Accretion Processes in Magnetic Cataclysmic Variables
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Introduction

I give a presentation based largely on X-ray grating spectroscopic observations of magnetic cataclysmic variables (CVs), interacting binaries in which the accretion flow is controlled by the \( \sim 0.1-100 \) MG magnetic field of the white dwarf.

I concentrate on:

- Physics aspects that are characteristic of these systems, such as high plasma densities and the effects of photoexcitation, photoionization, and fluorescence of the white dwarf surface and other plasma in the system.
- The relatively few systems for which we have good data (e.g., AM Her, EX Hya, AE Aqr).

The talk will include a minimal number of:

- light curves
- log-log plots
- broad-band spectral fits (no “mo wa po”).
Magnetic CVs come in two “flavors,” polars and intermediate polars

**Polars**

- $B \sim 10^{-100}$ MG
- No accretion disk
- Synchronous rotation

**Intermediate Polars**

- $B \sim 0.1-1$ MG
- Truncated accretion disk
- Asynchronous rotation

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In either case, X-rays are produced at and below the accretion shock.

\[ kT_{\text{shock}} = \frac{3}{8} \mu m_H GM_{\text{wd}}/R_{\text{wd}} \]

\[ \sim \text{tens of keV} \]

\[ kT_{\text{bb}} = \left( \frac{L_X}{4\pi\sigma f R_{\text{wd}}^2} \right)^{1/4} \]

\[ \sim \text{tens of eV} \]

Figure courtesy of Vadim Burwitz
Example: *HEAO-1 A2 & A4 spectra of AM Her*

EUVE SW spectra of VV Pup, AM Her, & QS Tel (RE 1838–461)

Vennes et al. (1995), Paerels et al. (1996), Rosen et al. (1996)
EUVE SW spectrum of AM Her

$kT_{bb} = 22.8$ eV
$N_H = 7.4 \times 10^{19}$ cm$^{-2}$

Absorption edges:
- Ne VI 2s$^2$2p $\lambda 78.5$
- Ne VI 2s2p$^2$ $\lambda 85.1$

Discrete absorption features:
- Ne VIII 2s-3p $\lambda 88.1$
- Ne VIII 2p-3d $\lambda 98.2$

BUT: The observation was not “dithered” and other than the 98.2 Å line, these features have not been seen in subsequent observations.

EUVE SW spectra of nine polars

Discrete absorption features:
AM Her: 76.1, 98.2 Å (Ne VIII 2p-3d)
AR UMa: 116.5 Å (Ne VII 2s2p-2s3d)
QS Tel: 98.2, 116.5 Å

Mauche (1999, in Annapolis Workshop on Magnetic CVs)
EUVE SW spectra of nine polars

Spectral ($kT, N_H$) and hence physical ($A_{\text{spot}}$, $L_{\text{bol}}$) parameters are highly dependent on the assumed spectral model.

Mauche (1999, in Annapolis Workshop on Magnetic CVs)
Chandra LETG spectrum of AM Her

See also Burwitz et al. (2002, ASPC, 261, 137); Burwitz (2006, in High Resolution X-ray Spectroscopy: Towards XEUS and Con-X)
Chandra LETG spectrum of AM Her in and out of eclipse

Phase-dependent spectrum implies a structured emission region.
Two types of X-ray spectra in CVs

Cooling Flow\(^1\): Non-magnetic\(^*\)

- Steady-state isobaric radiative cooling.

Photoionized\(^2\): Magnetic

- Strong H- and He-like ion emission but weak Fe L-shell emission.

\(^*\)With one exception: EX Hya [however, see Luna et al. (2010) {next slide}].

EX Hya has weak broad photoionization emission features

Broad component is formed in the pre-shock accretion flow, photoionized by radiation from the post-shock flow.

Division into two classes is no longer so clear-cut (see also Mukai 2009).
Contrary to indications from ASCA SIS spectra, the Fe K lines of magnetic CVs are not significantly Compton broadened.
H/He-like line ratios used to measured $kT_{\text{shock}} = 15.4^{+5.3}_{-2.6}$ keV hence $M_{\text{wd}} = 0.48^{+0.1}_{-0.6} \, M_\odot$ assuming $kT_{\text{shock}} = \frac{3}{8} \mu m_H G M_{\text{wd}} / R_{\text{wd}}$ and $R_{\text{wd}} = 7.8E8 \left[ (M_{\text{wd}}/1.44M_\odot)^{2/3} - (M_{\text{wd}}/1.44M_\odot)^{2/3} \right]^{1/2} \, \text{cm}$.

ASCA SIS spectrum of EX Hya, continued


Perfect gas law:
\[ kT_2 = 3 \mu m_H v_2^2 \]

Strong shock:
\[ v_2 = v_1/4, \quad \rho_2 = 4 \rho_1 \]

Free-fall from infinity:
\[ v_1 = (2GM_{wd}/R_{wd})^{1/2} \]

\[ kT_s = \frac{3}{8} \mu m_H GM_{wd}/R_{wd} \]

\[ h \ll R_{wd} \]

\[ T_{ion} = T_e \]

optically thin thermal brems cooling

Constant pressure:
\[ T/T_s \approx (z/h)^{2/5} \]

\[ \Rightarrow M_{wd} = 0.48^{+0.10}_{-0.06} M_\odot \]
**EUVE SW 180 ks spectrum of EX Hya**

Lines from Ne VII–VIII and Fe XVIII–XXIII \( \Rightarrow T \sim 10^6-7 \) K.

Emission measure and volume \( \Rightarrow n_e > 10^{13-15} \text{ cm}^{-3} \).

Chandra HETG 500 ks spectrum of EX Hya

Brickhouse et al. (2006, BAAS, 38, 346)
Comparison of EX Hya (blue) and HR 1099 (red)

EX Hya is missing lines of Fe XVII λ17.10, Fe XX λ12.80, Fe XXI λ12.26, and has an inverted Fe XXII λ11.92/λ11.77 ratio.

The He-like forbidden (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 in EX Hya

$T_{bb} = 0$ K  
$T_{bb} = 30$ kK

Absence of He-like forbidden 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.

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<td>Fe XVII</td>
<td>281</td>
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Fe XVII

Mauche, Liedahl, & Fournier (2005)
Fe XVIII

Mauche, Liedahl, & Fournier (2005)
Fe XIX

Mauche, Liedahl, & Fournier (2005)
Fe XX

Red: $10^{10}$ cm$^{-3}$  Blue: $10^{18}$ cm$^{-3}$

Mauche, Liedahl, & Fournier (2005)
Fe XXI

Mauche, Liedahl, & Fournier (2005)
Mauche, Liedahl, & Fournier (2005)
Fe XXIII

Mauche, Liedahl, & Fournier (2005)
Mauche, Liedahl, & Fournier (2005)
Grotrian diagrams for Fe XVII and Fe XXII

Density constraints for EX Hya from Fe XVII $\lambda$ 17.10/ $\lambda$ 17.05 and Fe XXII $\lambda$ 11.92/ $\lambda$ 11.77

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

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

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

Dynamically-derived $M_{\text{wd}}$ agrees with the value obtained from the Fe XXV/XXVI line ratio in the ASCA SIS spectrum of EX Hya (Fujimoto & Ishida 1997).

Or does it? Beuermann & Reinsch (2008) have since revised $K_{\text{sec}}$ and hence $M_{\text{sec}}$.


$\gamma = 1.3 +/- 2.3 \text{ km s}^{-1}$

$K_{\text{wd}} = 58.2 +/- 3.7 \text{ km s}^{-1}$

$M_{\text{wd}} = 0.49 +/- 0.13 \, M_{\odot}$
AE Aqr: many things to many people

Patterson (1979): Oblique Rotator


WKH (1997): Diamagnetic Blobs

Terada et al. (2008): Cosmic Ray Accelerator
4T VMEKAL fit gives $kT = 0.14, 0.59, 1.21, \text{ and } 4.6 \text{ keV}, \text{ which is cool for an IP.}$

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

He-like N, O, and Ne $f/(r+i)$ line ratio is consistent with $n_e \sim 10^{11}$ cm$^{-3}$.

Correlated flares and the 33 s white dwarf spin pulse are observed in the optical through X-ray wavebands.

The radio light curve is uncorrelated with the other wavebands, implying that the radio flux is due to independent processes.
Chandra HETG spin pulse

Phase offset of $0.232 \pm 0.011$ cycles relative to the de Jager et al. (1994) spin ephemeris.

- White dwarf is spinning down at a rate that is slightly less than that predicted by the de Jager et al. (1994) quadratic ephemeris.

Spin phase offset variations correspond to a pulse time delay of $a \sin i = 2.17 \pm 0.48$ s.*

- X-ray source follows the motion of the white dwarf around the binary center of mass.

*A similar result was derived by de Jager (1995).

Spectrum is reasonably well fit by a Gaussian emission measure distribution with a peak at $\log T(K) = 7.16$, a width $\sigma = 0.48$, $\text{Fe/Fe}_\odot = 0.44$, other metals $Z/Z_\odot = 0.76$, $EM = 8 \times 10^{53} \text{ cm}^{-3}$, and $L_x = 1 \times 10^{31} (d/100 \text{ pc})^2 \text{ erg s}^{-1}$.

Chandra HETG He-like triplet \( f(i+r) \) line ratios

Red: \textit{XMM-Newton} RGS*
Blue: \textit{Chandra} HETG

Left: Density increases with temperature from \( n_e \sim 6 \times 10^{10} \text{ cm}^{-3} \) for N VI to \( n_e \sim 1 \times 10^{14} \text{ cm}^{-3} \) for Si XIII.

Right: Photoexcitation can mimic high densities, but (at least for the high Z elements) high \( T_{bb} \) and/or large dilution factors are required to explain the observed ratios.

\[ \Rightarrow \text{X-ray plasma is of high density and/or in close proximity to the white dwarf.} \]


Chandra HETG emission line radial velocities

Radial velocities don’t appear to vary on the white dwarf orbit phase!

(a) composite line profile technique

➤ This is an unexpected result, but differs from the predicted radial velocity of the white dwarf (gray shading) by only 2.3σ.

Radial velocities vary on the white dwarf 33 s spin phase, with two oscillations per cycle.

(b) composite line profile technique  
(c) cross-correlation technique  
(d) bootstrapped cross-correlation technique

➤ X-ray plasma is trapped on, and rotates with, the white dwarf’s dipolar magnetic field.

Summary of *Chandra* HETG observation of AE Aqr

- The (pulsating component of the) source of X-rays in AE Aqr follows the motion of the white dwarf around the binary center of mass.

- Contrary to the conclusions of Itoh et al. (2006), the majority of the plasma in AE Aqr has a density $n_e > 10^{11} \text{ cm}^{-3}$, hence its spatial extent is orders of magnitude less than their estimate of $5 \times 10^{10} \text{ cm}$.

- The radial velocity of the X-ray emission lines varies on the white dwarf 33 s spin phase, with two oscillations cycle and an amplitude $K \approx 160 \text{ km s}^{-1}$, broadly consistent with plasma tapped, and rotating with, the white dwarf’s dipolar magnetic field.

- These results are inconsistent with recent models* of an extended, low-density source of X-rays in AE Aqr, but instead support earlier models in which the dominant source of X-rays is of high density and/or in close proximity to the white dwarf.

- To paraphrase Bill Clinton, “It’s accretion, stupid.”

*Itoh et al. (2006); Ikshanov (2006); Venter & Meintjes (2007)