Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: Kumiko K. Nobukawa *et al* 2019 *J. Phys.: Conf. Ser.* **1181** 012040

Measurement of Low-Energy Cosmic Rays via the Neutral Iron Line

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Abstract. There has been little information of Galactic low-energy cosmic rays (LECRs) so far because observations of LECRs in the solar system are affected by solar modulation and there is no effective way of indirect measurement. When LECRs in the MeV energy band collide with neutral iron atoms in the interstellar medium, fluorescent X-rays at 6.4 keV are produced via inner-shell ionization of neutral iron atoms. We investigate the 6.4 keV line in supernova remnants (SNRs) as a prime candidate for the Galactic cosmic-ray origin. The line emission is discovered from 11 SNRs. The spectra and morphologies suggest that the 6.4 keV line is produced by LECRs interacting with cold gas. The proton energy density is estimated to be 10–100 eV cm^{-3}. Furthermore, we measure the distribution of the 6.4 keV line emission near the Galactic center. The intensity profile is very similar to that of molecular clouds. The most plausible origin of the enhancement is the LECR proton bombardment. The energy density of MeV protons is estimated to be $\sim$ 80 eV cm^{-3}. Since the diffusion length of MeV protons is short, they should be produced *in situ*. Surprisingly, there is no SNR in the vicinity, and thus another mechanism such as the stochastic acceleration would possibly work.

1. Introduction

Cosmic rays (mainly protons) below the knee energy are thought to be accelerated in the Galaxy. Supernova remnants (SNRs) are the prime candidate for the Galactic cosmic-ray origin. Gamma-ray observations have obtained evidence for acceleration of high-energy cosmic rays (HECRs; in the GeV–TeV band) and their spectrum in SNRs (e.g., [1],[2]). Furthermore they provide the implication for the distribution of the HECRs in the Galaxy [3]. On the other hand, to date there are very few observations that give us the information of the Galactic low-energy cosmic rays (LECRs). Since solar modulation affects LECR measurements inside the heliosphere, a direct and convincing observation is performed only by Voyager-I [4]. The indirect measurements of

LECRs are also limited. In principle, observations of gamma-rays from π^0-decays provide the information of high-energy protons above 280 MeV. Although the infrared and radio observations can measure the ionization rate via the absorption line of H_3^+ [5] and the $[DCO^+]/[HCO^+]$ abundance ratio [6], respectively, there still remain large uncertainties of CR density and spectral shape.

The neutral iron line can be an effective prove to investigate the LECRs. When LECR protons or electrons collide with neutral iron atoms in cold gas, the 6.4 keV line is produced via inner-shell ionization. Iron has high abundance in the interstellar medium and has high fluorescence yield, and hence the 6.4 keV line is the best among fluorescent X-rays from neutral heavy atoms. Furthermore, the X-ray continuum is also produced via bremsstrahlung (by electrons) or inverse bremsstrahlung (by protons). Since the continuum intensity is different between the proton and electron cases, the intensity ratio of the 6.4 keV line and continuum, or an equivalent width, is used to distinguish the irradiating particles are protons or electrons.

The purpose of this study is to investigate LECRs by measuring the particle-induced 6.4 keV line. We first focus on SNRs because they are the prime candidate for the Galactic CR origin, and then move to the Galactic ridge in order to examine whether there are some CR accelerators other than SNRs. We utilize the Suzaku data because the X-ray CCD camera (X-ray Imaging Spectrometer: XIS) aboard the satellite has advantages of a large effective area and a low and stable background especially in the iron K-shell band [7, 8].

2. Results

2.1. Supernova remnants

We started from the five SNRs: W28, Kes 67, Kes 69, Kes 78, and W44. They all are middle-aged or old SNRs ($\sim 10^4$–10^5 yr; see table 1), and three out of them, W28, Kes 69, and W44, are classified as mixed-morphology SNRs [9]. Furthermore, they all interact with molecular clouds (MCs) [10]. LECRs accelerated in individual SNRs can collide the MCs to produce the 6.4 keV line. Detailed analysis procedure and results are described in Nobukawa *et al.* (2018) [11]. For each SNR, we discovered that the 6.4 keV line emission is locally enhanced. The 6.4 keV line emission would associate with the cold gas, such as MCs and HI clouds for the five SNRs. This fact indicates that the 6.4 keV line is generated by cosmic rays interacting with the interstellar medium.

We extracted a spectrum from the region with a high line intensity in each SNR, and then stacked all the spectra. A clear enhancement of the 6.4 keV line in the stacked spectrum compared to the background one was found with more than 4.3σ confidence. We, then, obtained the equivalent width of the 6.4 keV line of ≥ 1 keV. This value favors the MeV protons origin [12]. We estimated the energy density to be more than 10–100 eV cm^{-3} based on the 6.4 keV line intensity and the density of the interacting clouds. Since the diffusion length of LECRs is short, LECRs should be produced quite near the region with the 6.4 keV line emission. Detection of the 6.4 keV line suggests that acceleration of LECRs would indeed occur in SNRs.

Including the five SNRs, the 6.4 keV line that is most likely due to LECRs has been detected from more than 10 SNRs. We summarize those results in table 1. Most part of the listed SNRs are known to be middle-aged or old. This might be caused by bias due to the sensitivity at the 6.4 keV line band. In young SNRs, acceleration is highly activated, and a considerable number of high-energy CR electrons are produced, which entails a high-intensity continuum via synchrotron radiation (e.g., SN1006 [13], RX J1713.7-3946 [14]). Also high bremsstrahlung emission comes from high temperature plasma of $kT =$ several keV. Furthermore, the ionization state of iron in the plasma is often lower than helium-like iron, and thus these SNRs show a iron line of $\sim$6.4 keV (e.g., RCW 86 [15], SN 1006 [16]). Even if the LECRs produce the 6.4 keV line in young SNRs, it can be buried in the continuum or the plasma emission. In middle-aged and old SNRs, on the other hand, it is plausible that the particle-induced 6.4 keV line is more detectable because the nonthermal continuum is suppressed, and in many cases plasma temperature have decreased so that the iron K-shell line is emitted with the intensity under the detection limit of the Suzaku/XIS.

More than a half of the SNRs with the 6.4 keV line are accompanied by gamma-ray emission (table 1). LECRs can be a seed particle of HECRs, and therefore one may guess that the distribution of the 6.4 keV line is associated with those of the GeV and very-high-energy (VHE; > 0.1 TeV) gamma-rays. Observations indicate that the distributions of the 6.4 keV line and gamma-ray emission are not always associated with each other. In case of W44, where the gamma-rays are supposed to be originated from the interactions between high-energy protons and molecular clouds [1], the GeV gamma-ray and 6.4 keV line regions well overlap [11]. On the other hand, the peak of the VHE gamma-ray emission in G323.7−1.0 is about $20'$ away from the 6.4 keV clumps (figure 1). The difference of the diffusion lengths between LECRs and HECRs can cause the discrepancy of the morphologies. It is possible that the escape effect from the acceleration site contribute to the morphology difference: HECRs have larger gyro radius and can escape faster (e.g., [17, 18]). Another possibility is that the particle acceleration is not effective and thus LECRs are produced but HECRs are not in the 6.4 keV region. Sensitive and detailed observations of gamma-rays with angular scales of at least a few arcmin are required in order to discuss their association with the 6.4 keV line.

Table 1. List of the SNRs from which the 6.4 keV line is detected. Errors are quoted at 68% confidence levels.

Object	6.4 keV intensity (10^{-8} ph s^{-1} cm^{-2} arcmin^{-2})	SNR age (yr)	Gamma-ray detection (GeV/VHE)
W28	0.8 ± 0.5 [11]	$\sim 36,000$ [19]	GeV[20], VHE[21]
Kes 67	3.6 ± 1.4 [11]	$\sim 100,000$ [22]	–
Kes 69	2.8 ± 1.0 [11]	$\sim 5,000$–10,000 [23, 24]	–
Kes 78	1.8 ± 0.9 [11]	13,000–63,000 [25]	GeV[20], VHE[26]
Kes 79	6.0 ± 1.3 [27]	$\sim 27,000$ [27]	–
W44	1.3 ± 0.6 [11]	$\sim 20,000$ [28]	GeV[1]
G323.7−0.1	4.1 ± 0.8 [29]	$\sim 100,000$ [29]	GeV[30], VHE[31]
G346.6−0.2	$4.9^{+1.4}_{-1.6}$ [32]	14,000–16,000 [33]	–
Kes 17	$3.8^{+1.0}_{-1.1}$ [32]	28,000–64,000 [34]	GeV [20]
N132D	$5.3^{+2.0}_{-2.2}$ [35]	$\sim 2,500$ [36]	GeV[37], VHE[38]
IC 443	0.54 ± 0.17 [39]	3,000–30,000 [40, 41]	GeV[1]

2.2. Near the Galactic center region

We also discovered the particle-induced 6.4 keV line in the Galactic ridge near the Galactic center [42]. We measured an intensity profile of the 6.4 keV line at $l \sim 3^\circ$, where the giant molecular clouds called the Bania's Clump 2 is located (figure 2; [43]). The profile of the 6.4 keV line is very similar to that of the ^{12}CO distribution. This indicates that the origin of the 6.4 keV line would be due to the molecular clouds bombarded by LECRs or irradiated by X-rays. Since there is no X-ray source that has enough luminosity to explain the line intensity in the vicinity, the cosmic-ray origin is the most plausible also in this case. The equivalent width is estimated to be 1.3 keV and the proton origin is favored.

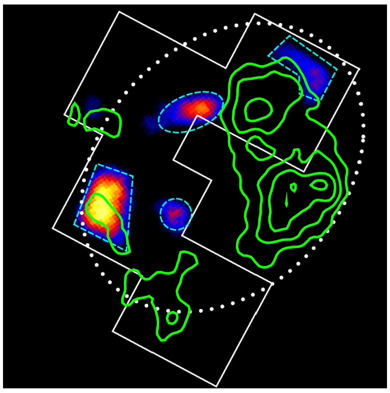

Figure 1. X-ray image of the 6.3–6.5 keV line band [29] obtained by the Suzaku/XIS, overlaid by the contours of the VHE gamma-ray emission [31]. The white solid line shows the fileds of view of the XIS. The white dashed ellipse roughly represents the shape of the radio shell.

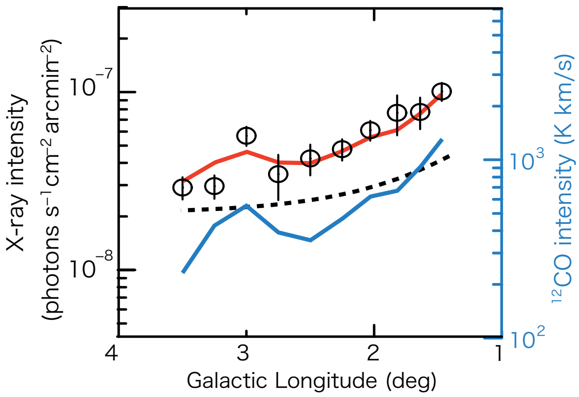

Figure 2. Intensity profile of the 6.4 keV line on the Galactic plane ($b = -0°.046$). Errors are quoted at 68% confidence levels. The dashed line shows a model that assumes the distribution symmetric with respect to Sgr A*. The blue line is the ^{12}CO intensity profile (the unit is on the right-side axis). The red line is the sum of the symmetric distribution model and the ^{12}CO intensity.

We estimated the energy density of LECR protons (0.1–1000 MeV) near the Galactic center to be 80 eV cm^{-3}. This is about one or two orders of magnitude higher than the energy density of CRs (> 3 MeV) in the local interstellar medium determined by the Voyager-I observation, ~ 1 eV cm^{-3} [44]. Whereas the LECRs should be generated *in situ*, there is no SNR in the vicinity. The LECRs should be produced by another mechanism (e.g. stochastic acceleration) in the Galactic disk.

Yamauchi *et al.* (2016) [45] and Nobukawa *et al.* (2016) [46] measured the intensity profile of the iron K-shell lines and global X-ray spectrum in the inner Galaxy by utilizing Suzaku, and argued that a significant fraction of the 6.4 keV line emission from the Galactic ridge can be due to local bombardment of LECRs to the molecular clouds. H_3^+ observations revealed that the ionization rate in the Galactic interstellar medium would be controlled by the proximity to local sites of particle acceleration [5]. Acceleration of LECRs can occur through the interstellar space by not only SNRs but also other mechanisms. It is our future work to compare between the intensity profile of the 6.4 keV line and those of GeV and VHE gamma-rays, which will provide a key to the CR production and propagation mechanism in the Galactic plane.

3. Conclusion

The neutral iron line at 6.4 keV can be an effective probe to investigate LECRs. We searched for the particle-induced 6.4 keV line in SNRs, and found it from 11 SNRs, most of which are middle-aged or old. Therefore, LECRs would be indeed accelerated in SNRs. Also the diffuse 6.4 keV line emission was discovered at $l = 1^\circ.5$–$3^\circ.5$. Since there is no SNR in the vicinity, other acceleration mechanisms other than SNR shocks seem to work in the Galactic ridge.

Acknowledgments

We thank the organizing committee of the 26th E+CRS and 35th RCRC for kind hospitality. We are grateful to all the members of the Suzaku team. KKN is supported by Research Fellowships of JSPS for Young Scientists. This work is supported by JSPS Numbers JP16J00548 (KKN), JP15H02090, JP17K14289 (MN).

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