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Reassessing Galactic Cosmic-Ray Sources Using GeV–PeV Gamma-Ray Spectra

Arunava Bhadra*
High Energy and Cosmic Ray Research Centre,
University of North Bengal, Rajarammunpur 734015, India

Prabir Banik†
Anbeshan Research Institute, Shibmandir, Siliguri 734011, India

Cosmic rays (Crs) with energies up to a few tens of PeV are generally believed to originate within our galaxy, while those exceeding a few EeV are thought to have extragalactic origins. Supernova remnants (SNRs) are widely considered the most likely sources of galactic CRs. Detecting high-energy gamma rays and neutrinos with appropriate flux levels from potential astrophysical sources could provide definitive evidence linking them to CR production. In this study, we critically evaluate the SNR paradigm in light of recent high-energy gamma-ray observations. Specifically, we examine the spectral indices of gamma-ray emissions from various SNRs based on multiple observations. Our key findings include: i) Not all SNRs function as PeVatrons, as their maximum CR energies fall below the expected knee energy. ii) The spectral indices of gamma-ray emissions from different SNRs vary significantly, contradicting theoretical predictions. Additionally, observations from the Large High Altitude Air Shower Observatory (LHAASO) suggest that several pulsars may act as CR PeVatrons. We also investigate the potential of pulsars as primary CR sources within our galaxy and find that PeV gamma-ray spectra from both SNRs and pulsars are softer than their GeV and TeV counterparts. These findings challenge the widely accepted SNR paradigm as the primary source of galactic CRs. Furthermore, the pulsars detected at PeV energies by LHAASO are also unlikely to be the dominant sources of galactic CRs.

I. INTRODUCTION

Cosmic rays (CRs) are a highly isotropic flux of relativistic particles, predominantly charged, that continuously reach the vicinity of the Earth from outer space. Despite extensive experimental and theoretical efforts, their exact origins remain uncertain. Owing to their electric charge, CRs are deflected by the Galactic magnetic field—except at the highest energies—preventing a direct reconstruction of their trajectories back to their sources. The observed near-isotropy of CRs is therefore generally attributed to their confinement and diffusion within the interstellar magnetic field. As a consequence, the energy density of CRs throughout the Galaxy is expected to be comparable to that measured locally near the Earth. Energetic considerations strongly suggest that CRs with energies up to at least the PeV scale (10^{15} eV) are predominantly of Galactic origin. If CRs with a comparable energy density were instead distributed throughout extragalactic space,

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* aru_bhadra@yahoo.com
† pbanik74@yahoo.com

the required power output of their sources would be unrealistically large. In addition, the gamma-ray background produced by CR interactions with intergalactic gas would significantly exceed observed levels. At energies above $\sim$ 1 EeV (10^{18} eV), CRs are generally believed to be of extragalactic origin. This inference follows from the fact that, in a typical interstellar magnetic field of a few microgauss, the Larmor radius of such high-energy particles exceeds the size of the Milky Way, preventing their confinement and isotropization. Despite more than a century of research since their discovery, the origin of cosmic rays thus remains an open and fundamental problem in astroparticle physics [1–3].

The prevailing theoretical framework identifies supernova remnants (SNRs) as the primary sources of non-solar Galactic CRs, particularly at energies up to ~ 100 PeV [1, 2]. Together with the current understanding of CR transport in the Galaxy, this picture is commonly referred to as the *supernova remnant paradigm for the origin of Galactic cosmic rays*. Assuming a canonical energy conversion efficiency of about 10%, whereby a fraction of the kinetic energy released in a supernova explosion is transferred to CRs, the Galactic supernova rate is, in principle, sufficient to sustain the observed CR energy density. However, the argument that supernovae alone can account for the entire observed CR population with an efficiency of $\sim 10\%$ is incomplete. The CR energy density ρ may be expressed as

$$\rho = \frac{4\pi}{\beta c} \int_{E_{\min}}^{E_{\max}} E \frac{dN}{dE}\, dE, \tag{1}$$

where β and c have their usual meanings. Because the differential CR energy spectrum follows a steep power law with a spectral index of ~ 2.7, the contribution to the energy density is dominated by the lower-energy end of the spectrum rather than by $E_{\max}$. Crucially, this relation must hold for all values of $E_{\min}$, not only for the lowest energies accessible to observations. Therefore, the CR production spectrum at the source must, after accounting for transport effects, consistently reproduce the observed spectrum while satisfying the global power requirement across the entire energy range. The spectral index of the production spectrum thus plays a central role in assessing the viability of any proposed CR source class.

A well-established mechanism for transferring bulk kinetic energy into non-thermal particle energy is diffusive shock acceleration (DSA), which operates naturally at collisionless shocks in SNRs. Observationally, the CR energy spectrum follows a power law with a spectral index of approximately -2.7 at energies beyond solar modulation up to a few PeV [1, 2, 4]. In contrast, standard DSA predicts a source spectrum close to a power law with an index near -2.0 for strong shocks [2, 5]. The difference between the production and observed spectral indices is generally attributed to energy-dependent diffusive propagation in the interstellar medium. A major challenge within this paradigm concerns the maximum energy achievable in SNR shocks. For example, in a $\sim$ 1000-year-old SNR with a shock velocity of $\sim$ 3000 km s^{-1}, the maximum proton energy attainable under standard conditions is only a few TeV. It has been proposed, however, that accelerated particles can excite magnetic turbulence, leading to significant magnetic-field amplification. Within the framework of non-linear DSA, such amplification may allow particles to reach energies of order Z times the "knee" energy (~ 3 PeV), where Z is the atomic number. At this energy, the observed CR spectrum steepens, with the spectral index changing from ~ -2.7 to ~ -3.1.

Primary CRs interacting with ambient matter and radiation fields in their source environments are expected to produce high-energy gamma rays and neutrinos. High-energy gamma-ray and neutrino astronomy, therefore, provides powerful and relatively direct probes of CR acceleration sites. Over the past two decades, advances in both space- and ground-based observatories have transformed our view of the high-energy universe. At GeV energies, the *Fermi* Large Area Telescope (Fermi-LAT) has been conducting an all-sky survey since 2008, detecting 6,658 Galactic and extragalactic gamma-ray sources during its first 12 years of operation [6]. At TeV energies, ground-based imaging atmospheric Cherenkov telescopes (IACTs) have identified more than 200 very-high-energy (VHE) gamma-ray sources, although their limited duty cycles restrict their suitability for long-term surveys. Extensive air shower arrays, by contrast, offer continuous sky coverage. The Large High Altitude Air Shower Observatory (LHAASO), located at an altitude of 4,410 m in China, combines three detector systems (WCDA, KM2A, and WFCTA) and has already detected 90 sources above 1 TeV and 43 sources above 100 TeV, with a sensitivity of about 12 milli-Crab units (CU) [7, 8]. In parallel, the IceCube Neutrino Observatory—the first gigaton-scale neutrino detector—has searched for neutrino emission from the Milky Way, reporting evidence for diffuse emission along the Galactic plane, although no Galactic point sources have yet been identified [9]. Together, these facilities enable multi-messenger investigations of CR origins through complementary gamma-ray and neutrino observations.

Gamma rays in astrophysical environments are produced primarily through interactions involving relativistic protons and electrons. Relativistic electrons generate gamma rays via inverse Compton scattering of low-energy photons, while high-energy protons interact with ambient matter, producing neutral pions that subsequently decay into gamma rays. A key feature of hadronic gamma-ray emission is that its spectral index closely traces that of the parent CR population [10]. When diffusive propagation effects are taken into account, the gamma-ray spectral index expected from CR interactions at the source typically lies in the range -2.1 to -2.4 for energies below the knee, with a gradual softening from 2.5 to 2.7 at higher energies.

In this context, the objective of the present work is to assess the consistency of observed gamma-ray spectral indices with theoretical expectations for viable classes of Galactic CR accelerators, using recent advances in very-high-energy gamma-ray astronomy. We focus in particular on Galactic SNRs and pulsars. The remainder of the paper is organized as follows. In the next section, we outline the expected spectral characteristics of gamma rays produced by CR interactions with ambient matter in source environments. Section III presents an analysis of gamma-ray spectral indices of Galactic SNRs observed by Fermi-LAT, IACTs, and LHAASO. Section IV examines gamma-ray spectral indices of a sample of pulsars in light of recent LHAASO observations. In Sect. V, we discuss the implications of our results for Galactic CR sources, and Sec. VI summarizes our conclusions.

II. EXPECTED SPECTRAL INDEX OF GAMMA-RAYS FROM THE SNRS AND PULSARS

For a falling power law cosmic rays production spectrum as given below

$$\frac{dN}{dE} = KE^{-\alpha}, \tag{2}$$

where K denotes the proportionality constant and α is the spectral index, the emissivity of π^0 mesons produced in interactions of cosmic rays with the ambient matter (protons) of density n_H is given by [11, 12],

$$Q_{\pi}^{pp}(E_\pi) = cn_H \int_{E^{th}(E_\pi)}^{E^{max}} \frac{dN}{dE}\frac{d\sigma}{dE_\pi}(E_\pi, E)dE\ . \tag{3}$$

Here $E^{th}(E_\pi)$ represents the threshold energy, determined based on kinematic considerations necessary to produce a pion with energy E_π. The term $d\sigma/dE_\pi$ denotes the differential inclusive cross-section for producing a pion with energy E_π in the lab frame through the specified process. The resulting gamma ray emissivity due to decay of π^0 mesons is given by,

$$Q_\gamma^{pp}(E_\gamma) = 2\int_{E_\pi^{min}(E_\gamma)}^{E_\pi^{max}} \frac{Q_{\pi^0}^{pp}(E_\pi)}{(E_\pi^2 - m_\pi^2)^{1/2}} dE_\pi, \tag{4}$$

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 inclusive cross section to produce a pion with energy E_π can be expressed as [11, 13],

$$\frac{d\sigma}{dE_\pi}(E_\pi, E) \simeq \frac{\sigma_0}{E} F_\pi(x, E), \tag{5}$$

where $x = E_\pi/E$. The inelastic part of the total cross section of p-p interactions (σ_0) has a weak energy dependance, the empirical fitting of accelerator results gives [14]

$$\sigma_0(E) = 34.3 + 1.88L + 0.25L^2\, mb, \tag{6}$$

where $L = \ln(E/TeV)$. The energy distribution of secondary pions also has a weak dependence on primary energy of the proton when expressed in terms of the variable x [14]. Consequently, the energy spectrum of gamma rays produced by the interaction of cosmic rays with ambient matter should resemble that of cosmic rays.

The spectrum of cosmic rays in a SNR is typically very close to E^{-2} [15]. In the case of pulsars, two different scenarios may arise. In one scenario, particles are accelerated by a large-scale electric field in the magnetosphere, which is expected to develop due to the rotating magnetic dipole of the pulsar [16, 17]. In this case, the energy spectrum will be harder, with a spectral index of approximately -1.0 [16]. In the other scenario, particles are primarily accelerated in the pulsar wind nebula through diffusive shock acceleration (DSA) following their injection from the pulsar. In this case, the spectrum will be much softer, with a spectral index of around -3.0 [18].

III. ANALYSIS OF THE SPECTRAL INDICES OF GAMMA-RAYS FROM THE SNRS OF OUR GALAXY

The estimated fluxes of TeV gamma rays from supernova remnants (SNRs) located within a few kiloparsecs are well above the detection sensitivities of modern gamma-ray telescopes [10]. Despite this, comprehensively classifying SNRs in gamma rays remains challenging. Certain objects have been identified as SNRs based on their spectral morphology and multiwavelength characteristics. To date, approximately 40 SNRs have been firmly identified in GeV gamma-ray energies. In very high energy (VHE) and ultra-high energy (UHE, above 100 TeV) gamma-ray observations, the numbers of confirmed sources are 20 and 3, respectively [19].

Figure 1 illustrates the spectral indices of GeV gamma rays from 32 classified SNRs (whose locations reasonably overlap with SNRs observed in the radio band) from the first Fermi-LAT SNR catalog [20]. These sources were observed by Fermi-LAT over a 36-month period from August 4, 2008, to August 4, 2011, with a minimum threshold energy of 1 GeV. In addition to

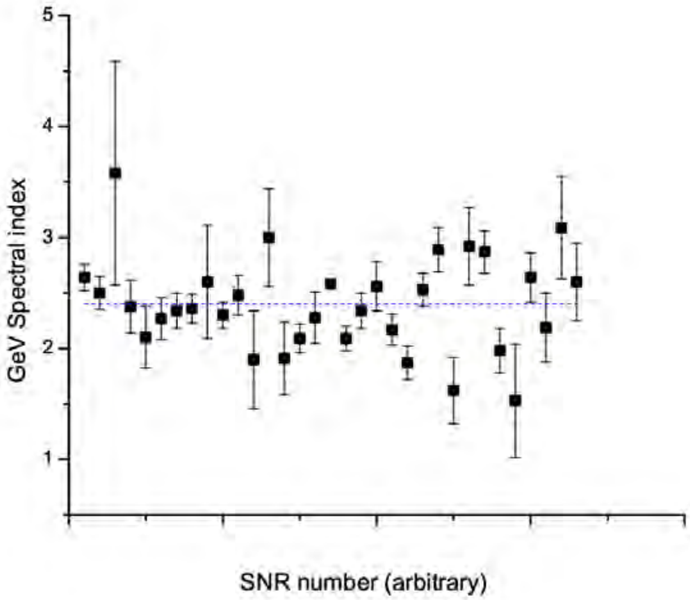

FIG. 1. Spectral indices of Fermi-LAT observed and confirmed SNRs. The dashed line represents the average spectral index of the sample.

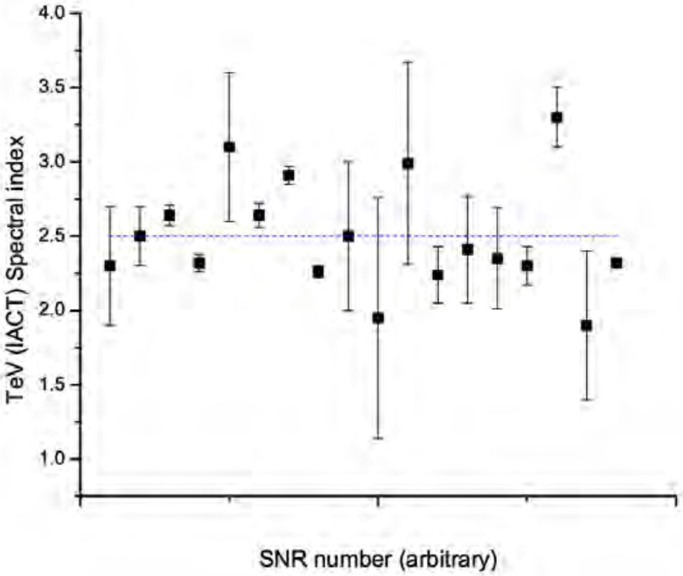

FIG. 2. Same as Fig. 1 but for IACT-observed and confirmed SNRs at TeV energies.

statistical errors, systematic uncertainties arise primarily from interstellar emission modeling and effective area calibration. The mean spectral index of GeV gamma-ray emission from these SNRs is 2.40 ± 0.10, with a standard deviation of 0.26.

IACTs have detected TeV gamma rays from about 20 confirmed SNRs, of which 18 are also observed in GeV energies [19]. The spectral indices of these sources are shown in Fig. 2. Due to limited exposure times and smaller sample sizes, the uncertainties in the estimated spectral indices

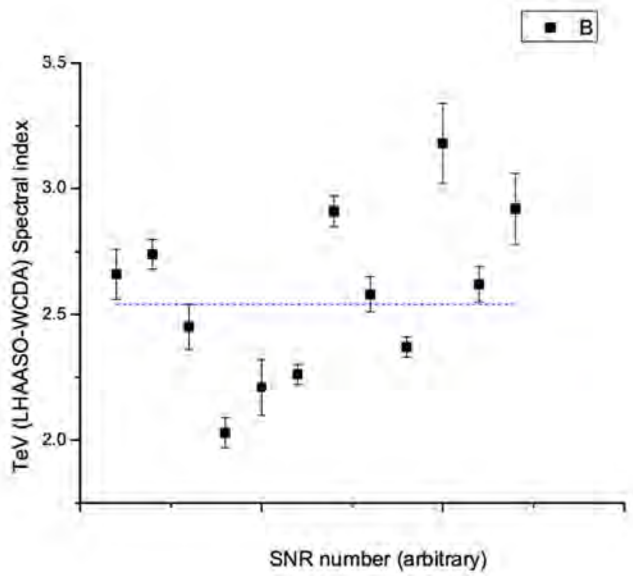

FIG. 3. Same as Fig.1 but for LHAASO-WCDA observed SNRs at TeV energies. The dashed line represents the average spectral index of the sample.

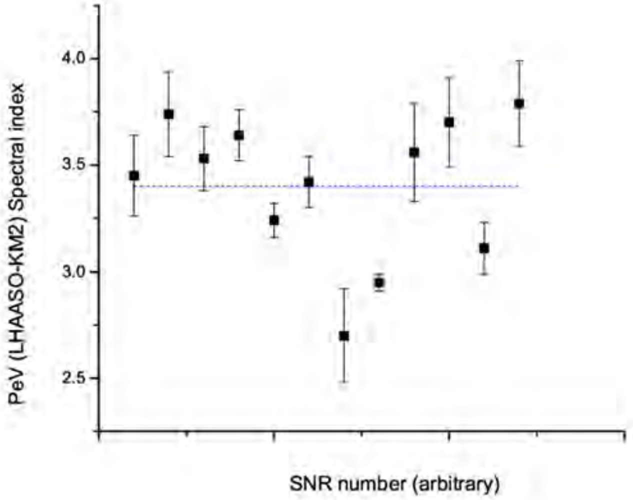

FIG. 4. Same as Fig. 1 but for LHAASO-KM2A observed SNRs with energy threshold 100 TeV. The dashed line represents the average spectral index of the sample.

are relatively larger compared to Fermi-LAT and LHAASO results. The mean spectral index of TeV gamma-ray emission from IACT-detected SNRs is 2.46 ± 0.07, with a standard deviation of 0.30.

The WCDA of the LHAASO observatory has detected TeV gamma rays from around 12 SNRs, including newly identified ones [8]. The spectral indices of these sources are shown in Fig. 3. The mean spectral index of TeV gamma-ray emission from WCDA-detected SNRs is 2.55 ± 0.09, with a standard deviation of 0.33. Similarly, the KM2A detector of the LHAASO observatory has detected TeV gamma rays from about 12 SNRs, including new sources [8]. The spectral indices

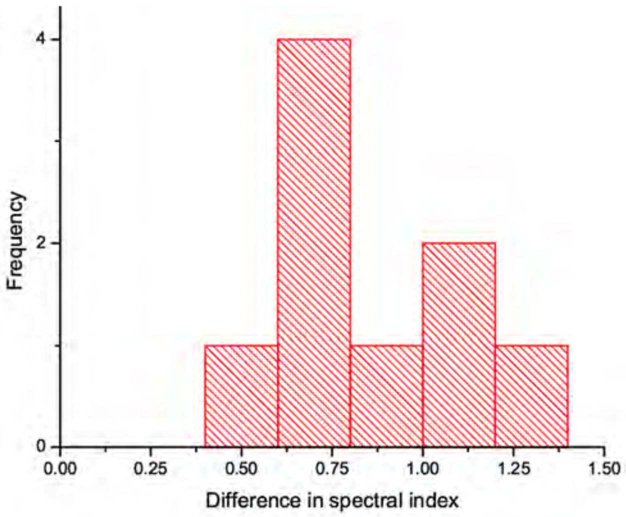

FIG. 5. Histogram showing the differences in spectral indices for the same SNRs as measured by KM2A and WCDA.

of these sources are presented in Fig. 4. The mean spectral index of PeV gamma-ray emission from KM2A-detected SNRs is 3.40 ± 0.10, with a standard deviation of 0.34. Given that galactic CRs extend to energies of at least a few PeV with a power-law spectrum characterized by a single spectral index, the gamma rays produced by these CRs in their source environments should exhibit a constant spectral slope up to a few hundred TeV. However, as noted above, the spectral slope of gamma rays from SNRs with a threshold energy of 100 TeV is significantly softer than that observed at TeV energies. Figure 5 displays a histogram of the differences in spectral indices for the same SNRs as measured by KM2A and WCDA.

TABLE I. Estimated spectral indices of observed PeV gamma-ray emission from SNRs.

SNRs	**WCDA**	**KM2A**
γ-Cygni J2019+407 $\mathrm{G}78.2+02.1$	2.91 ± 0.06	3.56 ± 0.23
$\mathrm{G}106.3+02.7$	2.26 ± 0.04	2.95 ± 0.04
W51 $\mathrm{J}1922+1403$	2.62 ± 0.07	3.79 ± 0.20
W51 $\mathrm{J}1924+1609$	2.54 ± 0.08	3.61 ± 0.22

The three confirmed SNRs detected by both the WCDA and KM2A detectors of the LHAASO observatory are W51C, γ-Cygni, and G106.3+02.7 (also identified as 1LHAASO J2228+6100u) [8]. SNRs that interact with surrounding molecular clouds (MCs) provide direct evidence of SNRs accelerating cosmic-ray (CR) nuclei. Prior to LHAASO, gamma-ray spectral measurements of these interacting SNRs were limited to energies below approximately 10 TeV. W51C is a notable example of an interacting SNR, recognized for its prominent π^0-decay feature in the gamma-ray spectrum. Located approximately 5.5 kpc away and estimated to be around 30,000 years old, W51C is widely believed to be interacting with the molecular cloud associated with the nearby star-forming region W51B. Recent LHAASO observations have detected gamma rays at energies

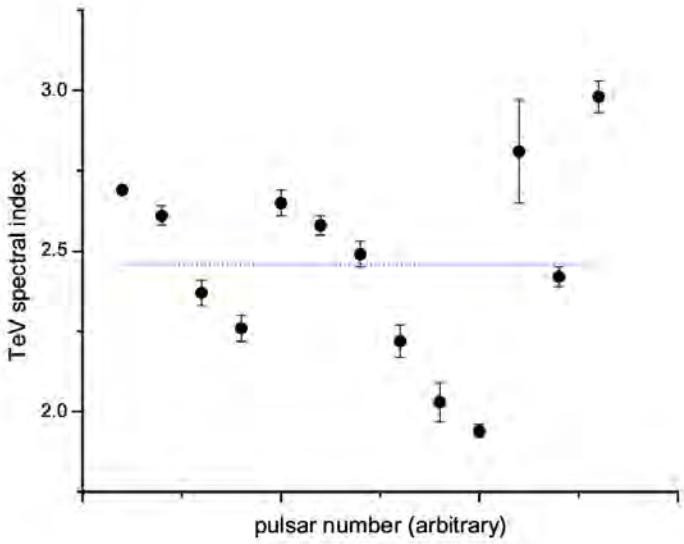

FIG. 6. Same as Fig. 1, but for a sample of LHAASO-WCDA observed pulsars at TeV energies. The dashed line represents the average spectral index of the sample.

reaching 100 TeV from the molecular clouds surrounding W51C. Table I presents the spectral indices of gamma-ray emissions from the three SNRs observed by LHAASO in the Milky Way [8]. For W51C, the gamma-ray emissions from nearby regions $J1922 + 1403$ and $J1924 + 1609$ are included. Observations reveal that the spectral indices of gamma-ray emissions from different SNRs vary significantly, even at lower energies. The steep gamma-ray spectra observed in several SNRs by Fermi-LAT and LHAASO are inconsistent with the predictions of DSA theory for cosmic rays in SNRs. This inconsistency is particularly notable, as no alternative mechanism to DSA.

IV. ANALYSIS OF THE SPECTRAL INDICES OF GAMMA-RAYS FROM THE PULSARS

In 2021, the LHAASO Collaboration reported the observation of ultrahigh-energy photons, reaching up to 1.4 PeV, from 12 Galactic gamma-ray sources [21]. However, the collaboration did not provide gamma-ray spectra for all of these sources, and some were not included in their first source catalog. Of the 12 Pevatron sources detected by LHAASO up to 2021, nine are associated with known pulsars or pulsar wind nebulae (PWNe) [21]. From the LHAASO first catalog, spectral data are available for seven such pulsar candidates [8]. The spectral indices of these sources are presented in Figs. 6 and 7 for WCDA and KM2A observations, respectively. The mean spectral index of the TeV gamma-ray emission from WCDA-detected pulsars is 2.46 ± 0.08, with a standard deviation of 0.30. For KM2A observations, the mean spectral index of the pulsars/PWNe is 3.14 ± 0.10, with a standard deviation of 0.37.

V. DISCUSSION

The recent gamma-ray observations reveal several noteworthy features:

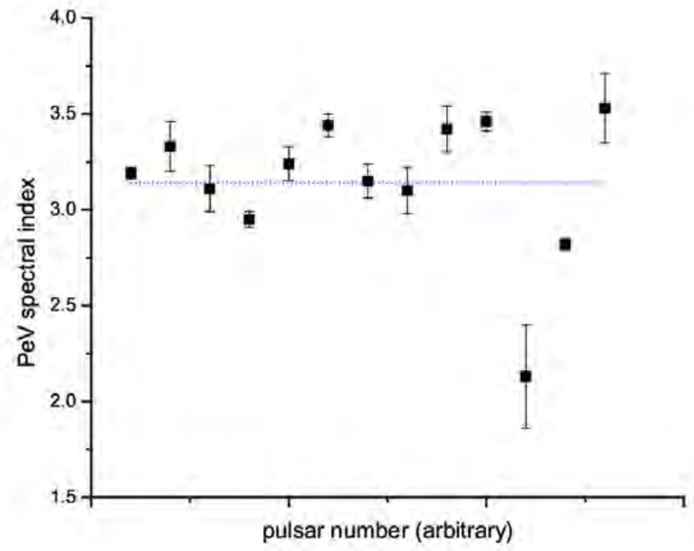

FIG. 7. Same as Fig. 1, but for a sample of LHAASO-KM2A observed pulsars at PeV energies. The dashed line represents the average spectral index of the sample.

(i) the spectral indices of gamma rays from both SNRs and pulsars/PWNs are not single-valued but show significant dispersion, and

(ii) the spectral indices of both SNR and pulsar gamma rays are considerably softer in the PeV energy range compared to the TeV range.

The diffusive shock acceleration (DSA) mechanism suggests that the spectral slope of accelerated charged particles in an SNR should follow a power law with a spectral index close to -2. The magnitude of the spectral slope depends on the compression factor at the shock, i.e., on the Mach number of the plasma ejected in a supernova (SN) explosion. It is unlikely that the compression ratio varies significantly among SNRs. The mean spectral index of gamma rays from SNRs in the GeV–TeV energy range is found to be nearly 2.5, which corresponds to a compression ratio of about 3. This, in turn, implies that the Mach number of the plasma ejected in an SN explosion is only about 3. An important question is whether the gamma-ray spectral index varies with the evolutionary stage (age) of an SNR. Considering different types of SN and their environments, Caprioli *et al.* [15] made a quantitative estimate of changes in the overall CR spectrum during the first few tens of thousands of years of evolution. Their theoretical study found that the spectrum typically remains a power law with a spectral index close to -2, despite varying initial conditions. The issue of age dependence of the photon index was examined by the Fermi collaboration, who plotted the 1–100 GeV photon index versus age for Fermi-observed SNRs [19]. Their findings revealed that younger SNRs tend to have harder spectra compared to middle-aged (interacting) SNRs, though the index values for both classes show significant dispersion.

In Fig. 8, we plot the TeV photon index against SNR age for remnants observed in both GeV and TeV ranges (by IACT). For SNR ages, we rely on TeVCAT data [22]. No significant dependence of the TeV photon index on SNR age is found; the Pearson correlation coefficient is 0.21. A central issue concerns the maximum attainable energy. The maximum energy that can be reached by a cosmic-ray particle in an ordinary SNR, when the remnant expands into a medium of density

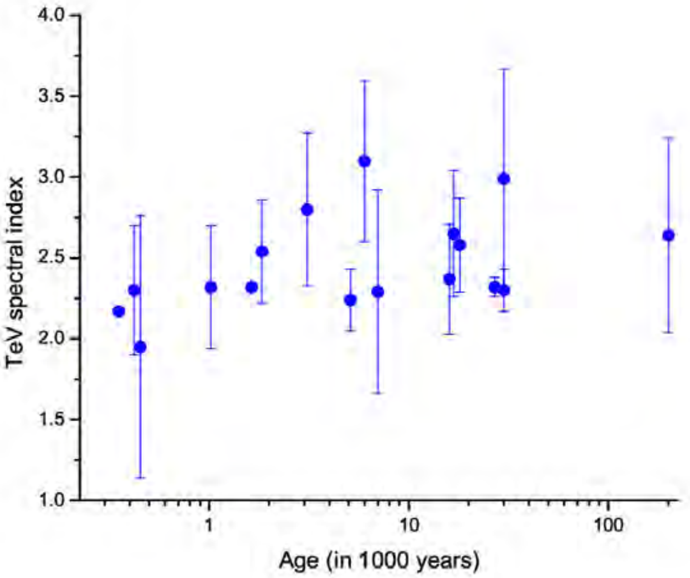

FIG. 8. Variation of TeV photon spectral index with SNR age.

$N_H\ cm^{-3}$, is given by [23, 24]:

$$E_{max} \simeq 4 \times 10^5 Z \left(\frac{E_{SN}}{10^{51}\ erg}\right)^{1/2} \left(\frac{M_{ej}}{10 M_\odot}\right)^{-1/6} \left(\frac{N_H}{3 \times 10^{-3}\ cm^{-3}}\right)^{-1/3} \left(\frac{B_o}{3 \mu G}\right)\ GeV, \quad (7)$$

where E_{SN} and M_{ej} are the kinetic energy and mass of the ejecta, respectively, and B_o is the magnetic field of the SNR. The maximum energy achievable for proton primaries falls short of the knee of the cosmic-ray energy spectrum by more than an order of magnitude. However, this limitation may be mitigated by amplification of the effective magnetic field strength at the shock, driven by magnetic waves induced by accelerated cosmic rays [23, 25, 26]. With such amplification, SNRs might reach the knee of the spectrum for protons and potentially the second knee for iron nuclei.

Analyses of GeV–TeV gamma-ray emission from several SNRs, based on observations by Fermi-LAT, VERITAS, and MAGIC, indicate that the maximum achievable energy in these remnants is significantly below the knee energy [27]. The LHAASO observatory detected very high-energy gamma-ray emission from Cassiopeia A and IC 443, but only through the WCDA detector. In contrast, the absence of gamma-ray flux from these SNRs in KM2A observations places strict upper limits on flux above 25 TeV. Recently, Banik [28] showed that the observed gamma-ray spectra of these two SNRs can be consistently explained if the maximum energy of cosmic-ray protons in these remnants is around 100 TeV. This challenges the assumption in the SNR paradigm that the maximum attainable energy in all SNRs reaches a few PeV.

Martí-Devesa *et al.* [29] recently analyzed multi-wavelength data from the Fermi Large Area Telescope on SN 2023ixf, a Type II supernova in the nearby galaxy M101. Their findings suggest that, under reasonable assumptions, the maximum efficiency of cosmic-ray acceleration could be as low as 1%, contrasting with the commonly assumed 10% in typical supernovae. Another key consideration is that if SNRs are indeed the primary sources of cosmic rays, they must accelerate not only protons but also heavier nuclei in the correct proportions. Furthermore, the maximum energy of heavier nuclei should scale as Z times that of protons, where Z is the atomic number. To explain recent gamma-ray observations, the energy conversion efficiency for a mixed cosmic-ray composition must be nearly twice that of a purely protonic composition [27]. While no strict upper limit exists for conversion efficiency, achieving such high values remains a significant challenge.

VI. CONCLUSION

The supernova remnant (SNR) paradigm has long served as the standard framework for explaining the origin of Galactic cosmic rays (CRs), supported by energetic arguments and the theoretical appeal of diffusive shock acceleration (DSA). However, recent high-quality gamma-ray observations extending into the PeV energy range now allow this paradigm to be tested more stringently.

In this work, we have examined the spectral properties of gamma-ray emission from Galactic SNRs and pulsars using data from Fermi-LAT, ground-based Cherenkov telescopes, and the LHAASO observatory. Several robust observational trends emerge from this analysis:

(i) Not all SNRs act as PeVatrons; in many cases, the inferred maximum energy of accelerated particles falls well below the knee of the cosmic-ray spectrum.

(ii) The gamma-ray spectral indices of SNRs show substantial source-to-source dispersion at GeV and TeV energies, which is difficult to reconcile with simple, universal implementations of DSA operating under similar shock conditions.

(iii) For both SNRs and pulsars detected by LHAASO, the gamma-ray spectra above ~ 100 TeV are significantly softer than those observed at lower energies, suggesting either intrinsic limitations of particle acceleration or strong energy-dependent escape effects at the highest energies.

(iv) No statistically significant correlation is found between the photon spectral index and the age of SNRs, indicating that evolutionary effects alone are unlikely to explain the observed diversity of spectra.

(v) Many SNRs detected at GeV and TeV energies remain undetected at PeV energies, even with the sensitivity of current air-shower experiments.

These findings indicate that the SNRs and pulsars presently observed at PeV energies are unlikely, by themselves, to account for the bulk of Galactic cosmic rays up to the knee. Rather than definitively ruling out SNRs as CR accelerators, our results point to limitations of the simplest versions of the SNR paradigm and underscore the importance of factors such as source environment, time-dependent acceleration, and energy-dependent particle escape. Despite significant theoretical and observational progress, the origin of Galactic cosmic rays remains unresolved. Future observations with improved sensitivity and energy coverage—such as those anticipated from the Cherenkov Telescope Array, extended neutrino detectors, and larger-statistics LHAASO data—will be crucial for disentangling the roles of different source classes and for establishing a more complete and self-consistent picture of cosmic-ray production in the Milky Way.

Finally, it is important to note that a comprehensive understanding of the origin of Galactic cosmic rays may require serious consideration of additional source classes beyond SNRs and pulsars. Potential contributors include massive star clusters, superbubbles [30], collective effects of clustered supernovae [31], black holes [32] and even normal stars [33, 34].

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