X-ray Grating Spectroscopy of Cataclysmic Variables

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Accretion geometry and X-ray emission regions of nonmagnetic CVs & polars

Nonmagnetic CV (dwarf nova, novalike variable)

Magnetic CV (polar)
Accretion geometry and X-ray emission regions of intermediate polars (EX Hya)

Hellier et al. (1987); Rosen, Mason, & Córdova (1988)
EUVE SW and Chandra LETG spectra of dwarf novae in outburst

- OY Car ($i = 83^\circ$)
- WZ Sge ($i = 77^\circ$)
- U Gem ($i = 70^\circ$)
- SS Cyg ($i = 50^\circ$)
EUV SW and *Chandra* LETG spectra of dwarf novae in outburst

- OY Car (*i* = 83°)
- WZ Sge (*i* = 77°)
- U Gem (*i* = 70°)
- SS Cyg (*i* = 50°)
Chandra LETG spectra of dwarf novae in outburst

- WZ Sge ($i = 77^\circ$)
- U Gem ($i = 70^\circ$)
- SS Cyg ($i = 50^\circ$)
Optical & *EUV* DS light curves of OY Car

EUV flux is not eclipsed by the white dwarf

Model of the EUVE SW spectrum of OY Car

Model of the *Chandra* LETG spectrum of SS Cyg

Chandra LETG spectrum of WZ Sge

O VI 2s-2p
\[ \lambda_{150} \text{ (Chandra)} \]
\[ \lambda_{1032,1038} \text{ (FUSE)} \]

Wheatley & Mauche (2007, in preparation)
**XMM** EPIC light curves and spectra show two sources of X-ray emission in UX UMa.

- **Hard X-ray flux is eclipsed**
- **Soft X-ray flux is not**

Multi-$T$↓$N_H$

$kT \sim 5$ keV↑$N_H$

Two types of X-ray spectra in CVs

Chandra HETG spectra of nonmagnetic CVs

SU UMa

WX Hyi


TT Ari

V603 Aql

Chandra HETG spectra of SS Cyg in quiescence and outburst

X-ray flux decreases in outburst, lines broaden.

Mauche et al. (2005, in Astrophysics of CVs & Related Objects)
**Chandra** HETG spectra of U Gem in quiescence and outburst

X-ray flux *increases* in outburst, lines broaden.

Mauche et al. (2005, in Astrophysics of CVs & Related Objects)
Chandra HETG spectrum of V603 Aql

Cooling flow model with $kT_{\text{max}} = 20$ keV

Chandra HETG spectra of IPs

← Fluorescent Fe line

GK Per

AO Psc

V1223 Sgr

YY Dra

EX Hya
Detail of *Chandra* HETG spectrum of GK Per

![Graph showing spectrum with peaks labeled Al XI and Ne IX RRC.](image)
*Chandra* HETG spectrum of EX Hya (an IP with $P_{\text{binary}} = 98$ min, $P_{\text{spin}} = 67$ min, $i \approx 77^\circ$)

500 ks observation, N. Brickhouse, PI
EX Hya is missing lines of: Fe XVII $\lambda 17.10$, Fe XX $\lambda 12.80$, Fe XXI $\lambda 12.26$, and has an inverted Fe XXII $\lambda 11.92/\lambda 11.77$ ratio.

All the He-like $f$ lines are missing in EX Hya.

Mauche (2002, in Physics of CVs and Related Objects)
He-like $R = z/(x+y) = f/i$ line ratios

$T_{bb} = 0$ K  

$T_{bb} = 30$ kK

Absence of He-like $f$ lines in EX Hya is plausibly due to photoexcitation.

Mauche (2002, in Physics of CVs and Related Objects)
Theoretical Fe L-shell spectra

…were calculated with the Livermore X-ray Spectral Synthesizer (LXSS), a suite of IDL codes that calculates spectral models as a function of temperature and electron density using primarily HULLAC atomic data.

The following spectra are based on models with:

<table>
<thead>
<tr>
<th>Ion</th>
<th>levels</th>
<th>radrate</th>
<th>colrate</th>
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<tbody>
<tr>
<td>Fe XXIV</td>
<td>76</td>
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<td>Fe XXIII</td>
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<td>Fe XIX</td>
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<tr>
<td>Fe XVIII</td>
<td>456</td>
<td>141,229</td>
<td>93,583</td>
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<tr>
<td>Fe XVII</td>
<td>281</td>
<td>49,882</td>
<td>33,887</td>
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</tbody>
</table>

Fe XX

Fe XXII

Grotrian diagrams for Fe XVII and Fe XXII

Density constraints from Fe XVII $\lambda_{17.10}/\lambda_{17.05}$ and Fe XXII $\lambda_{11.92}/\lambda_{11.77}$

**Fe XVI:** $n_e > 2 \times 10^{14}$ cm$^{-3}$


**Fe XXII:** $n_e \sim 1 \times 10^{14}$ cm$^{-3}$

Radial velocity variations of the X-ray emission lines of EX Hya

\[ \gamma = 1.3 \pm 2.3 \text{ km s}^{-1} \]
\[ K = 58.2 \pm 3.7 \text{ km s}^{-1} \]
\[ M_{\text{wd}} = 0.49 \pm 0.13 \text{ M}_\odot \]

Dynamically-derived white dwarf mass agrees with the value obtained from the Fe XXV/XXVI line ratio in the ASCA SIS spectrum of EX Hya (Fujimoto & Ishida 1997).

**Chandra** HETG spectrum of AE Aqr (an IP with $P_{\text{binary}} = 9.88$ hr, $P_{\text{spin}} = 33.08$ s, $i \approx 60^\circ$)

Different physical models for AE Aqr:

- Oblique rotator model
- Magnetic propeller model

Patterson (1979)  
Wynn, King, & Horne (1997)
XMM EPIC & RGS spectra of AE Aqr

4T VMEKAL:

\[ kT = 0.14, 0.59, 1.21, \& \; 4.6 \text{ keV} \]

(cool for an IP)

He-like N, O, & Ne density diagnostics from the XMM RGS spectrum of AE Aqr

\[ n_e \sim 10^{11} \text{ cm}^{-3} : \text{low for a magnetic CV} \]

X-ray, UV, optical, & radio light curves of AE Aqr

Optical: Ioannou (Skinakas), Welsh (Laguna), CBA, & AAVSO
Radio: Abada-Simon & Desmurs

Strong correlation of the flares in the X-ray, UV, and optical, but not in the radio.

Mauche et al. (2007, in preparation)
Pulse-timing delays of AE Aqr

Optical:
\[ a \sin i = 2.04 \pm 0.13 \text{ s} \]
de Jager et al. (1994)

HST FOS UV:
\[ a \sin i = 1.93 \pm 0.03 \text{ s} \]
Eracleous et al. (1994)

Chandra HETG X-ray:
\[ a \sin i = 2.17 \pm 0.48 \text{ s} \]
Mauche (2006)*

Pulsating optical, UV, & X-ray source follows the motion of the white dwarf.

AE Aqr spin-phase light curves and radial velocity variation

\[ \frac{GM}{Rc^2} \sim 50 \text{ km s}^{-1} \]

\[ \gamma = 33 \pm 24 \text{ km s}^{-1} \]
\[ K = 154 \pm 38 \text{ km s}^{-1} \]
\[ \phi_0 = 0.012 \pm 0.020 \]

X-ray emission line radial velocities consistent with emission from two poles. Mauche (2007, in preparation)
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