Suzaku & NuSTAR X-Ray Spectroscopy of γ Cas and HD 110432

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1. Introduction

**Approach**

- Let’s assume Be/WD is right & find what we learn.
  - a) Which sub-type of WD binaries?
  - b) What are properties of WDs ($M_{WD}$, $B_{WD}$, etc.)?
  - c) What are predicted and tested?

- X-ray spectroscopy: established for “classical” (late-type companion) WD binaries.
  - X-rays governed by WD, not by companion.
  - Apply physical models of classical WDs to γCas analogues & see if any/none explains γCAs.
  - Previous work of γCAs based on phenomenological spectral models.
1. Introduction

Classical WD binaries X-rays

- Nuclear fusion
  - Steady: SSS (very soft, \( L_x = 10^{37} \) erg/s; Kahabka+97)
  - Erruptive: CNe (Starrfield+16)
- Accretion (Mukai17)
  - Non or weakly magnetic (B<0.1 MG)
  - Moderately or strongly magnetic (B>0.1 MG)

Secondary (late-type)
- “Catacrismic” if dwarf
- “Symbiotic” if giant

Secondary (late-type)
UV from disk
X-ray from WD

Classical WD binaries SED

- SS Cyg (catacridmic)
- WD BL
- WD Disk
- X-ray
- EUV
- Optical
- K5V

Energy (eV)

Flux density (erg/s/cm²/Å)

Wavelength (Å)
1. Introduction  
2. Analysis  
3. Discussion  
4. Summary  

Classical WD binaries SED
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Classical WD binaries SED
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**Brightest duo w. hard X-rays**

<table>
<thead>
<tr>
<th>Object</th>
<th>RA (J2000.0)</th>
<th>Dec</th>
<th>Observatory/Instrument</th>
<th>Sequence number</th>
<th>Observation date (UT)</th>
<th>$t_{\text{exp}}$ (ks)</th>
<th>$CR^\dagger$ (s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ Cas</td>
<td>00$^h$56$^m$38$^s$</td>
<td>+60$^\circ$44'08&quot;&quot;</td>
<td>Suzaku/XIS, PIN</td>
<td>4060400100</td>
<td>2011/07/13–14</td>
<td>55.4</td>
<td>11/0.59</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NuSTAR/FPMA, B</td>
<td>30001147002</td>
<td>2014/07/24–25</td>
<td>31.0</td>
<td>6.5</td>
</tr>
<tr>
<td>HD 110432</td>
<td>12$^h$42$^m$50$^s$</td>
<td>–63$^\circ$03’31”&quot;</td>
<td>Suzaku/XIS, PIN</td>
<td>4030020100</td>
<td>2008/09/09–10</td>
<td>25.3</td>
<td>2.5/0.64</td>
</tr>
</tbody>
</table>

* Net exposure time.

† Source count rate of XIS (FI)/PIN for Suzaku and FPMA for NuSTAR in all energy bands.
Magnetic accreting WD

- Called polars (B>10 MG) or IPs (B=0.1-10 MG) in classical WD binaries.
- X-rays from accretion column.
- PSAC model (Aizu+73, Wu+94, Cropper+98,99, Suleimanov+05, Yuasa+10, Hayashi+14, 18).

Accretion column

Magnetic field

Strong shock

$T=T_{\text{shock}}$

Dipole field

Direct

$\int dz \ L_x(T(z)) dz$

Reprocessed (Fe fluorescence + Compton)

$T=0$

$z=0$

$z=h$

WD surface
1. Introduction

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Magnetic accreting WD

1. Strong shock (Rankine-Hugoniot)

\[ v_0 = 0.25 \sqrt{2GM_{\text{WD}}/(R_{\text{WD}} + h)} \]
\[ \rho_0 = \frac{a}{v_0}, \]
\[ P_0 = 3av_0, \]
\[ T_0 = 3\frac{\mu m_H}{k}v_0^2, \]

2. M-R relation (Nauenberg72)

\[ R_{\text{WD}} = 0.78 \times 10^9 \left[ \left( \frac{1.44 M_\odot}{M_{\text{WD}}} \right)^{2/3} - \left( \frac{M_{\text{WD}}}{1.44 M_\odot} \right)^{2/3} \right]^{1/2} \text{ cm} \]

3. Fluid dynamics

\[ P = \frac{\rho k T}{\mu m_H} \text{ (EOS)} \]
\[ \frac{d}{dz} (\rho v S) = 0 \text{ (Mass)} \]
\[ \rho v \frac{dv}{dz} + \frac{dP}{dz} = \rho F \]
\[ F = -\frac{GM_{\text{WD}}}{(R_{\text{WD}} + z)^2} \text{ (Momentum)} \]
\[ \frac{d}{dz} \left[ v \left( \frac{1}{2} \rho v^2 + \frac{\gamma P}{\gamma - 1} \right) \right] = \rho F - \varepsilon \text{ (Energy)} \]

Free parameters

\[ M_{\text{WD}}, M_x/S, i \]
\[ M_x = \frac{L}{GM_{\text{WD}}} \]

Strong shock

\[ z=h \]

\[ z=0 \]

WD surface
Magnetic accreting WD

- Examples in classical WD binaries (IPs).

**Hayashi+14**

**V1223 Sagittarii**

**Yuasa+10**

**EX Hydrae**
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Magnetic accreting WD

- Bad fits w. Tbabs*PSAC (no reproc.)
Magnetic accreting WD

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- Bad fits w. Tbabs*PSAC (no reproc.)
- Improved by
  - Reflection comp
  - Partial NH. (Seen in almost all IPs).
### 1. Introduction

#### Summary

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameter</th>
<th>( \gamma \text{Cas} )</th>
<th>HD 110432</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Fixed values)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance(^{†})</td>
<td>( D ) (pc)</td>
<td>188</td>
<td>420</td>
</tr>
<tr>
<td>( \text{tbabs}^{‡} )</td>
<td>( N_H ) ( (10^{20} \text{ cm}^{-2}) )</td>
<td>1.45</td>
<td>15.8</td>
</tr>
<tr>
<td>(Fitted values(^{*}))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{tbpcf} )</td>
<td>( N_H ) ( (10^{22} \text{ cm}^{-2}) )</td>
<td>( 0.66^{+0.02}_{-0.01} )</td>
<td>( 0.94^{+0.03}_{-0.02} )</td>
</tr>
<tr>
<td>Covering fraction</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \text{acrad} )</td>
<td>( M_{\text{WD}} ) (( M_{\odot} ))</td>
<td>( 0.72^{+0.04}_{-0.06} )</td>
<td>( 0.81^{+0.03}_{-0.03} )</td>
</tr>
<tr>
<td>( Z ) (solar(^{§}))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>log ( a ) (g cm(^{-2}) s(^{-1}))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( i_r ) (degree)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Derived values(^{</td>
<td></td>
<td>}))</td>
<td></td>
</tr>
<tr>
<td>( L_X ) (erg s(^{-1}))</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \dot{M}<em>X ) (( M</em>{\odot} ) yr(^{-1}))</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

\[
\chi^2_{\text{red}} \text{ (d.o.f.)} \quad 1.23 \text{ (2312)} \quad 1.42 \text{ (212)}
\]
Non-mag accreting WD

- Called DNe in classical WD binaries.
- X-rays from boundary layer (at qDNe, NL)
- Cooling flow model (Pandel+05, Wada+17) + reprocessed comp.

Physical models (e.g., Hertfelder & Kley17) not matured to fit X-ray spec.
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Non-mag accreting WD

- Examples in classical WD binaries (DNe).

Wada+17

Pandel+05

Non-mag accreting WD

- Bad fits w. Tbabs*mkcflow (no reproc.)
Non-mag accreting WD

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- Bad fits w. Tbabs*mkcflow (no reproc.)
- Improved by
  - Reflection comp
  - Partial NH. (Seen in some DNe).
### 1. Introduction

### 2. Analysis

<table>
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</tr>
<tr>
<td>Angle</td>
<td>$i_t$ (degree)</td>
<td>65</td>
<td>59</td>
</tr>
<tr>
<td>$tbabs$ ‡</td>
<td>$N_H$ ($10^{20}$ cm$^{-2}$)</td>
<td>1.45</td>
<td>15.8</td>
</tr>
</tbody>
</table>

(Fitted values*)

<table>
<thead>
<tr>
<th>$tbpcf$</th>
<th>$N_H$ ($10^{22}$ cm$^{-2}$)</th>
<th>$0.94^{+0.01}_{-0.02}$</th>
<th>$1.36^{+0.05}_{-0.03}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Covering fraction</td>
<td></td>
<td>$0.486 \pm 0.003$</td>
<td>$0.893 \pm 0.005$</td>
</tr>
<tr>
<td>$mkcflow$</td>
<td>$T_{\text{max}}$ (keV)</td>
<td>$25.0^{+0.13}_{-0.12}$</td>
<td>$48.2^{+1.7}_{-2.9}$</td>
</tr>
<tr>
<td>$Z$ (solar)</td>
<td></td>
<td>$0.41^{+0.01}_{-0.01}$</td>
<td>$1.23^{+0.07}_{-0.10}$</td>
</tr>
<tr>
<td>$\dot{M}<em>X$ ($10^{-10} M</em>\odot$ yr$^{-1}$)</td>
<td></td>
<td>$1.61^{+0.01}_{-0.01}$</td>
<td>$1.82^{+0.14}_{-0.03}$</td>
</tr>
<tr>
<td>$reflect$</td>
<td>$d\Omega/2\pi$</td>
<td>$0.27^{+0.01}_{-0.01}$</td>
<td>$0.52^{+0.05}_{-0.06}$</td>
</tr>
<tr>
<td>$gauss$</td>
<td>$EW_{Fe}$ (eV)</td>
<td>$54^{+3}_{-4}$</td>
<td>$90^{+4}_{-5}$</td>
</tr>
<tr>
<td>$\chi^2_{\text{red}}$ (d.o.f.)</td>
<td></td>
<td>$1.27$ (2313)</td>
<td>$1.52$ (200)</td>
</tr>
</tbody>
</table>

* The errors indicate a 1σ statistical uncertainty.
Comparison to classical WDs

- $T_{\text{max}}/M_{\text{WD}}, \dot{M}_x, S/4\pi R_{\text{WD}}^2$ compatible w. classical.
- $M_{\text{WD}}$ agrees opt $M_2$ ($\gamma$Cas); derived (HD110432).

0.8$\pm$0.4 Mo (Smith+12)
Comparison to classical WDs

- γCas, HD110432 OK w. accreting WD models.
- Which is more likely -- mag or non-mag?  
  - Remains inconclusive.
Mag vs non-mag (1) Partial $N_H$

- Among classical accreting WDs, partial $N_H$ seen in
  - Almost all mag WDs (Ramsay+08).
  - Some non-mag WD w. high incl. (Mukai+09, Pandel+05).

- $\gamma$CAs smaller $N_H$ & covering frac than classical w. partial $N_H$. 
Mag vs non-mag (2) Fe L

- Dichotomy known in high-res spec at 10-12, 15-17 Å (Mukai+03).
- γCas exhibits Fe L.
- Qualitative criteria needed.

Mag vs non-mag (3) Fe Kα

- Inconclusive due to overlapping distribution.

- V1223 Sgr (IP)
- U Gem (qD)
- TT Ari (NL)
- HD110432

- γCas

<table>
<thead>
<tr>
<th></th>
<th>γCA</th>
<th>qDNe</th>
<th>NL</th>
<th>IPs</th>
<th>Polars</th>
<th>Symb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numbers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Log EW (eV)</td>
<td>1.0</td>
<td>1.5</td>
<td>2.0</td>
<td>2.5</td>
<td>3.0</td>
<td></td>
</tr>
</tbody>
</table>
Summary

- Working hypothesis: γCAs = Be/WD.
- Physical models (mag & non-mag) applied.
- Two γCAs well fit, including Fe Kα & Compton.
- Reasonable range of parameters wrt classical WDs.
  - $M_{\text{WD}}$ agrees opt $M_2$ (γCas); derived (HD110432).
  - Other properties ($M_X$, incl., $S/4\pi R_{\text{WD}}^2$) estimated.
- Mag vs non-mag inconclusive yet.
  - Partial $N_H$, Fe L, Fe Kα EW.
- Future time-domain behavior important.
  - $P_{\text{spin}}$, DNe, CNe.
Future time-domain (1) \( P_{\text{spin}} \)

- \( P_{\text{spin}} \) in X-rays: defining characteristics of IPs.
- Expected if \( \gamma \)CAs have mWD for small \( S/4\pi R_{\text{WD}}^2 \)
- \( P_{\text{spin}} \sim 1 \text{d} (\sim 10^{-2} \text{ mHz}) \) predicted (Apparao02) from analogy to Be/NS (Corbet+, Waters & v Kerkwijk89).

MAXI 8yr PSD. Barycentric corrected.

Probably an artifact.
1. **Introduction**  
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**Future time-domain (2) DNe**

- If akin to DNe, X-ray spectra should change.
  - Low $M$: hard & bright (quiescent)
  - High $M$: soft & faint (outburst)

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![Graphs showing energy vs counts s^{-1} keV^{-1}](image.png)

Future time-domain (3) CNe

- γCas, HD110432 too small $M_{\text{WD}}$ & $M$ for a CN.
- Others may have sufficiently large $M_{\text{WD}}$ & $M$.

Kato+14