A CANDIDATE NEUTRON STAR ASSOCIATED WITH GALACTIC CENTER SUPERNOVA REMNANT SAGITTARIUS A EAST

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ABSTRACT

We present imaging and spectral studies of the supernova remnant (SNR) Sagittarius (Sgr) A East from deep observations with Chandra. The spatially resolved spectral analysis of Sgr A East reveals the presence of a two-temperature thermal plasma \((kT \sim 1\) and \(5\) keV) near the center of the SNR. The central region is dominated by emission from highly ionized Fe-rich ejecta. We estimate a conservative upper limit to the total Fe ejecta mass of the SNR, \(M_{Fe} \leq 0.27 M_\odot\). Comparisons with standard SN nucleosynthesis models suggest that this Fe mass limit is consistent with a Type II SN explosion for the origin of Sgr A East. On the other hand, the soft X-ray emission extending toward the north of the SNR can be described by a single-temperature \((kT \sim 1.3\) keV) thermal plasma with normal chemical composition. This portion of the SNR is thus X-ray emission from the heated interstellar medium rather than the metal-rich stellar ejecta. We point out that a hard pointlike source CXOGC J174545.5–285829 (the so-called cannonball) at the northern edge of the SNR shows X-ray characteristics unusual among other Galactic center sources. The morphological, spectral, and temporal characteristics of this source suggest identification as a high-velocity neutron star. Based on the suggested Type II origin for the SNR Sgr A East and the proximity between the two, we propose that CXOGC J174545.5–285829 is a high-velocity neutron star candidate, born from the core-collapse SN that also created the SNR Sgr A East.

Subject headings: Galaxy: center — ISM: individual (Sagittarius A East) — supernova remnants — X-rays: general — X-rays: ISM

1. INTRODUCTION

Sagittarius (Sgr) A East, a part of the Sgr A complex in the Galactic center, is an extended radio source with an angular size of \(2.7 \times 3.6\) (Ekers et al. 1983). The nonthermal radio spectrum (radio spectral index \(\alpha = 0.76\), where \(S \sim \nu^{-\alpha}\)) and the shell-like morphology suggested an identification as a supernova remnant (SNR) for Sgr A East (Jones 1974; Ekers et al. 1975, 1983). The Röntgensatellit (ROSAT), the Advanced Satellite for Cosmology and Astrophysics (ASCA), and the BeppoSAX satellite detected diffuse X-ray emission from Sgr A East, but extensive analysis was not feasible because of the limited detector capabilities (Predehl & Trümper 1994; Koyama et al. 1996; Sidoli et al. 1999).

Recently, observations with the high angular resolution instruments aboard the Chandra X-Ray Observatory clearly resolved the diffuse X-ray emission inside the Sgr A East radio shell (Maeda et al. 2002, hereafter M02). The Chandra data revealed a centrally peaked X-ray morphology of Sgr A East. The X-ray emission originates from a hot plasma with an electron temperature \(kT \sim 2\) keV, showing strong Fe \(\alpha\) lines from highly ionized elemental species of S, Ar, Ca, and Fe. The estimated low mass of the hot gas \((\sim 2 \times 10^{54} M_\odot)\) and the total thermal energy \((E_{th} = 2 \times 10^{49}\) ergs) indicated a single-SNR origin for Sgr A East (M02). The Chandra data revealed that the Fe-rich ejecta is concentrated near the center of the SNR, while other elemental species are uniformly distributed over the SNR. M02 further suggested that Sgr A East is a metal-rich, mixed-morphology SNR from a Type II SN explosion of a \(13\)–\(20 M_\odot\) progenitor.

Sgr A East was also observed with the XMM-Newton Observatory (Sakano et al. 2004, hereafter S04). The results from the XMM-Newton data analysis were also consistent with a single-SNR interpretation for Sgr A East. S04, however, found that a two-temperature thermal plasma \((kT \sim 1\) and \(4\) keV) was required in order to adequately describe the observed X-ray emission-line features. The measured metal abundance patterns and the estimated Fe ejecta mass suggested either a Type Ia or a Type II origin. A weak 6.4 keV “neutral” Fe line feature was also detected with the XMM-Newton data. This neutral Fe line was attributed to irradiation by Sgr A East of the molecular clouds, which are also interacting with Sgr A East (S04). The discrepancies between the Chandra and the XMM-Newton data might have been caused by the low photon statistics of the Chandra data (S04). Effects of the relatively poor angular resolution of the XMM-Newton data may not be ruled out, either.

Since the early Chandra observations of Sgr A East presented by M02, we have performed follow-up observations of the Galactic center with Chandra as part of the monitoring program of the Galactic center supermassive black hole candidate Sgr A\(^*\) (Baganoff et al. 2003). As of 2002 June, the total exposure of Chandra observations of the Galactic center reached \(600\) ks, representing the deepest X-ray observations of the Galactic center. Utilizing the wealth of these deep observations, we have presented the complex nature of the pointlike and diffuse X-ray emission features in the Galactic center in a series of publications (Baganoff et al. 2003; Muno et al. 2003b, 2003c, 2004a, 2004b; Park et al. 2004b). The current deep Chandra data...
increased the photon statistics of Sgr A East by an order of magnitude, compared with that of M02. Taking advantage of the deep Chandra exposures, in this paper we present spatially resolved spectral analysis of Sgr A East, which was infeasible with previous data. This approach is effective for the analysis of the ejecta material, excluding substantial contamination from the swept-up interstellar medium (ISM), as successfully demonstrated with other Galactic SNR studies (e.g., Park et al. 2004a). The large-scale, global spectral analysis of Sgr A East has been performed with the previous Chandra and XMM-Newton observations, which revealed overall spectral parameters and thermal characteristics of the SNR (M02; S04). Rather than present such general characteristics, we concentrate in this work on the origin of Sgr A East in the context of the SN explosion types. In particular, we draw attention to a hard pointlike source detected in the northern edge of Sgr A East. The overall X-ray characteristics suggest that this source is a candidate high-velocity neutron star (NS) associated with the SNR Sgr A East. The observations are briefly described in § 2. The X-ray image and spectral analyses of the SNR Sgr A East and the candidate NS are presented in §§ 3 and 4, respectively. We discuss key characteristics of the SNR and the NS candidate in § 5. Finally, a summary is presented in § 6.

2. OBSERVATIONS AND DATA REDUCTION

Since 1999, the Galactic supermassive black hole candidate Sgr A* has been monitored with the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2003) on board Chandra (Table 1). As of 2002 June, by combining 11 Chandra ACIS observations (except for ObsID 1561a, which was severely contaminated by a bright transient source within the field of view [FOV]; Muno et al. 2003a), the total exposure has reached ~590 ks, which is the deepest ever observation of the Galactic center region in X-rays. We utilized the data reduced by Muno et al. (2003c), as we briefly describe here. We first applied the algorithm developed by Townsley et al. (2002b) to correct the spatial and spectral degradation of the ACIS data caused by radiation damage, known as charge transfer inefficiency (CTI; Townsley et al. 2000). We then screened the data by status, grade, and the flight timeline filter. We have also removed observation time intervals of strong flaring in the background. All individual event files were then reprojected to the tangent plane at the radio position of Sgr A* (R.A. = 17h45m40s, decl. = -29°00'28"118 [J2000.0]) in order to generate the composite data. The detailed descriptions of the data reduction process and the resulting broadband raw image from the composite data can be found in Muno et al. (2003c).

3. SGR A EAST

3.1. X-Ray Images

The center of the Sgr A East radio shell is ~50" northeast of Sgr A*, and thus the entire SNR Sgr A East was imaged within the 17' × 17' FOV of the ACIS-I array during the Sgr A* monitoring observations. A true-color X-ray image of the Sgr A East is presented in Figure 1. Each subband image has been exposure-corrected utilizing the exposure map produced by Muno et al. (2003c) and adaptively smoothed to achieve a signal-to-noise (S/N) ratio of 4 by using the CIAO tool csmooth. Sgr A* is marked near the center of the image. The bright X-ray feature around Sgr A* is emission from a massive star cluster within the inner parsec of the Galactic center. The bright diffuse X-ray emission to the immediate east of Sgr A* is the SNR Sgr A East. As reported with previous Chandra observations by M02, X-ray emission from Sgr A East is centrally enhanced with no apparent shell-like features (Fig. 1). The enhancements of the blue emission around the center of the SNR are remarkable. As we discuss in § 3.2, this enhanced hard X-ray emission is primarily from the Fe He line emission. The outskirts of the SNR show soft X-ray emission. Also evident is red, soft X-ray emission extending toward the northern side of the SNR, the so-called plume (M02; Baganoff et al. 2003). M02 suspected the existence of a high-velocity NS at the tip of the plume, which is physically associated with Sgr A East. With the deep exposure, a hard pointlike source CXOGC J174545.5 was indeed detected there (Muno et al. 2003c). This hard pointlike source might thus be the predicted high-velocity NS candidate, which might have also produced the bow shock–like plume: hereafter, we name this NS candidate the “cannonball.” We discuss the cannonball in detail in §§ 4 and 5.1.

3.2. Equivalent-Width Images

In order to examine the overall distributions of the diffuse emission-line features from Sgr A East, we construct “equivalent-width” (EW) images for the detected atomic emission lines, following the method described in Park et al. (2004b). After removing all detected point sources from the broadband image (see Muno et al. [2003c] for details of the point-source detection), subband images for the line and continuum bandpasses were extracted for each spectral line of interest. These subband images were adaptively smoothed to achieve an S/N ratio of 3. The underlying continuum was calculated by logarithmically interpolating between images made from the higher and lower energy “shoulder” of each broad line. The estimated continuum flux was integrated over the selected line width and subtracted from the line emission. The continuum-subtracted line intensity was then divided by the estimated continuum on a pixel-by-pixel basis to generate the EW images for each element. In order to avoid noise in the EW maps caused by poor photon statistics near the CCD chip boundaries, we have set the EW values to zero where the estimated continuum flux is low. As discussed in Park et al. (2004b), contaminations from the cosmic X-ray background and the particle background, neither of which have been subtracted in the EW generation, are insignificant in the EW images. Although the adaptive smoothing may introduce spurious faint features, the bright, arcminute-scale features are confirmed by our spectral fits (see below) and are certainly real. Therefore, we focus on these bright features in order to qualitatively investigate the overall variation in the X-ray line emission of Sgr A East.
Fig. 1.—(a) Exposure-corrected true-color image of Sgr A East from the composite data of 11 Chandra ACIS observations: red represents the 1.5–4.5 keV band photons, green represents 4.5–6.0 keV, and blue represents the 6.0–8.0 keV band. Each subband image has been adaptively smoothed, and the detected point sources have not been removed. (b) Gray-scale, broadband (1.5–8.0 keV) ACIS image of Sgr A East. Darker gray scales indicate higher intensities. This broadband image is unsmoothed and has not been exposure corrected. The ACIS-I chip gaps are evident: i.e., the whitish (or low intensity) lanes bisecting the SNR north-south and east-west. Some key features within the FOV and regions used for the spectral analysis are marked.
We present the Fe He line ($E \sim 6.6$ keV) EW image of Sgr A East in Figure 2. The energy band selections for the line and continuum to generate this EW image are presented in Table 2. The Fe He line EW is strongly enhanced within an ~40$''$ diameter region near the center of the SNR. This Fe EW distribution is consistent with the central concentration of the Fe abundance in Sgr A East as reported with the previous Chandra and XMM-Newton observations (M02; S04). The high Fe EW at the center of the SNR is thus most likely caused by the enhanced Fe abundance there, displaying the distribution of Fe-rich stellar ejecta material. (Note that the bright X-ray emission at the position of Sgr A* is featureless in the Fe EW image. This is reasonable for the continuum-dominated X-ray spectrum from Sgr A* [Baganoff et al. 2003], which further supports the utility of our EW images.) In contrast to the central Fe-rich region, the northern plume region of the SNR does not show an enhancement in Fe, which suggests that it is produced by emission from shocked ISM having metal abundances close to the average value at the Galactic center.

Unlike Fe, the EW maps of other elemental species S, Ar, and Ca do not show any significant spatial structure, and we do not explicitly present those EW images. The uniform EW distributions of other species are also consistent with the previously reported elemental abundance distributions across Sgr A East.

### 3.3. X-Ray Spectra

We perform a spatially resolved spectral analysis of Sgr A East utilizing high angular resolution ACIS data. For the spectral analysis of our CTI-corrected data, we use the response matrices appropriate for the spectral redistribution of the CCD, as generated by Townsley et al. (2002a). Because of various roll
angles of the individual ACIS observations and the moderate angular extension of the SNR ($\sim 3\arcmin$), Sgr A East has been detected on different ACIS-I chips, depending on the roll angles. However, observations taken with deep exposures between 2002 February and 2002 June (ObsID 2943 in Table 1), which represents $\sim 90\%$ of the total exposure, had similar roll angles. Small sections of the SNR have thus been detected on a single CCD for the majority of the observations. For instance, although the bright, central Fe-rich region (i.e., the region labeled “center” in Fig. 1b) was detected on either the ACIS-I1 or the ACIS-I3, depending on the roll angles, $\sim 91\%$ of the total counts in the 1–8 keV band were detected on the ACIS-I1. We thus use detector responses appropriate for the chip positions of the source region on the ACIS-I1 for the central region spectrum. We used the same method for other regional spectra. We binned the data to contain a minimum of 30–50 counts per channel for the spectral fittings. Even though we corrected the data for the CTI, there remain some residual effects of small gain shifts, which are usually insignificant in the spectral analysis. The gain shift at $\sim 1\%$ level may, however, confuse the spectral analysis of strong emission lines in a relatively narrow energy band, such as the Sgr A East spectrum containing strong Fe K lines between $E \sim 6.4$ and 6.9 keV. We inspected any residual gain shifts with the ACIS-I calibration data (ObsID 61184) taken close to our deepest observations (2002 May 25). We found that there were $\sim 0.1\%$–$1\%$ gain shifts, depending on the detector positions. We thus included a “gain fit” in the initial spectral fittings and then adjusted the gain according to the best-fit gain shift. The adjusted gain shifts are typically small ($\sim 0.6\%$) and are consistent with those from the calibration data.

The background estimates for the spectral analysis of Sgr A East are difficult because X-ray background emission in the vicinity of Sgr A East shows complex spectral and spatial structure. We were particularly cautious about the background emission features from the neutral Fe K ($E \sim 6.4$ keV) and the H-like Fe K ($E \sim 6.96$ keV) lines, because line emission from these species is prevalent across the Galactic center region (Park et al. 2004b; Muno et al. 2004a). We considered several background regions that are source-free and represent the Fe line features. We eventually used the combined background

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**TABLE 2**

| Elements | Line (eV) | Low$^a$ (eV) | High$^a$ (eV) |
|----------|----------|--------------|--------------|
| Fe (He)  | 6510–6690| 5000–5730     | 7470–8500    |

$^a$ The high- and low-energy bands around the selected line energies used to estimate the underlying continuum.
emission from three regions that, we believe, adequately represent the “average” background spectrum for Sgr A East. The adopted background regions are presented in Figure 3. The spectral analysis and discussion in §§3.3.1 and 3.3.2 are based on this background selection.

3.3.1. Central Region

We first extracted and fitted the spectrum of the ~14″ × 24″ region containing the bright, Fe-rich emission at the core of the SNR (labeled “center” in Figs. 1 and 2). This region selection was also intended to include the central region with the highest broadband intensity, while excluding the chip gap. Even with the small angular size of ~20″, the “center” spectrum contains significant photon statistics of ~7000 counts and clearly shows the strong Fe Heα line at E ~ 6.6 keV (Fig. 4). Since M02 and S04 consistently found that thermal plasma in a collisional ionization equilibrium (CIE) can adequately describe the Sgr A East spectrum, we fitted the “center” spectrum with a CIE model (vmekal in XSPEC) absorbed by interstellar gas (we have also fitted the spectrum with a nonequilibrium ionization [NEI] model, and the best-fit ionization timescale was indeed high [n_e ≈ 10^{12} cm^{-3} s^{-1}], indicating a CIE plasma condition). The fitted absorption column was large (N_H ≈ 1.5 × 10^{22} cm^{-2}), which is consistent with the Galactic center location of the SNR. The electron temperature (kT ~ 2 keV) is consistent with that reported by M02. The high Fe abundance of a few times solar is also in agreement with the results of M02 and S04.

Although a single-temperature CIE model can describe the observed spectrum, we recognized a residual “hump” at E ~ 7 keV above the best-fit model, which appears to be a weak Fe Lyα line feature (E ~ 6.96 keV). In fact, the relatively poor fit (χ^2/N = 1.4) was primarily caused by this excess emission. Our attempts to remove these residuals by adopting background subtraction from various regions (including the same background regions used by M02 and S04) were not successful. We thus conclude that this residual emission originates from the SNR. The detection of the Fe Lyα line is indeed statistically significant (~7σ). This excess emission at E ~ 7 keV due to the H-like Fe line is important because an additional hot plasma component is required in order to fit this feature. The two-temperature CIE model can then improve the overall fit significantly (χ^2/N ~ 1.0; Fig. 4). In this two-component fit, we varied S, Ca, Ar, and Fe abundances, while keeping them common to both components. All other species were fixed at solar abundance because the contribution from those elemental species in the fitted energy band is negligible. We also assumed the same foreground column for both components. The results of this two-component spectral fit are presented in Tables 3 and 4. The fitted Fe abundance is high (~5.8 solar), while those for S (~0.7), Ar (~1.8), and Ca (~1.4) are relatively low.

The electron temperatures from the best-fit model are kT ~ 1 and 5 keV, which are consistent with the results from S04. Although the electron temperature for the hard component, kT ~ 5 keV, appears to be unusually high for an SNR spectrum, such a temperature is required to properly describe the detected Fe Lyα line feature. This highly ionized H-like Fe line emission was not detected by the early Chandra observations with short exposures (M02). It was, however, suggested by the XMM-Newton data (S04) and is now confirmed by our deep Chandra observations. S04, with the XMM-Newton data, also reported detection of “neutral” Fe line emission (E ~ 6.4 keV) from Sgr A East. Although more prominent in the peripheral regions of the SNR, the neutral Fe K line was reportedly detected in the central regions of the SNR with XMM-Newton (photon flux ~3 × 10^{-6} photons cm^{-2} s^{-1} within a 28″ radius; S04). Our deep, high angular resolution Chandra data do not require such a neutral Fe line feature in order to describe the observed spectrum. We place a 2σ upper limit of 1.1 × 10^{-6} photons cm^{-2} s^{-1} on the 6.4 keV Fe line photon flux.

3.3.2. Plume Regions

We extract the spectrum of the plumelike feature from a region between the Fe-rich center and the cannonball (the region labeled “plume” in Figs. 1 and 2). The spectrum contains ~5300 counts and can be fitted with a single-temperature (kT ~ 1.3 keV) CIE plasma model (Fig. 5). In this fit, the elemental abundances for

| Region  | N_H (10^{22} cm^{-2}) | kT_{soft} (keV) | kT_{hard} (keV) | EM_{soft} (10^{57} cm^{-3}) | EM_{hard} (10^{57} cm^{-3}) | χ^2/N |
|---------|------------------------|----------------|----------------|-----------------------------|-----------------------------|-------|
| Center  | 18.9^{+3.0}_{-3.0}     | 1.05^{+0.19}_{-0.11} | 5.28^{+0.66}_{-0.57} | 7.1^{+5.5}_{-2.5}            | 0.3^{+0.1}_{-0.1}           | 167.9/163 |
| Plume   | 14.7^{+2.0}_{-1.9}     | 1.3^{+0.2}_{-0.1}     | ...             | 1.8^{+0.6}_{-0.6}            | ...                         | 100.5/83  |
| North   | 13.0^{+1.0}_{-1.0}     | 1.00^{+0.15}_{-0.10} | 10.9^{+1.1}_{-4.3} | 3.2^{+1.0}_{-1.3}            | 0.05^{+0.04}_{-0.02}        | 139.7/110 |

Notes.—The errors are 2σ uncertainties.
S, Ar, Ca, and Fe were varied freely, while abundances for other species were fixed at solar (Tables 3 and 4). The Fe He line is significantly weaker (e.g., EW/C24 800 eV) than the central region spectrum (e.g., EW/C24 2500 eV). The Fe abundance is also considerably lower than the central region and is consistent with solar. These results indicate that the plume is emission primarily from a shocked ISM rather than from metal-rich ejecta. In contrast to the central region, hard excess emission at $E_k$7 keV due to the Fe Ly line feature is not substantial in the plume region: i.e., the line detection is only marginal ($\chi^2_{red} \sim 1.1$ vs. 1.2). The fitted metal abundances also do not change when a two-temperature model is used. Although there appears to be a small contribution from the high-temperature ($kT \sim 5$ keV) component, the overall spectrum from the plume region is thus dominated by the soft component ($kT \sim 1$ keV). Therefore, we hereafter discuss the plume spectrum based on the single-temperature model, as presented in Tables 3 and 4.

We then extract the spectrum from a region between the center and the plume (the region labeled “north” in Figs. 1 and 2). This regional spectrum contains $\sim$7600 counts. The Fe He line is substantially weaker than the central region, similar to the plume spectrum. On the other hand, as in the central region spectrum, hard excess emission at $E \gtrsim 7$ keV was noticeable for the north region spectrum when fitted with a single-temperature model. We thus fit this regional spectrum with a two-temperature CIE plasma model in the same way as for the central region (Fig. 6). The fitted parameters from the two-temperature model are presented in Tables 3 and 4. The fitted parameters are generally consistent with those from the central region. Note, however, that the Fe abundance in the north region is significantly lower than that of the central region. As with the other regions, we found that the 6.4 keV line is not evident in the observed north region spectrum, with an upper limit to the line flux of $3.7 \times 10^{-7}$ photons cm$^{-2}$ s$^{-1}$ ($2\sigma$).

4. CXOGC J174545.5–285829: THE CANNONBALL

4.1. X-Ray Morphology

M02 speculated that a high-velocity NS associated with the SNR Sgr A East might exist at the tip of the plume. With deep observations, a hard pointlike source was indeed detected at the edge of the plume and designated as CXOGC J174545.5–285829 (the so-called cannonball) by Muno et al. (2003c). Figure 7 presents the soft- and hard-band images of the cannonball. In fact, at the edge of the plume, there are two pointlike sources separated by $\sim$3": the cannonball detected exclusively above $E \sim 3$ keV and a soft source, CXOGC J174545.2–285828, detected mostly below $E \sim 2$ keV (Fig. 7). The soft source CXOGC J174545.2–285828 exhibits long-term variability (Muno et al. 2004b) and has an optical counterpart in the USNO-B1.0 catalog (No. 0610-0600649, $m_B = 15.27$), both of which suggest that this soft source is a foreground star.

Figure 7 reveals that the cannonball may not be truly point-like but is apparently extended: i.e., a cometary shape with a bright, pointlike head and a tail extending generally southward, which is roughly tracking back to Sgr A East. Although this source was detected $\sim$2′ off-axis, the apparent extended morphology is not caused by the point-spread function (PSF). In Figure 8b, the one-dimensional source intensity distribution in the north-south direction is compared to that of the off-axis...
PSF at the same position. The extended nature of the cannonball toward the south is unambiguously revealed. In Figure 8a, we present a PSF-deconvolved source image, using a maximum-likelihood algorithm (Richardson 1972; Lucy 1974). For comparison, the deconvolved image of the soft source CXOGC J174545.2—285828 (the source in the right-hand side of the image) is also presented. The cannonball shows a significantly extended structure, which confirms the cometary morphology suggested by the raw image and the projected intensity profile. The soft source, in contrast, appears to be resolved further into two pointlike sources. The photon statistics of the two sources, the cannonball and CXOGC J174545.2—285828, are similar (~1000–1200 counts), and thus the morphological difference between the two is unlikely a statistical artifact. The angular extent of the cannonball’s tail is ~3′, which corresponds to a projected physical size of ~0.1 pc (hereafter, we use a distance of 8 kpc to the Galactic center; Reid 1993).

4.2. X-Ray Spectrum

The cannonball has been detected on various detector positions of the ACIS-I array because of the different roll angles for the individual observations. These various detector positions include on-chip and chip-gap positions, as well as different rows within the CCD. We thus use detector responses appropriate for each observation to average over all the observations for the spectral analysis of the combined data. For six observations (ObsIDs 242, 1561b, 2951, 2952, 2953, and 2954) in which the source was detected on an on-chip position, the source photons are relatively evenly spread over the ACIS-I0 (46% of the total) and the ACIS-I3 (54% of the total). We thus made a weighted sum (by detected counts) of the redistribution matrix function (RMF) files appropriate for the source locations of each CCD. The corresponding ancillary response functions (ARF) were also averaged by weighting the counts detected in the individual observations.

The source spectrum of the cannonball is extracted from an ~1′8 radius circular region centered on the source position. We tested the background spectrum separately from three regions: i.e., an annulus of inner radius ~5″ and outer radius ~6.5 centered on the source position, a circular region of radius ~11″ in the northeast side of the source, and a 10″ × 60″ box-shaped region along the CCD chip gap (for ObsIDs 2943, 3663, 3392, 3393, and 3665) to the north of the source. The choice of these background regions resulted in no significant differences in the spectral fits. In the following discussion of the spectral analysis, we assume the rectangular background region along the chip gap (Figs. 1 and 3), because this background region consistently represents the source “flux variation” caused by the on- and off-chip positions. We binned the source spectrum in order to contain 20 or more counts per channel. The spectrum can best be fitted with a power law (Fig. 9) and the best-fit parameters are

![Fig. 8.—(a) Deconvolved Chandra ACIS images of the cannonball (left source) and CXOGC J174545.2—285828 (right source). The image has been smoothed with a Gaussian of σ = 0.75 for the purpose of display. (b) Source intensity profiles projected in the north-south direction taken from the raw ACIS image. The histogram represents the cannonball, and the projected PSF at the source position is overlaid with a dotted curve.](image)

![Fig. 9.—Chandra ACIS spectrum of the cannonball. The upper plot is the on-chip spectrum, and the lower plot is the chip-gap spectrum. The best-fit power-law model is overlaid.](image)
presented in Table 5. Because of the relatively low photon statistics (~1000 counts), the spectrum can also be fitted with thermal plasma models. The best-fit electron temperature is remarkably high \((kT \sim 25 \text{ keV})\), with extremely low metal abundances. This high temperature might not be entirely unreasonable for sources like cataclysmic variables. Although unlikely, a thermal origin of the X-ray spectrum of the cannonball may thus not be completely ruled out.

5. DISCUSSION

5.1. The Cannonball: A High-Velocity Neutron Star?

The spectral and morphological characteristics of the cannonball are very unusual among the sources detected within the ACIS FOV of the Galactic center: i.e., it is a bright source with a hard, continuum-dominated X-ray spectrum having no Fe line emission. This source also shows no long-term variability (Muno et al. 2004b). The cannonball is one of only two sources of the \(\sim2300\) Galactic center X-ray sources cataloged by Muno et al. (2003c) that share such unusual X-ray characteristics. We discuss this unique source in §5.1.1 and 5.1.2. The observed X-ray nature of the cannonball suggests an identification as a high-velocity NS in the Galactic center. Based on its proximity to Sgr A East, we therefore propose that the cannonball may be a candidate NS born from the SN explosion that also produced the SNR, Sgr A East.

5.1.1. Spectrum and Morphology

The X-ray spectrum of the cannonball is best fitted with a power law \((\Gamma \sim 1.6)\), which is typical for nonthermal synchrotron emission from a NS magnetosphere. The implied high foreground absorption is consistent with that of Sgr A East, in agreement with a Galactic center location near the SNR. Assuming a Galactic center location, the estimated X-ray luminosity \((L_X \sim 3.1 \times 10^{33} \text{ ergs s}^{-1})\) is also typical for a pulsar and/or pulsar wind nebula (PWN; e.g., Becker & Aschenbach 2002).

The deep Chandra images unambiguously reveal the cometary morphology of the cannonball. The tail is faint (only \(\lesssim100\) photons), and the estimated physical size is \(\sim0.1\) pc. This tail size is consistent with cometary tails detected from other Galactic high-velocity pulsars, such as the Geminga pulsar (Caraveo et al. 2003), PSR B1853+01 (Petre et al. 2002), and PSR J1509–5850 (D. Sanwal et al. 2005, in preparation).

The tail points roughly toward the south, consistent with the direction of the center of Sgr A East, given its limited photon statistics. The sky position of the source is also interesting: i.e., the cannonball is located, in projection, just inside the radio shell boundary of Sgr A East, while sitting on the tip of the X-ray plume. These X-ray morphologies are suggestive of a high-velocity NS, moving toward the north, for the origin of the cannonball. Considering an SNR age of \(\sim5000–10,000\) yr (Mezger et al. 1989; Uchida et al. 1998; M02; S04) and the angular separation of \(\sim2\) between the source and the center of the SNR, a velocity of \(v \sim 455–912\) km s\(^{-1}\)/sin \(\beta\), where \(\beta\) is the angle between the line of sight and the actual traveling direction of the NS, is implied. This velocity range is in good agreement with that of typical high-velocity pulsars in the Galaxy (Cordes & Chernoff 1998).

We can make an independent estimate of the velocity of the candidate NS by assuming that the plume is a bow shock produced as the high-velocity NS encounters the ISM. Based on the conical shape of the plume as seen by the red emission feature in Figure 1a, we estimate an opening angle of \(\theta \sim 55^\circ\). The Mach number \(M_a = [\sin (\theta/2)]^{-1}\) is thus \(\sim2.2\). The velocity of the candidate NS is then \(v = c_M = \sim880\) km s\(^{-1}\). In this estimate, we assumed a sound speed of the ambient gas \(c_s = (\gamma kT/\mu m_p)^{1/2} \sim 400\) km s\(^{-1}\), where \(\gamma = 5/3\) for a monatomic, adiabatic gas, \(\mu = 1\) for protons, \(m_p\) is the proton mass, and \(kT \sim 1\) keV for the plasma in the plume region. We note that, in the velocity estimation from the Mach number, we used the projected opening angle for the bow shock. If the inclination angle of the bow shock was significant, the actual, deprojected opening angle could have been smaller; thus a higher velocity would have been derived. Nonetheless, the velocity estimates from the two methods are in plausible agreement.

A third velocity estimate can be derived by assuming that this NS candidate produced a PWN that has reached pressure equilibrium with the ISM. Assuming that the X-ray spectrum of the cannonball is primarily from a PWN of the NS, we can derive the rotational spin-down energy loss \(\dot{E}\) by using an empirical relationship between \(\dot{E}\) and the power-law photon index of the PWN,

\[
\Gamma_{\text{PWN}} = 2.36 - 0.021 \dot{E}_{40}^{-1/2},
\]

where \(\dot{E}_{40}\) is the spin-down power in units of \(10^{40} \text{ ergs s}^{-1}\) (Gotthelf 2003). The best-fit photon index of \(\Gamma_{\text{PWN}} = 1.6\) implies \(\dot{E} \sim 7.6 \times 10^{46} \text{ ergs s}^{-1}\). We can assume a pressure balance between the ram pressure of the PWN, \(P_{\text{PWN}} = E/(4\pi R^2)\), where \(R\) is the PWN radius for a spherical geometry, and the thermal pressure of the plume region, \(P_{\text{th}} = 2\pi ke\), the best-fit volume emission measure (EM) from the plume region implies an electron density of \(n_e \sim 7.4 f^{1/2} \text{ cm}^{-3}\), where \(f\) is the X-ray-emitting volume filling factor (we assumed a half-conical volume with a circular base of radius \(\sim25^\circ\) and a height \(\sim50^\circ\) for the plume region). The best-fit thermal plasma model for the plume region then implies \(P_{\text{th}} = E_{40} \sim 3.1 \times 10^{38} \text{ ergs cm}^{-3}\). (The PWN radius is accordingly estimated to be \(R \sim 2.5 \times 10^{16}\) cm, which corresponds to \(\sim0.2\) at \(d \sim 8\) kpc. This small \(R\) is consistent with the pointlike detection of the head of the source by the ACIS.) The \(P_{\text{PWN}}\) may be equivalent to the external ram pressure \(\epsilon_{\text{ke}} = \rho v^2\) (where \(\rho\) is the mass density of the ISM derived from the plume region spectrum). The velocity is then derived to be \(v \sim 550\) km s\(^{-1}\). We note that there were a number of assumptions in these estimates, e.g., the pressure balance \(P_{\text{PWN}} = P_{\text{th}} = \epsilon_{\text{ke}}\), the \(\dot{E}\) estimate from the best-fit photon index of the PWN spectrum, and the bow shock origin for the plume. Considering various assumptions and embedded uncertainties in the above three approaches for the velocity estimates,
the agreement among all three results is remarkable. The consistency among these independent estimates of the velocity thus lends all of them additional credibility.

5.1.2. Temporal Characteristics

No evidence for long-term (observation by observation) variability of the cannonball was detected (Muno et al. 2004b). The proximity of this source to the chip gap during the long series of observations makes it difficult to determine whether there is short-term (within individual observation periods) variability. With a $2-10$ keV band flux of $\sim 1.9 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$, the cannonball is one of the brightest sources detected in the ACIS FOV: i.e., the 5th brightest in terms of the photon flux, and the 18th brightest in the number of counts among $\sim 2300$ cataloged Galactic center sources (Muno et al. 2003c). According to Muno et al. (2004b), $\sim 80\%$ of the short-term variables have a maximum photon flux lower than the photon flux of the cannonball. About 94% of the long-term variables also have a maximum flux lower than the cannonball flux (Muno et al. 2004b). For comparison, the nearby soft source CXOGC J174545.2$-$285828, with similar photon statistics, was identified as a long-term variable (Muno et al. 2004b). The non-variability of the cannonball is thus unlikely a statistical artifact, but should correspond to the true nature of this object. The constant light curve with a long time basis of $\sim 3$ yr, particularly at the “high” flux level of this source, is remarkably unusual among the Galactic center sources. This nonvariability over a few years indicates that the cannonball is unlikely a background active galactic nucleus (AGN) and supports a NS identification. In fact, based on the log $N$--log $S$ relation for the contribution from extragalactic sources in the Galactic center (Muno et al. 2003c), a low probability of $\sim 1.2 \times 10^{-4}$ for a detection of a background extragalactic source at the flux level of the cannonball within the plume region is implied.

The discovery of a pulsar at the position of the cannonball would conclusively identify this source as a NS. Our deep Chandra observations, however, used the standard 3.2 s time frame, which may not be adequate for a pulsar search. We, therefore, searched for pulsations in a 40 ks archival XMM-Newton EPIC observation pointed at Sgr A$^*$ (observation sequence number 0111350101). The EPIC PN instrument has a relatively short EPIC observation pointed at Sgr A$^*$ (observation sequence number 0111350101). The EPIC PN instrument has a relatively short angular resolution of the EPIC instrument, the two sources, the cannonball and CXOGC J174545.2$-$285828, are not resolved. In order to discriminate contamination from the nearby soft source CXOGC J174545.2$-$285828, we extract the source photons only from the hard band ($3-10$ keV). We then detect $\sim 460$ counts from the cannonball. With these XMM-Newton data, we do not detect significant evidence of a pulsar. We place an upper limit of $\sim 40\%$ on the pulsed fraction between $5 \times 10^{-5}$ and 6.8 Hz. If the cannonball is a pulsar associated with Sgr A East and thus has an age of $\sim 10,000$ yr, it may have a Vela pulsar--like periodicity of $\sim 100$ ms. This pulsation period is beyond the detectability of the used XMM-Newton time resolution. The presence of a pulsar for this NS candidate cannot thus be ruled out yet. Follow-up X-ray and/or radio observations with high time resolution instruments would therefore be helpful for the pulsar search for this NS candidate.

5.2. Sgr A East: Fe Ejecta Mass

The enhancement of strong Fe K line emission at the center of the SNR is remarkable. This Fe line emission is most likely from the Fe-rich stellar ejecta from the progenitor, which was heated by the reverse shock. Assuming that the Fe-rich central region represents the bulk of the total Fe mass ejected from the progenitor star, this Fe-rich material provides a useful opportunity to investigate the progenitor mass and thus the SN explosion type of Sgr A East.

In order to estimate the total Fe ejecta mass, we first consider a simple geometry in which all Fe ejecta material is concentrated within the central $\sim 40''$ diameter region where the Fe EW is the highest (e.g., Fe EW $\geq 1400$ eV in Fig. 2). We estimate the electron density based on the measured EM from the spectral fit of the central region (the region labeled “center” in Fig. 1b). We use a spherical geometry with an elliptical cross section (major and minor axis radii of $12''$ and $7''$, respectively) for the X-ray--emitting volume of the central region. A path length of 1.55 pc was assumed, corresponding to the $\sim 40''$ angular extent of the Fe enhancement at the center of the SNR. The X-ray--emitting volume of $V = 1.82 f \times 10^{35}$ cm$^3$ is thus used for the density estimate. We, for simplicity, assume “pure” Fe ejecta for the estimate of the electron density: i.e., all electrons originate from the ionized Fe. Considering the dominant ionization states presented by two-temperature plasma, we assume an electron-Fe ion density ratio of $n_e = 24 n_{Fe}$ for the He-like Fe. We also use the best-fit Fe abundance of 5.8 times solar for each of the soft and the hard components. Considering the large difference in the plasma temperatures of the two components, they are unlikely cospatial (e.g., S04). We thus assume that each component occupies a separate volume and maintains a pressure equilibrium: i.e., $n_e T_e = n_{Fe} T_{Fe}$ and $f_s = f_h$, where $n_e$ and $n_{Fe}$ are electron densities, $T_e$ and $T_{Fe}$ are electron temperatures, and $f_s$ and $f_h$ are volume filling factors for the soft and the hard component, respectively. The best-fit electron temperatures ($k T_e = 1.05$ and 5.28 keV) correspond to $f_s = 0.48 f_h$ and $f_h = 0.52 f_s$. The best-fit EMs then imply Fe ion densities of $n_{Fe,s} = 0.096 f^{-1/2} \text{cm}^{-3}$ and $n_{Fe,h} = 0.019 f^{-1/2} \text{cm}^{-3}$, where $n_{Fe,s}$ and $n_{Fe,h}$ are Fe ion densities for the soft and the hard component, respectively. If we assume a spherical volume with a diameter of $\sim 1.55$ pc and with a dominant isotope $^{56}$Fe, the total Fe mass, $M_{Fe} = 56(n_{Fe,s} + n_{Fe,h}) m_p V$, is then estimated to be $M_{Fe} \sim 0.15 f^{-1/2} M_\odot$. Because of our pure Fe ejecta assumption, this Fe mass is an upper limit.

The standard SN nucleosynthesis models indicate that $M_{Fe} \sim 0.5 \ldots 0.8 M_\odot$ for the Type Ia SNe (e.g., Nomoto et al. 1997b). The Type II models show a wide range of Fe mass depending on the progenitor masses: e.g., $M_{Fe} \sim 0.15 M_\odot$ for a $13 \ldots 15 M_\odot$ progenitor and $M_{Fe} \sim 0.05 \ldots 0.08 M_\odot$ for a $18 \ldots 70 M_\odot$ progenitor (e.g., Nomoto et al. 1997a). The estimated upper limit on the Fe mass for Sgr A East ($M_{Fe} \sim 0.15 M_\odot$) is thus consistent with a Type II origin from a $13 \ldots 15 M_\odot$ progenitor. If our Fe mass estimates were significantly affected by the ISM contribution, the progenitor mass could be larger.

Although the total Fe mass, as estimated by assuming a simple spherical geometry, provided a useful constraint on the progenitor mass, we can also entertain a contribution to the total Fe mass of the SNR from the region where Fe is marginally enhanced. Inclusion of this additional Fe mass may provide an even more conservative limit on the progenitor mass. The Fe EWs are moderately enhanced in an extended region just outside the $\sim 40''$ Fe core (i.e., the region between the Fe EWs of the 800 and 1400 eV contours in Fig. 2). This region can be represented by a spherical shell with an outer diameter of $\sim 1'$ and an inner diameter of $\sim 40''$. The Fe abundance in this region appears to be $\sim 3$. We thus consider the contribution from this moderately Fe-rich region to the total Fe mass of the SNR. We assume that the path length through the outer shell region (foreground and background of the Fe core in projection) is $\sim 50\%$ of that for the
inner Fe core for the adopted geometry. With the pure ejecta assumption, we consider that $n_e$ and $n_{\text{Fe}}$ are simply proportional to the Fe abundance ratio between the two regions (i.e., 5.8 for the inner core and 3 for the outer shell). The contribution from the shell region to the measured EM is then $\sim 10\%$. We thus use the fitted EMs from the central region by assuming an $\sim 90\%$ contribution from the inner Fe core ($\sim 1.55$ pc diameter, corresponding to $\sim 40'\,\text{angular size at 8 kpc}$) and an $\sim 10\%$ contribution from the outer shell ($\sim 0.39$ pc thickness, corresponding to $\sim 10'\,\text{angular size at 8 kpc}$). We also assume the same fractional volume filling factors ($f_e = 0.48f$ and $f_{\text{Fe}} = 0.52f$) as above.

The derived total Fe densities are $n_{\text{Fe}} \sim 0.107f^{-1/2}$ cm$^{-3}$ for the inner Fe core and $n_{\text{Fe}} \sim 0.038f^{-1/2}$ cm$^{-3}$ for the outer shell. We then estimate the total Fe mass from the $\sim 1'\,\text{diameter region}$, $M_{\text{Fe}} \sim 0.27f^{-1/2} M_\odot$, which is $\sim 80\%$ larger than that derived merely from an $\sim 40'\,\text{angular diameter spherical core}$. This Fe mass is again a conservative upper limit because of the pure Fe ejecta assumption. We find that this upper limit of the total Fe mass of Sgr A East is still considerably lower than that expected from Type Ia models. On the basis of these derived Fe mass limits, we suggest that Sgr A East was produced likely by a core-collapse SN explosion of a massive progenitor star. A core-collapse origin for the SNR Sgr A East then supports the proposed SNR-NS association between Sgr A East and the cannonball.

We note, however, that a Type Ia origin for Sgr A East might not be completely ruled out yet. Considering the relatively old age of the SNR, one might speculate that a significant fraction of the Fe-rich ejecta has already been intermixed with the ambient ISM. The apparent lack of abundance enhancements from other high-Z elemental species may support this scenario. In such a case, the derived upper limits of Fe ejecta mass could be underestimated. If the amount of “missing” Fe ejecta mass were sufficiently large (i.e., several times larger than the observed Fe ejecta mass), the “true” total Fe ejecta mass might have been large enough to be consistent with a Type Ia origin for Sgr A East.

5.3. Comments on Fe Lines

The high angular resolution of the ACIS, coupled with the deep exposure, should be useful to investigate some controversial results between previous Chandra (M02) and XMM-Newton (S04) observations of Sgr A East: i.e., the XMM-Newton data reported line emission from highly ionized H-like Fe and low-ionization state “neutral” Fe, as well as the strong Fe, $\text{He}_\alpha$ line (S04), while the previous Chandra data showed only a strong Fe, $\text{He}_\alpha$ line without H-like and neutral Fe lines (M02). These differences in the detected Fe line features resulted in discrepancies in the plasma temperatures ($kT \sim 2$ keV for the Chandra data vs. $kT \sim 1$ and 4 keV for the XMM-Newton data).

Our data from the deep Chandra observations show evidence of Fe K line emission from the highly ionized H-like Fe atoms, which confirms the results reported with the XMM-Newton data. The detected H-like Fe K line feature ($E \sim 6.96$ keV) requires an extremely high temperature plasma of $kT \sim 5$ keV in addition to the $kT \sim 1$ keV component, which also confirms the results obtained with the XMM-Newton. We thus attribute the discrepancies between M02 and S04 on the H-like Fe line features to the poor photon statistics of the previous Chandra data. The hard-component plasma temperature is, however, unusually high for an SNR, and the interpretation of its origin is difficult. The peculiar interstellar environments in the Galactic center, such as unusually high magnetic fields, might be responsible for this high temperature. For instance, Muno et al. (2004a) reported the existence of very high temperature ($kT \sim 8$ keV) thermal plasma prevailing in the Galactic center regions.

On the other hand, we detect no significant evidence for the neutral Fe line emission from Sgr A East, in contrast to the results from the XMM-Newton observation. It is notable that the sky position of Sgr A East is on the northeastern side of Sgr A*, where the background 6.4 keV neutral Fe line emission (and other emission-line features) of the Galactic center region prevails (Park et al. 2004b). The reported detection of the neutral Fe line with the XMM-Newton thus might have resulted from the inclusion of background diffuse emission and point sources in the spectrum of Sgr A East, neither of which could be properly accounted for, because of the poorer angular resolution of XMM-Newton. It is important to avoid confusion caused by the complex background line emission in the Galactic center for the spectral analysis of Sgr A East. The deep exposure and the superb angular resolution of our Chandra data allowed us to use small regions for the spectral analysis. For instance, our central region is an order of magnitude smaller in the source area than the central region used by S04, while achieving good photon statistics. We also utilized background regions that thoroughly represent all emission-line features around Sgr A East. The detected point sources were not removed in the XMM-Newton data analysis (S04). Because faint point sources in the Galactic center regions are typically neutral Fe line sources (Muno et al. 2004b), the contribution from the unremoved point sources in the XMM-Newton data may also be responsible for the reported 6.4 keV line there (S04). In order to test these technical differences between S04 and the current work, we extracted the spectrum from a relatively large region ($\sim 28''$ radius) around the center of Sgr A East without removing the detected point sources. We used the same background region as used in S04. We then made an $\sim 4\sigma$ detection of the 6.4 keV line. The best-fit photon flux from the neutral Fe line was $\sim 2.5 \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$, which was consistent with that reported by S04. We thus conclude that the previously reported 6.4 keV line emission from Sgr A East with the XMM-Newton data (S04) was residual contamination from the Galactic center background emission.

6. SUMMARY AND CONCLUSIONS

We presented the results from imaging and spectral analyses of the SNR, Sgr A East in the Galactic center, using deep Chandra observations. We confirm the central concentration of Fe-rich stellar ejecta in Sgr A East. The X-ray spectrum from the central regions of the SNR shows X-ray line emission from highly ionized He-like and H-like Fe. These Fe line features require multiple temperature thermal plasma with $kT \sim 1$ and 5 keV in order to properly describe the observed spectrum. The strong Fe lines imply overabundant Fe in the center of the SNR. On the other hand, the soft X-ray emission extending to the northern side of the SNR can be described with a single-temperature ($kT \sim 1.3$ keV) thermal plasma with solar abundances. This northern plume is thus likely X-ray emission from the shocked ISM rather than metal-rich SN ejecta.

A hard pointlike source (the so-called cannonball) detected at the northern edge of the plume, designated as CXOGC J174545.5–285829 in the Galactic center source catalog, shows remarkably unusual X-ray characteristics. The morphological, spectral, and temporal properties of this source are suggestive of an identification as a high-velocity NS. The estimated Fe ejecta mass of Sgr A East is consistent with a Type II SN for the origin of Sgr A East. Based on the suggested Type II origin for Sgr A East, the likely identification of the cannonball as a high-velocity NS, and the proximity between the cannonball and Sgr A East, we propose that these objects compose an SNR-NS association in the Galactic center. We note, however,
that follow-up pulsar searches with high time-resolution X-ray and/or radio observations at the position of the cannonball will be needed in order to make a conclusive identification of a NS for this object.

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REFERENCES

Baganoff, F. K., et al. 2003, ApJ, 591, 891
Becker, A., & Aschenbach, B. 2002, in Proc. 270th WE-Heraeus Seminar on Neutron Stars, Pulsars, and Supernova Remnants, ed. W. Becker, H. Lesch, & J. Trümper (MPE Rep. 278; Garching: MPE), 64
Caraveo, P. A., Bignami, G. F., De Luca, A., Mereghetti, S., Pellizzoni, A., Mignani, R. P., Tur, A., & Becker, W. 2003, Science, 301, 1345
Cordes, J. M., & Chernoff, D. F. 1998, ApJ, 505, 315
Ekers, R. D., Goss, W. M., & Schwarz, U. J. 1975, A&A, 43, 159
Ekers, R. D., van Gorkom, J. H., Schwarz, U. J., & Goss, W. M. 1983, A&A, 122, 143
Garmire, G. P., Bautz, M. W., Ford, P. G., Nousek, J. A., & Ricker, G. R., Jr. 2003, Proc. SPIE, 4851, 28
Gotchelf, E. V. 2003, ApJ, 591, 361
Jones, T. W. 1974, A&A, 30, 37
Koyama, K., Maeda, Y., Sonobe, T., Takeshima, T., Tanaka, Y., & Yamauchi, S. 1996, PASJ, 48, 249
Lucy, L. B. 1974, AJ, 79, 745
Maeda, Y., et al. 2002, ApJ, 570, 671 (M02)
Mezger, P. G., Zylka, R., Salter, C. J., Wink, J. E., Chini, R., Kreysa, E., & Tuffs, R. 1989, A&A, 209, 337
Muno, M. P., Baganoff, F. K., & Arabadjis, J. S. 2003a, ApJ, 598, 474
Muno, M. P., Baganoff, F. K., Bautz, M., Brandt, W. N., Garmire, G. P., & Ricker, G. R., Jr. 2003b, ApJ, 599, 465
——. 2003c, ApJ, 589, 225
——. 2004a, ApJ, 613, 326
——. 2004b, ApJ, 613, 1179
Nomoto, K., Hashimoto, M., Tsujimoto, T., Thielemann, F.-K., Kishimoto, N., Kubo, Y., & Nakasato, N. 1997a, Nucl. Phys. A, 616, 79
Nomoto, K., Iwamoto, K., Nakasato, N., Thielemann, F.-K., Brachwitz, F., Tsujimoto, T., Kubo, Y., & Kishimoto, N. 1997b, Nucl. Phys. A, 621, 467
Park, S., Hughes, J. P., Slane, P. O., Burrows, D. N., Roming, P. W. A., Nousek, J. A., & Garmire, G. P. 2004a, ApJ, 602, L33
Park, S., Muno, M. P., Baganoff, F. K., Maeda, Y., Morris, M., Howard, C., Bautz, M. W., & Garmire, G. P. 2004b, ApJ, 603, 548
Petre, R., Kuntz, K. D., & Shelton, R. L. 2002, ApJ, 579, 404
Predehl, P., & Trümper, J. 1994, A&A, 290, L29
Reid, M. J. 1993, ARA&A, 31, 345
Richardson, W. H. 1972, J. Opt. Soc. Am., 62, 55
Sakano, M., Warwick, R. S., Decourchelle, A., & Predehl, P. 2004, MNRAS, 350, 129 (S04)
Sidioli, L., Mereghetti, S., Israel, G. L., Chiappetti, L., Treves, A., & Orlandini, M. 1999, ApJ, 525, 215
Townsley, L. K., Broos, P. S., Chartas, G., Moskalenko, E., Nousek, J. A., & Pavlov, G. G. 2002a, Nucl. Instrum. Methods Phys. Res. A, 486, 716
Townsley, L. K., Broos, P. S., Garmire, G. P., & Nousek, J. A. 2000, ApJ, 534, L139
Townsley, L. K., Broos, P. S., Nousek, J. A., & Garmire, G. P. 2002b, Nucl. Instrum. Methods Phys. Res. A, 486, 751
Uchida, K. I., Morris, M., Serabyn, E., Fong, D., & Meseroll, T. 1998, in IAU Symp. 184, The Central Regions of the Galaxy and Galaxies, ed. Y. Sofie (Dordrecht: Kluwer), 317