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Recent Results on Supernova Remnants at Highest Energies

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Supernova remnants (SNRs) are now established as cosmic particle accelerators through observations of nonthermal emissions from radio to gamma rays in the past decades. In the context of Galactic cosmic-ray origin, one of the key questions is if SNRs are capable of accelerating protons with sufficiently high efficiency to explain the cosmic-ray spectrum below the knee. At least for some SNRs, gamma-ray emissions in the GeV band are solidly attributed to decay of neutral pions, providing long-awaited evidence for proton acceleration. The next and current burning question is if protons are accelerators up to the knee at ∼ PeV. We review recent results with particular emphasis on this topic and also discuss future prospects.

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1. Status of the Field

Supernova remnants (SNRs) have long been considered as the prime candidates for acceleration sites of Galactic cosmic rays, which are believed to extend up to the knee energy at ~ 3 PeV. The power-law spectrum of cosmic rays can naturally be explained by the diffusive shock acceleration mechanism that should be working in the expanding shocks of SNRs. Also, energy density of cosmic rays in the interstellar medium can be supported by SNRs if $\sim$ 1–10% of kinetic energies released by SN explosions ($E_{\rm SN} \sim 10^{51}$ erg per explosion) are poured into accelerated particles. Nonthermal emissions detected in SNRs, such as synchrotron in the radio band, have been providing evidence that particles are actually accelerated in their shocks. Synchrotron X-rays, detected first in SN 1006 with ASCA [1] and then in various young SNRs, revealed that electrons are accelerated up to $\gtrsim$ TeV energies there. Similar evidence, but in a more direct way, is obtained through observations of very-high-energy (VHE) gamma rays [2]. VHE gamma rays are generated either by leptonic processes such as inverse Compton scattering of VHE electrons off cosmic microwave background photons, or by hadronic processes such as π^0 decay. In either case, detection of VHE gamma rays clearly indicate particle acceleration at least to the energies of detected photons.

If SNRs are indeed acceleration sites of Galactic cosmic rays, they must accelerate protons (and ions), which constitute a dominant part of cosmic rays, up to PeV energies. Recent gamma-ray observations in the GeV band with Fermi LAT and AGILE clearly identified the characteristic spectral signatures of π^0-decay emissions in some SNRs such as IC 443 and W44 [3, 4], firmly indicating proton acceleration in the SNRs. However, the gamma-ray spectra of those SNRs break or cut off far below PeV [5]. Thus, the next burning question to be answered would be if SNRs are proton accelerators up to PeV energies, so-called PeVatrons. In what follows, we review the recent results and future prospects on this topic.

2. Where to Search for PeVatron SNRs

We can give a simple estimate of maximum energies of protons accelerated in SNRs following Lagage & Cesarsky (1983) [6]. The timescale for diffusive shock acceleration is written as

$$t_{\rm acc} = \frac{20}{3}\frac{c r_g}{{v_s}^2}\eta, \tag{1}$$

where r_g, v_s, and η are the proton gyroradius, shock velocity, and gyrofactor, respectively. By equating this timescale and the age of the SNR $t_{\rm age} = R/v_s$, where R is the radius of the SNR, the maximum attainable energy of accelerated protons is obtained as

$$E_{\rm max} \approx 460 \left(\frac{v_s}{10^4~{\rm km~s^{-1}}}\right)\left(\frac{B}{10~\mu{\rm G}}\right)\left(\frac{R}{10~{\rm pc}}\right)\eta^{-1}~{\rm TeV}. \tag{2}$$

Therefore, a necessary condition for PeVatron SNRs is high shock velocity, and thus young SNRs would be the prime candidates.

Figure 1 presents gamma-ray spectra of π^0-decay emissions computed with different values of $E_{\rm max}$. The parent protons are assumed to have a spectral form of $dN/dE \propto E^{-s}\exp(-E/E_{\rm max})$. All the curves are computed with the “standard” index of $s = 2$. This figure tells us that gamma-ray emissions of a PeVatron SNR should extend to ∼ 100 TeV without indications of a spectral cutoff. Most of young SNRs, however, have gamma-ray spectra that cut off well below this energy. Examples include sources such as Cassiopeia A [8] and the prototypical TeV-bright SNR RX J1713.7−3946 [9]. Figure 2 shows the GeV-to-TeV gamma-ray spectrum of RX J1713.7−3946 obtained with Fermi LAT and H.E.S.S. [9], which has a cutoff at a gamma-ray energy of ∼ 10 TeV. If the emission is attributed to π^0 decay, the cutoff energy can be translated to proton energy substantially lower than PeV, $E_{\rm max} = 93 \pm 15$ TeV [9]. The situation is similar also for other examples.

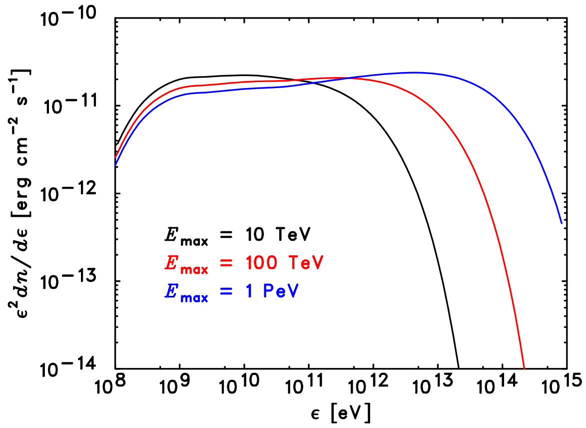

Figure 1: Spectra predicted for π^0-decay gamma rays computed based on the prescription by Kafexhiu et al. (2014) [7]. The black, red, and blue curves represent models with $E_{\rm max}$ = 10 TeV, 100 TeV, and 1 PeV, respectively.

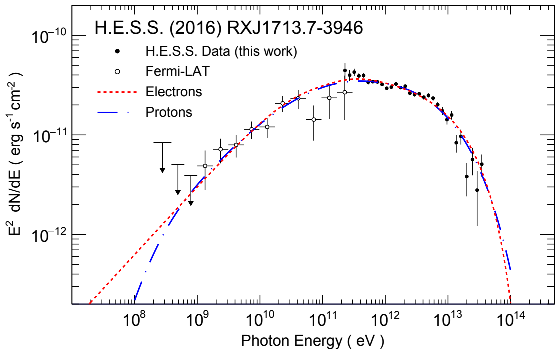

Figure 2: Gamma-ray spectrum of SNR RX J1713.7−3946 with Fermi LAT and H.E.S.S. The figure is taken from H.E.S.S. Collaboration (2018) [9].

What the gamma-ray spectrum of SNRs such as RX J1713.7−3946 means is that the currently detected SNRs are not PeVatrons. A possible scenario would be that those SNRs were PeVatrons in the past only for a short period and that the accelerated PeV protons have already escaped from the SNR shocks. As the shock velocity gradually decreases in the Sedov phase, the maximum proton energy confined in the shocks also decreases and the highest-energy protons are injected into the interstellar medium [10]. The runaway protons shine through π^0-decay emissions when they interact with dense gas in nearby molecular clouds and produce π^0 mesons [11]. Gamma rays from nearby gas clouds thus contain information on particle acceleration in the SNR in the past. Gamma rays from gas clouds surrounding SNRs are indeed discovered, for example, in the W28 region with H.E.S.S. [12] and in the W44 region with Fermi LAT [13], and would be interpreted well as runaway particle emissions in this scenario.

3. Gamma-ray Searches for PeVatron SNRs

Gamma-ray observations obviously play a key role in PeVatron SNR searches. Some VHE gamma-ray sources possibly associated with SNRs are proposed as PeVatron candidates such as HESS J1641−463 [14]. Its gamma-ray spectrum was found to be fit well with a hard ($\Gamma \simeq 2$) power law without spectral cutoffs in the bandpass of H.E.S.S. As discussed in the previous section, PeVatrons are expected to have hard spectra extending to $\sim$ 100 TeV energies. In searching for such sources, air shower experiments, which can cover $>$ 10 TeV ranges with high sensitivity and with wide field-of-view, are very promising, and have already discovered some PeVatron candidates. One of the examples is the SNR G106.3+2.7. In the vicinity of the SNR, gamma rays above 10 TeV are detected with Milagro [15], HAWC [16], Tibet ASγ [17], and LHAASO [18]. Figure 3 presents a significance map of the region obtained with Tibet ASγ. In a follow-up study with MAGIC, the authors discuss a scenario where protons having escaped from the SNR in the past interact with dense gas surrounding the SNR and radiate through π^0 decay [19]. Follow-up observations with multi-wavelength (or multi-messenger) data would be necessary to reveal the nature of PeVatron SNR candidates.

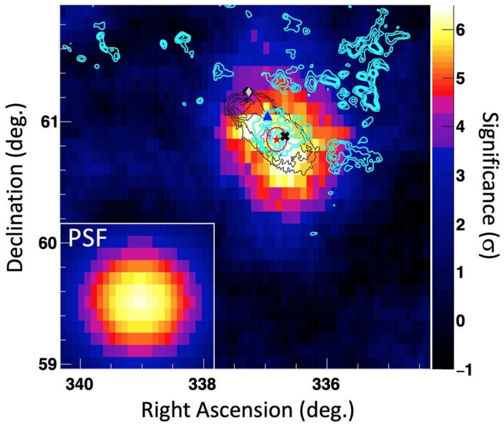

Figure 3: Significance map of the region around the SNR G106.3+2.7 as obtained with Tibet-ASγ from Tibet ASγ Collaboration (2021) [17].

Whenever one searches for PeVatrons in gamma rays, it is always essential to disentangle hadronic π^0-decay emissions from leptonic emissions. A caveat here is that π^0-decay spectra sometimes are harder than expected and can mimic inverse Compton scattering spectra particularly when discussing emissions from clumpy gas clouds. Since the diffusion coefficient is larger for higher-energy particles, they can penetrate deep into the core of the cloud. Thus, higher-energy protons effectively encounter more target gas for π^0 production, making π^0-decay spectra much harder than expected for uniform gas distribution [20]. The hard gamma-ray spectrum of RX J1713.7−3946 (figure 2) can actually be reproduced well with π^0-decay models [21]. Given that, it is important to discuss emission mechanisms not solely from gamma-ray spectra but also using other means such as detailed comparison between spatial distributions of gamma rays and interstellar gas [22].

4. PeVatron SNR Signatures Expected in Hard X-rays

PeVatron searches can also be carried out through observations messengers other than gamma rays. In addition to π^0 mesons, charged pions ($\pi^\pm$) are produced in pp inelastic scattering. Charged pions decay to $\mu^\pm$ and then to $e^\pm$ as

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu, \quad \pi^- \longrightarrow \mu^- + \bar{\nu}_\mu, \tag{3}$$

$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu, \quad \mu^- \longrightarrow e^- + \bar{\nu}_e + \nu_\mu. \tag{4}$$

We can probe accelerated protons through observations of VHE neutrinos and also synchrotron emission from $e^\pm$ produced in the above decay chain, so-called secondary electrons. VHE neutrinos work as unique messengers since they are produced only through hadronic interactions. IceCube(-Gen2) and KM3NeT will be able to detect signals of, or set stringent upper limits to neutrino emissions from SNRs in our Galaxy [23], and we will be able to constrain proton proton maximum energies based on them.

Synchrotron emissions from secondary electrons can be harder than those from directly accelerated electrons (i.e., primary electrons), which is the key characteristics of this emission channel. According to equation 2, the magnetic field in the shock is required to be amplified to $\gtrsim 100\ \mu$G to accelerate protons to $\sim$ PeV. Under such a strong magnetic field, primary electrons suffer severe synchrotron cooling as they are accelerated, which inevitably limits their maximum energies and makes a spectral cutoff at $\lesssim$ keV in the synchrotron spectrum. In the case of secondary electrons, on the other hand, they gain energies as protons during being accelerated and thus their maximum energy would not be limited effectively by any cooling processes. Their synchrotron spectra, therefore, can extend well above $\sim$ keV as demonstrated in figure 4. As can be seen in this figure and also as pointed out by Celli et al. (2020) [25], secondary synchrotron spectra have much shallower cutoffs than π^0-decay gamma-ray spectra from the same parent protons, making this radiation in hard X-rays a powerful tool for PeVatron searches. Sensitive observations of SNRs and nearby clouds are important in this context, and can be carried out with current and future hard X-ray missions such as NuSTAR, FORCE [26], and HEX-P [27].

5. “Indirect” Searches for PeVatron SNRs

Although we so far discussed “direct” PeVatron SNR searches through detection of emissions from $\sim$ PeV protons, we can search for “indirect” signature of PeVatrons in SNRs. The X-ray stripes in Tycho’s SNR, shown in figure 5 (a), are suggested as such a signature by Eriksen et al. (2011) [28], who reached the conclusion by ascribing the gaps between the stripes to the diameter of gyro-motion of accelerated protons.

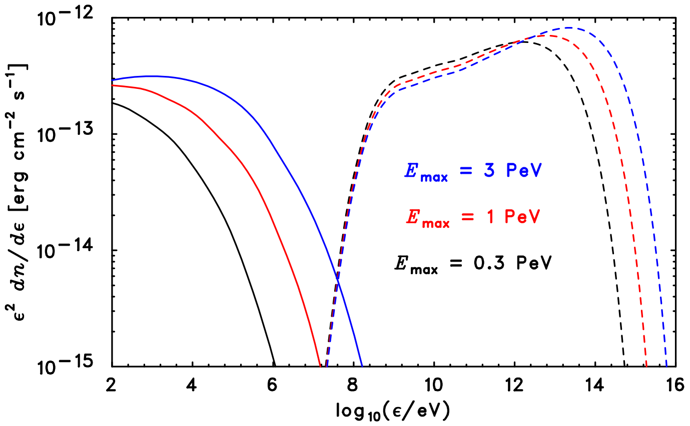

Figure 4: Synchrotron spectra of secondary electrons (solid) and π^0-decay spectra from the same parent protons (dashed). The colors correspond to different assumptions for $E_{\rm max}$ of parent protons: 0.1 PeV (black), 1 PeV (red), and 3 PeV (blue). The computation was performed based on the works by Kafexhiu et al. (2014) [7] and Kelner et al. (2006) [24].

Strong magnetic fields can also be regarded as "indirect" evidence. Significant magnetic field amplification is required for protons to reach PeV energies in SNRs (equation 2). We can, therefore, claim that the SNR has at least ability to accelerate protons to PeV energies if its magnetic field is observed to be amplified. Again a good example would be the X-ray stripe structure of Tycho's SNR, which were found to be time-variable [29, 30], as shown in figure 5(b). If we apply the same line of arguments as in Uchiyama et al (2007) [31] did for time-variable filaments in RX J1713.7−3946, the timescale of the flux increase and decrease of the stripes indicates a magnetic field strength of $\sim$ 100 μG. With the amplified magnetic field, protons would be accelerated to energies close to PeV energies in this SNR.

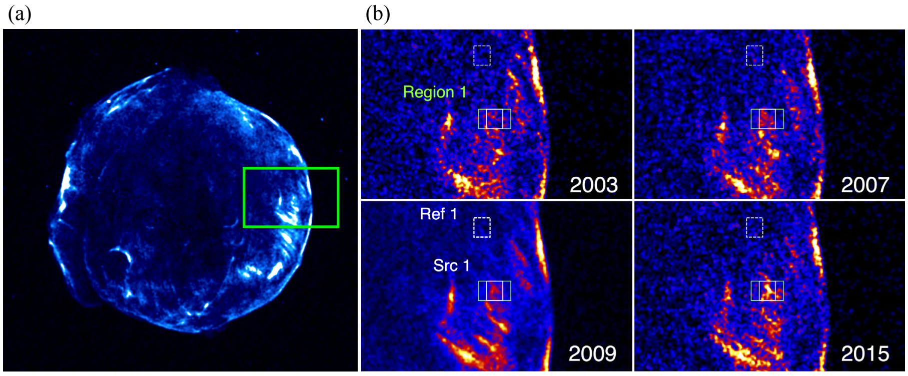

Figure 5: (a) Chandra X-ray image of Tycho's SNR in 4.1–6.1 keV. The stripes are clearly visible on the western side of the SNR. (b) Zoom-in views of the green square region in (a) as observed in 2003, 2007, 2009, and 2015, where time-variable feature was discovered [29].

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