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X-ray Emission from Galactic Plane

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Abstract We report several important results obtained from recent Galactic X-ray survey observations, in particular ASCA Galactic center and plane surveys and our Chandra deep survey on the $(l, b) \approx (28.^\circ 5, 0.^\circ 0)$ region. Strong hard X-ray diffuse components are observed from Galactic ridge, center and bulge, and they have both thermal and non-thermal spectral components. Dozens of discrete and extended sources have been discovered on the Galactic plane, which also indicate thermal and/or non-thermal X-ray energy spectra. They are often associated with radio sources and are considered to be SNR candidates. Most of the hard X-ray point sources in the outer part of the Galactic plane are considered to be background AGNs, while fraction of the Galactic hard X-ray sources (such as quiescent dwarf novae) increases toward the Galactic center. Most of the soft X-ray sources on the Galactic plane are presumably nearby active stars.

Key words: Galactic Plane – X-rays – Galactic Diffuse Emission – Supernova Remnants – X-ray sources

1 INTRODUCTION

Presence of hard X-ray ($\geq$ 2 keV) emission from the Galactic plane has been recognized since early 1980's. HEAO1 reported detection of the hard X-ray emission from the Galactic "ridge", whose integrated luminosity is $\sim 10^{38}$ erg s^{-1} and energy spectrum is softer than that of the cosmic X-ray background (Worrall et al. 1982). A more precise scanning observation was made with EXOSAT (Warwick et al. 1985), which manifested global distribution of the hard X-ray emission over the Milky way. The extended hard X-ray emission was observed both from the Galactic "ridge" and "bulge" regions.

The Tenma satellite performed several pointing observations on the Galactic "blank" fields, and detected the omnipresent ∼6.7 keV iron K-line emission (Koyama et al. 1986). This is an evidence that the Galactic hard X-ray emission is associated with highly ionized plasmas,

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corresponding to $kT \approx 6-10$ keV. The Ginga satellite also carried out Galactic scan observations to study distribution of the diffuse emission. Thanks to its large effective area, Ginga was able to map the distribution of the diffuse emission using iron K-line intensities, so that contrast of the diffuse emission relative to the bright point sources is significantly enhanced. In this manner, distribution of the diffuse emission along the Galactic plane was precisely measured (Yamauchi and Koyama 1993), and concentration of the hot plasma around the Galactic center (Koyama et al. 1989) was revealed.

2 ASCA GALACTIC SURVEY

All the hard X-ray observations before 1993 were carried out with non-imaging instruments, in which sensitivity is limited by source confusion. Consequently, it was hardly possible to resolve dim point sources from diffuse emission, and to know how much the point source contribution to the Galactic diffuse emission would be. The ASCA mission, launched in 1993, was the first imaging satellite in the hard X-ray band (Tanaka, Inoue and Holt 1994). Above 2 − 3 keV, the interstellar medium is essentially transparent, so that ASCA was for the first time able to search for those hard X-ray sources embedded deeply in the Galactic plane that had not been detected by previous soft X-ray imaging observations.

In particular, ASCA carried out systematic survey observations on the Galactic plane and Galactic center regions, and acquired unbiased Galactic hard X-ray imaging data. The ASCA Galactic plane and center region survey was made to cover the Galactic inner disk ($|l| < 45°, |b| < 0.°4$) and the Galactic center region ($|l| < 2°, |b| < 2°$) with successive pointings of about 10 ksec exposure each. In addition, there are plenty of non-uniform pointing observations of the Galactic sources or blank fields.

Most of the ASCA Galactic plane and center survey observation data have been analyzed, and those results are published. In the following, some of the highlights are summarized below.

Point Source Survey: More than 200 X-ray sources have been resolved in the ASCA Galactic plane and center survey, among which ∼60 % of the sources are unidentifed. ASCA for the first time made a $\log N$-$\log S$ curve of Galactic X-ray sources in the 2 − 10 keV band down to $\sim 3 \times 10^{-13}$ erg s^{-1} cm^{-2} (Sugizaki et al. 2001). The $\log N$-$\log S$ curve in this flux range was approximated by a power-law with a slope of ∼ 0.8, which is flatter than that for the extragalactic sources (Figure 2). Locations and properties of the new X-ray sources discovered in the ASCA surveys are compiled in Sugizaki et al. (2001) and Sakano et al. (2002).

Supernova Remnants and Supernova Remnant Candidates: ASCA detected X-rays from 30 cataloged radio Supernova Remnants (SNRs) in the surveyed region, among which 17 SNRs were

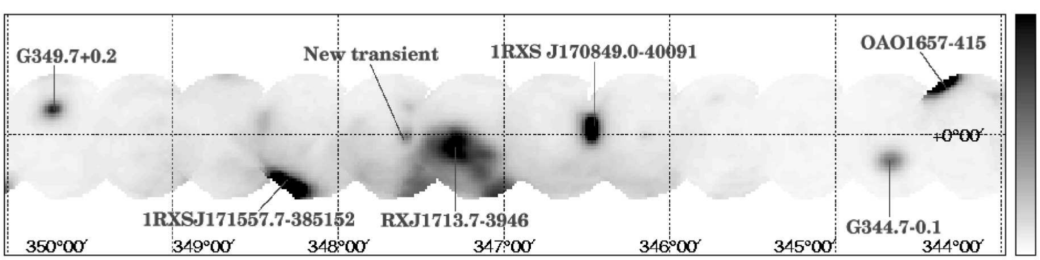

Fig. 1 X-ray image of a part of the ASCA Galactic Plane Survey shown with Galactic coordinates.

for the first time detected in X-rays. In Figure 1, two radio SNRs, G344.7–0.1 and G349.7+0.2 are clearly seen, whereas they were undetected in ROSAT. The crescent-like shell feature at $l \sim 347^\circ$ is the northwest shell of RX J1713.7–3946, a SNR discovered with ROSAT. The ASCA hard X-ray spectrum of RX J1713.7–3946 shows non-thermal feature without emission lines (Koyama et al. 1997), which is a reminiscence of SN1006 (Koyama et al. 1995). Later, RX J1713.7–3946 turned out to be a TeV gamma-ray source (Enomoto et al. 2002), just like SN1006 (Tanimori et al. 1998). These non-thermal X-ray and gamma-ray emission are considered to be due to synchrotron emission from extremely energetic electrons ($\geq$ TeV), which are presumably accelerated by the Fermi mechanism in the expanding SNR shells.

ASCA also discovered several unidentified extended sources, some of them show thin thermal X-ray spectra, while others indicate non-thermal spectra. These sources may be considered as X-ray SNR candidates (see Section 5).

X-ray Pulsars: Following new X-ray pulsars have been discovered in ASCA survey and other pointing observations: 1RXS J170849.0–400910 ($P = 11$ s; Sugizaki et al. 1997), AX J1740.1–2847 ($P = 729$ s; Sakano et al. 2000), AX J1749.2–725 ($P = 220$ s; Torii et al. 1998b), AX J1820.5–1434 ($P = 152$ s; Kinugasa et al. 1998), AX J183220–0840 ($P = 1549$ s; Sugizaki et al. 2000), AX J1841.0–0536 ($P = 4.7$ s; Bamba et al. 2001a) and AX J1845.0–0300 ($P = 7$ s; Torii et al. 1998a). In addition, ASCA discovered several X-ray sources with flat power-law spectra with large absorption, which is a characteristics of binary X-ray pulsars. XMM Galactic plane scan survey may be able to detect coherent pulsations from these sources.

Galactic Ridge X-ray Emission: ASCA found that the Galactic Ridge energy spectra in $0.5 - 10$ keV are well represented by two temperature components (Kaneda et al. 1997). The low temperature component has a temperature $kT \sim 0.8$ keV and a low ionization degree. Its surface brightness is consistent with the SNR origin. The high temperature component may be represented with a temperature of $kT \sim 7$ keV in non-ionization equilibrium state (Kaneda et al. 1997). From the fluctuation analysis of the hard X-ray ridge emission, it was found that the upper limit of the discrete sources to contribute to the ridge emission is $\sim 2 \times 10^{31}$ erg s^{-1} (Sugizaki et al. 1999). At this flux limit, ASCA was not able to conclude if the Galactic ridge X-ray emission is composed of numerous discrete sources or truly diffuse emission.

3 CONTRIBUTION OF THE POINT SOURCES

Chandra's excellent spatial resolution ($\sim 0.5''$) revolutionized our X-ray view of the Milky way. With $\sim$100 ksec exposure, Chandra is able to detect point sources down to a flux of $\sim 3 \times 10^{-15}$ erg s^{-1} cm^{-2} in 2–10 keV, that is about two orders of magnitudes better than ASCA. In Figure 2, we show Chandra $\log N$-$\log S$ curve in $2 - 10$ keV for the Galactic plane ($l = 28\overset{\circ}{.}5$; Ebisawa et al. 2001) and Galactic center (Sgr B2 region; Senda 2002). Remarkably, the $\log N$-$\log S$ curve on the Galactic plane does not indicate clear excess of the Galactic sources compared to the extragalactic $\log N$-$\log S$ curve. This indicates that most of the hard X-ray sources on the Galactic plane are background AGNs at the Chandra flux limit (Ebisawa et al. 2001). The integrated point source X-ray flux above $\sim 3 \times 10^{-15}$ erg s^{-1} cm^{-2} is only ~ 10 % of the total hard X-ray flux in the field of view, which indicates the Galactic ridge emission is truly diffuse (Ebisawa et al. 2001). On the other hand, in the Galactic center region, there are obviously numerous dim point hard X-ray sources (Figure 2; Senda 2002), which are presumably mostly quiescent dwarf novae and show thermal iron K-line emission (Wang, Gotthelf and Lang 2002). Still, the integrated point source flux is $\sim$10 % of the total flux from the Sgr B2 region, and most of the hard X-ray emission has truly diffuse origin (Senda 2002).

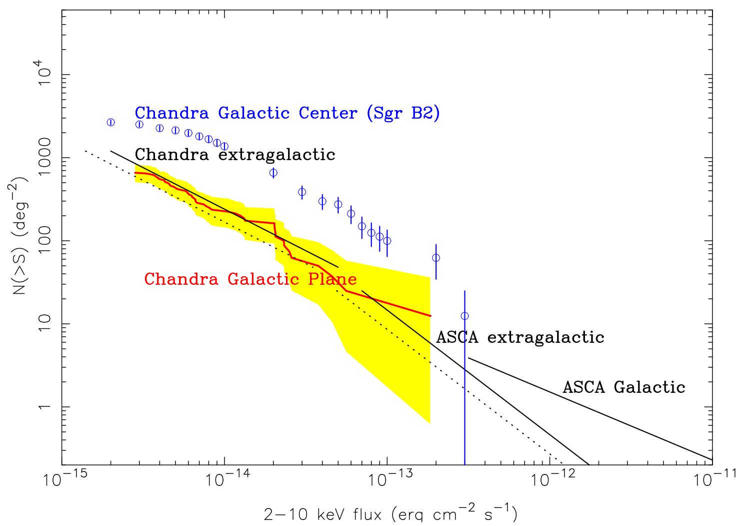

Fig. 2 $\log N$-$\log S$ curve in the 2–10 keV band made from Chandra Galactic plane (red line with 90 % error range in yellow; Ebisawa et al. 2001) and Sgr B2 field (blue; Senda 2002).ASCA Galactic $\log N$ - $\log S$ curve (Sugizaki et al. 2001), and ASCA (Ueda et al. 1999) and Chandra (Giacconi et al. 2001) extragalactic ones are shown together.

4 ENERGY SPECTRA OF THE GALACTIC DIFFUSE EMISSION

X-ray energy spectra of the diffuse emission from Galactic center, bulge and plane are very similar in shape (Tanaka 2002). They have thermal and non-thermal continuum components, and prominent emission lines from highly ionized iron and other heavy elements. The power-law like non-thermal component extends above ∼10 keV (Yamasaki et al. 1997; Valinia and Marshall 1998), and smoothly connects to the Galactic diffuse gamma-ray emission (Gehrels and Tueller 1993; Valinia, Kinzer and Marshall 2000).

Galactic diffuse X-ray emission is very energetic. Energy density of the ridge emission, $\sim 10\,\mathrm{eV\ cm^{-3}}$, is one or two orders of magnitude higher than those of cosmic rays, Galactic magnetic fields or any other constituents in the interstellar space. Energy source of the diffuse emission is not elucidated yet, but several attractive theories have been proposed, such as interstellar-magnetic reconnection (Tanuma et al. 1999), or interactions of cosmic low-energy electrons (Valinia et al. 2000) or heavy irons (Tanaka 2002) with interstellar medium.

Precise X-ray line study is likely to be a key to resolve origin of the Galactic diffuse emission. Iron K-line emission feature observed with ASCA has a complex structure, and may not be explained by a single equilibrium thermal plasma. Kaneda et al. (1997) proposes a non-ionization equilibrium plasma model, which yields a single ∼6.6 keV line with a moderate width corresponding to composition of different ionization states. Valinia et al. (2000) proposes a composite model of the 6.67 keV line from thermal equilibrium plasma and the 6.4 keV line due to interaction of cosmic-ray electrons and neutral interstellar matter. On the other hand, Tanaka (2002) claims presence of the 6.97 keV line which may be attributed to electron capture by the cosmic naked iron nuclei. These different models seem to explain the observed ASCA spectra. Accumulation of more Chandra and XMM data, as well as observations by future missions, will eventually tell us the definitive answer through precise X-ray spectroscopy.

5 DISCOVERY OF EXTENDED AND DISCRETE SOURCES

More than a dozen of diffuse and discrete sources have been discovered with ASCA and other Galactic surveys. Most of them are associated with known diffuse radio features, but some of them are discovered in X-rays for the first time.

Search for non-thermal X-ray emitting SNRs similar to SN1006 or RX J1713.7–3946 is very important for the study of global energy balance of the cosmic ray. In the ASCA Galactic plane survey, four such X-ray SNR candidates have been discovered; G28.6–0.1 (Bamba et al. 2001b), G11.0+0.0, G25.5+0.0 and G26.6–0.1 (Bamba et al. 2002). All these sources have power-law slopes of 1.6 to 2.1, without emission lines. Only G28.6–0.1 is associated with a previously known radio source (Helfand et al. 1989).

In contrast to the non-thermal sources, several diffuse and discrete sources near the Galactic center such as G0.0–1.3 (Sakano et al. 2002) and G0.570–0.018 (Senda, Murakami and Koyama 2002) show thermal spectra with prominent emission lines. These thermal sources are likely to be young SNRs heated by blast waves.

The diffuse X-ray feature in the G28.6–0.1 region has been closely studied with ASCA (Bamba et al. 2001b) and Chandra (Ueno et al. 2003). The diffuse feature is more clearly seen in hard X-rays (> 2 keV) than in soft X-rays. While the extended hard X-ray feature (named AX J1843.8–0352) shows a non-thermal spectrum with a slope of $\sim$2.1, a blob-like soft X-ray feature (named CXO J18435.1–035828) is found to be embedded and associated with the radio emission. CXO J18435.1–035828 has a thermal spectrum with prominent emission lines. Presumably, emission mechanism of these thermal and non-thermal components from discrete sources are related to those of the global diffuse emission from Galactic center, bulge and plane (Section 4).

6 ORIGIN OF THE POINT SOURCES

Characteristics of the point X-ray sources detected with Chandra on the Galactic plane at $l \approx 28^\circ\!.5$ has been studied, down to the fluxes $\sim 3 \times 10^{-15}$ erg s^{-1} cm^{-2} (2–10 keV) or $\sim 7 \times 10^{-16}$ erg s^{-1} cm^{-2} (0.5–2 keV) (Ebisawa et al. 2002). If the sources are classified with hardness ratio (HR) between 0.5–3.0 keV and 3.0–8 keV, the softest sources with HR≈ -1 are most numerous, and the population decreases up to HR≈ 0.5, then again increases toward HR=1. This dichotomy indicates that there are two main populations of the point X-ray sources classified with the spectral hardness.

Hard X-ray sources are considered to be mostly background AGNs from the argument of the source number density (Section 3). In fact, average hydrogen column densities toward these sources ($\sim 8 \times 10^{22}\,\mathrm{cm}^{-2}$) are consistent with the value through the Galactic plane. However, some of the hard X-ray point sources show flat spectra (power-law slope ~ 1) and iron line feature. These point sources are candidates of Galactic hard X-ray sources such as quiescent dwarf novae (e.g., Mukai and Shiokawa 1993). Soft X-ray sources have low temperature (≤ 1 keV) thin thermal spectra, and low hydrogen column density ($\leq 10^{22}$ cm^{-2}), and some of which show X-ray flares. These facts suggest that most of the soft X-ray sources are nearby X-ray active stars.

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