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Observational Clues of Galactic Cosmic Rays — from X-ray Point of View —

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Abstract

X-ray observations are the strong tool to study nonthermal phenomena in the universe. Detecting synchrotron X-rays is the direct evidence of accelerated electrons in the magnetic field, and thermal X-rays from the background plasma of the acceleration sites show us their physical parameters such as temperature, density, and so on. Recent X-ray observations show us the discrepancy of the standard model of Galactic cosmic ray acceleration in supernova remnants and pulsar wind nebulae, such as high acceleration efficiency, amplification of magnetic field on the shock, escape from the shock, and so on. In this paper, we will introduce how present X-ray observatories, and near-future X-ray observatories will, contribute the understanding Galactic cosmic ray acceleration beyond the standard model, together with radio, optical, and gamma-ray observations.

Keywords:
acceleration of particles, ISM: supernova remnants, pulsars: general, X-rays: ISM

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1. Introduction

The origin of cosmic rays is one of the biggest problems since the discovery 100 years ago [1, 2]. It is widely believed that shocks of supernova remnants (SNRs) are the most prausible acceleration sites of Galactic cosmic rays below the knee energy via diffusive shock acceleration mechanism (DSA; [3]). However, we have no crucial evidence to confirm it. Pulsar wind nebulae (PWNe) are also believed as powerful electron/positoron accelerators [4]. One of the difficulties is from the interstellar magnetic field; charged particles, the main component of cosmic rays, change their direction due to the Lorentz force with the interstellar magnetic field, and forget their original direction. As a result, we cannot know the direction of accelerators from the direction of cosmic rays. On the other hand, when they emit photons, we can detect the acceleration sites directly. In fact, Koyama et al. (1995)[5] discovered synchrotron X-rays from the shocks of the SNR SN 1006 and confirmed that shocks of SNRs are electron acceleration sites up to ~TeV range. Now, several SNRs are known as a particle accelerators with synchrotron X-rays [6, 7, 8]. We, however, still have several key issues to understand the cosmic ray acceleration.

1. The injection from background thermal plasma to relativistic particles is not measured yet.
2. The acceleration mechanism including the origin of turbulence is not clear.
3. Accelerated particles must escape from the acceleration site in order to be cosmic rays, but we have no direct evidence of the escape

In this paper, we discuss how present X-ray missions such as Chandra, XMM-Newton, and Suzaku, solve part of these problems and how the near-future missions such as ASTRO-H and NuStar will solve them.

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2. Energy injection from the thermal plasma to accelerated particles

2.1. Acceleration Efficiency of Electrons

The accelerated particles are confined on the shock due to the magnetic field. When the magnetic field is turbulent and amplified due to the efficient cosmic ray acceleration [9], the electrons cannot runaway from the shock, and the scale length becomes small.

With the excellent spatial resolution of Chandra, Bamba et al. (2003) [10] discoverd that synchrotron X-rays are concentrated on the thin filaments on the shock of the northeastern limb of SN 1006, implying that the magnetic field on the shock are amplified and particle acceleration efficiency is higher than expected. It is also discovered that the thin synchrotron X-ray filaments are common in young SNRs [11, 12]. Figure 1 shows the Chandra X-ray image of young SNRs.

The turbulence of the magnetic field is very high, up to Bohm limit ($(\delta B/B)^2 \sim 1$)[14]. This is due to the back-reaction of high efficiency particle acceleration. Similar results is also from time variability of synchrotron X-ray knots on young SNRs [13].

2.2. Acceleration Efficiency of Protons

The shock of SNRs have huge kinetic energy of $\sim 10^{51}$ erg. It is divided into the thermal energy of downstream plasma, the kinetic energy of shock, and the energy of accelerated particles. The ratio is determined by the Rankine-Hugoniot relation;

$$kT = \frac{2(\gamma-1)}{(\gamma+1)^2}\mu {v_s}^2 \ , \qquad (1)$$

$$\gamma = 5/3 \ \text{ for ideal gas} \ , \qquad (2)$$

where v_s is the shock velocity. If the gas is ideal, or the acceleratation efficiency is negligible, about $\sim 20\%$ kinetic energy of the shock goes to the thermal energy of the downstream plasma. As mentioned in the previous subsection, on the other hand, it is believed that the energy injection efficiency from the background thermal plasma to accelerated particles is rather high. In such a case, γ becomes smaller up to $4/3$, and as a result, the downstream plasma cannot heat up compared with the plasma without acceleration. In other words, accelerated particles steals energy from the downstream plasma as shown in Figure 2. The precise measurement of thermal energy of downstream plasma leads the measurement of the energy injected to the accelerated particles.

2.2.1. Energy injection measurement using gratings

Recently, Katsuda et al. (2013)[15] showed precise measurement of the doppler shift and broadening of the oxygen line from the ejecta knots of the young SNR, Puppis A, using XMM-Newton grating (RGS). From the doppler shift of the line, it is estimated that the velocity of the ejecta is around 1500 km s^{-1}. If the plasma is the ideal gas (no acceleration), the oxygen temperature can be estimated to be $\sim$ 130 keV. On the other hand, the estimated temperature from the line broadening is less than 30 keV, which is significantly smaller than the expected value from the shock velocity. This result may suggest the efficient energy injection to the accelerated particles. However, we should be careful on the non-equilibrium state of supernova remnant plasma; the density of the plasma is too small ($n_e \sim 1$ cm^{-3}) to be in equilibrium in the age of supernova remnants ($n_e t \sim 10^{13}$ s cm^{-3}).

2.2.2. Energy injection measurement using ASTRO-H

How to solve this problem? The problem with XMM-Newton grating is that we can measure such a line shift and broadening only for oxygen due to the limited energy band and statistics. Another difficulty is that we can use grating only for point-like or tiny knots, and it is difficult to use for most of supernova remnant emission. If we can make similar measurements for other lines, we can check the element dependence of the discrepancy. With the wide energy coverage up to iron K lines and large effective area of ASTRO-H SXS [16], we will be able to determine the temperature decrease for various elements in the same plasma. The ratio of the temperature decrease should be same among elements if it is due to the stolen energy by the accelerated particles, and we will determine the energy injection for the first time. The precise determination of the plasma condition in non-equilibrium is also important for this study (Sawada, M., private communication).

3. Acceleration efficiency and maximum energy of accelerated particles

3.1. acceleration efficiency and background plasma

It is unknown that the background depencdency for the acceleration efficiency. Shocks running into dence matter will have more amplified magnetic field, on the other hand, those in low density will have longer time scale before deacceleration. RCW 86 is an ideal target to untangle these problems; it is a young SNR with its age of ∼1800 years, with clumpy thermal and non-thermal X-ray shells [8]. Tsubone et al. (2014)[17] has