X線分光撮像衛星XRISMによる天の川銀河中心超新星残骸Sgr A Eastの元素組成比の測定
(Measurement of Abundances in the Galactic Center Supernova Remnant Sgr A East Using XRISM)

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Sgr A East is a supernova remnant near the supermassive black hole Sgr A*, with its origin and relation to past Sgr A* activity still debated.
Using XRISM's first high-resolution spectroscopy, we resolved fine structures in highly ionized Fe Kα lines. Their ratios confirm recombining plasma, and the plasma parameters and narrow lines suggest rapid cooling through adiabatic expansion or past photoionization by Sgr A*.
We also detected a strong radiative recombination continuum, tightening constraints on the plasma state. Resolve's high energy resolution reduced uncertainties, enabling measurements of the abundance ratios.

Supernova Remnant at the Center of the Milky Way Galaxy: Sgr A East

- Sgr A East is a mixed-morphology supernova remnant with high-temperature plasma inside a radio shell (Fig. 1). It overlaps with Sgr A* along the line of sight. Some studies (e.g., Maeda+02) suggest that Sgr A* may lie within Sgr A East and interact with it.

- With Suzaku/XIS, Ono+19 detected an excess of radiative recombination continuum (RRC) from highly ionized Fe, indicating a recombining plasma (RP) state rather than collision-ionization equilibrium (CIE). They proposed that photoionization by a past Sgr A* flare was the origin of the RP. However, strong Galactic Center X-ray Emission (GCXE) introduced uncertainty in the RRC detection.

- With Chandra/ACIS, Zhou+21 measured abundance ratios (Mn/Fe, Ni/Fe), suggesting the Iax-type supernova origin (pure turbulent deflagration). But limited energy resolution left uncertainty in resolving Ni XXVII Heα, Fe XXV Heβ, and satellite lines (Fig.2).

- Sgr A East is an interesting supernova remnant in both its supernova origin and its RP state.
- Past X-ray CCD spectroscopy exhibits significant uncertainty.

Fig. 1 : Sgr A East X-ray (2-8 keV, Chandra, cyan) + Radio (8.3 GHz, VLA, red) image (Zhou+21)

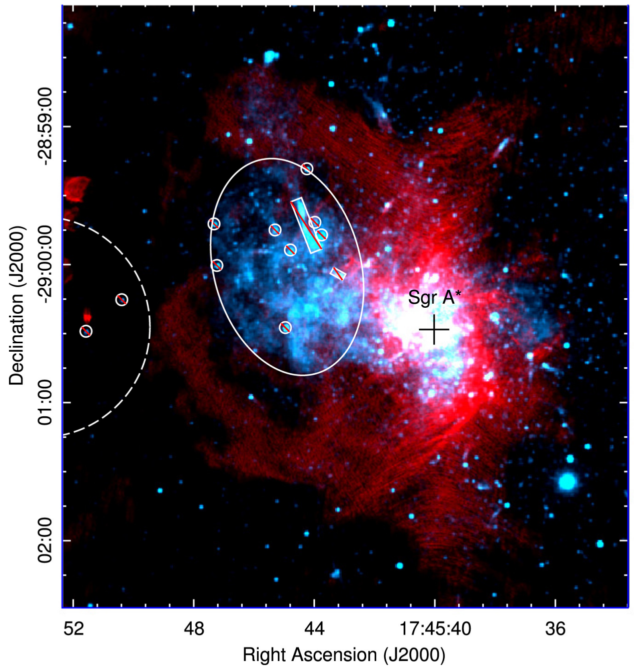
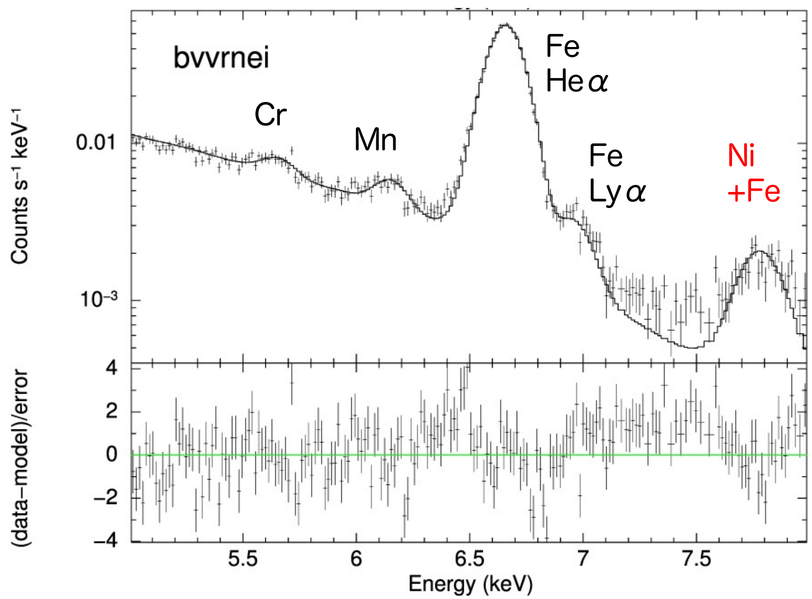


Fig.2 : Chandra/ACIS Sgr A East X-ray spectrum (Zhou+21)



First XRISM Result of Sgr A East (XRISM Collaboration 25) : Spectral Analysis in the Fe Kα Band

- During the XRISM performance verification (PV) phase, the region including Sgr A East was observed for ~130 ks (OBSID 300044010, 2024/2/26-2/29, Fig. 3).
- First, we focused on the spectral analysis in the Fe Kα band (Fig. 4) with a phenomenological model (Table 1) to suppress uncertainty due to the contamination of the GCXE and bright transient AXJ 1745.6-2901.
- We resolved the fine structures of the highly ionized Fe Kα emission lines (Fe XXV Heα w,x,y,z and Fe XXVI Ly$\alpha_{1,2}$) and measured the velocity dispersion from the line widths.

Fig. 3 : Xtend (left) ・ Resolve (right) 6.5-6.8 keV X-ray image (XRISM Collaboration 25)

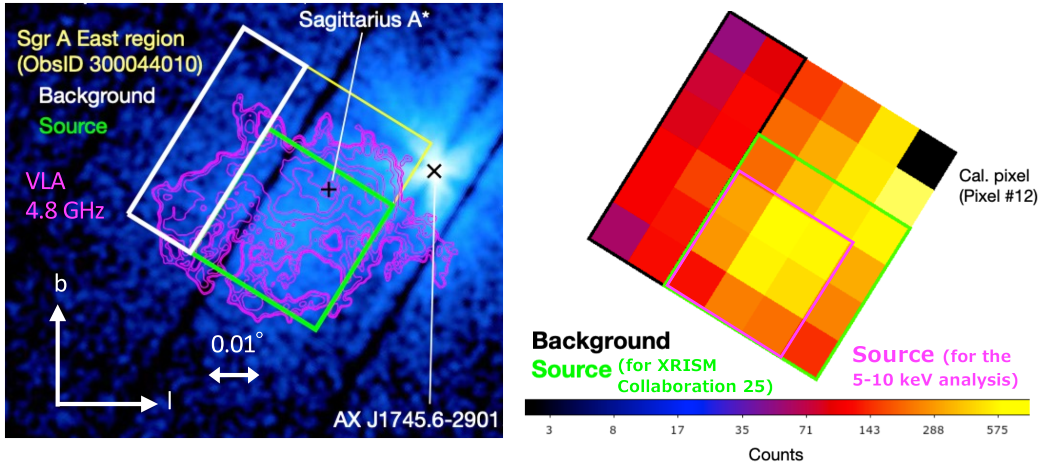


Fig. 4 : Resolve X-ray spectrum of the Fe Kα band (XRISM Collaboration 25)

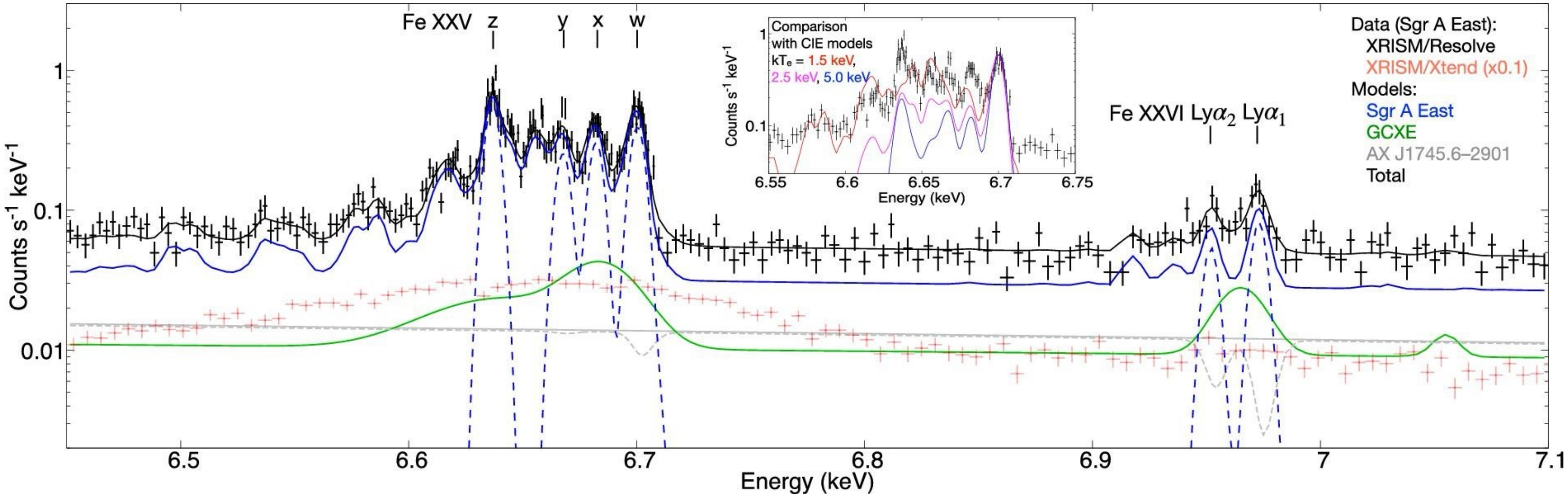


Table 1 : Key parameters of the best-fit phenomenological model (XRISM Collaboration 25)

Broadening (km s^{-1})	109 ± 6
Redshift	$(2 \pm 5) \times 10^{-5}$
Lorentzian flux (10^{-5} ph s^{-1} cm^{-2})	
Heα z (6636.58 eV)	3.19 ± 0.17
Heα y (6667.55 eV)	1.43 ± 0.14
Heα x (6682.30 eV)	1.71 ± 0.14
Heα w (6700.40 eV)	2.30 ± 0.16
Lyα_1 (6973.07 eV)	0.49 ± 0.08
Lyα_2 (6951.86 eV)	0.33 ± 0.07

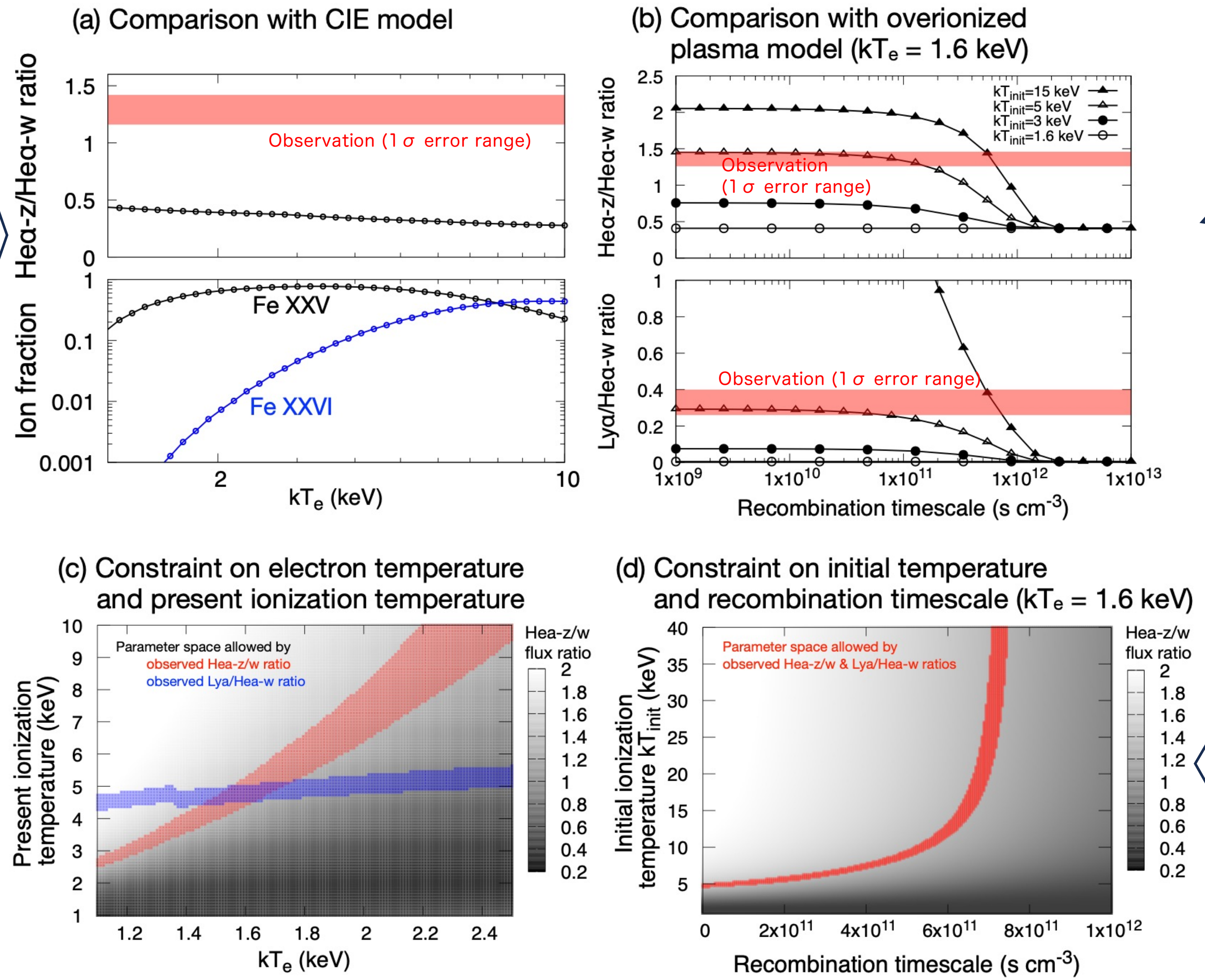
First XRISM Result of Sgr A East (XRISM Collaboration 25) : Plasma Diagnostics Using the Fe Kα Line Intensity Ratios

- We used the Fe Kα line intensity ratios to constrain the plasma state, which is less susceptible to background and calibration uncertainties (Fig. 5).
- These results were published as XRISM Collaboration 25 (PASJ, 77,1,L1-8, CA : H. Suzuki et al.).

Fig. 5 : Comparison of the Fe Kα line intensity ratios and AtomDB model (XRISM Collaboration 25).

・The observed Heα-z/Heα-w is larger than 1. CIE cannot explain this. It strongly supports RP.

・Contributions from resonance scattering and charge exchange are negligible (in detail, see XRISM Collaboration 25).



・RP can explain the observed Heα-z/Heα-w and Lyα/Heα-w ratios.

・The line intensity ratios constrained the state of the RP.

・Electron temperature $kT_e \sim 1.6$ keV

・Recombination time scale $nt < 8\times10^{11}$ s/cm^3

・Initial ionization temperature $kT_{init} > 5$ keV

Spectral Analysis in the 5-10 keV Band Using AtomDB

- Going beyond XRISM Collaboration 25, we analyzed the 5-10 keV band to perform plasma diagnostics including the RRC structure, and determine the Cr-Ni abundance ratios (Fig. 6, 7).
- To increase photon statistics, we made both Resolve and Xtend spectra and fitted both simultaneously.
- The spectra from the source and background regions were fitted with the following model simultaneously (Table 2).
    - Sgr A East : 2RP (bvrnei, Smith+01, AtomDB v3.1.2) + nonthermal component, basically the same model as Ono+19.
    - GCXE : Model adjusted using Resolve data (OBSID 300046010) based on Uchiyama+13.
    - AXJ 1745-2901: Spectral model based on XRISM/Resolve observation (Tanaka+ submitted).

Fig. 6 : Resolve・Xtend spectrum and best-fit model (AtomDB used. Only the spectra of the source region are shown.)

Preliminary
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Table 2: Key parameters of the best-fit model (AtomDB) (w 90% error)

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Spectral Analysis in the 5-10 keV Band Using AtomDB

Fig. 7 : Resolve spectrum and best-fit model (The source region only shown. AtomDB used. Same as Fig. 8, enlarged near Cr, Mn, Fe, Ni emission lines.)

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Spectral Analysis in the 5-10 keV Band Using SPEX

- The source region spectrum, after subtracting the background (GCXE + AXJ 1745) and low-temperature components, was fitted using SPEX (v.3.08.02, test ver. by Liyi Gu of SRON) for the high-temp. RP (Fig. 8, Table 2).
- The Fe satellite line near 7.69 keV is more accurately reproduced by SPEX than by AtomDB (Fig. 9).
- The Cr/Fe, Mn/Fe, and Ni/Fe ratios show agreement within 90% statistical error between AtomDB and SPEX.

Fig. 8 : Resolve spectrum and best-fit model (SPEX used)

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Fig. 9 : Resolve spectrum and best-fit model (SPEX used. Same as Fig.10, enlarged near the Ni lines.)

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Table 2 : Key parameters of the best-fit model (SPEX) (w 90% error)

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Heavy Element Abundances (Cr, Mn, Ni) in Sgr A East

- We overlaid our results to Fig. 4 in Zhou+21, comparing Sgr A East abundances with core-collapse (CC) and thermonuclear (TN) supernova models (Fig. 10).

Fig. 10 : Comparison of abundance ratios between Sgr A East (Chandra) and core-collapse (CC, a) and thermonuclear (TN, b-d) supernova models (Zhou+21, Figure 4). XRISM results added in red (AtomDB) and blue (SPEX) (with 90% error range).

Preliminary

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Constraints on the Origin of the Recombining Plasma

- The 5–10 keV band is described by 2RP (rnei or neil) + nonthermal component. The initial ionization temperature kT_{init} and recombination time scale $n_e\, t_{ionized}$ are constrained as below.
  - kT_{init} > 6 keV, 4000 (5 cm^{-3} /n_e) yr < $t_{ionized}$ < 6000 (5 cm^{-3} /n_e)
- With relatively high kT_{init}, possible origins of the RP are …
  - **Adiabatic expansion scenario** (Itoh & Masai 89)
    - After a shock wave passed through dense circumstellar material (CSM), adiabatic expansion of the plasma occurred, and the electrons rapidly cooled.
    - In this scenario, $t_{ionized}$ should be ~ the age of Sgr A East. The estimated ages of Sgr A East in previous studies (several thousands yrs, reviewed in Ehlerová+22) are consistent.
    - Dense CSM could suppress expansion, so the observed narrow lines might support this.
  - **Photoionization scenario** (Ono+19)
    - Past X-ray flares of Sgr A* photoionized the plasma.
    - In this scenario, $t_{ionized}$ should be ~ time elapsed since the X-ray flare. If Sgr A*'s X-ray luminosity L_{SgrA*} ~ 10^{40} erg/s several thousand yrs ago, it could explain the RP (Ono+19).
    - This connects continuously with the variability of Sgr A* suggested by X-ray reflection nebulae (L_{SgrA*} ~ 10^{39} erg/s several hundred years ago, Ryu+09, etc.) and X-ray outflows (L_{SgrA*} ~ 10^{44} erg/s several hundred thousand years ago, Nakashima+13, etc.).

Summary

- The Fe Kα fine structures and strong RRC revealed by XRISM/Resolve strongly support the RP state in Sgr A East. The origin can be adiabatic expansion or photoionization by Sgr A*.