach the second knee.

When estimating the gamma-ray contribution from SNRs, protons are usually considered as accelerated particles in SNRs. However, if SNRs are the true sites of cosmic rays, they should also emit other heavier nuclei. With this context, the purpose of the present work is twofold: First, we would like to examine the spectral behavior of produced gamma rays and the conversion efficiency in a few SNRs, considering that SNRs accelerate cosmic rays with the right composition [10]. Second, we would like to consider the maximum attainable energy in SNR as $Z\times 3\times 10^{15}$ eV, where Z is the atomic number, as may be achievable under amplified magnetic field scenarios, and we shall explore the consequences in the secondary gamma-ray spectrum.

The organization of this paper is as follows: In the next section, we shall describe the methodology for evaluating the TeV gamma-ray fluxes generated in interaction of cosmic rays with the ambient matter in SNRs. In Sec. III, we shall estimate the hadronically produced GeV–TeV gamma-ray fluxes from four young SNRs and one middle-aged SNR, which have been detected in the GeV to TeV energy ranges, and we will compare our estimates with the observed spectra. We shall discuss our results in Sec. IV and finally conclude in the same section.

II. METHODOLOGY

The cosmic ray production spectrum at the shock front of SNR shall follow a power law [5]:

$$\frac{dN}{dE} = KE^{-\alpha}, \quad (2)$$

where K denotes the proportionality constant and α is the spectral index. Here ξ is the fraction of the total energy of the supernova explosion E_{SN} transferred to the cosmic ray particles. The observed gamma-ray spectra from different SNRs are not always possible to describe in terms of the interaction of hadronic cosmic rays with ambient matter if the cosmic ray energy spectrum is taken to be a single power law [7]; instead, in some cases, a broken power law for the SNR-accelerated cosmic ray energy spectrum has to be considered. For a single power law (SPL), the proportionality constant K can be written as [11]

$$K = \frac{(\alpha-2)\xi E_{SN}}{E_{\min}^{2-\alpha}-E_{\max}^{2-\alpha}} \quad \text{if } \alpha>2$$
$$= \frac{\xi E_{SN}}{\ln(E_{\max}/m_p c^2)} \quad \text{if } \alpha=2, \quad (3)$$

where $E_{\min}$ is the minimum energy and $E_{\max}$ is the maximum energy attainable by a cosmic ray particle in the SNR.

On the other hand, for a broken power law (BPL), the proportionality constant K takes the form

$$K = \xi E_{SN}\left[\frac{(E_b^{2-\alpha_1}-E_{\min}^{2-\alpha_1})}{(2-\alpha_1)}+\frac{E_b^{\alpha_2}}{E_b^{\alpha_1}}\frac{(E_{\max}^{2-\alpha_2}-E_b^{2-\alpha_2})}{(2-\alpha_2)}\right]^{-1} \quad \text{if } E_{CR}\le E_b$$
$$= \xi E_{SN}\left[\frac{(E_b^{2-\alpha_1}-E_{\min}^{2-\alpha_1})}{(2-\alpha_1)}\frac{E_b^{\alpha_1}}{E_b^{\alpha_2}}+\frac{(E_{\max}^{2-\alpha_2}-E_b^{2-\alpha_2})}{(2-\alpha_2)}\right]^{-1} \quad \text{if } E_{CR}> E_b, \quad (4)$$

where α_1 and α_2 are the spectral indices below and above the break energy E_b of the primary cosmic ray spectrum in SNR, respectively, and E_{CR} is the energy of an accelerated cosmic ray nuclei.

The shock-accelerated cosmic rays interact with the ambient matter (protons) of density n_H and produce neutral pions (π^0) along with the other particles. The emissivity of so-produced π^0 mesons is given by [12,13]

$$Q_{\pi}^{Ap}(E_{\pi}) = cn_H\int_{E_N^{th}(E_{\pi})}^{E_N^{\max}}\frac{dn_A}{dE_N}\frac{d\sigma_A}{dE_{\pi}}(E_{\pi},E_N)dE_N, \quad (5)$$

where $E_N^{th}(E_{\pi})$ is the threshold energy per nucleon, determined through kinematic considerations required to produce a pion with energy E_{π}. Here $d\sigma_A/dE_{\pi}$ is the differential inclusive cross section for the production of a pion with energy E_{π} in the lab frame by the stated process. We have used the following model with parametrization of the differential cross section for the inclusive cross section as given by [12,14]:

$$\frac{d\sigma_A}{dE_\pi}(E_\pi, E_N) \simeq \frac{\sigma_0^A}{E_N} F_\pi(x, E_N), \qquad (6)$$

where $x = E_\pi/E_N$. The inelastic part of the total cross section of p-p interactions (σ_0) is given by [15]

$$\sigma_0(E_N) = 34.3 + 1.88L + 0.25L^2 \text{ mb}, \qquad (7)$$

where $L = \ln(E_N/\text{TeV})$. We consider two different kinds of A dependence—$A^{3/4}$ [12,16] and A [17]—in the nuclear enhancement factor; the former one ($A^{3/4}$) approximately takes into account the A dependence of the inelastic cross section [16], and the latter one also considers the fact that only a fraction of projectile nucleons take part in the interaction, not all of which leads to overall A enhancement.

We use the empirical function that well describes the results obtained with the SIBYLL code by numerical simulations for the energy distribution of secondary pions, as given below [15]:

$$F_\pi(x, E_N) = 4\beta B_\pi x^{\beta-1}\left(\frac{1-x^\beta}{1+rx^\beta(1-x^\beta)}\right)^4 \times\left(\frac{1}{1-x^\beta}+\frac{r(1-2x^\beta)}{1+rx^\beta(1-x^\beta)}\right)\left(1-\frac{m_\pi}{xE_N}\right)^{1/2}, \qquad (8)$$

where $B_\pi = a + 0.25$, $\beta = 0.98/\sqrt{a}$, $a = 3.67 + 0.83L + 0.075L^2$, $r = \frac{2.6}{\sqrt{a}}$, and $L = \ln(E_N/\text{TeV})$.

The resulting gamma-ray emissivity due to the decay of π^0 mesons is given by

$$Q_\gamma^{Ap}(E_\gamma) = 2\int_{E_\pi^{\min}(E_\gamma)}^{E_\pi^{\max}} \frac{Q_{\pi^0}^{Ap}(E_\pi)}{(E_\pi^2 - m_\pi^2)^{1/2}} dE_\pi, \qquad (9)$$

where the minimum energy of a pion is $E_\pi^{\min}(E_\gamma) = E_\gamma + m_\pi^2/(4E_\gamma)$, required to produce a gamma-ray photon of energy E_γ.

The differential flux of gamma rays reaching the Earth, therefore, can be written as

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma) = \frac{1}{4\pi D^2} Q_\gamma^{Ap}(E_\gamma), \qquad (10)$$

where D is the distance between the SNR and the Earth. Therefore, if the explosion energy, ambient matter density, and distance of a SNR are known, the differential flux from that SNR can be evaluated from the above equation. In the next section, we will estimate the fluxes of a few SNRs using the above expressions.

III. TEV GAMMA-RAY FLUXES FROM A FEW SNRS

In order to compare the theoretical expectation of high-energy gamma rays with observations, at least a few individual SNRs with known values of relevant physical parameters are required; these are available at present. We have considered a general theoretical framework based on DSA, taking the simple one-zone model (i.e., the GeV and TeV gamma-ray production regions fully overlap). For the individual SNRs considered here, the parameters like explosion energy, ambient matter density, and the distance of the source are known from other considerations. We only choose the spectral index of the SNR-accelerated cosmic rays in each individual SNR so that the derived gamma-ray spectrum for the object reasonably matches with the observed spectrum.

TeV gamma rays have so far been detected from more than ten shell-type SNRs by the Cerenkov telescopes [18]. Nearly half of them are detected by Fermi as well in the GeV energy range. Here we would consider four young shell-type SNRs and one middle-aged SNR which are emitters of gamma rays in both the GeV and TeV energy ranges.

Note that the cosmic ray composition at the source should differ from the observed abundances [10] due to propagation effects [19]. In fact, due to nuclear fragmentation, the composition at the source is expected to be slightly heavier. As a first approximation, we shall consider the cosmic ray composition in SNRs to be the same as the observed cosmic ray composition. We shall further take the same power-law index for each of the nuclear species.

A. Cassiopeia A

Cassiopeia A (Cas A) is the youngest known supernova remnant of age about 350 years [20] and located at a distance of 3.4 kpc from the Earth [21]. It is a type-IIb supernova from a star of large initial mass, estimated to be between 15 and 25 $M_\odot$ by the observations of the scattered light echo from the supernova explosion [22]. Cas A is observed in almost all the wavebands—e.g., radio, optical, x rays, and gamma rays (see references in Ref. [23]). In GeV gamma rays, the source has been observed by FERMI-LAT [23], whereas the HEGRA [24], MAGIC [25], and VERITAS [26] telescopes detected the source at TeV energies. It is a unique Galactic astrophysical source for studying the origin of Galactic cosmic rays as well as high-energy phenomena in extreme conditions due to its brightness in different wavelengths. A recent model [27] reproduced the observations of the angle-averaged radii and velocities of the forward and reverse shocks and characterized it by a total ejected energy $E_{SN} = 2.3 \times 10^{51}$ erg with an envelope mass $M_{env} = 4\ M_\odot$ [27]. X-ray observations predict that the remnant is currently still interacting with the wind with a postshock density ranging between 3 and 5 cm^3 at the current outer radius of the remnant, $r_{SN} \sim 2.5$ pc.

The observed GeV–TeV gamma-ray spectrum from Cas A can be explained by hadronic interactions of cosmic rays with the ambient (proton) matter, when a power-law spectrum of protons with a power law index 2.3 is considered and the maximum energy of cosmic ray protons is taken as 100 TeV [23]. A harder spectrum with power-law index 2.1 also describes the observed spectrum when an exponential cutoff at 10 TeV is adopted [23].

We have estimated the gamma-ray flux produced in the hadronic interaction of cosmic rays with the ambient protons, taking cosmic rays with the observed mixed composition accelerated in the SNR, and considering the maximum attainable energy to be $Z \times 3 \times 10^{15}$ eV. Our results are shown in Fig. 1 along with the observed spectrum. It is found that a BPL energy spectrum of accelerated cosmic rays with spectral index $\alpha = -1.7$ below 50 GeV and $\alpha = -2.45$ above 50 GeV reproduces the observed GeV–TeV gamma-ray data well by interacting with the ambient matter. The efficiencies of conversion of the supernova explosion energy require 10% for protons, and 16.5% and 14% for mixed composition with nuclear enhancement proportional to $A^{3/4}$ and A, respectively. It is noticed that around and above 100 TeV, the flux is significantly higher when the maximum energy of the cosmic rays is taken as $Z \times 3$ PeV than that the flux due to a maximum energy of 200 TeV. Future large-area telescopes like CTA, therefore, should able to probe the maximum attainable energy up to which cosmic rays can accelerate in supernova remnants like Cas A.

B. Tycho supernova remnant

Tycho's SNR, one of the youngest remnants in the Galaxy, originated from a type Ia supernove in 1572 due to a thermonuclear explosion of a binary system. Fermi has observed Tycho in the GeV energies [28], whereas the VERITAS Collaboration observed the source in the 1–10 TeV range. The observed overall gamma-ray spectrum of Tycho is found to be consistent with the early theoretical predictions [6]. A single power law with a photon index of 2.1–2.2 can describe the GeV–TeV energy spectrum well [29,30].

We have made the same kind of analysis as we did for Cas A. The distance of the source from the Earth is not very conclusively determined; we have taken the distance to be 2.8 kpc [31]. The density of the ambient matter is 0.9 cm^3, and the explosion energy is 1.2×10^{51} ergs [32,33]. We find that a single power-law accelerated cosmic ray energy spectrum with the spectral index $\alpha = -2.3$ describes the GeV–TeV observed gamma-ray data well, as shown in Fig. 2. For protons, a 12% efficiency of conversion of supernova explosion energy to cosmic ray energy can explain the experimental results, whereas 19.8% and 16.8% conversion efficiency has to be taken for nuclear enhancement by $A^{3/4}$ and A, respectively, to explain the observations with mixed primaries.

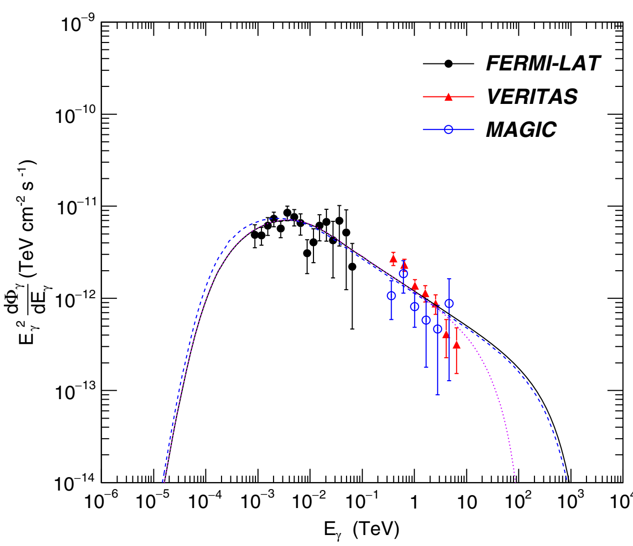

FIG. 1. Estimated differential energy spectrum of gamma rays reaching at the Earth from the Cas A SNR. The black continuous line and blue dashed line denote the gamma-ray flux for SNR-accelerated pure protons and mixed primaries, respectively. The pink dash-dotted line denotes the gamma-ray flux considering a maximum attainable energy of cosmic ray protons of 200 TeV.

C. SN1006

The SN 1006 remnant source appeared in the southern sky on 1 May 1006 and was recorded by Chinese and Arab astronomers. In recent years, the source has been detected in the GeV gamma-ray energy range by Fermi [34] and in TeV energies by the HESS telescope [35]. The gamma-ray flux from SN1006 is, however, quite low—just about a% of the Crab flux. The gamma-ray flux is found mainly concentrated in two extended regions, one in the northeast and another in the southwest. The observed overall gamma-ray spectrum can be interpreted as a consequence of the interaction of supernova shock-accelerated cosmic rays (protons) with the ambient matter. In such a scenario, the

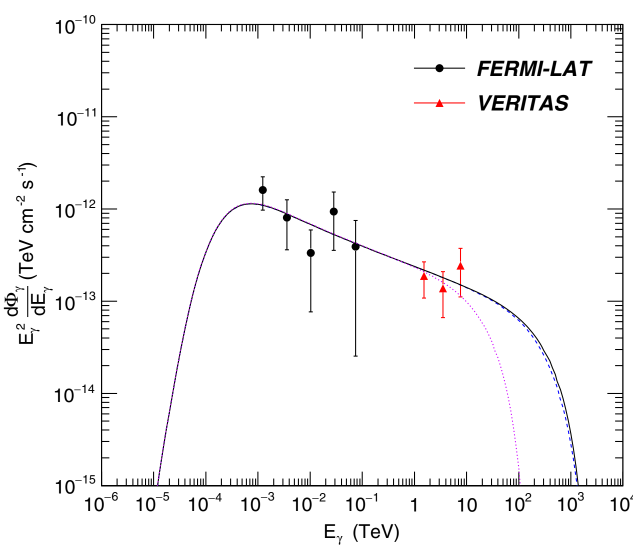

FIG. 2. Same as Fig. 1, but for SNR Tycho.

power-law spectral index may be taken either as 2.3 above 1 TeV with essentially no upper cutoff and a harder spectral index (<2.0) below 1 TeV, or as a single flat power law with index ∼2.0 with an exponential cutoff at 80 TeV [35].

A distance of 2.2 kpc for SN1006 was reported by Winkler *et al.* [36] by comparing the optical proper motion with an estimate of the shock velocity derived from optical thermal line broadening assuming a high-Mach-number single-fluid shock [35]. We consider the explosion energy of the supernova to be $E_{SN} = 2.4 \times 10^{51}$ ergs [37]. SN 1006 is about 500 pc above the Galactic plane, where the external gas density is rather low: $n_H = 0.08$ cm^{-3} [35,37]. The estimated differential gamma-ray flux reaching the Earth from this SNR is shown in Fig. 3 along with the observations by the FERMI-LAT and HESS telescopes. The observed data can be explained well by considering the spectral index of accelerated cosmic ray spectra in the SNR $\alpha = -2.05$. A significant flux difference has been noticed above 100 TeV between the scenarios with the maximum energy of cosmic rays 3 PeV and 200 TeV. When we consider the proton as a primary cosmic ray spectrum up to 200 TeV, the conversion efficiency of 10% is needed to fit the FERMI-LAT and HESS observational data. Instead, if the energy of primary protons is extended up to 3 PeV, a 11.5% efficiency of energy conversion is required; whereas for mixed primaries, the efficiency has to be taken as 16% and 12.5% considering nuclear mass enhancement factors $A^{3/4}$ and A, respectively.

D. RX J1713.7-3946

RX J1713.7-3946 is a young shell-type SNR located in the Galactic plane within the tail of the constellation Scorpius, and the age of the object is 1600 years [38]. It is one of the best-studied SNRs from which both nonthermal x rays and TeV gamma rays are detected. The CANGAROO Collaboration in 1998 [38,39] reported the first detection of TeV gamma-ray emission from the SNR, and it was confirmed by the subsequent observations with CANGAROO-II in 2000 and 2001 [40]. Later, a resolved image of the source in TeV gamma rays [41] was obtained by the HESS Collaboration, and it was reported that the gamma-ray emission from RX J1713.7-3946 arises mainly in the shell.

The observation of the source in the GeV energy region by the Fermi telescope suggests a hard photon spectrum with a power-law spectral index 1.50 ± 0.11. The overall GeV to TeV energies can be explained by cosmic ray interactions with ambient matter, assuming a very hard spectrum of protons with power-law index 1.7 and an exponential cutoff at 25 TeV. The estimated upper cutoff (at 25 TeV) raises doubt on the acceleration of cosmic ray particles to PeV energies by the RX J1713.7-3946 SNR.

The distance of the SNR from the Earth is ∼1 kpc, and the radius of the shell is about 10 pc. The ambient matter density of the SNR is ∼1 cm^{-3} [38]. The total mechanical explosion energy of the supernova is taken as $E_{sn} = 1 \times 10^{51}$ eV.

The calculated high-energy gamma-ray flux from the SNR reaching Earth is given in Fig. 4. The observed data can be explained well, assuming the spectral index of the energy spectrum of SNR accelerated cosmic rays to be $\alpha = -1.8$. When we consider the proton as a primary cosmic ray spectrum up to 100 TeV, 15% of the total explosion energy is needed in accelerated particles to fit the FERMI-LAT and HESS observational data. If a primary cosmic ray proton spectrum up to 200 TeV is considered, then a 17% efficiency of such energy conversion is required. Again, if a primary cosmic ray proton spectrum

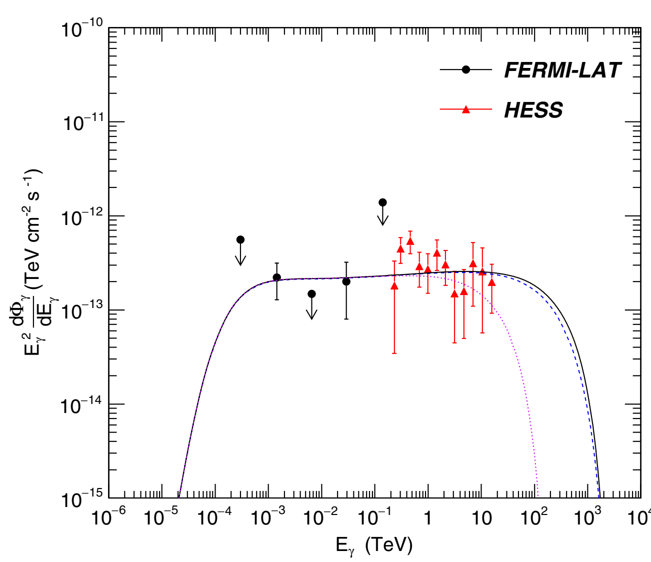

FIG. 3. Same as Fig. 1, but for SNR SN1006.

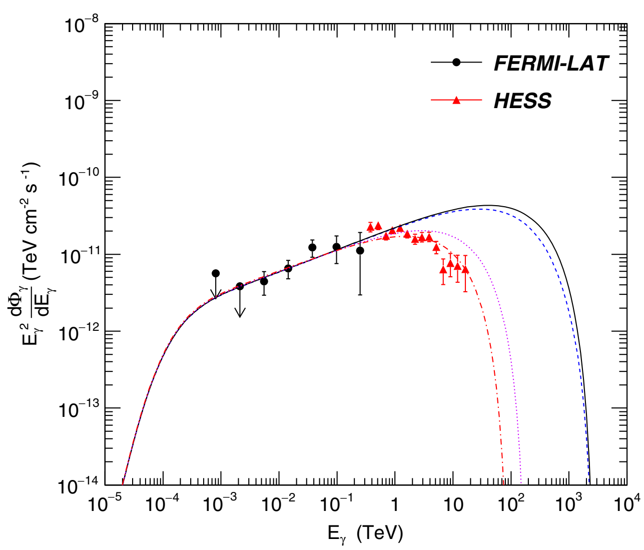

FIG. 4. Same as Fig. 1, but for SNR RX J1713.7-3946. The red dash-dotted line denotes the gamma-ray flux considering a maximum attainable energy for cosmic rays of 100 TeV.

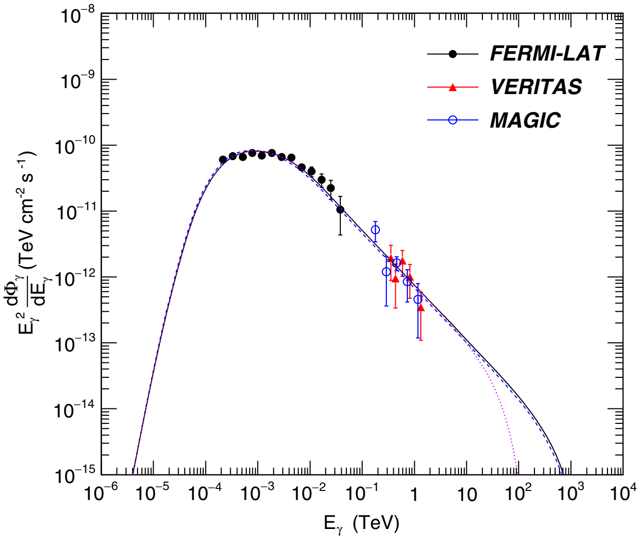

FIG. 5. Same as Fig. 1, but for SNR IC 443.

up to 3 PeV is considered, then 30% efficiency of such energy conversion is needed. For mixed primaries with a rigidity dependent cutoff, 32% and 22% efficiencies of conversion are needed for the nuclear mass enhancement factors $A^{3/4}$ and A, respectively.

E. IC 443

Gamma-ray emission from two middle-aged SNRs, IC443 and W44, is detected over sub-GeV to TeV energies. The observation of the spectral continuum down to 200 MeV from these two sources is often attributed to a neutral pion emission. Both are asymmetric shell-type SNRs. The gamma-ray emission from W44 comes from two regions of the SNR, which are likely to be embedded molecular clusters, but not from the entire SNR. We therefore choose IC 433 to examine here.

IC 443 is located off the outer Galactic plane at a distance of nearly 1.5 kpc [42]. It is a strong x-ray source. The EGRET telescope first detected gamma-ray flux from the source above 100 MeV [43]. The Major Atmospheric Gamma Imaging Cerenkov (MAGIC) telescope first detected TeV gamma rays from IC 433 [44]. Later, Fermi observed the source in the GeV energy range [45], and VERITAS confirmed the TeV gamma emission from the SNR [46]. The MAGIC detection is displaced towards the south from the EGRET source, and it was argued that the MAGIC-detected TeV emission from IC 433 essentially comes from a giant cloud in front of the SNR [47].

The explosion energy is not clearly known by any other means. Hence, we take the standard value $E_{sn} = 1 \times 10^{51}$ eV. The molecular environment suggests $n_H = 20$ cm^{-3} [8]. The estimated high-energy gamma-ray flux from the SNR reaching Earth following Eqs. (2)–(10) is displayed in Fig. 5 along with the Fermi and MAGIC observed data points. Here we consider a broken power law for the SNR accelerated cosmic ray energy spectrum, and it is found that a spectral index of $\alpha = -2.1$ below 30 GeV and $\alpha = -2.9$ above it fits the observed data well. A 10% efficiency of conversion is needed for pure accelerated protons to explain the observed gamma-ray spectrum; whereas 17.5% and 15.5% efficiencies of conversion are required for the mixed composition with nuclear enhancement factors $A^{3/4}$ and A, respectively, to explain the observed spectrum.

TABLE I. Model fitting parameters for the SNRs, where ξ_1 is measured considering the wounded nuclei approach and ξ_2 is measured considering the nuclear enhancement approach.

Supernovae	Model	Composition	$E_{\rm cut}$ (eV)	E_b (GeV)	α	ξ_1 (%)	ξ_2 (%)
Cas A	BPL	p	2×10^{14}		$\alpha_1 = -1.7$,	10	10
		p	3×10^{15}	50	$\alpha_2 = -2.45$	10	10
		mixed	$Z \times 3 \times 10^{15}$			16.5	14
Tycho	SPL	p	2×10^{14}			12	12
		p	3×10^{15}	...	−2.3	12	12
		mixed	$Z \times 3 \times 10^{15}$			19.8	16.8
SN 1006	SPL	p	2×10^{14}			10	10
		p	3×10^{15}	...	−2.05	11.5	11.5
		mixed	$Z \times 3 \times 10^{15}$			16	12.5
RX J1713.73946	SPL	p	1×10^{14}			15	15
		p	2×10^{14}			17	17
		p	3×10^{15}	...	−1.8	30	30
		mixed	$Z \times 3 \times 10^{15}$			32	22
IC 443	BPL	p	2×10^{14}		$\alpha_1 = -2.1$,	10	10
		p	3×10^{15}	30	$\alpha_2 = -2.9$	10	10
		mixed	$Z \times 3 \times 10^{15}$			17.5	15.5

IV. DISCUSSION

The main effect of considering cosmic ray nuclei with the right abundances instead of pure protons on the secondary gamma-ray spectra is the need of higher conversion efficiency. The conversion efficiencies required to match the gamma-ray spectra of each of the SNRs considered here is shown in Table I. Note that the SNR energy output in the Galaxy can supply the energy budget required to maintain the present population of cosmic rays if the overall efficiency of conversion of the explosion energy into cosmic ray particles is of the order of 10%. Nearly the same conversion efficiency is required to explain the high-energy gamma-ray emission observed from different SNRs in the Galaxy in terms of interactions of SNR accelerated protons with the ambient matter, and therefore the scenarios (cosmic ray density and gamma-ray emission from SNRs) are mutually consistent. However, when mixed composition is invoked in evaluating the gamma-ray spectrum, a higher efficiency is needed. Such higher conversion efficiency seems also necessary to maintain the observed cosmic ray energy density over a long period, as the gamma-ray observations already indicate that all the SNRs are not the generators of hadronic cosmic rays.

A point to note is that the slope of the spectra of accelerated cosmic rays required to explain the observed gamma-ray spectra in different SNRs is not unique. It is important to understand how such energy spectra of SNR-accelerated cosmic rays with deviating spectral slopes lead to cosmic ray energy spectra with a universal spectral slope.

In recent theoretical developments of the DSA theory in SNRs, it is argued that a significant amplification of the magnetic field occurs as a result of the pressure gradient of the accelerating cosmic rays, and thereby protons might be accelerated in SNRs up to the knee energy of the spectrum, whereas heavier nuclei will have Z times higher energy that of the proton. In such a scenario, the gamma-ray flux from young SNRs would be significantly higher at a few tens of TeV, and higher energies than the flux correspond to cosmic rays with a maximum energy limited to 200 TeV or so. The next generation of gamma-ray telescopes like CTA should be able to discriminate between these two scenarios of maximum energy. There is a possibility that the higher-energy cosmic ray particles might have already escaped from the SNRs considered here, but it is quite unlikely that even for the young SNR Cas A such leakage has happened already, since in the standard DSA scenario, particles up to PeV energies are likely to be confined in the remnant over a period of 10^4 years or so [3,48].

V. CONCLUSION

There is now broad consensus that the bulk of the cosmic rays with energies at least up to the second knee are originated in Galactic SNRs, where they are accelerated by DSA processes in supernova blast waves driven by expanding SNRs. It is now also generally believed that higher-energy (>200 TeV) particles are accelerated in the early phases of the supernova explosion (i.e., in young SNRs), though so far there is no experimental support in favor of this SNR paradigm. Further, if SNRs are true generators of Galactic cosmic rays, they should accelerate not only protons but also different cosmic ray nuclei with the proper abundances. The gamma rays produced in the interaction of SNR-accelerated cosmic rays with ambient matter may contain the imprints of such features (the acceleration of cosmic ray nuclei to PeV energies). To explore such signatures in this work, we estimate the hadronically produced high-energy (GeV–PeV) gamma rays to be emitted by individual SNRs, considering that (i) SNRs accelerate cosmic ray particles with mass compositions consistent with the observed mass composition of cosmic rays, and (ii) the maximum attainable energy of cosmic rays in SNRs is $Z \times 3 \times 10^{15}$ eV, which is needed to explain the cosmic ray spectrum up to 100 PeV, including the knee and the second knee features. Comparing with observations, we evaluated the conversion efficiency, and we also obtained the gamma-ray spectrum up to PeV energies, which is beyond the upper energy limit of detection of the presently operating telescopes but is within the reach of the forthcoming gamma-ray telescopes like CTA.

The nature of gamma-ray emission spectra from SNRs is found to be almost independent of the type of SNR-accelerated cosmic ray nuclei if the spectral slope of each nuclei species is taken to be the same. The energy spectra of cosmic ray heavier nuclei are harder than that of cosmic ray protons. If such a feature is adopted, the SNR-produced gamma-ray spectrum is expected to be a slightly harder one than what we found. An interesting point is that to match the high-energy gamma-ray spectrum from individual SNRs with SNR-accelerated cosmic ray nuclei instead of pure protons, the conversion efficiency has to be taken to be nearly double (∼20%) in comparison to those produced by pure proton cosmic rays. A conversion efficiency of the order of 20% is not unrealistic, but of course it is more demanding. The density of SNR ambient matter and the total explosion energy are two important parameters in our estimation of the gamma-ray flux. We have taken the values obtained by previous authors from different considerations. But still some uncertainties remain on these parameters, and thereby the absolute values of efficiencies are also somewhat uncertain.

Regarding the issue of the maximum energy of cosmic rays in SNRs, we compare two different scenarios: 2×10^{14} eV, which is the theoretical upper limit under a normal magnetic field picture, and $Z \times 3 \times 10^{15}$ eV, which seems achievable under an amplified magnetic field situation. The latter (Pevatron) scenario is, in fact, essential for the SNR origin model of Galactic cosmic rays. We find that both the scenarios can somewhat describe the observed gamma-ray spectra of all the SNRs considered in this work except for RX J1713.7-3946. In the case of RX J1713.7-3946, the maximum cosmic ray energy appears to be much lower, and it is more likely that gamma-ray emission from RX J1713.7-3946 is leptonic in origin. The Pevatron scenario in fact better describes the TeV gamma-ray observations from SNRs at Tycho and SN1006. The two stated scenarios give significantly different fluxes above a few tens of TeV, and therefore the experiment HAWC or upcoming experiments like CTA should be able to discriminate between the two maximum energy pictures.

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