Particle Acceleration in Young Supernova Remnants with Nonthermal X-ray and Gamma-ray Observations

Naomi Tsuji

Ph.D. Thesis

Department of Physics
Graduate School of Science
Rikkyo University

Nishi Ikebukuro, Toshima-ku, Tokyo, 171–8501, Japan

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Contents

Abstract

Chapter 1 presents the introduction of this thesis. The origin of cosmic rays, high energy particles filling the Universe, has been unsettled since the discovery in 1912. Galactic cosmic rays with energy lower than ~PeV have been considered to be accelerated in shock waves of supernova remnants. In spite of observational and theoretical studies, many facets of this idea, such as detailed mechanism of particle acceleration and maximum attainable energy, remain ambiguous. These issues are partly attributed to poor determination of diffusion, which is important in the acceleration theory. The scientific objective of this thesis is to place observational constraints on the diffusion coefficient at the very site of particle acceleration, namely, shock waves of supernova remnants. We perform a systematic analysis of young SNRs at the relatively young stage at which the acceleration is believed to be most effective and the maximum energy is expected to be achieved. This is quite meaningful in two respects; the origin of galactic cosmic rays and the physics of the particle acceleration.

Chapter 2 gives an overview of cosmic rays, particle acceleration, and supernova remnants, which are needed to understand this thesis. First we explained the energy spectrum of CRs, spectral breaks at a few PeV and EeV, and other features brought with latest detectors and experiments. We summarized the idea of "SNR paradigm" (supernova remnants as the origin of galactic cosmic rays) and the important observational results. Diffusive shock acceleration is a widely accepted theory of particle acceleration in shock waves of supernova remnants. We presented the details of this theory, as well as diffusion and turbulent magnetic field, which characterize motion of particles in the vicinity of SNR shocks. Accelerated particles in SNRs emit electromagnetic (EM) waves through synchrotron radiation, inverse Compton (IC) scattering, bremsstrahlung, and π^0 decay in pp interaction. The radiation processes are briefly presented. Finally, we derived analytical solutions of electrons and radiation near the SNR shocks, which were obtained in Zirakashvili & Aharonian (2007).

In Chapter 3, we briefly summarize instruments used for data analyses in this thesis. We made use of *Chandra*, *NuSTAR*, and H. E. S. S. for soft X-ray, hard X-ray, and TeV gamma-ray observations, respectively. *Chandra* was launched in 1999. The data in this thesis were taken by CCD cameras (Advanced CCD Imaging Spectrometer (ACIS)) after being reflected and focused by the onboard Walter-I X-ray telescope, providing us with images and spectra. The sensitive energy band is 0.4–10 keV, and the angular resolution is 0.5 arcsec, which is the best value among X-ray satellites. *NuSTAR*, launched in 2012, has hard X-ray telescopes and CdZnTe detectors onboard, and enables us to retrieve spectroscopy in 3–79 keV. Since contamination of stray light was reported as serious issues in *NuSTAR*, we presented a method to deal with it in details. A combination of *Chandra* and *NuSTAR* allows to measure the spatially resolved spectra in the broad energy range. H. E. S. S. is one of the Imaging Atmospheric Cherenkov Telescopes (IACTs) and has been in operation since 2004. Cosmic gamma ray produces an air shower emitting Cherenkov light, which is detected in the ground five telescopes. The energy and arrival direction of the primary gamma ray can be determined by event reconstruction of shower images. Images and spectra in 0.1–100 TeV are obtained with H. E. S. S.

In Chapter 4, we systematically analyze 11 young SNRs, including all historical SNRs, to measure the cutoff energy, thus shedding light on the nature of particle acceleration at the early stage of SNR evolution. The nonthermal-dominated spectra in filament-like narrow structures are selectively extracted and used for spectral fitting because our model assumes that accelerated electrons are concentrated in the vicinity of the shock front due to synchrotron cooling. The cutoff energy parameter (ε_0) and shock speed ($v_{\rm sh}$) are related as $\varepsilon_0 \propto v_{\rm sh}^2 \eta^{-1}$ with a Bohm factor of η. Six SNRs provide us with spatially resolved ε_0–$v_{\rm sh}$ plots across the remnants, indicating a variety of particle acceleration. The observed ε_0–$v_{\rm sh}$ relation is nicely reproduced with the theoretical prediction with a constant value of η (Kepler's and Tycho's SNRs). The estimated η parameters are dependent on the shock obliquity (SN 1006) and on the variable number density (Cassiopeia A). Our assumption

of the cooling-limited electron might not be applicable to G1.9+0.3, and the inner region in the NW rim of RX J1713.7−3946. With all SNRs considered together, the systematic tendency of η clarifies a correlation between η and age of t (or the expansion parameter of m) as $\eta \propto t^{-0.46}$ ($\eta \propto m^{4.5}$) (i.e., η decreases as the SNR evolves). This is interpreted as the magnetic field becomes more turbulent and self-generated, as particles are accelerated at a greater rate with time. We also present the properties of η with different types of supernova explosions and with reverse shock. In addition, we demonstrate a possibility of PeVatron (accelerator of PeV particles) because the maximum energy achieved in SNRs can be higher if we consider the newly observed time dependence on η.

In Chapter 5, we apply the same prescription presented in Chapter 4 to the TeV gamma-ray spectra of SNRs. There are two problems to be addressed: the gamma-ray spectrum here is assumed to be dominated by leptonic components (inverse Compton scattering radiation), but this is very controversial in some SNRs. The other issue is that the gamma-ray spectrum was obtained as an integrated spectrum over a larger area, and thus lost its local and smaller structures, such as a thin rim or a filament, because of the limited spatial resolution. We found the cutoff shape of the TeV gamma-ray spectrum is nicely reproduced by the model of IC emitted from electrons limited by cooling and Bohm diffusion, resulting in the cutoff energy parameter of the parental electron of 20–50 TeV. Combined with the shock speed, we estimate Bohm factor, which tends to be slightly larger than that estimated with X-ray observations. This could be attributed to different regions to extract the X-ray and gamma-ray spectra and an underestimation of magnetic field strength probably caused by the spatial difference of the spectra. Future gamma-ray telescopes (e.g., Cherenkov Telescope Array (CTA)), would provide us with more spatially resolved spectra in the TeV gamma-ray range, allowing to determine Bohm factor with higher accuracy.

In Chapter 6, we investigate the validity of Bohm diffusion ($D \propto E^{\alpha}$ with $\alpha = 1$) near the SNR shock by using the spectral shape of the particle (electron) distribution. Expanding calculation of Zirakashvili & Aharonian (2007), we derived the spectral cutoff shape with arbitrary α and obtained the full-energy-band analytical expressions of the electron distribution, and the corresponding synchrotron and IC radiation. The difference in α shows an apparent distinction in the higher energies (e.g., the spectrum becomes flattened for the smaller α). We applied the models with $\alpha = 0$, $1/3$, and 1, which respectively correspond to constant, Kolmogorov, and Bohm diffusion regimes, to the nonthermal X-ray and TeV gamma-ray spectra presented in Chapter 4 and Chapter 5. The spectral fitting, unfortunately, does not enable us to demonstrate the different values of α due to the limited statistics of the current data, in particular, in the higher energy domains. However, a combination of X-ray and gamma-ray results suggested that the α parameter can be more constrained, as already Vela Jr. may show an indication of $\alpha = 1/3$. The future gamma-ray telescope, CTA, will provide us with more spatially resolved TeV gamma-ray observations, allowing to compare with X-ray observations with greater accuracy. This would put a tight constraint on α, that is, the corresponding self-generated turbulent spectrum which is difficult to access and demonstrate with theoretical studies or with numerical simulations.

Chapter 7 presents the summary and conclusions.