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Systematic trends and variety of particle acceleration processes in supernova remnants as promising Galactic cosmic-ray accelerators

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Supernova remnants are believed to be promising sources of Galactic cosmic rays. One of the principal questions is whether they are accelerating particles up to the maximum energy of Galactic cosmic rays (∼PeV). In this work, we systematically modeled the gamma-ray spectra of 38 remnants to constrain the particle-acceleration parameters of freshly accelerated particles with the contribution of released particles remaining nearby taken into account. The average maximum energy during lifetime was found to be < 20 TeV $(t_{\rm M}/1~{\rm kyr})^{-0.8\pm0.2}$ with $t_{\rm M}$ being the age at the maximum, which reaches PeV if $t_{\rm M} < 10$ yr. The maximum energies even at similar ages were fount to have a variety of 1–2 dex from object to object. In order to further investigate such environmental dependences, we then studied supernova remnant RCW 86, where shock velocities are measurable and both thermal and non-thermal X-rays are spatially mixed. The non-thermal X-ray parameters showed clear correlations with plasma density, not with shock velocity, indicating that particle acceleration physics in this remnant is controlled by the ambient density. This can be qualitatively understood with a magnetic-field amplification via shock-cloud interactions.

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1. Introduction

Galactic cosmic rays are high-energy particles with an energy spectrum approximated by a power-law and a maximum energy of $\approx 10^{15.5}$ eV ($\approx$ 3 PeV). Their acceleration sites are still unclear despite of more than 100 yr investigations. Supernova remnants (SNRs) are thought to be the most promising acceleration sites that provide these high-energy particles. According to analytical models for diffusive shock acceleration, these sources are believed to actually supply particles with energies of $\lesssim$ PeV (e.g., [1, 2]).

Gamma-ray observations have revealed that charged particles are accelerated to energies above TeV (10^{12} eV) in young SNRs. Most of these SNRs feature, however, spectral turnovers at energies below PeV. Recently, Tibet Air-Shower array and LHAASO (Large High Altitude Air Shower Observatory) observations have identified a number of PeV accelerators (PeVatrons) [3, 4], which includes only a few SNRs. These results suggest that PeV particles accelerated in early evolutionary phases have already escaped (e.g., [5–10]), or that there are almost no PeVatron SNRs. Other scenarios have also been proposed in which SNRs in specific conditions become PeVatrons: e.g., very young SNRs in dense environments [11].

In this paper, we summarize our recent observational studies in investigation of the maximum attainable energy of SNRs. In Section 2, we describe a systematic study of gamma-ray emitting SNRs, starting from parameter extraction processes base on [12–16]. We find a systematic trend of the maximum attainable energy and amount of energy, both gradually decreasing with time. Our conclusion is that SNRs can be PeVatrons only if they accelerate particles efficiently when they are very young such as less than 10 yr. We also find a large scatter of the maximum energy at similar ages, which implies the existence of a significant dependence on environments. For further investigation of such an environmental dependence, we have recently been focusing on individual remnants. Section 3 describes the case with RCW 86 partly based on [17]. We find that plasma density plays an important role in particle acceleration processes. Our results and interpretations are summarized in Section 4.

2. Systematic study

2.1 Parameter extraction: Thermal X-ray properties

We obtain SNR ages and physical parameters of acceleration sites from X-ray data. The acceleration sites are filled with hot plasmas, which emit optically-thin thermal emission originating from electrons and ions. From the line intensities and their ratios and continuum shape, one can identify the plasma properties including electron temperature, ionization state, metal abundances, and emission measure. With the parameter set which best explain the data, one can calculate the dynamical age of the remnant and the plasma age, which corresponds to ionization (or recombination) timescale. Figures 1 shows thermal X-ray spectra from two SNRs, HB 21 and G359.1−0.5 as an example [12, 13]. By carefully examining the background signals (sky and detector), we conclude that HB 21 is one of the oldest remnants with a very soft gamma-ray spectrum, while G359.1−0.5 is a middle-aged remnant with still hard gamma-ray emission.

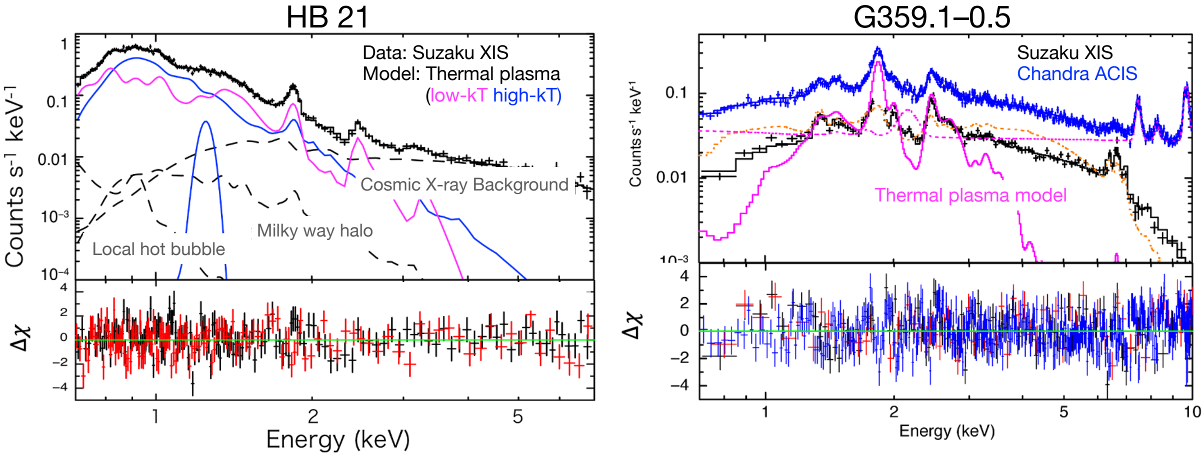

Figure 1: X-ray spectra and best-fit plasma models for the supernova remnants HB 21 and G359.1−0.5. The solid and dashed lines represent the spectral models for the source and background, respectively. The figures are from [12] (HB 21) and [13] (G359.1−0.5).

2.2 Parameter extraction: Gamma-ray spectral properties

We describe the essence of our analysis and results performed in [16]. Details of the sample selection can be found in [16]. Basically, we use the gamma-ray emitting SNRs found in 1st Fermi-LAT supernova remnant catalog or a previous systematic study. In our work, hadronic emission is assumed to dominate the gamma rays, which seems to be the case at least for several SNRs based on their spectral shapes and energetics (e.g., [18]). Figure 2 describes the assumed theoretical gamma-ray spectrum and several observational spectra. The exponential cutoff energy ($E_{\rm cut}$) or break energy ($E_{\rm br}$) of a gamma-ray spectrum reflect the maximum energies of fresh accelerated particles [9, 19, 20]. If particles no longer accelerated do not significantly contribute to the emission, an exponential-like cutoff feature is expected. On the other hand, if the contribution of escaping particles cannot be ignored, the gamma-ray spectrum will be similar to a broken power-law. Since generally we cannot distinguish between these two situations without detailed information of acceleration sites, the gamma-ray spectral data are fitted with both an exponential cutoff power-law model and a broken power-law model. By fitting the Fermi, H.E.S.S., MAGIC, and VERITAS spectra, we obtain parameters such as spectral index, cutoff, break, and hardness ratio.

2.3 Parameter extraction: Reliability of supernova remnant age estimates

In order to discuss time dependence of particle-acceleration properties quantitatively, we evaluate the uncertainties in SNR age estimation using systems with reliable age measurements $t_{\rm r}$, either the historical age, light-echo age, $t_{\rm kin,ej}$ (kinematic age of free-moving ejecta knots), or $t_{\rm kin,NS}$ (kinematic age of associated neutron star) [14]. First, we measure $t_{\rm kin,NS}$ for available systems by estimating the geometric centers of the SNR shells. The velocities of neutron stars are taken from multi-epoch radio observations. Then we "calibrate" the general age estimates, which are applicable for most cases (dynamical age and plasma age), by comparing them with the reliable estimates $t_{\rm r}$. The sample for this section consists of the SNRs with known historical or light-echo ages, $t_{\rm kin,ej}$,

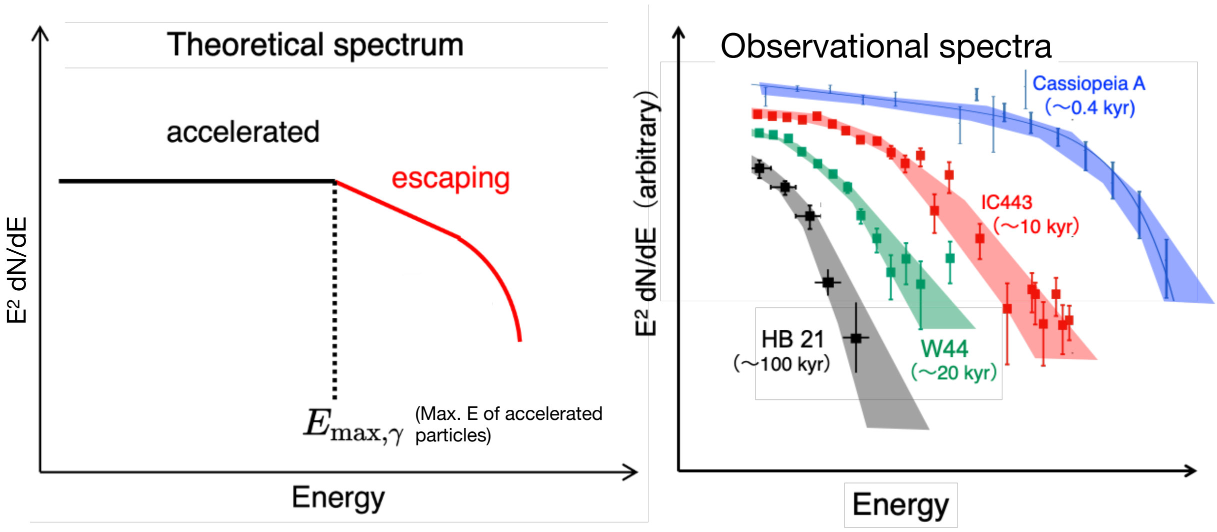

Figure 2: Theoretical (left) and observational (right) gamma-ray spectra of supernova remnants. The observational spectra are from [18, 21, 22].

or measurable $t_{\mathrm{kin,NS}}$. We use the resultant 24 systems. The best age t_{b} is defined for each source, which is the most reliable estimate. Details of the sample are explained in [14].

Ideally, where a symmetric supernova explosion occurs in a uniform ambient density, the SNR will have a circular shell and so the geometric center can be easily determined. In reality, however, the observed SNR shapes are not simply circular. Thus, we model the projected morphology of the SNR shell with an ellipse as a simple enough yet better alternative to a circle and estimate the geometric center. Then we can calculate $t_{\mathrm{kin,NS}}$ using the neutron star position and velocity.

For all the 24 systems, we compare t_{r} including $t_{\mathrm{kin,NS}}$ discussed above with dynamical and plasma ages. The dynamical and plasma ages are found to be in good agreement with their t_{r} within a factor of four. Therefore, we tentatively conclude that a systematic error of a factor of four is associated with the general age estimates.

2.4 Results: Time dependence of maximum acceleration energy and variety

Figures 3 shows the maximum energy estimate and confined energy estimate over age. Both show general decreasing trends with age with large scatters, which are consistent with previous studies [23, 24]. The E_{cut}–t_{b} and E_{br}–t_{b} plots are modeled with a power-law model, and the best-fit functions are obtained as $E_{\mathrm{cut}} = 1.3^{+1.1}_{-0.67}$ TeV $(t_{\mathrm{b}}/1\ \mathrm{kyr})^{-0.81\pm0.24}$ and $E_{\mathrm{br}} = 270^{+240}_{-130}$ GeV $(t_{\mathrm{b}}/1\ \mathrm{kyr})^{-0.77\pm0.23}$. Thus, based on our simple extrapolation with an assumption of the Sedov evolution, only the remnants younger than $\sim$ 10 yr have a chance to become PeVatrons. This scenario matches some theoretical works [8, 10, 11]. The time dependence of $\propto t^{-0.8}$ is different from that expected in the simplest regime, Bohm limit ($t^{-0.2}$) [25], and requires wave damping via shock-ISM (interstellar medium) collisions (e.g., [5, 20, 26, 27]. We also find a large variety of the maximum energy estimates even at similar ages: we quantify this variety to be 1–2 orders of magnitude.

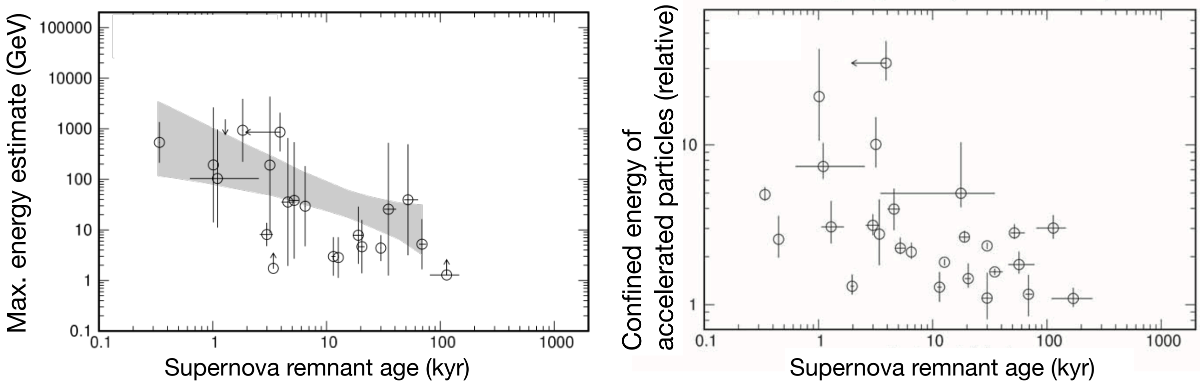

Figure 3: Estimates of the maximum energy of accelerated particles (left) and amount of confined energy (right).

3. Investigation of parameter dependence on environments: X-ray study of RCW 86 with Chandra

In order to further investigate the parameter dependence on environments, here we focus on the SNR RCW 86, which is young, bright, large, and most importantly, both thermal and non-thermal X-rays are measurable at a large fraction of the emission region. Using X-ray data with Chandra, we measure proper motions of filament structures and outer edges and thermal and non-thermal parameters of different regions. Here we only describe the main results obtained in our studies. For detailed analysis procedures and results, please refer to [17].

Figure 4 shows the density dependence of the non-thermal flux from different regions. Both two different regions with different properties of interacting clouds show clear correlations between plasma density and non-thermal flux. Interestingly, the two regions show opposite tendencies, probably indicating a quite different properties of the acceleration sites. A simple interpretation is that a shock interacting with a uniform cloud decelerates rapidly and the acceleration performance declines accordingly. However, if the shock is interacting with a clumpy medium, regions with dense clumps can amplify magnetic-field turbulence, and thus the acceleration performance can be enhanced [29]. Although we have not yet reached a quantitative understanding of these results, we have confirmed from observations that acceleration performance is strongly affected by plasma density, which is a basic parameter of acceleration sites.

4. Conclusion

In our recent studies, we investigated the systematic time dependence and variety of acceleration performance of SNRs. We first collected physical parameters necessary for our study: SNR age, environmental parameters, and properties of accelerated particles. We then calibrated general age estimates using reliable estimates available only for specific systems. As a result, the general age estimates were found to agree with the reliable estimates within a factor of four. A systematic analysis of 38 gamma-ray emitting SNRs using their thermal X-ray and gamma-ray properties was performed. A spectral modeling on their gamma-ray spectra has allowed us to constrain the

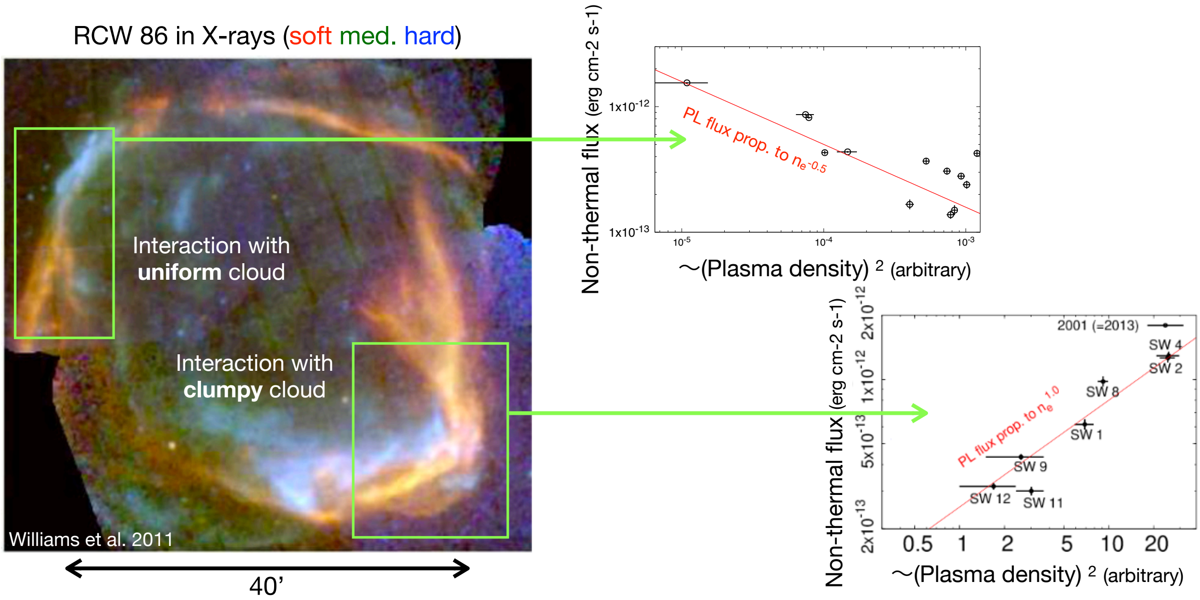

Figure 4: X-ray image of the supernova remnant RCW 86 (left) and plasma-density dependence of non-thermal X-ray parameters extracted from two regions (right). The image is shown on the equatorial coordinates.

particle-acceleration parameters. The maximum energy estimate of freshly accelerated particles was found to be well below PeV for our sample.

The general time dependences of the maximum energy estimates for our sample, $\propto t^{-0.8}$, cannot be explained with the simplest acceleration condition of the Bohm limit. The estimated average maximum energies of accelerated particles during lifetime $\lesssim$ 20 TeV $(t_M/1\ \mathrm{kyr})^{-0.8}$ are well below PeV if the age at the maximum t_M is $\sim$ 100–1000 yr. However, if the maximum energy during lifetime is realized at younger ages such as $t_M < 10$ yr, it can become higher and reach PeV. On the other hand, the maximum energies during lifetime are suggested to have a large variety of 1–2 orders of magnitude from object to object.

In order to further investigate such a dependence on environments, we finally focused on the SNR RCW 86, where proper motions, thermal and non-thermal X-ray properties are available. We found that non-thermal parameters strongly correlate with plasma density, and the correlations are opposite for two different regions with different properties of the interacting clouds. Although we have not yet reached a quantitative understanding of these results, we have confirmed from observations that acceleration performance is strongly affected by plasma density, which is a basic parameter of acceleration sites.

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