ASCA DISCOVERY OF DIFFUSE 6.4 keV EMISSION NEAR THE SAGITTARIUS C COMPLEX: A NEW X-RAY REFLECTION NEBULA

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ABSTRACT

We present an ASCA discovery of diffuse hard X-ray emission from the Sgr C complex with its peak in the vicinity of the molecular cloud core. The X-ray spectrum is characterized by a strong 6.4 keV line and large absorption. These properties suggest that Sgr C is a new X-ray reflection nebula that emits fluorescent and scattered X-rays via irradiation from an external X-ray source. We found no adequately bright source in the immediate Sgr C vicinity to fully account for the fluorescence. The irradiating source may be the Galactic nucleus Sgr A*, which was brighter in the past than it is now, as is suggested from observations of the first X-ray reflection nebula Sgr B2.

Subject headings: Galaxy: center — ISM: clouds — ISM: individual (Sagittarius C) — reflection nebulae — X-rays: ISM

1. INTRODUCTION

The Galactic center (GC) region of our Galaxy is a unique concentration of stars and molecular clouds, in addition to Sgr A*, a $2.6 \times 10^6 M_\odot$ massive black hole (MBH) at the gravitational center (for a recent review, see Genzel & Eckart 1999). The inner $\sim 100$ pc region of the Galaxy is a site of a nuclear starburst and consequently should be populated by a variety of X-ray sources, such as X-ray binaries, supernova remnants, and young stellar clusters. ASCA binaries, supernova remnants, and young stellar clusters. ASCA revealed diffuse emissions of $2$ extent centered at Sgr A* and an asymmetrical structure extending $1^\circ$ along the Galactic plane (Koyama et al. 1996; Maeda et al. 1998). The spectral characteristics were most remarkable, exhibiting many K-shell lines from highly ionized atoms, with particularly enhanced emission from He-like (6.70 keV) and H-like (6.97 keV) irons.

Early Chandra results confirmed the ASCA findings and resolved numerous X-ray structures: X-ray binaries, diffuse structures, emission from the supernova remnant Sgr A East, emission from individual stars within the Sgr A region, and a possible X-ray counterpart to the massive black hole Sgr A* with a luminosity of only $10^{33}$ ergs s$^{-1}$ (Baganoff et al. 2001), which is extremely low compared to typical massive black holes.

Among these many X-ray objects, the most massive molecular cloud in the Galaxy, Sgr B2, is extraordinary. It exhibits a very peculiar spectrum with a strong emission line at 6.4 keV, a low-energy cutoff below 4 keV, and a pronounced edge structure at 7.1 keV. The X-ray image is shifted from the core of the molecular cloud toward the GC by about 1.3 (Murakami et al. 2000a). Recently, Chandra confirmed these results: the extended structure of the 6.4 keV line image with a convex shape pointed toward Sgr A* and its offset morphology from the cloud core (Murakami et al. 2000b). A numerical simulation demonstrated that the offset morphology and the line- and edge-dominated spectrum are well reproduced by the reflection of external X-rays coming from the direction of the GC (Fig. 2 of Murakami et al. 2000a; also in Sunyaev & Churazov 1998). Based on this, Murakami et al. (2000a) proposed that Sgr B2 is a new class of X-ray object, an X-ray reflection nebula (XRN). However, there is no adequately bright source in the immediate Sgr B2 vicinity to fully account for the fluorescence. They suspected that the most likely source is an X-ray outburst from the MBH at Sgr A*, despite its considerable distance from Sgr B2 (Koyama et al. 1996; Murakami et al. 2000a). Their model requires an outburst of $L_X \sim 10^{39}$ ergs s$^{-1}$ for at least 10 yr and must have stopped at most 30 yr ago to avoid detection by earlier X-ray astronomical instruments. Such an outburst from a $10^6 M_\odot$ MBH, perhaps caused by a surge in accretion rate, is consistent with the behavior of active galactic nuclei.

The XRN scenario and the putative past X-ray outburst of the Galactic nucleus Sgr A* may indicate that there should be many other XRNs in the GC region. We therefore examined the archival ASCA data of the GC region in detail and found another XRN candidate in the Sgr C region, located at the same projected distance as Sgr B2 from the GC, but in the opposite direction.

2. OBSERVATION

The ASCA observations of Sgr C were made on 1993 October 4. All four focal plane instruments, two Solid-State Imaging Spectrometers (SIS0, SIS1) and two Gas Imaging Spectrometers (GIS2, GIS3), were operated in parallel, pro-
providing four independent data sets. Details of the instruments, the telescopes, and the detectors are found in Burke et al. (1991), Tanaka, Inoue, & Holt (1994), Serlemitsos et al. (1995), Gotthelf (1996), Makishima et al. (1996), and Ohashi et al. (1996). Each of the GISs was operated in PH mode, with the standard bit assignment, while the SIS was operated in 4 CCD bright mode. The data were postprocessed to correct for spatial-gain nonlinearity. Data taken at geomagnetic cutoff rigidities lower than 6 GV, at elevation angles less than 5° from the Earth rim, or during the passage through the South Atlantic Anomaly were excluded. After these filterings, the net observing time was 20 ks.

3. ANALYSIS AND RESULTS

The key characteristic of XRNs is a strong iron line at 6.4 keV (Koyama et al. 1996; Sunyaev & Churazov 1998; Murakami et al. 2000a); hence, we made a narrow energy-band image with a central energy of 6.4 keV and a width of twice the energy resolution (FWHM): 5.8–7.0 keV for the GIS. Figure 1 shows the GIS image overlaid with the contour map of the cold cloud density distribution contour of the radio observation of CS with the radial velocity of [120 to [110 km s⁻¹ (Fig. 3 in Tsuboi, Handa, & Ukita 1999). The position accuracy is about 5″ for the radio map and 24″ for the GIS image (Gotthelf et al. 2000). The 6.4 keV band image shows an X-ray peak (inner region of the solid circle) near the molecular cloud core CO 359.4−0.0 (Oka et al. 1998), which is one of the giant molecular clouds in the Sgr C complex, with a mass of ~10⁶ M⊙. We therefore suspect that the X-ray emission is associated with the molecular cloud Sgr C, although a more detailed comparison will require more accurate positional observations both in X-rays and radio bands.

We made X-ray spectra using the X-ray photons in a circle of radius around the X-ray peak (see Fig. 1). Since the Sgr C region is in the large-scale GC plasma (Koyama et al. 1996), the spectrum may be contaminated by the emission of He- and H-like iron lines (6.70 and 6.97 keV). In order to properly subtract these highly ionized iron lines, the background region is selected as a radius region with the same Galactic latitude (dotted circle in Fig. 1). Figure 2 shows the background-subtracted GIS spectrum. We made a model spectrum with a power-law continuum and a Gaussian line, folding with the ASCA response function, and fit it to the data. Because of the limited statistics, we fixed the power-law photon index α to be 2.0 [number of photons N(E)dE ∝ E⁻αdE, where E is the total luminosity ....... L₄₋₁₀ keV (10⁻³⁴ ergs s⁻¹) 5.0 3.0 Reduced χ²(dof) ...... 0.80 (20) 0.63 (14)

TABLE 1

Fitting Results of Sgr C to a Phenomenological Spectral Model

| Model Components | Parameter | GIS       | SIS       |
|------------------|-----------|-----------|-----------|
| Absorption       | \(N_H\)   | 12.6⁻²⁺³  | 9.7⁻²⁺³   |
| Continuum        | Photon index | 2.0 (fixed) | 2.0 (fixed) |
|                  | Flux (2–10 keV) | 30⁻²⁺₁ | 20⁻²⁺₁ |
| Fe line          | Center energy (keV) | 6.28⁻¹⁻₀.₁ | 6.38⁻¹⁺₀.₁ |
|                  | Flux \(b\) | 3.5⁻¹⁺₁ | 2.7⁻¹⁺₁ |
|                  | Equivalent width (keV) | 0.8⁻¹⁻₀.₅ | 1.1⁻¹⁻₀.₅ |
| Total luminosity | \(L_{4⁻₁₀ \text{keV}} (10⁻³⁴ \text{ergs s}⁻¹)\) | 5.0 | 3.0 |
| Reduced \(\chi^2\) (dof) | 0.80 (20) | 0.63 (14) |

Note.—The errors are at 90% confidence level.

\(a\) The equivalent hydrogen column density for the solar abundances in units of \(10^{22} \text{H cm}⁻²\).

\(b\) In units of \(10⁻⁵ \text{photons s}⁻¹\ cm⁻²\). The fluxes are not corrected for absorption.
photon energy], the same value as assumed for Sgr B2 (Koyama et al. 1996; Murakami et al. 2000a). The fit is acceptable, with the best-fit parameters shown in Table 1. The central energy of the line appears at $6.28^{+0.15}_{-0.11}$ keV, in agreement with the fluorescent line from neutral irons. The line equivalent width and absorption column density are both very large: $\sim 0.8$ keV and $1.3^{+0.3}_{-0.4} \times 10^{23}$ H cm$^{-2}$, respectively. Since the Galactic diffuse background may not be uniform, we checked the ambiguity of the background selection. We selected three other background regions with the same Galactic latitude as the source region and fitted them with the same model. The best-fit parameters of the line central energy and the absorption are in the range of statistical errors. The absorbed flux differs a little larger than the error; however, this flux variation is not serious for the discussion in 4.

Adding two narrow Gaussian lines at 6.4 and 6.7 keV on a power-law continuum, we found that the 6.7 keV line from highly ionized iron is very weak; the upper limit of $9 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ is about one-quarter of the best-fit value of the 6.4 keV line. We thus conclude that the emission line from the Sgr C cloud is dominated by the fluorescent line from cold irons.

We also made an SIS spectrum from the same region of GIS and fitted it with the same model as the GIS. The best-fit spectral parameters are shown in Table 1 and are consistent with those obtained from the GIS spectrum. Because of the limited statistics, the SIS spectrum does not further constrain the spectral parameters. We thus discuss the X-ray properties of Sgr C using the spectral parameters obtained with GISs only.

4. DISCUSSION

4.1. Is Sgr C a New XRN?

We have found a hard X-ray enhancement near the Sgr C cloud on the 6.4 keV line map. The spectrum shows a strong fluorescent line at 6.4 keV and the large absorption in the low-energy band. These properties are good evidence that Sgr C is a new XRN (Sunyaev & Churazov 1998; Murakami et al. 2000a).

Murakami et al. (2000a) analyzed the spectrum of Sgr B2, the XRN, and found that the equivalent width of the 6.4 keV line is $2.9^{+0.3}_{-0.5}$ keV and the column density of hydrogen is $8.3^{+2.5}_{-2.0} \times 10^{23}$ H cm$^{-2}$. Those of Sgr C are $0.8^{+0.4}_{-0.3}$ keV and $1.3^{+0.4}_{-0.3} \times 10^{23}$ H cm$^{-2}$, respectively.

The absorption of Sgr C is smaller than that of Sgr B2 by an order of magnitude. This is reasonable because the mass of the Sgr C cloud is about one-seventh that of the Sgr B2 cloud (Oka et al. 1998); in spite of a rather similar geometrical size. In fact, using the Sgr C cloud size of $\sim 28$ pc (Oka et al. 1998), we can roughly estimate the column density to be $4 \times 10^{22}$ H cm$^{-2}$, which is almost equal to $1.3 \times 10^{23}$ H cm$^{-2}$, after taking account of the interstellar absorption to the Sgr C cloud of $\sim 10^{23}$ H cm$^{-2}$ (Sakano et al. 1998).

The absorption column of $4 \times 10^{22}$ H cm$^{-2}$ is in the optically thin range near 6.4 keV and above 7.1 keV; hence, unlike Sgr B2, the 6.4 keV emission region should overlap the molecular core. This is in agreement with the observation, although the observational results still have significant uncertainty.

4.2. Irradiating Source of XRNs

In the optically thin case, the X-ray intensity of an XRN is simply proportional to the amount of the scattering matter and the flux of the irradiating X-rays. The absorption-corrected luminosity of the 6.4 keV line from Sgr C is $4 \times 10^{33}$ ergs s$^{-1}$ within a 27 radius circular region. The required luminosity of the X-ray source irradiating Sgr C would be about $3 \times 10^{39} (d_{\text{sgr c}}/100$ pc)$^2$ ergs s$^{-1}$, where $d_{\text{sgr c}}$ is the distance from the irradiating X-ray source to Sgr C.

The brightest nearby X-ray source is 1E 1740.7−2942, which lies only $\sim 0.4$ from Sgr C. During the present observation, its luminosity was $\sim 3 \times 10^{36}$ ergs s$^{-1}$ in the 2–10 keV band (Sakano et al. 1999). This luminosity, however, is 2 orders of magnitude less than that required to account for the fluorescent X-rays from Sgr C. Even if we accumulate the X-ray fluxes from all cataloged bright X-ray sources near the GC (Sakano 2000), we can explain only 2% of the reflected luminosity of Sgr C. This fact strengthens the scenario that the X-rays from Sgr C, as well as those from Sgr B2, are due to the reflection from an irradiating source that was very bright in the past but is presently dim. The X-ray fluxes of Sgr B2 and Sgr C can be consistently explained by one irradiating source, if it is located at almost the same distance from both the XRNs. This position falls near the Galactic nucleus Sgr A*, and the X-ray luminosity should be as luminous as $3 \times 10^{39}$ ergs s$^{-1}$ about 300 yr ago, the light travel time from Sgr A* to Sgr B2 and Sgr C.

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