A Candidate Neutron Star within the Radio Shell of Sgr A East

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Abstract. We present imaging and spectral analyses of Sgr A East from deep Chandra observations. A nearby hard point-like source CXOGC J174545.5-285829 (dubbed the cannonball) appears to be a high-velocity neutron star. The estimated total Fe mass of Sgr A East supports a core-collapse origin from a massive star. Based on these results and the proximity between the features, we propose that the cannonball is a candidate neutron star created by the supernova that also produced the remnant Sgr A East.

1. Introduction

Sagittarius (Sgr) A East is an extended radio source (angular size $\sim 2'7 \times 3'6$) which encompasses the Galactic center supermassive black hole candidate Sgr A* [1]. The non-thermal radio spectrum and the shell-like morphology suggested an identification of a supernova remnant (SNR) for Sgr A East [1]. The first detailed X-ray study of Sgr A East was performed with the Chandra X-Ray Observatory by Maeda et al. [2]. X-ray emission from Sgr A East was centrally-peaked and originated from a hot thermal gas ($kT \sim 2$ keV) showing strong He$\alpha$ lines from highly-ionized elements of S, Ar, Ca, and Fe. The estimated X-ray emitting mass and thermal energy were low, which indicated a single supernova origin for Sgr A East, rather than multiple SNRs or a hyper-energetic explosion. Maeda et al. also suggested a core-collapse origin (the progenitor mass $\sim 13-20 M_\odot$) for Sgr A East based on the metal abundance ratios [2]. The results from the observations of Sgr A East with the XMM-Newton Observatory by Sakano et al. were generally consistent with those from the Chandra [3]. XMM-Newton, however, detected Fe Ly$\alpha$ line emission ($E \sim 6.96$ keV) as well as the Fe He$\alpha$ line ($E \sim 6.7$ keV), which required the presence of hotter gas with $kT \sim 4$ keV in addition to a $kT \sim 1$ keV plasma [3]. Sakano et al. suggested that the observed metal abundance pattern could indicate either a Type Ia or a core-collapse origin [3].
As of 2002 June, our continuous Chandra monitoring observations of the Galactic center accumulated a total exposure of \( \sim 600 \) ks, which is an order of magnitude deeper than that which was available after the initial Chandra observation [4]. We here present the results from these deep Chandra data. We focus on the spatially-resolved spectroscopy of the Fe-rich stellar ejecta and the study of a nearby candidate neutron star, in the context of the origin of Sgr A East. While we make a brief presentation of the main results in this paper, the detailed description of the data analysis and the extensive discussion of the results can be found in Park et al. [5].

2. Sgr A East: X-Ray Images

A “true-color” X-ray image of Sgr A East is presented in Fig. 1. The enhancements of the blue emission around the center of the SNR are remarkable. The X-ray line equivalent width (EW) images show that this enhanced hard X-ray emission is primarily from the Fe He\( \alpha \) line emission (Fig. 2). The high Fe EW at the center of the SNR is most likely caused by the enhanced Fe abundance there, and indicates the distribution of Fe-rich stellar ejecta (§ 3). Red, soft X-ray emission extending toward the northern side of the SNR, the so-called “plume”, is also evident (Fig. 1) [2, 4]. With the deep exposure, a hard point-like source (CXOGC J174545.5−285829) is detected at the “tip” of the plume (Fig. 1) [6]. This hard point-like source is a candidate high-velocity neutron star (see §§ 4, 5, & 6 for more discussion), which might have also produced the bow shock-like plume: we name CXOGC J174545.5−285829 “the cannonball”.

Figure 1. The exposure-corrected Chandra image of Sgr A East. Red: 1.5−4.5 keV, Green: 4.5−6.0 keV, Blue: 6.0−8.0 keV. Each sub-band image has been adaptively smoothed and the detected point sources have not been removed.

Figure 2. Gray-scale EW image of Fe He\( \alpha \) line (\( E \sim 6.6 \) keV) from Sgr A East. Linear gray-scales (darker gray-scales are higher EWs) range from 200 eV to 2500 eV with three contours at 800 eV, 1400 eV, and 2000 eV. Some key features within the field of view and regions used for the spectral analysis are marked.
3. Sgr A East: X-Ray Spectra

The “center” region (Fig. 2) clearly shows the strong Fe He\(\alpha\) line at \(E \sim 6.6\) keV (Fig. 3). A single temperature thermal plasma model (\(kT \sim 2\) keV) cannot adequately describe the observed spectrum, because of the residual feature at \(E \sim 7\) keV, which is most likely the weak Fe Ly\(\alpha\) line (\(E \sim 6.96\) keV). The detection of the Fe Ly\(\alpha\) line is statistically significant (\(\sim 7\sigma\)). A hot plasma component with \(kT \sim 5\) keV, in addition to the \(kT \sim 1\) keV gas, is required in order to properly fit the Fe Ly\(\alpha\) line and the overall spectrum (Fig. 3 & Table 1). Additionally, a strong enhancement of the Fe abundance is evident (Table 2), indicating the presence of the Fe-rich stellar ejecta at the center of the SNR. The best-fit two-temperature thermal plasma model is presented in Fig. 3 and Tables 1 & 2.

The “plume” region (Fig. 2) can be fitted with a single-temperature (\(kT \sim 1.3\) keV) thermal plasma model (Fig. 4, Tables 1 & 2). The Fe He\(\alpha\) line is significantly weaker than the center region. The Fe abundance is consistent with the solar value, which is considerably lower than in the central region. These results indicate that the plume is emission from shocked ISM rather than from metal-rich ejecta. The Fe Ly\(\alpha\) line feature is not substantial in the plume region, and thus the hot component (\(kT \sim 5\) keV) is not necessary to describe the X-ray spectrum.

![Figure 3. The Chandra/ACIS spectrum of the “center” region. The best-fit two-temperature thermal plasma model is overlaid.](image1)

![Figure 4. The Chandra/ACIS spectrum of the “plume” region. The best-fit single temperature thermal plasma model is overlaid.](image2)

Table 1. Results of Spectral Fittings of Sgr A East

| Region  | \(N_H\) \((10^{22}\) cm\(^{-2}\)) | \(kT_{soft}\) (keV) | \(kT_{hard}\) (keV) | \(EM_{soft}\) \((10^{57}\) cm\(^{-3}\)) | \(EM_{hard}\) \((10^{57}\) cm\(^{-3}\)) | \(\chi^2/\nu\) |
|---------|----------------|----------------|----------------|----------------|----------------|----------------|
| Center  | 18.9\(^{+2.3}_{-1.8}\) | 1.05\(^{+0.19}_{-0.13}\) | 5.28\(^{+0.66}_{-0.57}\) | 7.1\(^{+5.5}_{-2.8}\) | 3\(^{+0.1}_{-0.1}\) | 167.9/163 |
| Plume   | 14.7\(^{+1.5}_{-1.9}\) | 1.32\(^{+0.24}_{-0.11}\) | - | 1.8\(^{+0.6}_{-0.6}\) | - | 100.5/83 |

\(^a\)The errors are 2\(\sigma\) uncertainties.

Table 2. Best-Fit Metal Abundances of Sgr A East

| Region  | S     | Ar    | Ca    | Fe    |
|---------|-------|-------|-------|-------|
| Center  | 0.69\(^{+0.74}_{-0.56}\) | 1.76\(^{+0.80}_{-0.72}\) | 1.37\(^{+0.80}_{-0.56}\) | 5.81\(^{+1.65}_{-1.11}\) |
| Plume   | 1.91\(^{+0.96}_{-0.69}\) | 1.20\(^{+0.65}_{-0.58}\) | 2.50\(^{+0.77}_{-0.71}\) | 0.96\(^{+0.38}_{-0.27}\) |

\(^a\)Abundances are with respect to solar.

\(^b\)The errors are 2\(\sigma\) uncertainties.
4. The Cannonball: X-Ray Morphology

A hard point-like source is detected at the edge of the plume and is designated as CXOGC J174545.5–285829 by Muno et al. [6], the so-called cannonball [5]. (There is another point-like source, CXOGC J174545.2–285828, just $\sim 3''$ west to the cannonball. The soft spectrum, the long-term variability, and the detection of an optical counterpart identify this source as a foreground star [7].) The cannonball is apparently extended with a cometary tail directing southward, which roughly traces back to Sgr A East (Figs. 5a & 6a). The deconvolved image and the comparison with the detector PSF show that the extended morphology of the cannonball is intrinsic and is not caused by the PSF (Fig. 6). The angular extent of the tail is $\sim 3''$, which corresponds to a projected physical size of $\sim 0.1$ pc (Hereafter, we assume $d \sim 8$ kpc to the Galactic center [8]).

Figure 5. The Chandra/ACIS image of the cannonball. (a) The hard band (3 – 8 keV) image. (b) The soft band (0.8 – 2 keV) image. Darker gray-scales are higher intensities.

Figure 6. (a) The 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 $\sigma = 0.5''$ for the purpose of display. Note that the soft source to the west of the cannonball is resolved into two point-like sources. (b) The source intensity profile 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 dashed curve.
5. The Cannonball: X-Ray Spectrum

The spectrum of the cannonball can be fitted with a power law (Fig. 7). The best-fit parameters are summarized in Table 3. The high foreground absorption indicates its co-spatial location with Sgr A East in the Galactic center. The best-fit photon index and the derived X-ray luminosity are then consistent with the typical values from Galactic pulsars [9]. Because of the relatively low photon statistics (~1000 counts) and the heavy absorption, the spectrum may also be fitted with thermal plasma models with a very high electron temperature ($kT \sim 25$ keV) but with extremely low metal abundances. Thus, although unlikely, a thermal origin of the X-ray spectrum of the cannonball (e.g., a cataclysmic variable) cannot be completely ruled out.

![Graph showing X-ray spectrum of the cannonball.](image)

**Figure 7.** The X-ray spectrum of the cannonball. The upper and lower plots are the spectrum where the source was detected on-chip and on the ACIS-I chip-gap, respectively, due to the various roll-angles. The best-fit power law model is overlaid.

| $\Gamma^a$ | $N_H^a$ $(10^{22} \text{ cm}^{-2})$ | $f_X (2-10\text{keV})^a$ | $L_X (2-10\text{keV})^a$ | $\chi^2/\nu$ |
|------------|-------------------------------|----------------|------------------------|-----------|
| 1.59$^{+0.58}_{-0.39}$ | 16.5$^{+3.3}_{-3.2}$ | 1.9$^{+3.6}_{-1.2}$ | 3.1 | 37.0/46 |

The errors are 2$\sigma$ uncertainties.

6. Discussion

The spectral characteristics of the cannonball are consistent with an identification of a pulsar in the Galactic center. The cometary tail (~0.1 pc) extends southward, toward the center of Sgr A East. The projected sky position of the cannonball is just *interior* to the radio shell boundary of Sgr A East while sitting on the tip of the X-ray plume. These spectral and morphological X-ray characteristics suggest that the cannonball may be a high-velocity neutron star, moving toward the north away from the SNR Sgr A East.

We estimate the velocity of the cannonball using three independent methods. Assuming an age of ~5000 – 10000 yr for Sgr A East [2, 3, 10], and taking the angular separation of ~2$'$ between the cannonball and the center of the SNR, we find $v \sim 455 - 912$ km s$^{-1}$/sin$\beta$, where $\beta$ is the angle between the line of sight and the actual traveling direction of the cannonball. Secondly, assuming that the plume is a bow-shock produced by the cannonball, we estimate an opening angle of $\theta \sim 53^\circ$ for the bow-shock and thus the Mach number $Ma = [\sin(\theta/2)]^{-1}$ is ~2.2. The velocity is then $v = c_s Ma = \sim 880$ km s$^{-1}$ (we here use the 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 plasma in the plume region). We
may also derive the pulsar velocity by assuming pressure equilibrium between the pulsar wind nebula (PWN) and the ambient medium. The best-fit photon index of the cannonball ($\Gamma = 1.6$) implies $E \sim 7.6 \times 10^{36}$ ergs $s^{-1}$ based on an empirical relationship between $E$ and the power law photon index of the PWN [11]. For the pressure balance among the the PWN, thermal and ram pressures of the ambient ISM, $P_{\text{PWN}} = E/(4\pi c R^2)$ = $P_{\text{th}}$ ($= 2n_e kT = \epsilon_e (= \rho c^2$), the velocity is derived to be $v \sim 550$ km $s^{-1}$. In these estimates, $n_e$ is $\sim 7.4$ cm$^{-3}$ from the best-fit volume emission measure ($EM$) of the plume, and $\rho$ is the mass density of the ISM derived from the spectral analysis of the plume region. The radius of the PWN, assuming a spherical geometry, is derived to be $R \sim 2.5 \times 10^{16}$ cm which corresponds to $\sim 0''/2$ at $d \sim 8$ kpc. This small $R$ is consistent with the pointlike detection of the “head” of the cannonball by the ACIS.

Considering various assumptions and embedded uncertainties in the above three independent approaches for the velocity estimates, the agreement among all three results are remarkable. Moreover, the estimated velocity range is in good agreement with that of typical high-velocity pulsars in the Galaxy [12], which lends these estimates additional credibilidad.

No evidence for long-term (observation by observation) variability of the cannonball was detected [7]. The constant light curve with a long time-basis of $\sim 3$ yr is remarkably unusual among the Galactic center sources. This non-variability over a few years indicates that the cannonball is unlikely a background AGN, and supports the neutron star identification. The logN-logS relation for the contribution from extragalactic sources in the Galactic center [6] indicates a low probability of $\sim 1.2 \times 10^{-4}$ for the detection of a background extragalactic source at the flux level of the cannonball within the plume region. We then searched for pulsations from the cannonball with a 40-ks archival XMM-Newton/EPIC observation pointed at Sgr A*.

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.

Assuming that the Fe-rich central region represents the bulk of the total Fe mass ejected from the progenitor star, the total Fe mass estimate can be useful to infer the progenitor mass. We consider some simple geometries in which all Fe ejecta material is contained within the central $\sim 40'' - 60''$ diameter region where the Fe EW is the highest (Fig. 2). We, for simplicity, also assume a “pure” Fe-ejecta case for the estimate of the electron density: i.e., all electrons originate from the ionized Fe ($n_e \sim 24n_{Fe}$ for the case that the He-like Fe dominates). The best-fit $EM$s from the spectral analysis of the center region imply Fe ion density of $n_{Fe} \sim 0.11 f^{-1/2}$ cm$^{-3}$, where $f$ is the volume filling factor for the X-ray emitting gas. We then estimate the total Fe mass of Sgr A East to be $M_{Fe} \sim 0.15 f^{2} - 0.27 f^{1} M_\odot$, depending on the assumed geometries (The details of the Fe mass calculation can be found in Park et al. [5]). These Fe mass estimates are upper limits because of the pure ejecta assumption. If a significant contribution from H is considered, these Fe mass estimates only become smaller. The estimated Fe mass upper limits are then consistent with a Type II origin from a $13 - 15 M_\odot$ progenitor when compared with standard supernova nucleosynthesis models [13, 14], unless a significant fraction of the Fe-rich ejecta ($\sim$several times larger than the observed Fe ejecta mass) has already been intermixed with the ambient ISM. The suggested Type II core-collapse origin of Sgr A East is self-consistent with the proposed SNR-neutron star association between Sgr A East and the cannonball.

7. Conclusions

The observed X-ray nature of the cannonball suggests an identification as a high-velocity neutron star in the Galactic center. The estimated Fe ejecta mass of Sgr A East supports a core-collapse origin for the SNR. Based on its proximity to Sgr A East, we therefore propose that the cannonball may be a candidate neutron star born from the supernova explosion which also produced the SNR Sgr A East. We note that the discrepancies between the previous results from the early Chandra and the XMM-Newton observations (e.g., the presence of Fe Lyα line and the extremely hot component ($kT \sim 5$ keV) of the X-ray emitting gas) can be resolved by
the high resolution, high photon statistics data from the deep *Chandra* observations.

The non-detection of the pulsation from the cannonball remains an issue for the neutron star identification. However, the limited timing resolution of the archival EPIC/PN data (73.4 ms) did not allow us to search for periods shorter than \(\sim 147\) ms. The presence of a pulsar for the cannonball thus cannot be ruled out yet. Follow-up X-ray and/or radio observations with high time resolution instruments would therefore be essential for the conclusive identification of the cannonball.

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