Suzaku studies of magnetic cataclysmic variables and the Galactic Ridge X-ray Emission

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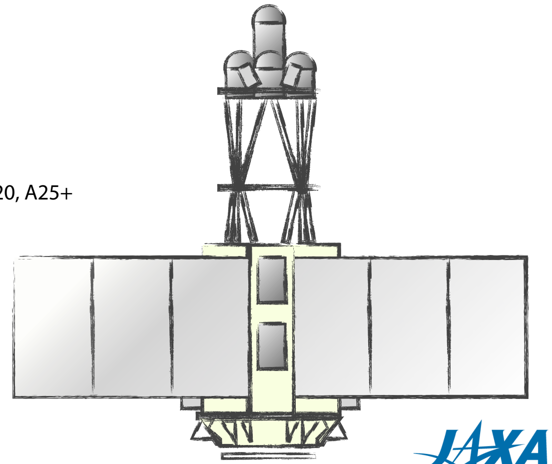
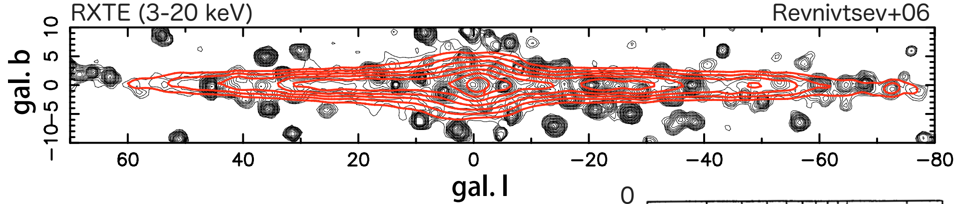
Publications:
Yuasa, Nakazawa, Makishima et al. 2010, A&A, 520, A25+
Yuasa, Ph.D thesis, The University of Tokyo, 2010



Introduction

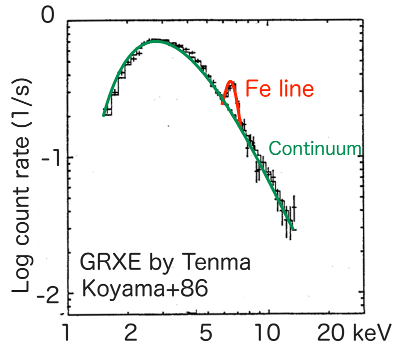
Galactic Ridge X-ray Emission (GRXE)

X-ray background emission observed along with the Galactic disk and the Galactic bulge. Total luminosity is ~10^{38} erg/s in 2-10 keV.
The origin of the GRXE has been one of great mysteries in X-ray astrophysics over 40 years (e.g. Cooke et al. 1969).



Spectral feature **(e.g. Koyama et al. 1986)**

- Continuum + Emission lines.
- Coexistence of lines from light (Si/S) and heavy (Fe) elements.
  - Multi-temperature plasma?



Questions

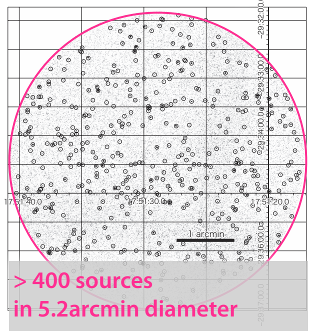
- What is the origin?
- What is the emission mechanism?

The origin of the GRXE

Recent findings from Chandra deep observation

- 1 Ms in the Galactic bulge.
- 80% of detected GRXE flux was resolved into point sources (Revnivtsev+09).
- Main candidates of dim point sources :
  coronal X-ray sources + **accreting WDs**.
  soft X-ray band — hard X-ray band
- To further improve imaging sensitivity is not feasible.

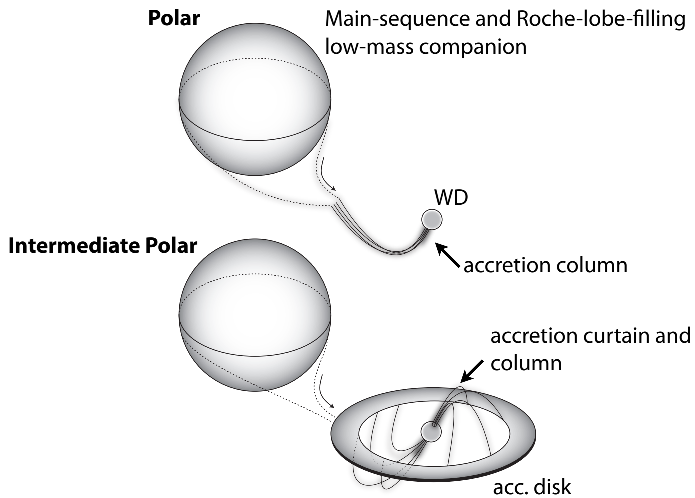
Chandra 1 Ms image



Our approach : Broad-band spectroscopic study

1. Construct a spectral model of **accreting WDs**, especially **intermediate polars (IPs)**, and then check its validity using data of nearby sources.
   - We concentrate on intermediate polars which have hardest spectra among accreting WDs.
   - WD masses can be estimated as by products in individual source analyses.
2. Use the IP spectral model to **spectroscopically decompose the GRXE**.

Studies of magnetic accreting WDs



Modeling a spectrum from an accretion column

Geometry and emission process

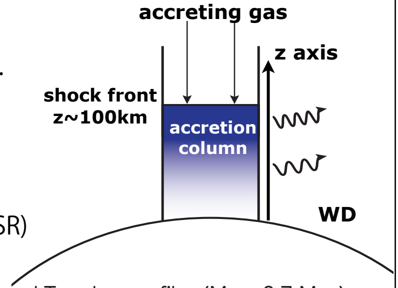
- Accreting matter freely falls along the B field lines.
- A shock converts bulk kinematic energy into internal energy. $kT_{\rm s} \propto \frac{GM_{\rm WD}}{R_{\rm WD}} > 10$ keV
- The heated gas cools in the post-shock region (PSR) via optically thin-thermal X-ray emission.
- Equating conservation laws leads to density, temperature, and velocity profiles in the PSR.

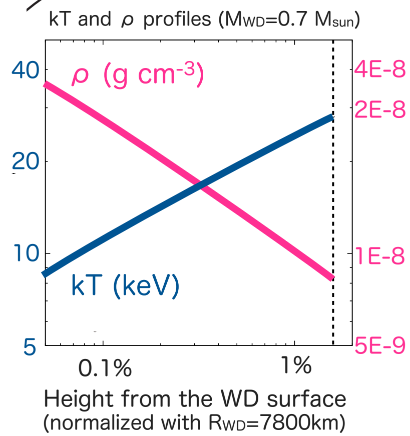
$$\frac{\mathrm{d}}{\mathrm{d}z}(\rho v) = 0, \quad \frac{\mathrm{d}}{\mathrm{d}z}(\rho v^2 + P) = -\frac{GM_{\rm WD}}{z^2}\rho,$$

$$v\frac{\mathrm{d}P}{\mathrm{d}z} + \gamma P \frac{\mathrm{d}v}{\mathrm{d}z} = -(\gamma - 1)\underline{\Lambda n^2}$$

thin-thermal cooling function (e.g. Schure+09)

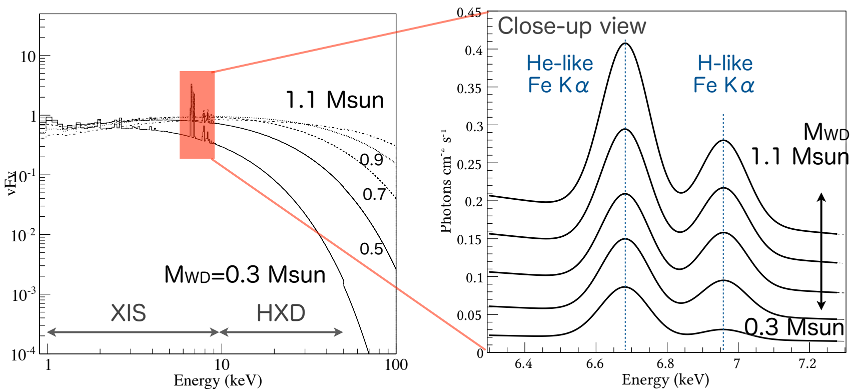
- The system reduces to an initial value problem of ODEs (Cropper+99, Suleimanov+05).
- Example of the $M_{\rm WD}$=0.7 $M_{\rm sun}$ case.





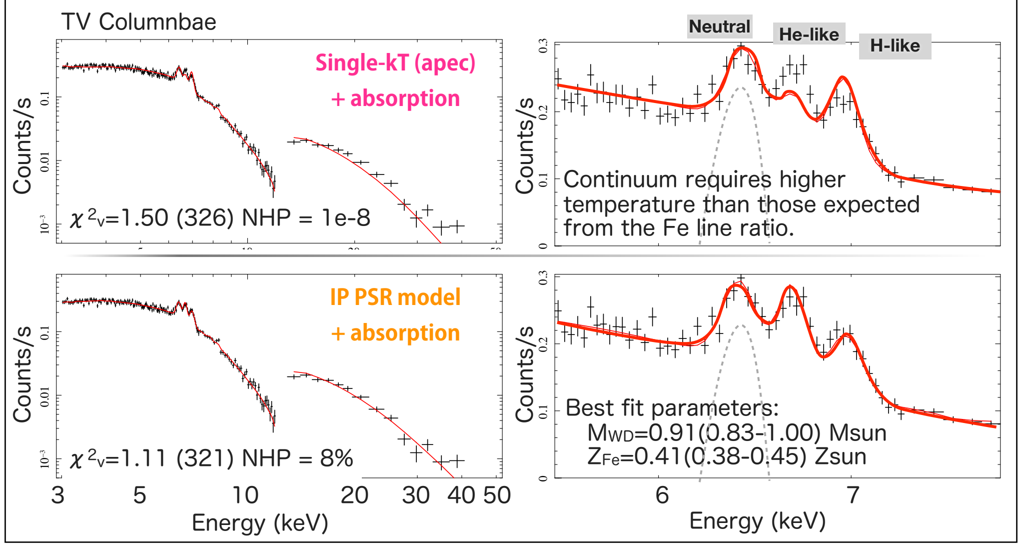
Construct a total spectrum

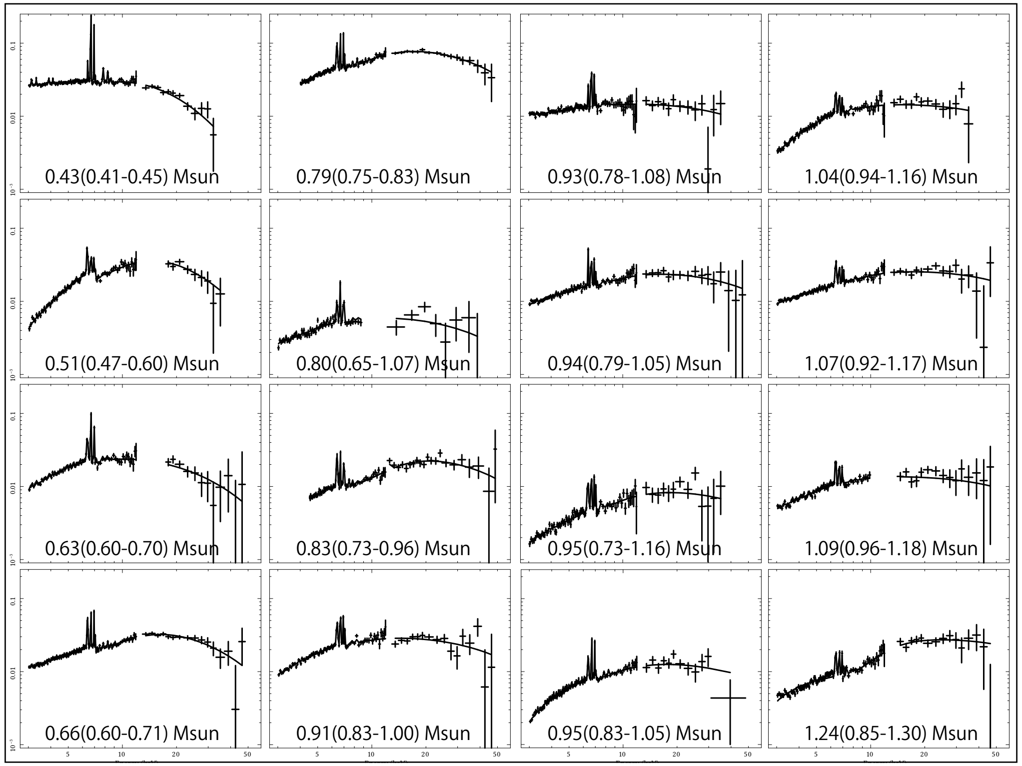
- APEC was convolved with the emissivity to produce a total spectrum. Thus, the model consists of multi-temperature emission.
- **M_{WD}** and **Fe abundance** are primary parameters of the model.
    - Updates from previous studies : emission lines + variable metal abundance
- Heavier masses result harder spectra, i.e. cutoff energy ∝ shock temp ∝ WD mass
- By fitting observed spectra, WD mass can be estimated.
    - Cutoff energy and Fe line ratio are important factors constraining the mass.



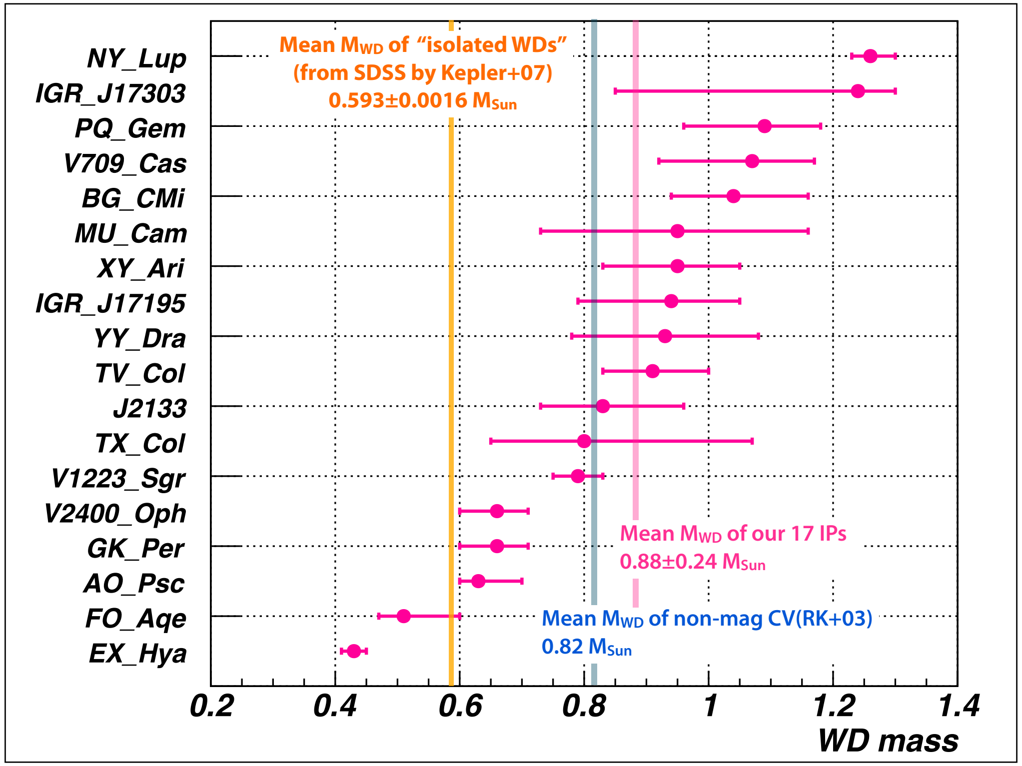
Spectral fitting with near-by IPs (Yuasa+10, A&A)

- The XIS clearly resolves three Fe lines. The HXD detects signals up to 40-50 keV.
- Single kT model (apec) → Fe lines and continuum **inconsistent.**
- The IP model successfully reproduced overall spectra and the Fe line structure.
  Note：In the present study the 6.4-keV Fe line was arbitrarily modeled using a Gaussian.

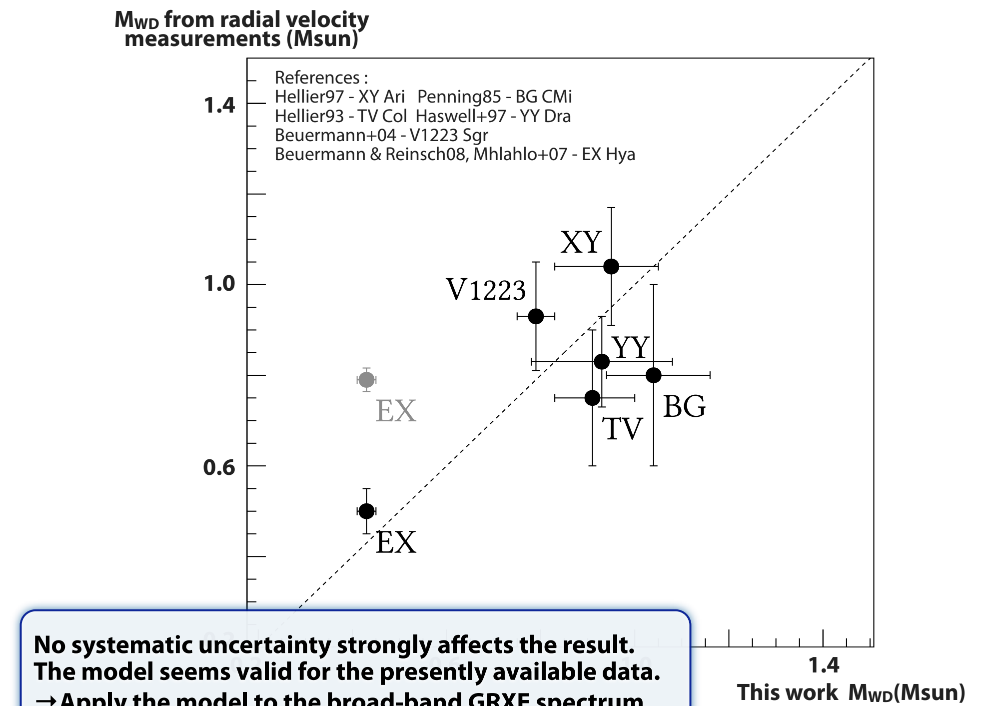




0.43(0.41-0.45) Msun
0.79(0.75-0.83) Msun
0.93(0.78-1.08) Msun
1.04(0.94-1.16) Msun
0.51(0.47-0.60) Msun
0.80(0.65-1.07) Msun
0.94(0.79-1.05) Msun
1.07(0.92-1.17) Msun
0.63(0.60-0.70) Msun
0.83(0.73-0.96) Msun
0.95(0.73-1.16) Msun
1.09(0.96-1.18) Msun
0.66(0.60-0.71) Msun
0.91(0.83-1.00) Msun
0.95(0.83-1.05) Msun
1.24(0.85-1.30) Msun



Mean M_{WD} of "isolated WDs"
(from SDSS by Kepler+07)
0.593±0.0016 M_{Sun}
NY_Lup
IGR_J17303
PQ_Gem
V709_Cas
BG_CMi
MU_Cam
XY_Ari
IGR_J17195
YY_Dra
TV_Col
J2133
TX_Col
V1223_Sgr
V2400_Oph
GK_Per
AO_Psc
FO_Aqe
EX_Hya
Mean M_{WD} of our 17 IPs
0.88±0.24 M_{Sun}
Mean M_{WD} of non-mag CV(RK+03)
0.82 M_{Sun}
0.2
0.4
0.6
0.8
1
1.2
1.4
WD mass

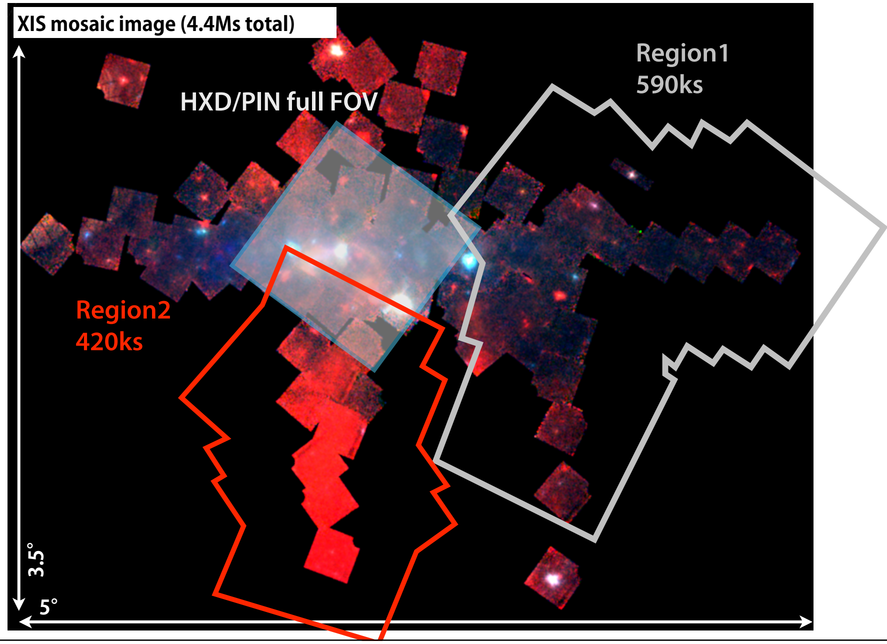


No systematic uncertainty strongly affects the result.
The model seems valid for the presently available data.
→Apply the model to the broad-band GRXE spectrum.

Spectral analysis of the GRXE

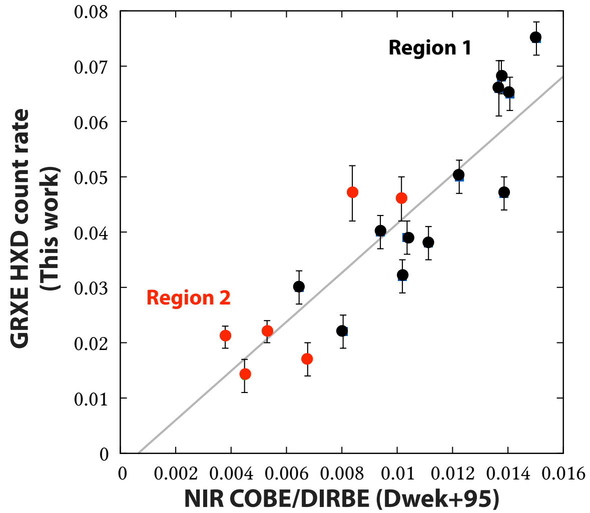
Suzaku GRXE observations

- 4.4 Ms exposure with 92 pointings in the Galactic Center region as of 2010.
- Selected fields "Region 1" and "Region 2" → Total exposure = 1Ms.



Correlation of GRXE and NIR

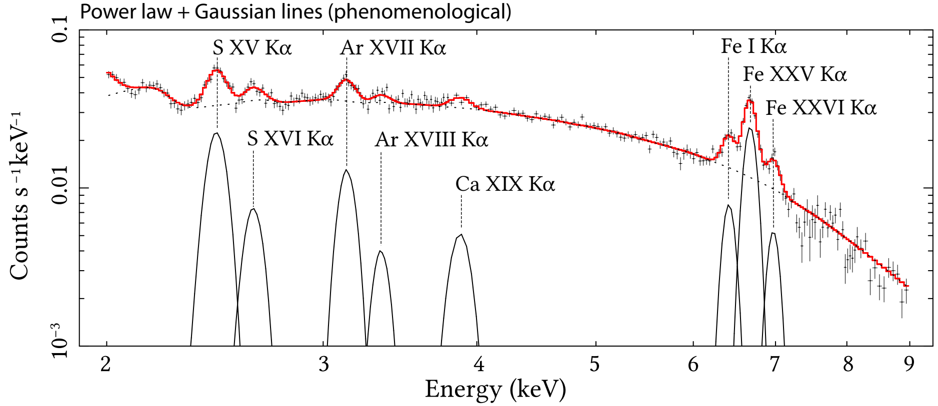
- Revnivtsev+06 reported nice correlation between the surface brightness of the GRXE and the NIR diffuse emission using RXTE Galactic plane scan data.
- Since NIR surface brightness traces the stellar density, the GRXE origin was suggested to have connection with it (i.e. stellar origin).
- The present Suzaku data also confirms this correlation.



Close-up view of the XIS spectrum

- Lines from lighter (S/Ar/Ca) elements coexist with those from Fe (reconfirmation of Ebisawa+08 with much higher statistics).
- This strongly indicates contributions from thermal emissions with different temperatures.
- At least two distinct plasma temperatures are necessary to reproduce the spectrum.

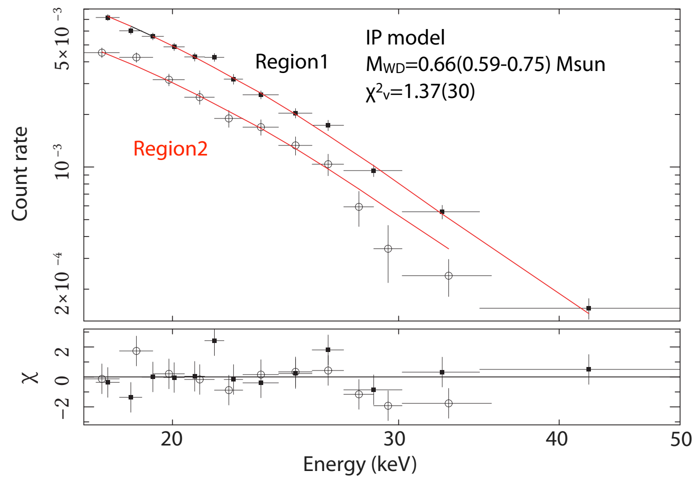
Power law + Gaussian lines (phenomenological)



S XV Kα	~ 25 eV	Ar XVII Kα	~ 40 eV	Fe I Kα	~ 75 eV
S XVI Kα	~ 35 eV	Ar XVIII Kα	~ 15 eV	Fe XXV Kα	~ 320 eV
		Ca XIX Kα	~ 25 eV	Fe XXVI Kα	~ 80 eV

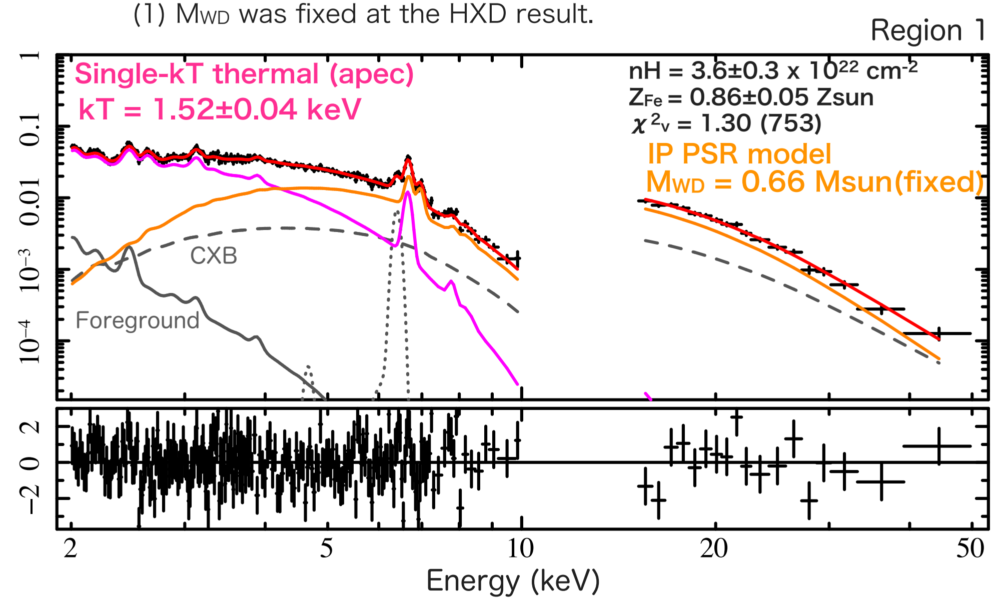
Fitting the GRXE in the hard X-ray band

- A power-law model gives a soft index, **Γ=2.8±0.2**, and extrapolation of this to lower energies contradicts with the XIS spectrum.
- Single-temperature thermal model gave the best fit at **kT=15.7 (13.7-18.4) keV**.
- The IP spectral model well reproduced the data with **M_{WD}=0.66 (0.59-0.75) M_{Sun}.**
  - This could be interpreted as a representative WD mass of IPs in the Galaxy. (c.f. ~0.5 M_{Sun} by Krivonos+07 with INTEGRAL data)



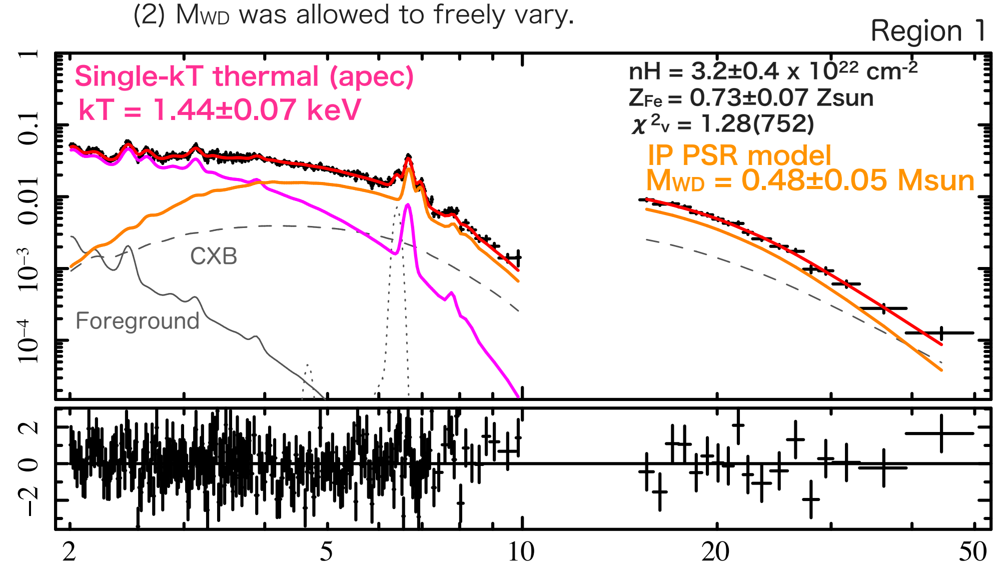
Broad-band decomposition

Fit with the IP PSR model + single-kT thermal model.
(1) M_{WD} was fixed at the HXD result.



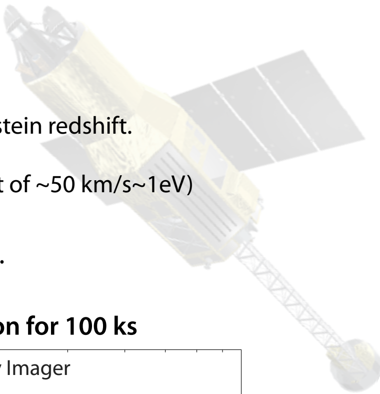
Broad-band decomposition

Fit with the IP PSR model + single-kT thermal model.
(2) M_{WD} was allowed to freely vary.



low-kT component ~1-1.5 keV → typical to **coronal sources (active binary stars)**
high-kT component~>10 keV → well reproduce by **the IP model**

The X-ray observatory ASTRO-H (2014-)



X-ray micro-calorimeter

~5 eV resolution (FWHM) at Fe K emission lines.

→ Resolves the fine structures.

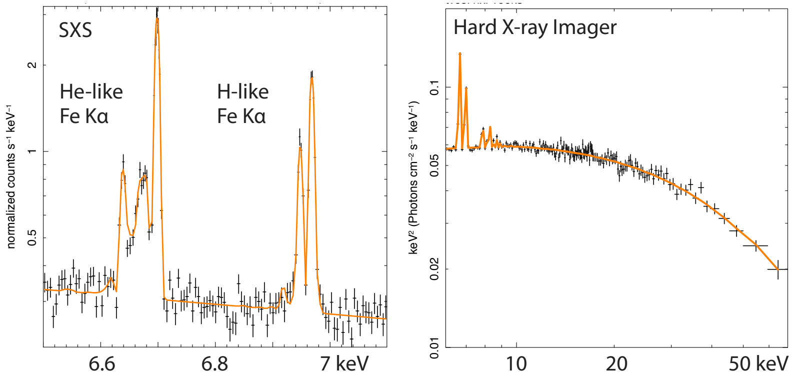
→ Direct measurements of plasma density, velocity, Einstein redshift.

→ Does the GRXE have red-shifted neutral Fe K line?
(if emitted from reflection from the WD surface, a shift of ~50 km/s~1eV)

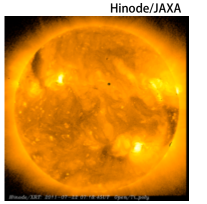
Hard X-ray Imager with a collection mirror

High statistics and imaging in the hard X-ray band.

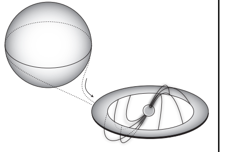
Simulation of the IP TV Col observation for 100 ks



Summary of results



- An X-ray spectral model for IPs was constructed, and its validity was confirmed by applying it to Suzaku spectra of 17 nearby IPs. WD mass estimates were obtained as byproducts.
- Broad-band GRXE spectra (2-50 keV) were extracted from 1-Ms Suzaku data.
  - Hard X-ray spectrum was well reproduced with the IP spectral model.
  - The temperature of the low-kT component is consistent with typical temperature of coronal sources such as active binary stars.



Conclusion

The present study precisely measured the GRXE spectrum over 1-50 keV, and decomposed it into to distinctive components which have physical counterparts such as active binary stars and accreting WD binaries.

Being complementary to the imaging result, this result also supports the point source scenario as the origin of the GRXE.

LogN-LogS of required point sources will be available in Q&A session.

Number density of hard X-ray sources

- The GRXE in the hard X-ray band could be explained by magnetic CVs.
- Surface number density :

$$N(>L) = N_0 \left(\frac{L}{L_0}\right)^{-\alpha}$$

- Integrated luminosity :

$$S = \int_{L_{\max}}^{L_{\min}} \frac{\mathrm{d}N(>L)}{\mathrm{d}L} \; L \; \mathrm{d}L$$

- ***α* = 1.0 - 1.5** (e.g. Muno+09)
- **S = 2.34×10³⁵ erg/s/HXD-FOV**
  (GRXE flux measured by the HXD)
- **L_{max} = 1.3×10³⁴ erg s⁻¹**
  (from absence of bright point sources inside the FOV)
- **L_{min}**
  case 1 : 2×10³⁰ erg s⁻¹ (Revnivtsev+09)
  case 2 : 3.8×10³¹ erg s⁻¹ (Muno+09)