PROCEEDINGS OF SCIENCE

First discovery of iron line emission generated by low-energy cosmic rays

K. K. Nobukawa[*a], **M. Nobukawa**[b], **S. Yamauchi**[a], **H. Uchiyama**[c], **K. Koyama**[d]

[a]*Department of Physics, Nara Women's University, Kitauoyanishimachi, Nara, 630-8506, Japan*
E-mail: kumiko@cc.nara-wu.ac.jp
[b]*Faculty of Education, Nara University of Education, Takabatake-cho, Nara, 630-8528, Japan*
[c]*Faculty of Education, Shizuoka University, 836 Ohya, Suruga-ku, Shizuoka, 422-8529, Japan*
[d]*Department of Physics, Graduate School of Science, Kyoto University, Kitashirakawa-oiwake-cho, Sakyo-ku, Kyoto, 606-8502, Japan*

Cosmic rays (CRs) in our galaxy are thought to be generated via diffusive shock acceleration. Gamma-ray observations have revealed that protons and/or electrons are accelerated to energies up to 100 TeV in supernova remnants (SNRs), and hence SNRs are the most plausible source of CR production. Whereas low-energy cosmic rays (LECRs) below the MeV band have important information on the initial acceleration mechanism, there has been very little information on LECRs due to lack of an effective probe. By interacting with neutral iron atoms in the interstellar medium, LECRs produce fluorescent X-ray line emission at 6.40 keV. The 6.40 keV line observation can be a probe to investigate LECRs. The Suzaku data analysis discovered the 6.40 keV line emission from several SNRs interacting with molecular clouds (W28, Kes 67, Kes 69, Kes 78, Kes 79, W44 and 3C391). The 6.40 keV line emission would be produced by MeV protons with the energy density of $>$ 10–100 eV cm^{-3}. Furthermore, we discovered the 6.40 keV line emission from a giant molecular cloud located near the Galactic center. The energy density of MeV protons is estimated to be $\sim$80 eV cm^{-3}. The diffusion length of MeV protons is very short, and thus the MeV protons should be produced *in situ*. Surprisingly, there is no SNR in the vicinity. The LECRs would possibly be generated by stochastic acceleration via Alfvén turbulence.

35th International Cosmic Ray Conference
10-20 July, 2017
Bexco, Busan, Korea

*Speaker.

PoS(ICRC2017)687

1. Introduction

Galactic cosmic rays (CRs) have been thought to be accelerated in shocks of supernova remnants (SNRs). X-ray observations by ASCA revealed that electrons are accelerated to energies of $\sim$100 TeV [1]. Observations of gamma-ray emission via π^0 decay have offered evidence that protons are accelerated in SNRs [2]. On the other hand, there has been little information of low-energy (below the MeV band) cosmic rays (LECRs). This is because LECRs coming from our galaxy are hardly observed inside the heliosphere due to the solar modulation. Only exception is Voyager-I, which has escaped the heliosphere [3]. Furthermore, there is no effective probe to indirectly measure LECRs so far.

Along the Galactic plane, there is diffuse X-ray emission which cannot be resolved into discrete sources (the Galactic ridge X-ray emission; GRXE) [4]. The GRXE is accompanied with K-shell lines from neutral iron (at 6.40 keV), helium-like iron (at 6.68 keV), and hydrogen-like iron (at 6.97 keV) [5]. We measured the distributions of these iron K-shell lines and the averaged GRXE spectrum, and found that a significant fraction of the neutral iron emission (the 6.40 keV line) of the GRXE is likely to originate from the interaction between LECRs and molecular clouds (MCs) [6, 7]. We then found that the 6.40 keV line can be a prove to investigate the LECRs.

2. Method

When LECRs are bombarded with the interstellar medium, in particular, MCs, the neutral iron line at 6.40 keV is produced via inner-shell ionization of neutral iron, and at the same time, the X-ray continuum is produced via inverse bremsstrahlung (for protons) or bremsstrahlung (for electrons). The cross section of iron K-shell ionization peaks at $\sim$ 10 MeV and $\sim$ 10 keV for protons and electrons, respectively [8]. The cross section for electrons has a sharp cut-off at 7.1 keV, while that for protons varies smoothly [8]. This difference of cross section results in the difference of the equivalent width (EW) of the 6.40 keV line between protons and electrons. The EW of the 6.40 keV line as a function of particle index is calculated by [8] and shown in figure 1. Here we adopt the iron abundance of 1–1.5 solar. The 6.40 keV line produced by electrons has the EW below $\sim$ 600 eV, while for protons the EW can be above 1 keV. Thus, we can distinguish the irradiating particles by the EW.

The 6.40 keV line can be produced also by X-rays with the energy higher than 7.1 keV (K-edge). In this case, the 6.40 keV lines is generated via photoionization, and the continuum is due to Thomson scattering. The EW in the X-ray scenario depends on the angle θ between the line of sight and the incident photon direction [9]. Figure 1 shows the EW as a function of photon index with the reflection angle $\theta = 90^\circ$, which gives the maximum EW. The 6.40 keV line produced by the X-ray irradiation has the EW below 1 keV and can be distinguished from the proton origin.

3. Result and Discussion

3.1 Eastern Region of Galactic Center

We have performed the 6.40 keV line survey on the Galactic plane $|l| < 4^\circ$ near the Galactic center using the *Suzaku* satellite, and investigated the intensity distribution of the iron lines at

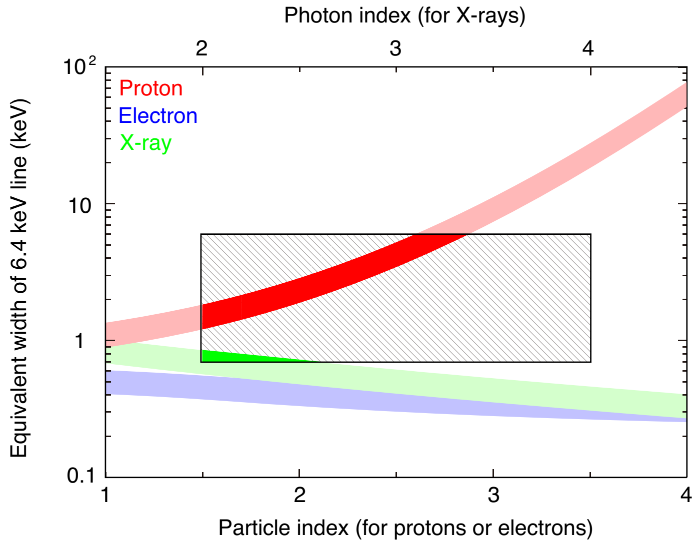

Figure 1: Equivalent widths of 6.40 keV for the X-ray, LECR electron, and LECR proton models shown with green, blue, and red lines, respectively [8, 9]. The solid rectangle indicates the constrained parameter space for the eastern region of Galactic center.

6.40, 6.68, and 6.97 keV, respectively. The detailed analysis is written in [10]. The 6.68 and 6.97 keV lines have symmetrical distributions between the eastern (positive l) and western (negative l) sides within $|l| = 1^\circ.5$–$3^\circ.5$. On the other hand, an asymmetrical distribution of the 6.40 keV line intensity was found (figure 2). The symmetrical model with the dashed curves well represents the data in the western side, whereas the data points in the eastern side significantly exceed the same model. This inconsistency indicates that the excess 6.40 keV line has a different origin from the 6.68, 6.97 keV lines. In order to examine the unknown origin, we compared the excess with the distribution of MCs. The red lines in figure 2 are the ^{12}CO line intensity taken by *NANTEN*, which nicely fills the residuals in the eastern side. The 6.40 keV line should be emitted from the cold interstellar gases.

We, then, made an X-ray spectrum of the excess component and fit the spectrum with a power law plus a Gaussian line at 6.40 keV (figure 3). The best-fit photon index of the continuum and the EW are 3 ± 1 and 1.3 ± 0.4 keV, respectively. If we take systematical uncertainty of statistical fluctuation of the symmetrical component into account, the EW value is constrained to be 0.7–5.9 keV. As is mentioned in Sec.2, the EW value is a key to distinguish the origin: X-rays, cosmic-ray protons, or electrons. The allowed parameter region is shown in figure 1. The electron origin is completely rejected. The X-ray origin is marginally accepted. Using the 6.40 keV line flux and the total mass of the molecular gas in the area, we should require an X-ray irradiating source with a unrealistic luminosity $L_X = 10^{40}(D/450~\mathrm{pc})^2$ erg s^{-1}, where D is the distance of the 6.40 keV line emitting region from the source. No source with such a luminosity is found in this area. Thus, the X-ray origin would be unlikely.

In the case of the proton origin, adopting the spectral index of -2.5 from the best-fit result (see figure1), we estimate the energy density of ~ 80 eV cm^{-3} in 0.1–1000 MeV. This value is

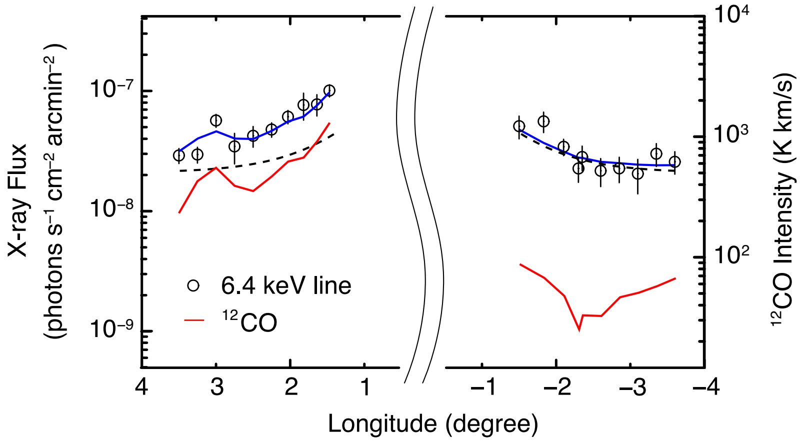

Figure 2: Intensity profile of the 6.40 keV line (circle) overlaid with the ^{12}CO intensity (red) [10]. The dashed lines well represents the distribution of the 6.40 keV line in the western side. A symmetric model cannot explain the eastern side. The blue lines are the sum of the symmetric distribution model and the ^{12}CO intensity multiplied by a constant factor.

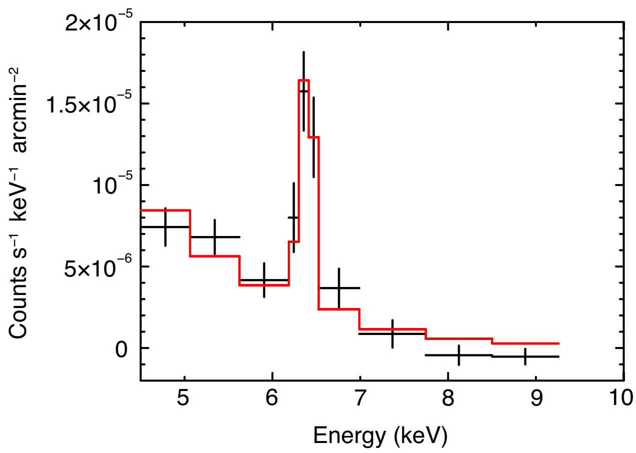

Figure 3: X-ray spectrum of the excess component in the eastern region of Galactic center. The solid line consists of a continuum with $\Gamma = 3$ and the 6.40 keV line with the equivalent width of 1.3 keV.

about two orders of magnitude higher than the average value 1 eV cm^{-3} of the cosmic rays [11]. The diffusion length of MeV protons is very short, and thus the MeV protons should be produced in situ. There is no possible accelerating source, such as a SNR, a pulsar wind nebula, or a highly-active black hole. Furthermore, since the excess 6.40 keV emission distributes about 2 degree, corresponding to 300 pc (at 8 kpc), acceleration by a single known object would be difficult. In the previous observations of the MCs, the gas velocity has a quite large dispersion of ~ 100 km s^{-1} [12]. In such a case, Alfvénic turbulence may occur and results in stochastic acceleration [13].

3.2 Galactic SNRs

SNRs are the most plausible source accelerating the Galactic cosmic rays. Our measurement of LECRs with the 6.40 keV line should be valid for SNRs. In fact, analyzing the *Suzaku* data of 3C391 and Kes79, [14, 15] reported detection of the 6.40 keV line which would originated from LECRs. We expanded the search for the 6.40 keV line to other SNRs located in the eastern region of the Galactic ridge, where 3C 391 and Kes 79 are located. We selected five SNRs (W28, W44, Kes 67, Kes 69, and Kes 78) which interact with MCs and carefully analyzed the archive *Suzaku* data in the 5–10 keV band. Detailed results will be reported by Nobukawa et al. (in prep).

We made the 6.40 keV line band image (figure 4). Non X-ray background was subtracted and the vignetting effect was corrected. One can see local enhancements of the 6.40 keV line in all the five SNRs. The SNRs are located on the Galactic plane ($5^\circ < l < 40^\circ$, $|b| < 1^\circ$), and hence the hard X-ray band above 5 keV is dominated by the Galactic background, i.e. the GRXE. We examined the spectra extracted from the regions where the 6.40 keV line emission is enhanced and their surrounding regions by fitting with a model consisting of a power law and Gaussian lines and measured the intensities of the 6.40 keV, 6.68 keV, and 6.97 keV lines. Comparing the iron K-shell lines between the enhanced and the surrounding regions, we found no excess in other iron lines than the 6.40 keV line. The significances of the 6.40 keV line enhancement are 1.6 σ, 2.7 σ, 2.9 σ, 2.0 σ, and 2.0 σ for W28, Kes 67, Kes 69, Kes 78, and W44, respectively.

SNRs can have an iron line at $\sim$ 6.4 keV originated from high temperature plasma in low ionization state $nt < 10^9$ s cm^{-3}. The enhance of the 6.40 keV line detected in this study can originate from the rarely ionized iron ejecta. However, the SNRs concerned are in a dense environment and interact with dense MCs (typically $n > 10^3$ cm^{-3}), and hence the plasma easily reaches a high ionization state in their evolution [16]. Furthermore, whereas SNRs from which the iron K-shell line is detected have higher electron temperature of $>$ 1 keV [16], All our samples have SNR plasma with electron temperature of $<$ 1.0 keV [17, 18, 19, 20] (Since no previous report is available for Kes 67, we analyzed the spectrum and obtained the temperature of 0.4$\pm$0.1 keV). On the other hand, since all the SNRs are associated with MCs, a natural explanation is the interaction between high-energy particles (X-rays or cosmic rays) and the MCs.

Because the spectrum extracted from each SNR had limited statistics, we co-added the spectra extracted from the enhanced and the surrounding regions, respectively, to study the origin of the 6.40 keV line quantitatively. We, then, subtracted the latter spectrum from the former one. In the same manner as the eastern region of the Galactic center (Sec. 3.2), the spectrum was fitted with a model of a power law plus the 6.40 keV line, resulting in the photon index of 1.5–8 and the equivalent width of $1.0^{+0.7}_{-0.4}$ keV. Assuming the iron abundance in the interstellar medium on the Galactic ridge of 1.0 solar, the electron origin cannot explain the result (see the lower limit of each line in figure 1). In the case of the X-ray origin, a source with the luminosity $L_X \sim 10^{38}(D/100\ \mathrm{pc})^2$ erg s^{-1} is required. No such a bright source is observed in the vicinity of the five SNRs. Therefore, the enhanced 6.40 keV line would come from the LECR protons.

We investigate a correlation between the morphologies of the 6.40 keV line emission and MCs (figure 4). In Kes 69 and W44, the 6.40 keV line and the MCs are well correlated, while it is not the case in other three samples. Although the spatial resolution is not good, HI clouds were detected in W28 and Kes 67. Their distributions seem to coincide with the peaks of the 6.40 keV line emission. For Kes 78, no good HI data have been taken. Using the averaged value of the column density $N_\mathrm{H} = 10^{22}$ cm^{-2}, the energy density of the LECR protons is calculated to be at least 10–100 eV cm^{-3}. Due to the Lorentz force and ionization loss, MeV protons hardly diffuse.

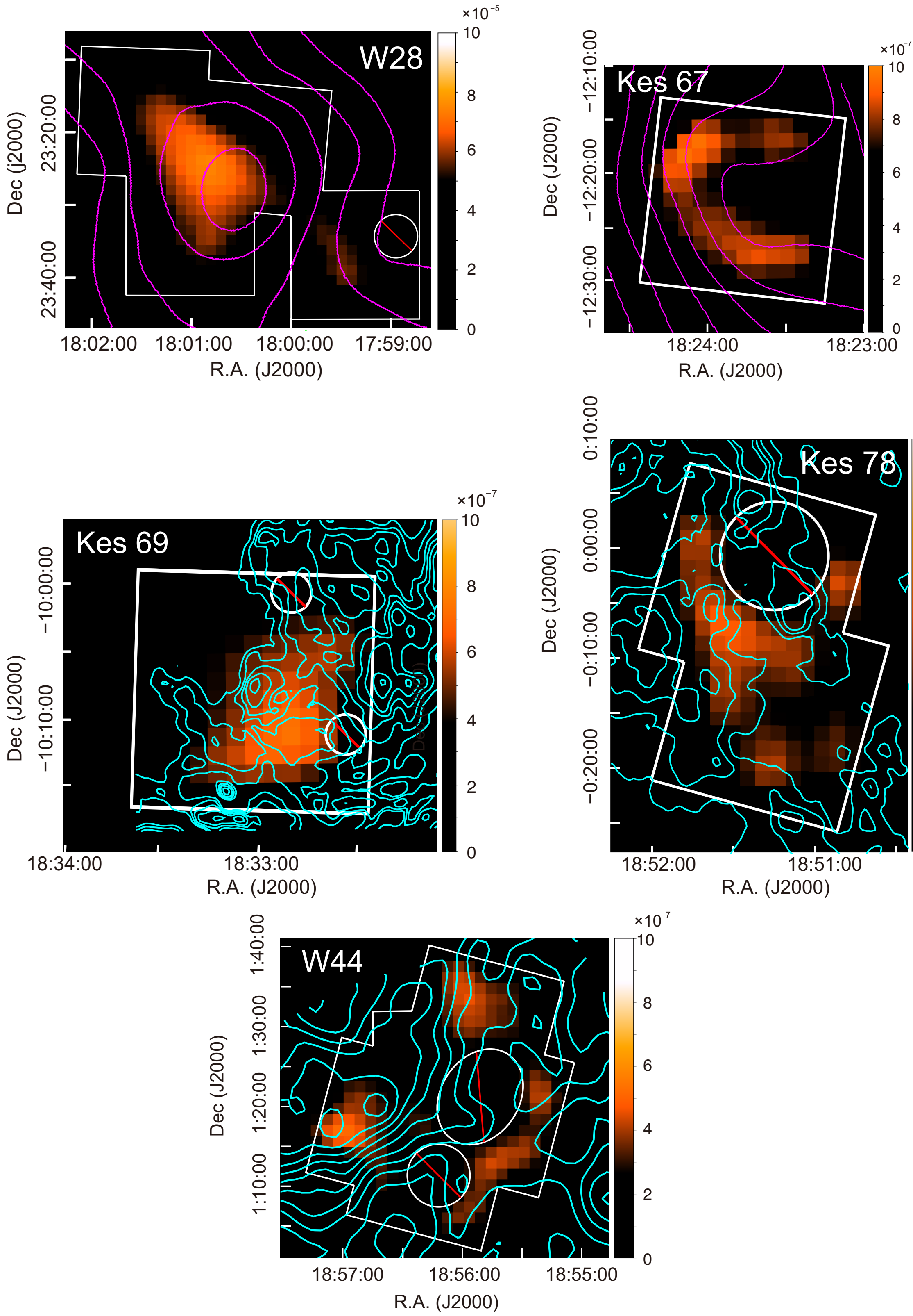

Figure 4: 6.40 keV line emission map (color) of the five SNRs. The contours are HI at 37.5 km s^{-1}, HI at 18.1 km s^{-1}, ^{13}CO ($J = 1$–0) at 80–84 km s^{-1}, and ^{12}CO ($J = 2$–1) at 40.0–50.3 km s^{-1}, for W28, Kes 67, Kes 69, Kes 78, and W44, respectively [21, 22, 23, 24, 25].

The 6.40 keV line emission should trace the site where MeV protons are generated by a shock interacting with the MCs or HI clouds.

4. Conclusion

We discovered the 6.40 keV line produced by LECR protons from the five SNRs (W28, Kes 67, Kes 69, Kes 78, W44, in addition to the previous detection in 3C391, Kes 79), and the eastern region of the Galactic center, with the energy densities of $>$ 10–100 eV cm^{-3} and $\sim$ 80 eV cm^{-3}, respectively. For the SNRs, the incident LECR protons are generated in situ, where the shock front contacts with MCs or HI clouds, and then produce the 6.40 keV line. On the other hand, in the eastern region of the Galactic enter, there is neither SNR, a pulsar wind nebula, nor a highly active black hole. Stochastic acceleration by Alfvén turbulence is a possible origin for the LECR protons.

Acknowledgement

This research was supported by a grant from the Hayakawa Satio Fund awarded by the Astronomical Society of Japan. KKN is supported by Research Fellowships of the JSPS for Young Scientists.

References

[1] K. Koyama, R. Petre, E.V. Gotthelf, U. Hwang, M. Matsuura, M. Ozaki, & S.S. Holt, *Evidence for Shock Acceleration of High-Energy Electrons in the Supernova Remnant SN1006*, *Nature* **378** (6554) 255–258.

[2] M. Ackermann et al., *Detection of the Characteristic Pion-Decay Signature in Supernova Remnants*, *Science* **339** (6) 807–811.

[3] E.C. Stone, A.C. Cummings, F.B. McDonald, B.C. Heikkila, N. Lal, & W.R. Webber, *Voyager 1 Observes Low-Energy Galactic Cosmic Rays in a Region Depleted of Heliospheric Ions*, *Science*, **341** (6142) 150–153.

[4] D.M. Worrall, F.E. Marshall, E.A. Boldt, & J.H. Swank, *HEAO 1 measurements of the galactic ridge*, *ApJ*, **255** 111.

[5] S. Yamauchi, et al., *Iron Emission Lines on the Galactic Ridge Observed with Suzaku*, *PASJ*, **61** (sp1) S225–S232.

[6] S. Yamauchi, K.K. Nobukawa, M. Nobukawa, H. Uchiyama, & K. Koyama, *Scale heights and equivalent widths of the iron K-shell lines in the Galactic diffuse X-ray emission*, *PASJ* **68** (4) 59.

[7] M. Nobukawa, H. Uchiyama, K.K. Nobukawa, S. Yamauchi, & K. Koyama, *Origin of the Galactic Diffuse X-Ray Emission: Iron K-shell Line Diagnostics*, *ApJ* **833** (2), 268.

[8] V. Dogiel, D. Chernyshov, K. Koyama, M. Nobukawa, & K.-S. Cheng, *K-Shell Emission of Neutral Iron Line from Sagittarius B2 Excited by Subrelativistic Protons*, *PASJ*, **63** (3) 535–541.

[9] M. Tsujimoto, Y. Hyodo, & K. Koyama, *Suzaku spectroscopic study of hard X-ray emission in the Arches cluster*, *PASJ*, **59** (sp1) S229–S235.

[10] K. K. Nobukawa, M. Nobukawa, H. Uchiyama, T. G. Tsuru, K. Torii, T. Tanaka, D. O. Chernyshov, Y. Fukui, V. A. Dogiel, & K. Koyama, *Enhancement of the 6.4 keV Line in the Inner Galactic Ridge: Proton-induced Fluorescence?*, *ApJL*, **807** (1) article.id L10.

[11] A. Neronov, D. V. Semikoz, & A. M. Taylor, *Low-Energy Break in the Spectrum of Galactic Cosmic Rays*, *PhRvL*, **108** (5) id 051105.

[12] K. Torii, et al., *A Detailed Observational Study of Molecular Loops 1 and 2 in the Galactic Center*, *PASJ*, **62** (5) 1307–1332.

[13] T. Amano, K. Torii, T. Hayakawa, & Y. Fukui, *Stochastic Acceleration of Cosmic Rays in the Central Molecular Zone of the Galaxy*, *PASJ*, **63** (6) L63–L66.

[14] T. Sato, K. Koyama, T. Takahashi, H. Odaka, & S. Nakashima, *Discovery of recombining plasma in the supernova remnant 3C 391*, *PASJ*, **66** (6) article.id 1249.

[15] T. Sato, K. Koyama, S-H. Lee, & T. Takahashi, *Suzaku spectra of a Type-II supernova remnant, Kes 79*, *PASJ*, **68** (SP1) article.id S8.

[16] H. Yamaguchi, et al., *Discriminating the Progenitor Type of Supernova Remnants with Iron K-shell Emission*, *ApJL*, **785** (2) L27.

[17] Sawada, M., & Koyama, K. *X-Ray Observations of the Supernova Remnant W28 with Suzaku. I. Spectral Study of the Recombining Plasma*, *PASJ*, **64** (4) 81.

[18] Bocchino, F., et al. *A population of isolated hard X-ray sources near the supernova remnant Kes 69*, *A&A*, **541** A152.

[19] Bamba, A., et al. *Discovery of X-Ray Emission from the Galactic Supernova Remnant G32.8−0.1 with Suzaku*, *ApJ*, **818** (1) 63.

[20] Uchida, H., et al. *Recombining Plasma and Hard X-Ray Filament in the Mixed-Morphology Supernova Remnant W 44*, *PASJ*, **64** (6) 141.

[21] Velázquez, P. F., Dubner, G. M., Goss, W. M., & Green, A. J. *Investigation of the Large-scale Neutral Hydrogen near the Supernova Remnant W28*, *ApJ*, **124** (4) 2145–2151.

[22] Dubner, G., Giacani, E., Reynoso, E., Goss, W. M., Roth, M., & Green, A. *Interaction of the Supernova Remnant G18.8+0.3 with the Surrounding Medium*, *ApJ*, **118** (2) 930–941.

[23] X. Zhou, Y. Chen, Y. Su, & J. Yang, *Discovery of Molecular Shells Associated with Supernova Remnants. I. Kesteven 69*, *ApJ*, **691** (1) 516–524.

[24] P. Zhou, & Y. Chen, *Molecular Environment and an X-Ray Spectroscopy of Supernova Remnant Kesteven 78*, *ApJ*, **743** (1) 4.

[25] S. Yoshiike et al., *The Neutral Interstellar Gas toward SNR W44: Candidates for Target Protons in Hadronic γ-Ray Production in a Middle-aged Supernova Remnant*, *ApJ*, **768** (2) 179.