Doctoral Dissertation (Censored)
博士論文 (要約)

Systematic Study of Escape Processes of Cosmic Rays from Supernova Remnants based on Gamma-ray and Thermal X-ray Properties
（ガンマ線・熱的 X 線放射の特性をもとにした超新星残骸からの宇宙線逃亡プロセスの系統的研究）

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Abstract

Galactic cosmic rays are high-energy particles which have the maximum energy of $\approx 10^{15.5}$ eV and the energy density of ~ 1 eV cm^{-3}. Although it has been more than 100 years from their discovery, their acceleration sites are still unclear. Supernova remnants (SNRs) are thought to be the most promising sources that can provide such a high maximum energy and high energy density. Recent gamma-ray studies have revealed that several SNRs actually accelerate particles to energies above 1 TeV (10^{12} eV). However, as the largest problem left, how the accelerated particles escape from SNR vicinities to become cosmic rays, i.e., the escape timescale and the escaping particles' energy distribution, and their dependence on environments remain unknown and should be addressed observationally.

In this work, a systematic study of gamma-ray emitting SNRs is conducted in order to measure the particle-acceleration and escape parameters and their dependence on environments. Three steps of data preparation are performed first. First step is an X-ray analysis of thermal plasmas in SNRs to obtain their physical parameters such as temperature, density, and ionization state. Two gamma-ray emitting SNRs which are important yet without sufficient plasma properties known, HB 21 and G359.1−0.5, are analyzied. Secondly, a systematic spectral modeling of the observational gamma-ray data is performed combining the *Fermi* spectral data of 15 SNRs extracted in this work and the individual gamma-ray spectra presented in literatures. Third step is a quantitative evaluation of the accuracy of SNR-age estimations. This is essential for temporal-evolution studies of SNR parameters, yet has not been investigated.

Using the data prepared above, a systematic analysis on 38 gamma-ray emitting SNRs is performed. First, average temporal evolution of the observational gamma-ray parameters are discussed. Then, the observational parameters are compared to an analytical model of particle escape to constrain physical parameters of particle-acceleration and escape environments.

Systematic decreasing trends of the gamma-ray parameters such as cutoff energy and break energy are found, which indicates the systematic temporal evolution of particle escape. The particle-escape timescale based on the total energy of confined protons is found to be 10–100 kyr. The time dependence of the systematic decreases of the cutoff energy and the break energy ($\propto t^{-(0.5\text{–}1.0)}$) cannot be explained with the simplest acceleration condition of the Bohm limit, and requires shock-ISM (interstellar medium) collisions. A comparison of the observational cutoff/break energies to the theoretical values suggests that the shock velocities in the gamma-ray emitting regions have been decreased significantly in general (e.g., due to a collision to dense medium), and that the maximum energy of acceleration during lifetime can reach $\lesssim 8$ PeV in general, even though the simply estimated maximum energies from observations are below it. Therefore, a scenario in which SNRs accelerate particles up to the energies of $\sim$ PeV in general is suggested in this work.

The maximum energy of acceleration during lifetime is suggested to vary among SNRs by $\sim$ three orders of magnitude, which can be explained by one order-of-magnitude variation of each of the fundamental parameters, e.g., acceleration efficiency and average ambient density. The maximum energy of emission from escaping particles is found to have $\lesssim$ one order-of-magnitude variation, which is naturally explained, e.g., by a factor-of-two variation of the spatial extent of interacting clouds.

This work provides the first measurements of the systematic particle escape with age and the variety of acceleration/escape parameters among SNRs. This will be the first step to quantify the effects of Galactic cosmic rays to the Galaxy evolution.