X-ray Study of Neutral Iron Line Emission in the Galactic Ridge: Contribution of Low-Energy Cosmic Rays

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The Galactic diffuse X-ray emission (GDXE) is unresolved X-rays prevailing along the Galactic plane [1]. One of the most remarkable features of the GDXE is strong K-shell lines of neutral, helium-like and hydrogen-like iron at 6.4 keV, 6.7 keV and 7.0 keV, respectively. A popular idea for the origin of the GDXE is a superposition of many faint point sources, such as cataclysmic variables (CVs) and coronally active binaries (ABs) because more than 80% of the GDXE has been resolved into point-like sources at a small area near the Galactic center [2]. However, the spectra of the GDXE are different from position to position [3]. If many point sources contribute to the GDXE, the spectra should be spatially uniform. Previous debate on the GDXE origin has been based on the results of limited spectral and spatial resolution. The aim of this dissertation is to reveal the origin of the GDXE, especially that of the 6.4 keV line emission along the Galactic plane. The X-ray charge coupled device camera, the XIS, onboard the Suzaku satellite provides lower background and larger effective area than ever before, and is the most suitable instrument for diffuse sources with the energy above 5 keV. We used in total 153 pointings with the total exposure time of 8.8 Ms.

We have measured the detailed spatial distributions (the scale heights) of the 6.4 keV line, and for comparison, those of the 6.7 keV and 7.0 keV lines and the continuum (5−8 keV) separately. We spatially separated the GDXE into the Galactic center X-ray emission (GCXE), Galactic bulge X-ray emission (GBXE) and Galactic ridge X-ray emission (GRXE). In the GRXE, while the scale height of the 6.7 keV line is roughly consistent with those of CVs and ABs, that of the 6.4 keV line is far smaller than those of CVs and ABs, but similar to that of molecular clouds. Furthermore clear enhancements of the 6.4 keV line relative to the 6.7 keV line are found at $1.°5< l < 3.°5$ (GC east) and $l = 20°$ regions. These enhancements are associated with molecular gas.

In order to constrain the origin of the enhancement in the GC east region, we extracted an X-ray spectrum; we made integrated X-ray spectra from the east ($1.°5 < l < 3.°5$) and west ($−3.°5 < l < −1.°5$) sides, and subtracted the latter from the former. The spectrum is explained by a prominent 6.4 keV line plus a power-law component. The equivalent width of the 6.4 keV line is ~1.3 keV [4]. In a similar way, we obtained a spectrum of the enhancement at $l = 20°$. We constructed integrated X-ray spectra from the $l = 20°$ region and from the data in the $10° < |l| < 30°$ and $|b| < 0.5°$ region, and extracted the difference as the spectrum of the excess emission. Also this excess spectrum is described by a power-law continuum plus a 6.4 keV line with the equivalent width of ~0.7 keV.

The spatial distribution of the 6.4 keV line intensity strongly indicates that the enhancements are emitted from neutral iron atoms in molecular gas; cosmic-ray protons, electrons, or X-rays should collide with the molecular gas. The equivalent width of the 6.4 keV line depends on the irradiating particles and their spectral index [5,6]. The large equivalent width (~1.3 keV) of the enhancement in the GC east region is hardly explained by the electron scenario. The longitudinal and latitudinal distributions of the excess emission disfavor the X-ray irradiation, either by Sagittarius A* or by nearby X-ray binaries. Then, the low-energy cosmic-ray (LECR) proton bombardment is the most probable origin. The proton energy density of ~80 eV cm^{-3} in 0.1–1000 MeV is required. For the $l = −20°$ region, all the scenarios are accepted based on the equivalent width. Since there is no possible

X-ray source in the vicinity, the cosmic-ray bombardment would be plausible. We obtained the energy density of ~20 eV cm^{-3} in the energy range of 0.1–1000 MeV and ~0.03 eV cm^{-3} in the energy range of 0.1–1000 keV for protons and electrons, respectively.

Even in the GRXE of non-excess areas, an assembly of CVs and ABs does not reproduce the spectra; at least a half of the 6.4 keV line emission cannot be explained. Thus, additional contribution by another source with a strong 6.4 keV line is required. Since the 6.4 keV line from molecular gas irradiated by X-rays, cosmic-ray protons and electrons have a large equivalent width (> 300 eV) [5,6], and the scale height of the 6.4 keV line emission is consistent with that of molecular gas, the 6.4 keV line should be dominated by the diffuse emission from molecular gas. The scattered photons from the interstellar gas originated from bright X-ray sources are less than 10% of the total 6.4 keV lines. Therefore, the most possible origin is LECRs. The energy densities of the LECRs would be ~10 eV cm^{-3} and ~0.01 eV cm^{-3} for protons and electrons, respectively.

The diffusion length of LECR protons (~MeV) or electrons (~keV) is only ~10 pc [5], and therefore they should be produced *in situ*. Supernova remnants and pulsar wind nebulae are the most popular candidates to generate the Galactic cosmic rays. In both the GC east and $l = -20°$ regions, no conventional source is found in the vicinity. The LECRs can be accelerated by stochastic acceleration or magnetic reconnection [7,8]. Also the case where protons induce the 6.4 keV line emission in the entire GRXE requires accelerators other than conventional sources. In the electron scenario, the energy density is much below the typical value of 1 eV cm^{-3} that is measured in the > 1 GeV band. The LECR electrons could be the secondary electrons that are produced via interaction of higher energy particles and the interstellar medium.

Our study demonstrates that the 6.4 keV line can be a unique probe to investigate the LECRs. The LECRs are affected by the solar modulation, and hence their intensity and spectral shape in the interstellar space cannot be measured inside the solar system. We found that their energy density could be one or two orders of magnitude higher than the canonical value of 1 eV cm^{-3} on the Galactic plane including the excess regions (in the proton origin). This means that the LECRs, which have been little focused on so far, should be taken into account in exploring characteristics of hydrodynamic process in the Galaxy.

The intrinsic width of the 6.4 keV line provides critical information to determination of the origin. Whereas electrons and X-rays generate a narrow line with the width <1 eV, a proton-induced fluorescence line would broaden to ~10 eV due to multiple simultaneous ionization [9]. ASTRO-H, the next Japanese X-ray satellite, will have a micro-calorimeter array with the excellent energy resolution of < 7 eV at 6 keV (FWHM), and is now ready to be launched. We will open a new insight for investing the Galactic cosmic rays via ASTRO-H observations of the GRXE.

References

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