Discoveries of 3 K-Shell Lines of Iron and a Coherent Pulsation of 593 s from SAX J1748.2–2808

Masayoshi Nobukawa, Katsuji Koyama, Hironori Matsumoto, and Takeshi Go Tsuru
Department of Physics, Graduate school of Science, Kyoto University, Sakyo-ku, Kyoto 606-8502
nobukawa@cr.sr.phys.kyoto-u.ac.jp, koyama@cr.sr.phys.kyoto-u.ac.jp

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Abstract

SAX J1748.2–2808 is a unique X-ray object with a flat spectrum and strong emission lines at 6.4–7.0 keV. The Suzaku satellite resolved the emission lines into 3 K-shell lines from neutral and highly ionized irons. A clear coherent pulsation with a period of 593 s was found from the Suzuki and XMM-Newton archives. These facts favor that SAX J1748.2–2808 is an intermediate polar, a subclass of a magnetized white dwarf binary (cataclysmic variable). This paper reports on details of the findings, and discusses the origin of this source.

Key words: Galaxy: center — stars: cataclysmic variables — stars: individual (SAX J1748.2–2808)

1. Introduction

SAX J1748.2–2808 was discovered with the Beppo-SAX satellite in the direction of the radio complex Sagittarius (Sgr) D (Sidoli et al. 2001), and was deeply re-observed with the XMM-Newton satellite (Sidoli et al. 2006). The X-ray spectrum was well-fitted with a power-law of photon index $\Gamma = 1.4$ plus a broad line of 0.43 keV ($1/\sigma$) with the center energy at 6.6 keV. The $N_H$ value was as large as $1.4 \times 10^{23}$ cm$^{-2}$ (Sidoli et al. 2006). SAX J1748.2–2808 was thus regarded as being one of the brightest samples of resolved point sources in the Galactic center region (GC) with Chandra deep-exposure observations (Muno et al. 2003, 2006). The integrated spectra of the point sources resemble that of the Galactic center diffuse X-rays (GCDX) in the iron line features close to 6.4–7.0 keV of the point sources. Furthermore, a broad line of SAX J1748.2–2808 was reported from either the Beppo-SAX or the XMM-Newton observations. The Suzaku satellite resolved the X-ray spectra favored that SAX J1748.2–2808 is an intermediate polar, a subclass of a magnetized white dwarf binary (cataclysmic variable). This paper reports on details of the findings, and discusses the origin of this source.

The XIS observations were made with the normal mode. The XIS pulse-height data for each X-ray event were converted to Pulse Invariant (PI) channels using the xispi software version 2007-03, and the calibration database version 2008-01-31. We removed the data during the epoch of low-Earth elevation angles of less than $5^\circ$ (ELV < 5$^\circ$), day Earth elevation angles of less than $10^\circ$ (DYE < 10$^\circ$), and the South Atlantic Anomaly. The good exposure times are listed in table 1. Although the XIS CCDs were significantly degraded by on-orbit particle radiation, the CCD performances were restored by the spaced-row charge injection technique (Uchiyama et al. 2009). Then, the overall spectral resolutions at 5.9 keV were $\sim 150$ and $\sim 170$ eV (FWHM) for the FI and BI CCDs, respectively. We analyzed the data using the software package HEASoft 6.4.1. For spectral fittings, we made XIS response files using xisrmfgen, and auxiliary files using xissimarfgen. Since the spectrum of the non-X-ray background (NXB) depends on the geomagnetic cut-off rigidity (COR) (Tawa et al. 2008), we obtained COR-sorted NXB spectra using xisnmfgen, from the night-Earth data released by the Suzaku XIS team.

SAX J1748.2–2808 was also in the filed of view of the XMM-Newton observations on Sgr D SNR and G0.9+0.1 on 2000 September and 2003 March, respectively. A pointing observation of SAX J1748.2–2808 was also made in 2005 February. X-ray data were obtained with the European Photon Imaging Camera (EPIC) (Strüder et al. 2001; Turner et al. 2001). We extracted the EPIC-PN spectrum and fitted it with a power law and a reflection component with the xspec software package. The best fit was obtained with $\Gamma = 1.4$ and $N_H = 1.4 \times 10^{23}$ cm$^{-2}$.
Table 1. Observation data list.

| Observatory/Instrument | Target            | Observation ID   | Date (yyyy/mm/dd) | Exposure time* (ks) |
|------------------------|-------------------|------------------|--------------------|--------------------|
| Suzaku/XIS            | Sgr D SNR         | 502020010        | 2007/09/06         | 139.1              |
| Suzaku/XIS            | G0.9+0.1          | 502051010        | 2008/03/11         | 138.8              |
| XMM-Newton/MOS        | Sgr D SNR         | 0112970101       | 2000/09/23         | 15.7               |
| XMM-Newton/PN         | Sgr D SNR         | 0112970101       | 2000/09/23         | 11.5               |
| XMM-Newton/MOS        | G0.9+0.1          | 0144220101       | 2003/03/12         | 49.5               |
| XMM-Newton/MOS        | SAX J1748.2−2808  | 0205240101       | 2005/02/26         | 50.2               |
| XMM-Newton/PN         | SAX J1748.2−2808  | 0205240101       | 2005/02/26         | 41.5               |

* After the data screening described in the text.

Fig. 1. X-ray image in the 3–7 keV band from the Suzaku observations on Sgr D SNR (a) and G0.9+0.1. The source regions of SAX J1748.2−2808 are given by the solid polygons, which trace the complicated point-spread function of the XRT in the field edge (see text). The dashed squares (excluding ellipses) are the local backgrounds. (c) Combined images of figures (a) and (b) near SAX J1748.2−2808 (stronger source) and S 12 (fainter source) (Sidoli et al. 2006).

The X-ray images taken with the XIS were analyzed for each observation separately. Since the Suzaku nominal position error is 20″ (Uchiyama et al. 2008), we fine-tuned the Suzaku position while referring to the positions of XMM-Newton sources. In the Sgr D SNR observation, we found an XMM-Newton source, S 10 (see table 4 of Sidoli et al. 2006). The XMM-Newton position is (α, δ) = (266°81562, −28°181511), while the Suzaku position is (α, δ) = (266°81737, −28°18065). We hence shifted the Suzaku coordinates by (Δα, Δδ) = (−0°00175, −0°001446).

After these fine-tunings of the Suzaku coordinates, we made the X-ray image shown in figure 1. We found two sources near to the edge of each field. These two sources coincide in position with S 3, i.e., SAX J1748.2−2808 (stronger source) and S 12 (fainter source) of the XMM-Newton observation within statistical errors of ≤5″.

In order to estimate the intensity ratio of the two sources, we made a projected profile along the line connecting SAX J1748.2−2808 and S 12 (see figure 1c). The profile was fitted with two Gaussians plus a liner function, as shown in figure 2. The widths (1-σ) of the Gaussian profiles approximate the projected point-spread function. The best-fit source fluxes (normalizations of the Gaussians) were determined to be 7.5 × 10⁻³ and 2.8 × 10⁻³ counts s⁻¹, for SAX J1748.2−2808 and for S 12, respectively.

3.2. Spectrum

Since the X-ray spectrum of XMM-Newton has already been reported, we show the Suzaku spectrum of SAX J1748.2−2808. The point-spread function of the XRT has complicated polygon-shape images, due to both the
4-segments structure of the XRT and image deformation near the field edge (Serlemitsos et al. 2007). We therefore extracted the spectra from the solid polygons in figures 1a and 1b, for the best S/N ratio within limited statistics.

The background spectra were obtained from a near-by sky, shown by the dashed squares, from which the dashed elliptical regions were excluded. The background spectra consist of non–X-ray background (NXB) and the local background (the cosmic X-ray background plus the Galactic center diffuse X-rays). Since the local background is affected by vignetting of the XRT, while the NXB is not, each background was treated separately. For both the source and the background data, we made COR distributions and composed the NXB spectra from the COR-sorted NXB data set (see section 2). We then subtracted the NXB extracted from the same detector areas. After NXB subtraction, we corrected the vignetting effect due to the different off-axis angles between the source and the background regions by multiplying the effective-area ratios for each energy bin of the local background spectra (the same process as Hyodo et al. 2008). We further subtracted the corrected local background from the source spectra. All source spectra of the two FIs from the two observations were co-added to increase the statistics.

We estimated the contamination of a near-by fainter source, S 12, by a ray-tracing simulation (xissim in the HEASoft package). The spectral shape of SAX J1748.2–2808 was assumed to be an absorbed power-law plus 3 Gaussian lines, whose parameters are the same as those given in table 2. This spectrum model is mentioned in the next paragraph. Since the fainter source, S 12, is too weak to allow a spectral analysis, its spectral shape was assumed to follow the same model of an absorbed black-body ($N_H = 10^{24} \text{ cm}^{-2}$, $kT = 1 \text{ keV}$), as shown by Sidoli et al. (2006). Using the flux ratio of SAX J1748.2–2808 and S 12 determined in subsection 3.1, we found that the contamination was ≤ 10% in the 3–10 keV band. We therefore ignore the contamination of S 12 in the following analysis and discussion.

The X-ray spectra of FI and BI were simultaneously fitted with an absorbed power-law plus one broad line, $\text{Abs} \times \text{(Power-Law + 1 Gaussian line)}$, which is the same model as that of the XMM-Newton by Sidoli et al. (2006). The best-fit (90% confidence range) photon index of the
Table 2. Best-fit parameters.

| Model: Abs × (Power-Law + 3 Gaussian lines) | Line energy (keV) | Flux (10^{-6} ph s^{-1} cm^{-2}) | Equivalent width (eV) |
|---------------------------------------------|------------------|-------------------------------|----------------------|
| 6.40 (6.39–6.47)                            | 1.5 (0.8–2.3)    | 140 (30–270)                  |
| 6.68 (6.66–6.72)                            | 1.9 (1.1–2.7)    | 180 (30–350)                  |
| 6.97 (6.94–7.46)                            | 1.3 (0.6–2.1)    | 130 (≤270)                    |
| Parameter                                   | Best-fit value   |                               |
| Photon index                                | 1.0 (0.8–1.3)    |                               |
| \(N_H\) (10^{23} cm^{-2})                  | 1.3 (1.0–1.7)    |                               |
| Flux (3–10 keV) (10^{-13} erg s^{-1} cm^{-2}) | 6.0 (5.7–6.2)    |                               |
| Luminosity\(^{1}\) (3–10 keV) (10^{33} erg s^{-1}) | 7.4 (7.0–7.6)    |                               |
| \(\chi^2/dof\)                             | 67.6/64          |                               |

| Model: Abs × (APEC + Neutral iron lines)    | Line energy (keV) | Flux (10^{-6} ph s^{-1} cm^{-2}) | Equivalent width (eV) |
|---------------------------------------------|------------------|-------------------------------|----------------------|
| 6.40 (fixed)                                | 2.1 (1.0–2.7)    | 160 (10–270)                  |
| 7.05 (fixed)                                | 0.26\(^{1}\)    | 23                            |
| Parameter                                   | Best-fit value   |                               |
| Temperature: \(kT\) (keV)                  | 12 (9–17)        |                               |
| Metal abundance (solar)                     | 0.57 (0.35–0.85) |                               |
| \(N_H\) (10^{23} cm^{-2})                  | 1.8 (1.6–2.1)    |                               |
| Flux (3–10 keV) (10^{-13} erg s^{-1} cm^{-2}) | 5.4 (5.2–5.7)    |                               |
| Luminosity\(^{1}\) (3–10 keV) (10^{33} erg s^{-1}) | 8.4 (8.0–8.8)    |                               |
| \(\chi^2/dof\)                             | 77.4/65          |                               |

\(^{1}\) Inclusive numbers in parentheses show 90% confidence range.

\(^{1}\) Absorption corrected. Distance toward SAX J1748.2–2808 is assumed to be 8.5 kpc.

\(^{1}\) The flux of the 7.05 keV line is constrained to be 0.125 of the 6.40 keV Line.

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**Thermal + neutral Iron lines**

![Graph showing thermal + neutral iron lines](https://example.com/graph.png)

**Fig. 4.** Same as figure 3, but the best-fit model of an absorbed thin thermal plasma (APEC) plus K-shell lines of neutral iron.
power-law, line center energy, and width (1σ) are 1.2 (0.8–1.5), 6.66 (6.54–6.77) keV, and 0.31 (0.21–0.39) keV, respectively ($\chi^2$/dof of 72.8/64). These parameter values are consistent with those of XMM-Newton within the statistical error. However, the Suzaku spectrum exhibits significant residuals near to energies of 6.4, 6.7, and 7.0 keV. We therefore fitted with a model of an absorbed power-law plus 3 narrow lines near to 6.40, 6.68, and 6.97 keV, Abs x (Power-Law + 3 Gaussian lines). Although the fittings were made simultaneously for the FI and BI spectra, we simply show the FI result in figure 3. The fit was improved with a $\chi^2$/dof of 67.6/64. The best-fit parameters are listed in table 2.

The best-fit line energies of 6.7 keV and 7.0 keV are likely to be due to K$\alpha$ lines from He-like and H-like irons at energies of 6.68 keV and 6.97 keV, respectively, while the 6.4 keV line would be a K$\alpha$ line from neutral iron. The 6.97 keV line may be contaminated by a K$\beta$ line (7.05 keV) of neutral iron. We therefore applied a more physical model: an absorbed thin thermal plasma (APEC) plus the 6.40 keV and 7.05 keV lines from neutral iron, Abs x (APEC + 6.40 keV + 7.05 keV lines). In this model, we fixed the flux ratio of the 6.40 keV and 7.05 keV lines to 1 : 0.125 (Kaastra & Mewe 1993). A simultaneous fit for the FI and BI spectra with $\chi^2$/dof of 77.4/65 is acceptable at the 90% confidence level, as is given in table 2. In figure 4, we show only the FI spectrum for simplicity.

3.3. Timing

We examined the long-term (8 years) X-ray flux history from the 5 observations listed in table 1. The X-ray fluxes were calculated by fitting the 3-line model in table 2. Parameters other than normalization (flux) are fixed. The resultant fluxes in the 3–10 keV band show no significant variation during the 8-year interval.

We then searched for a coherent pulsation in the 3–7 keV band from all of the observations listed in table 1. A Fast Fourier Transform (FFT) analysis revealed a clear peak at $\sim1.7 \times 10^{-3}$ Hz from all of the observations. We then searched for an accurate pulse period with the folding technique, and found a significant peak near to the trial period of 593 s. The best-fit pulse periods and errors are listed in table 3 for all of the observations. As an example, we show the Suzaku results from 2007: the power spectrum of FFT, periodogram, and folded light curve in figures 5a, 5b, and 5c, respectively.

The 593-s pulsation is likely to be a spin rotation of either a magnetic white dwarf or a neutron star in a binary system (see section 4). We, therefore, searched for orbital modulation

| Observatory (year/month) | Instruments | Pulse period (s)* |
|--------------------------|-------------|------------------|
| XMM-Newton (2000/09) MOS 1+2 | 592 ± 8     |
| XMM-Newton (2000/09) PN | 594 ± 8     |
| XMM-Newton (2003/03) MOS 1+2 | 593 ± 2     |
| XMM-Newton (2005/02) MOS 1+2 | 592 ± 3     |
| XMM-Newton (2005/02) PN | 593 ± 2     |
| Suzaku (2007/09) XIS 0+1+3 | 593.1 ± 0.4 |
| Suzaku (2008/03) XIS 0+1+3 | 592.8 ± 0.4 |

* Error is 1-σ of the Gaussian profile of the periodogram (e.g., figure 5b).
4. Discussion

We found a coherent pulsation of 593 s from SAX J1748.2–2808. This constrains the origin of this source to be either a magnetic CV or a HMXB pulsar. The 593-s period is among the slowest 10% of the pulse period in HMXB pulsars (Nagase et al. 1989; Liu et al. 2000), while the fastest 30% in magnetic CVs (Ritter & Kolb 2003). Thus, the spin period of 593 s favors a magnetic CV scenario, although a HMXB pulsar scenario is not firmly excluded.

The Suzaku spectrum resolved the broad line at 6.6 keV found in the previous XMM-Newton observation into, at least, three lines at 6.40, 6.68, 6.97 keV. The best-fit equivalent widths (EW) of these three lines are \( \sim 140 \) eV, \( \sim 180 \) eV, and \( \sim 130 \) eV, respectively. Ezuka and Ishida (1999) compiled the ASCA data and reported that the magnetic CVs exhibit 3 iron Kor lines at 6.4, 6.7, and 7.0 keV with mean EW values of \( \sim 100, \sim 200, \) and \( \sim 100 \) eV, respectively (see also Hellier et al. 1998), nearly the same as those of SAX J1748.2–2808.

The overall spectrum was also well fitted with a thin thermal plasma of 12-keV temperature with a sub-solar iron abundance, plus Kor (6.40 keV) and Kβ (7.05 keV) lines from neutral iron. Ezuka and Ishida (1999) also reported that the spectra of the magnetic CVs can be described by a thin thermal plasma model, plus a 6.4 keV line with a mean temperature of \( \sim 20 \) keV, closely resembling the Suzaku results of SAX J1748.2–2808. On the other hand, HMXB pulsars show a hard continuum spectrum, but it is a broken power-law, and not a thin thermal. HMXBs exhibit an iron emission line feature. However, the line feature is not complex, but is a single line, mostly at 6.4 keV (see table 3 of Nagase et al. 1989). These properties are different from those of SAX J1748.2–2808.

All of the above facts favor the idea that SAX J1748.2–2808 is a magnetic CV rather than a HMXB. The pulse period of 593 s is smaller than the possible orbital period, although we found no orbital modulation. Therefore, 593 s would be the spin period, and hence SAX J1748.2–2808 is an intermediate polar (IP), not a polar with synchronized spin and an orbital period. If the luminosity of SAX J1748.2–2808 is a typical value for an IP of \( \sim 10^{33} \) erg s\(^{-1}\) (Patterson 1994), then from the absorption-corrected flux of \( 1 \times 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\), the distance is estimated to be \( \sim 3 \) kpc. Thus, SAX J1748.2–2808 would be a foreground source, not a member of the GC sources.

Conversely, Sidoli et al. (2006) suspected that SAX J1748.2–2808 is located near the GC region at about 8.5 kpc, because it has a large absorption of \( 1.4 \times 10^{23} \) H cm\(^{-2}\). With this distance, they estimated the luminosity to be \( \sim 10^{34} \) erg s\(^{-1}\), significantly larger than any other magnetic CVs, and hence the authors declined to suggest a HMXB origin. We, however, note that a large fraction of the absorption of IPs is due to the circum-stellar gas, and the absorption value could be up to several \( \times 10^{23} \) H cm\(^{-2}\) (Ezuka & Ishida 1999). Therefore, the large absorption of SAX J1748.2–2808 would also be due to circum-stellar gas, rather than interstellar gas integrated along the long line of sight. This large amount of circum-stellar gas can be naturally explained as being the origin of the strong 6.4 keV line from neutral iron (see e.g., Ezuka & Ishida 1999).

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