# RESOLVING NON-THERMAL X-RAY KNOTS FROM THE GALACTIC CENTER WITH *CHANDRA* DEEP EXPOSURE OBSERVATION

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## Abstract

We have analyzed the $\sim$ 0.6 Ms *Chandra* deep exposure data and resolved several non-thermal X-ray knots located near the Galactic center (GC). In particular, we focused on three prominent X-ray knots which are aligned from the GC to the north-northwest direction. All of the three X-ray knots have an elongated shape toward the same direction (from GC to north-northwest). The major and minor axes of these knots are typically $\sim 6''$ and $\sim 2.5''$. The X-ray spectrum of each knot exhibits no line emissions, therefore their origin should be non-thermal. By comparing Very Large Array 6 cm and 20 cm continuum maps, we found radio structures are marginally coincident with these X-ray knots. Above observational results suggest that these knots are jet-like objects ejected from the Galactic nucleus (Sgr A*), so we also try to estimate the proper motion velocity of these knots. Although we can obtain the upper limit of their motion, it suggests that these knots have a possible correlation with > 400 years past activity of Sgr A*.

## 1 Introduction

*Chandra* and *XMM-Newton* detected flaring events from the position coincident with Sgr A* (Baganoff et al., 2001; Porquet et al., 2003), which is believed to be the nearest (and most probable) massive black hole ($M \sim 3.6\times10^6\ M_\odot$, e.g., Schoedel et al. (2002)) from the earth. However, no one can explain why the black hole is so quiet ($L_\mathrm{X} \leq 4\times10^{35}$ erg s$^{-1}$) now.

This quiet Sgr A* is in a sharp contrast to its violent surroundings which was revealed with past X-ray observations of *Ginga* and *ASCA*; the largely ($\sim 200\times150$ pc) extended diffuse hard X-rays and the strong 6.4 keV neutral iron line emissions from the giant molecular clouds near the Galactic center (GC). The former result requires huge energy injection event(s) amount to $\sim 10^{54}$ erg with the short time scale of recent $\sim 10^5$ years, while the latter can be interpreted as the fluorescent X-rays by an irradiation with external strong X-ray source(s) (Koyama et al., 1989, 1996; Yamauchi et al., 1990).

The early phase of the *Chandra* observations have successfully resolved X-ray supernova remnant candidates (Maeda et al., 2002; Senda, Murakami & Koyama, 2002), which may be the relics of the $10^{2-4}$ years past activity near the GC region. On the other hand, *ASCA* and *Chandra* observations of the giant molecular clouds (Sgr B2 and Sgr C) not only confirm the hypothesis of its origin of fluorescent X-rays, but

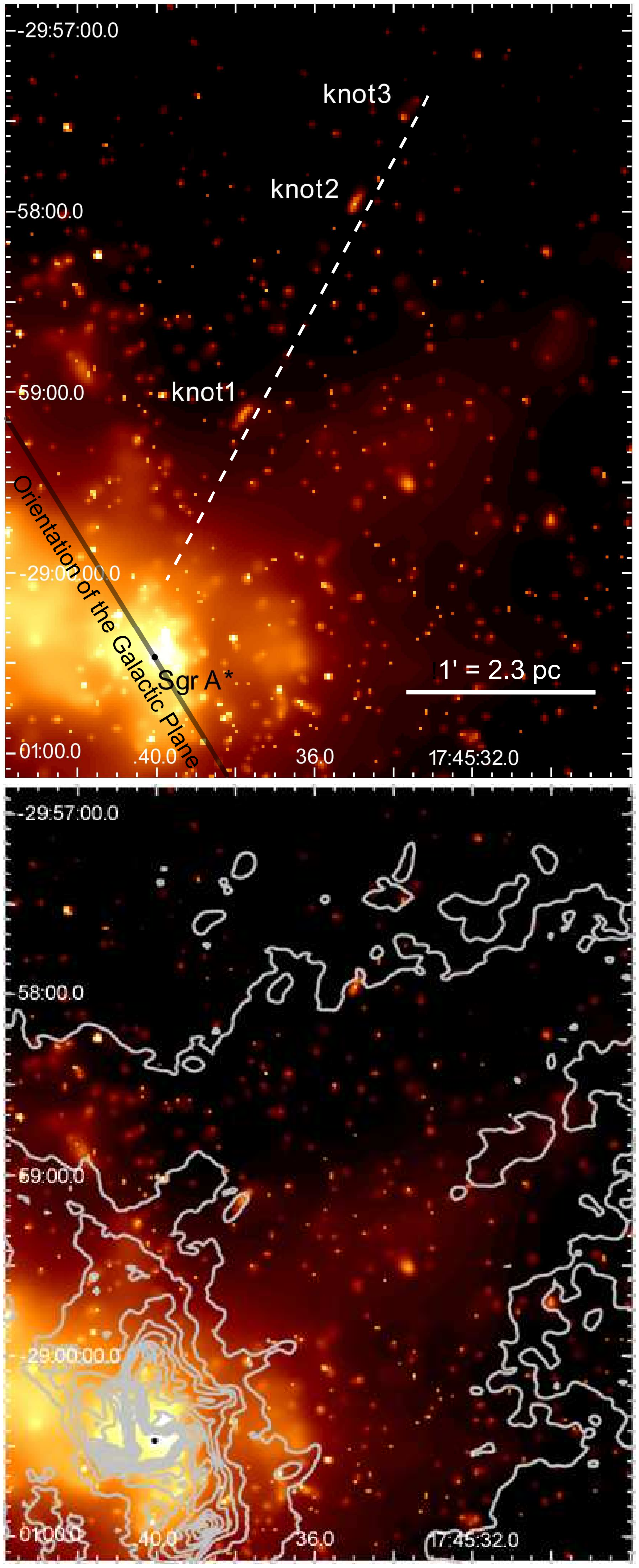

Figure 1: (a) An adaptively smoothed image of the X-ray knots with *Chandra* ACIS (3–8 keV). Exposure and vignetting effects are corrected. (b) VLA 6 cm radio continuum map overlaid on Fig. 1a.

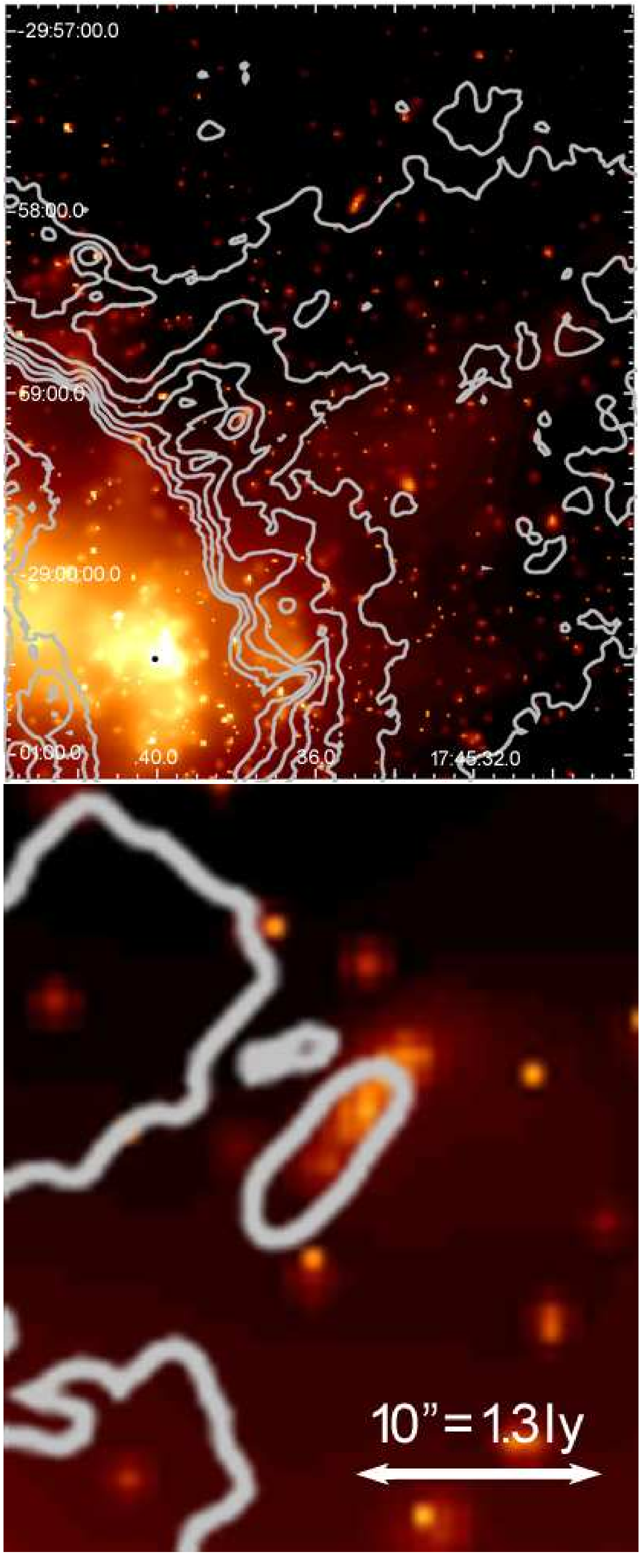

Figure 2: (a) VLA 20 cm radio continuum map overlaid on Fig. 1a. (b) A close-up image of knot 1 in Fig. 1b. We can see the X-ray intensity peak of knot 1 offset from the peak of the radio counterpart.

Table 1: *Chandra* observation log

| Obs. Date | Exposure (ks) |
|---|---|
| 1999 Sep 21 | 40.9 |
| 2000 Oct 26 | 35.7 |
| 2001 Jul 14 | 13.5 |
| 2002 Feb 19 | 12.4 |
| 2002 Mar 23 | 11.9 |
| 2002 Apr 19 | 11.6 |
| 2002 May 07 | 12.5 |
| 2002 May 22 | 34.7 |
| 2002 May 24 | 38.0 |
| 2002 May 25 | 166.7 |
| 2002 May 28 | 158.0 |
| 2002 Jun 03 | 90.0 |

also identify the irradiating source as the 300–1000 years past activity of Sgr A*, which should be as luminous as $L_X \sim 10^{39}$ erg s$^{-1}$ (Murakami et al., 2001a; Murakami, Koyama & Maeda, 2001b). These observational results suggest that Sgr A* and its vicinity had been quite active until recent past.

Furthermore, recent *Chandra* and *XMM-Newton* observations of the GC region have resolved several nonthermal X-ray filaments/threads with radio counterparts (Wang, Lu & Lang, 2002; Sakano et al., 2003; Lu, Wang & Lang, 2003). If their origin is synchrotron emission from high energy particles, they should directly trace the site where high energy particles are accelerated because X-ray emitting particles have extremely short lifetime due to the strong magnetic field near the GC. Hence these X-ray filaments suggest that high energy particle accelerations have occurred at the GC region.

Morris et al. (2003) reported that they resolved out a number of X-ray linear features close to the GC. In addition to some these linear features, We resolved a new X-ray linear feature near the "F". We also perform the detailed analysis of X-ray and radio emissions of these X-ray knots ( "E" and "F" in Fig. 3 of Morris et al. (2003)), then discuss their nature. Finally we briefly remark on our interpretation of them as jet-like objects which were continually ejected from Sgr A*.

## 2 Results

### 2.1 X-ray and radio images

To construct a fine X-ray image as shown in Fig. 1a, we merged twelve *Chandra* ACIS-I data sets as shown in Table 1. After excluding intervals of strong flaring time from each observation, we obtained ∼ 630 ks as a total effective exposure. Finally, an adaptive smoothing and a correction for exposure variations were performed (Fig. 1a). Radio contours are created from Very Large Array (VLA) archival data taken from NCSA/ADIL (http://adil.ncsa.uiuc.edu). Both X-ray color and radio contours are shown in log scale (Fig. 1, 2). Note that the 20 cm contour map around Sgr A* is saturated (Fig. 2a).

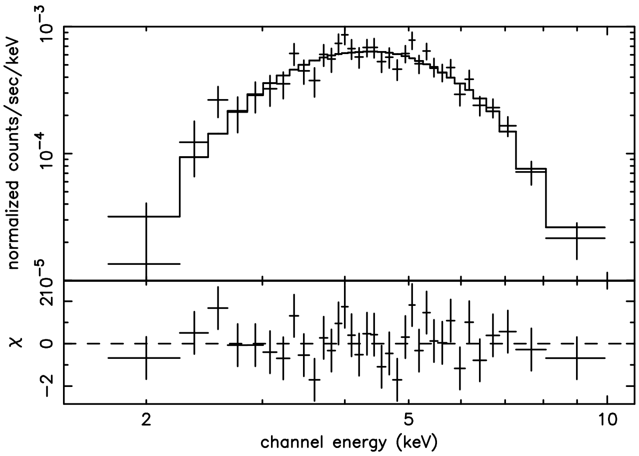

Figure 3: The X-ray spectrum of each knot obtained with *Chandra* ACIS-I. X-ray photons from knot 1–3 are merged, and the averaged ARF and response are used for the spectral fitting.

In Fig. 1a, We can see a number of diffuse X-ray features are resolved. Among them, we focused on three prominent X-ray linear structures in the north-northwest direction from the GC as the following reasons. (hereafter, we call them as knot 1, 2, and 3 as shown in Fig. 1a). First, knot 1, 2, and 3 are not only on the straight line (dashed line of Fig. 1a), but also elongated to the same direction of the line. Second, 6 cm radio continuum counterparts were found at the position of the knot 1–3 (Fig. 1b). Although knot 2 and 3 have marginal detection at the radio band, knot=1 has a clear correlation between X-ray and radio continuum (both 6 cm and 20 cm; Fig. 1b, and 2a). Moreover, when the alignment of the knots extrapolates toward the GC direction, it is smoothly connected to the radio structure called "Sgr A mini-spiral" (Fig. 1b).

### 2.2 X-ray spectra

At first, we fitted the X-ray spectrum of each knot with a power-law model including the effect of interstel-

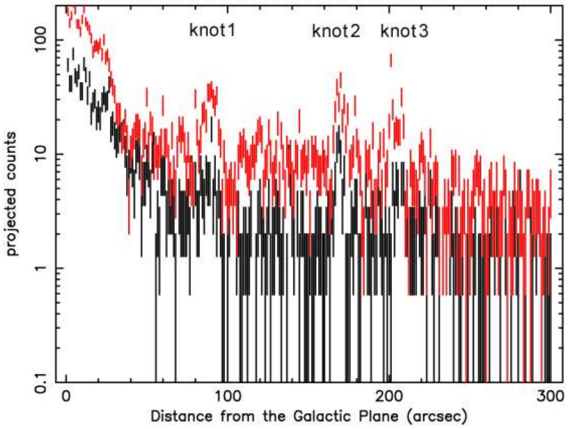

Figure 4: Surface brightness profile of the each X-ray knot. The red data represents projection of Data 1, while black data represents Data 2. Both profiles are made from 3–8 keV photons.

lar absorption. Best-fit parameters are shown in Table 2. Secondly, we made the merged X-ray spectrum of three knots (as shown in Fig. 3) then performed fitting with the same model. The result shows a beautiful power-law profile with a photon index of $\sim 1.5$ (Table 2). We also try fitting each spectra with a thin-thermal plasma model (MEKAL model; Mewe et al. (1985), Mewe et al. (1986), Kaastra (1992), and Liedahl et al. (1995)), but best-fit value of a plasma temperature was determined to be $> 70$ keV, which is too high for the temperature of a thermal plasma. Therefore we thought that the application of a thermal model is not realistic. These results lead us to conclude that the origin of the X-ray emission from these knots is non-thermal.

## 3 Discussion

### 3.1 A measurement of the proper motion of the X-ray knots

A measurement of a proper motion is the best method for proving whether these X-ray knots are originated from jet activity of the Galactic nucleus (Sgr A*). As listed in Table 1, *Chandra* had continually observed GC region for about 2.7 years; from September 1999 to June 2002. At first, we selected the earlier and latest observation data sets and merged as follows;

- Data 1: September 1999—October 2000
- Data 2: May 2002—June 2002

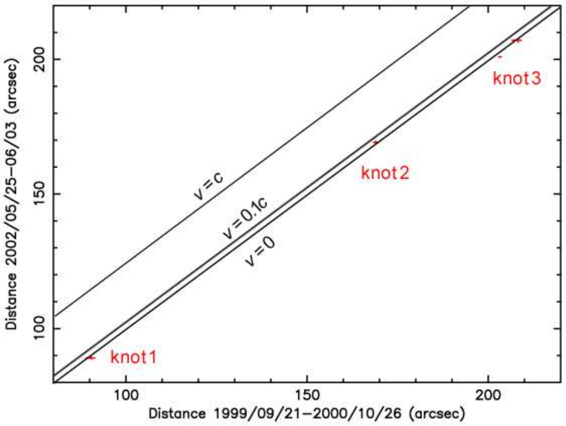

Figure 5: Plot the peak offset of each X-ray knot. Horizontal and vertical axes represent distance from Sgr A* to the each knot of the Data 1 and 2, respectively. The peak positions of the knot 1 and 2 are determined by a fitting the profile (Fig. 4) with single Gaussian, while knot 3 with two Gaussians because it has two peaks in surface brightness.

Secondly, We took surface brightness profiles projected to the line (white dashed line in Fig. 1a). The projection width from which we accumulate the photon is $6''$. The result is shown in Fig. 4. Comparing peak positions of each knot profile of Data 1 and Data 2, we estimated the proper motion of these knots for about 2 years intervals. As shown in Fig. 5, no significant proper motion is detected. A typical statistical error of the position offset is $\pm 0.5''$. It corresponds to $\pm 0.06$ light years, assuming that the distance from the GC to us is 8.0 kpc (Eisenhauer et al., 2003). From the above estimation, the upper limit of the projected velocity of the knots' proper motion is determined to be $\sim 0.03c$.

On the other hand, it is interesting that the knot 1 has a slight but significant offset ($\sim 3''$) from its radio counterpart (Fig. 2b). The VLA data was taken in 1985 (Yusef-Zadeh & Morris, 1987), so there is about 15 years interval. If the offset is due to the proper motion of the knot 1, its projection velocity is estimated to be $0.025c$, which is the consistent with the upper limit shown in the above estimation.

### 3.2 Possible relation between X-ray knots and the past activity of Sgr A*

Since the distance (in projection) from the GC to the knot 1–3 are about 10, 20, and 25 light years, respectively, they can be interpreted as the relics of the con-

Table 2: Best fit parameters of the spectra of the X-ray knots with a power-law model

| | Total Counts photons | Column Density ($N_{\rm H}$) $10^{22}$ H cm$^{-2}$ | Photon Index ($\Gamma$) $N(E) \propto E^{-\Gamma}$ | Luminosity ($L_{\rm X}$)* $10^{32}$ erg cm$^{-2}$ |
|---|---|---|---|---|
| Knot 1 | 501 | 8.5 (4.3–14) | 1.3 (1.2–2.2) | 4.6 |
| Knot 2 | 485 | 16 (9.1–21) | 2.3 (1.7–3.1) | 5.4 |
| Knot 3 | 295 | 10 (5.3–23) | 1.8 (0.3–2.7) | 3.8 |
| Merged | 1281 | 12 (9.5–15) | 1.5 (1.1–2.0) | 13 |

– The errors correspond to 90% confidence.

* Assuming the distance to the GC is 8.0 kpc (Eisenhauer et al., 2003).

tinual jet-like activity originated Sgr A*, which had been ejected $>$ 400 years ago if these knots has been moved at the velocity of $< 0.03c$. Note that this time scale totally coincides with the active period of Sgr A* predicted by the X-ray reflection nebula model (Murakami et al., 2001a; Murakami, Koyama & Maeda, 2001b).

## 4 Summary

- With $\sim$ 0.6 Ms *Chandra* deep exposure data, we resolved three prominent X-ray knots aligned to a line from the GC to the north-northwest direction.
- X-ray spectrum of each knot suggests their non-thermal origin.
- Radio continuum structures marginally coincide with these X-ray knots. In particular, knot 1 shows clear correlation with X-ray and radio (both 6 cm and 20 cm).
- From about two year *Chandra* data, no significant proper motion is detected. The upper limit of a proper motion velocity (in projection) is $\sim 0.03c$.

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