MULTIWAVELENGTH STUDIES OF ACCRETING WHITE DWARF BINARIES

Prof. Dr. Şölen Balman – METU

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ACCReTING WHITE Dwarfs

- **Cataclysmic Variables**
  - Roche Lobe overflow and disk accretion
  - Donor star is a late-type main sequence star
  - Orbital periods 1.4-14 hrs

- **AM CVn Stars**
  - Roche Lobe overflow
  - Degenerate binary WDs or a He-star-WD binary
  - Ultra Compact systems with binary periods 10-65 min.

- **Symbiotics**
  - Wind Accretion
  - Donor is a late-type giant -- mira variables
  - Orbital periods on the order of several years
NONMAGNETIC CVS

- **Dwarf Novae**
  
  continuous or sporadic mass accretion is interrupted every few weeks to months by intense accretion (outburst) of days to weeks. \((10^{39} - 10^{40} \text{ erg}, \Delta m=2-6)\)

  - **U Gem Type**: \(P_{\text{orb}} > 3\text{hrs}, \) No Superoutbursts
  - **Z Cam Type**: Standstills
  - **SU UMa Type**: \(P_{\text{orb}} < 2\text{hrs}\) Superoutbursts

- **Nova-like Variables**

- **Classical and Recurrent Novae** \((10^{43} - 10^{46} \text{ erg})\)
- **U Gem Type**
  - $P_{\text{orb}} > 3$ hrs,
  - no superoutburst

- **Z Cam Type**
  - Standstills

- **SU Uma Type**
  - $P_{\text{orb}} < 2$ hrs,
  - Superoutbursts
X-RAY EMISSION FROM NONMAGNETIC CVS

- Boundary Layer (BL)

- \[ L_{\text{BL}} \approx L_{\text{disk}} = GM_{\text{wd}} \dot{M}_{\text{acc}} / 2R_{\text{wd}} = L_{\text{acc}} / 2 \]

- Matter decelerates from Keplerian velocities to the slowly rotating WD


- Optically thick BL

  - \( \dot{M} > 10^{-9} M_\odot / \text{yr} \)
  - Optically thin BL \( \sim 10^8 \) K

- \( \dot{M} < 10^{-9} M_\odot / \text{yr} \)

- Soft X-rays \( \sim 10^5 \) K

- Hard X-rays
**DN in QUIESCENCE – X-rays**

- Low-mass accretion, $\dot{M}_{\text{acc}} = 10^{-12} - 10^{-10} M_\odot/\text{yr}$ ($L_x \sim 10^{30-32}$ erg/s), BL $\Rightarrow$ optically thin $\Rightarrow$ hard X-ray emission, Multi-temperature isobaric cooling flow model plasma emission with $T_{\text{max}} = 9-55$ keV (see Baskill+ 2005, Kuulkers+ 2006; Achille+ 2004; Pandel+ 2005, Rana+ 2006, Singh+ 2006, Byckling+ 2010, Balman+ 2011)

- Virial temperatures in CV disks are $10-45$ keV (0.4-1.1 $M_\odot$ WD) (Balman+ 2014)

**DN in OUTBURST – X-rays**

**DIM (Disk Instability Model; see Review by Lasota 2001, 2004)**


- $\dot{M}_{\text{acc}} = 10^{-10} - 10^{-8} M_\odot/\text{yr}$ (Knigge+ 2011)

- BL with $10^5 - 10^6$ K emitting in the soft X-ray to EUV (kT $\sim$ 5-30 eV), (Mauche+ 1995, 2004; Long+ 1996, Mauche & Raymond 2000, Byckling+ 2009)


- UV and X-ray delays in rise to outburst (w.r.t. Optical) (see Stehle & King 1999).

- During outburst -- no eclipses seen or much orbital variations.

- Detection of a radio emission from SS Cyg -- synchrotron emission from transient jet and other DN detections (Körding+ 2008, Russel+ 2016, Coppejans+ 2016)
DN SAMPLE CHARACTERISTICS

Av. recurrence time is 138 d  Av. DC is 5.8%

Coopejans+ 2015 CRTS sample
Eclipse Mapping of DN and disk structure

$T \propto r^{-3/4}$

Baptista & Borteletto 2004
V2051 Oph

Borges & Baptista 2005
V4140 Sgr

Biro 2000
DW UMa

with disk truncation
OY CAR

Z CHA

33 Nova-Likes

Puebla et al. 2007

Woods et al. 1990
Accretion Flows--Matter Fluctuations--Broadband Noise

In the framework of propagating matter fluctuations in the accretion disk
SS CYG

40 d, 15-20 d
6.6 hrs

Wheatley+ 2003
Russell+ 2016
\( N_H = (5.9 - 7.3) \times 10^{19} \text{ cm}^{-2} \)
\( kT = 20 - 25 \text{ keV} \)
\( L_{BB} = (1.7 - 4.3) \times 10^{33} \text{ erg/s} \)
\( V_{\text{rot}} \sim 2300 \text{ km/s} \)

Ishida et al. 2009

**SUZAKU**

Reflector size <7×10⁹cm

In outburst

Mauche 2004
$f_b = 9.7 \text{ mHz} \quad R_{in} = 3.3 \times 10^9 \text{ cm}$

$R_{in} = 1.1 \times 10^9 \text{ cm} \quad \Rightarrow 5.5 \times 10^9 \text{ cm}$
SU UMa

11-17 d
109.9 min

$kT_{qui} \sim 12$ keV
$kT_{out} \sim 4$ keV

$R_{wd} = 7.5 \times 10^8$ cm

Collins & Wheatley 2010

$R_{in} = 3.8 \times 10^9$ cm

Balman 2015

assuming $f_{br} = 0.1$ Hz
WZ SGE

July-August 2001
Superoutburst
6 days $kT_{\text{max}} \sim 0.7-1.3$ keV; $10^{21}$ cm$^{-2}$, $\Gamma=0.8-1.4$ erg/s
L$_{\text{th}} \sim 2.7 \times 10^{30}$

15 days $kT_{\text{max}} \sim 0.5-1.5$ keV; $10^{21}$ cm$^{-2}$, $\Gamma=0.2-1.1$ erg/s
L$_{\text{pow}} \sim 1.3 \times 10^{30}$

30 days $kT_{\text{max}} \sim 1.2-3.0$ keV; $10^{21}$ cm$^{-2}$, $\Gamma=1.5-2.0$ erg/cm$^2$/s
F$_{\text{pow}} \sim 5-6 \times 10^{-12}$

58 days $kT_{\text{max}} \sim 26-46$ keV; $10^{21}$ cm$^{-2}$
L$_{\text{x}} \sim 1.1 \times 10^{31}$ erg/s $\sim L_{\text{th}}$
L$_{\text{qui}} \sim (2.5-7.5) \times 10^{30}$ erg/s
Wheatley & Mauche 2005

V ≈ 840 km/s
Frequ x Power (rms/mean)^2

29 July 2011 (GC-mode data)
6 d after outburst

Frequency (Hz)

(22 Aug 2001, Chandra CC-mode)
30 d after outburst

f\_br = 1.1(\pm 0.5) mHz

(Balman 2014)
Collection of DN Power Spectra in Quiescence

(Balman & Revnivtsev 2012, Balman 2015)
UV Power Spectra

XMM-Newton OM
UVW1 filter 240-340 nm

(Balman & Revnivtsev 2012)
Optically thick disk truncation radius (transition rad.) and UV-X-ray Lags

SS Cyg (quiescence-XMM) 5.6+/-1.4 mHz 4.8+/-1.2 $\times 10^9$ cm 166-181 sec -4.3
SS Cyg (quiescence-RXTE) 4.5+/-1.3 5.5+/-1.8
RU Peg (quiescence) 2.8+/-0.5 8.2+/-1.5 97-109 -3.1
VW Hyi (quiescence) 2.0+/-0.6 8.1+/-2.5 103-165 -2.7
WW Cet (quiescence) 3.0+/-1.7 6.8+/-3.8 118-136 -3.6
T Leo (quiescence) 4.5+/-1.5 4.0+/-1.3 96-12 -3.7

(Balman & Revnivtsev 2012)
NOVA-LIKES : HIGH STATE CVS

- $\dot{M}_{\text{acc}} = \text{a few } \times 10^{-9}-10^{-8} M_\odot/\text{yr} -- \text{wind mass loss rates } \leq 1\% \text{ of the accretion rate with } 200-5000 \text{ km/s} \text{ (Long & Knigge 2002, Kafka & Honecutt 2004, Puebla+ 2011)}$

- Several divisions: VY Scl-types (occasional low states) and UX Uma-types (always high state) show emission lines; UX Uma stars show broad absorption features in the optical and/or UV spectra, RW Tri stars are eclipsing UX Uma systems (Warner 1995). SW Sex stars specific spectroscopic class with $P_{\text{orb}}$ 3-4 hrs (Rodrigues-Gil+ 2007)

- All NLs reside above period gap (concentration $\sim P_{\text{orb}}$ 3-4 hr) except BK Lyn
- Bipolar or rotationally symmetric winds and outflows. Best detected in the FUV with the P Cygni Profiles of the resonant doublet CIV (also Si IV, N V) (Guinan & Sion 1982, Sion 1985).
- Nonmagnetic CVs – wind lines modulated on the orbital period (e.g., 6 NL, 6 DN) (Prinja+ 2000, 2004; Kafka+ 2009)
- Complex mixture of high and low ionization state lines – possible condensed high density regions (FUV, UV) (Long & Knigge 2004, Long 2006, Noebauer+ 2010, Puebla+ 2011)
- No disk precession or superhump effects. Variability minutes to ~ 100 s.
- Existence of Single peaked lines in high inclination systems.
- Not much line variability below 100 s, lack of correlation between wind activity and system luminosity (Hartley+ 1992, Froning+ 2012)
- line-driven/radiative winds ... MHD needs to be considered?

**Mathews+ 2015**

![Graph showing RW Tri](image-url)
Nova-like boundary layers were first studied with Einstein IPC (0.2-4 keV, Patterson & Raymond 1985) and ROSAT (0.1-2.4 keV). The systems showed a hot optically thin component with $L_x < \text{a few } 10^{32}$ (kT$< 10$ keV) (see van Teeseling+ 1996, Schlegel & Singh 1995, Greiner 1998).

Following observations with ASCA, XMM-Newton, RXTE, Chandra & Swift indicates spectra with either double temperature plasma or Multi-temperature isobaric cooling flow model of X-ray emission with $L_x < \text{a few } 10^{32}$ (Mauche & Mukai 2002, Pratt+ 2004, Balman+ 2014, Page+ 2014, Zemko+ 2014).

No optically thick disk emission in X-rays is recovered, No Blackbody emission component (van Teseeling+ 1995, 1996, Balman+ 2014).

Host hottest WDs in CVs 40000-60000 K (Townsley & Gansicke 2009, Mizusawa+ 2010), also hotter WDs at the same Porb compared to Polars (Sion 1999, Araujo-Betancor+ 2005, Townsley & Gansicke 2009).

Few NLs are detected as variable radio sources -- optically thick synchrotron or gyrosynchrotron emission (Coppejans+ 2015).
Balman, Godon, Sion 2014 – NLs with \((0.3-1 \times 10^{-8} \, M_\odot/yr)\)

No optically thick emission component \(kT_{BB} < 7 \, \text{eV}\)

optically thin BLs merged with advective hot flows (ADAF-like flows). They show multi-temperature cooling flow-like plasma (where the power law index of \(T\) also diverges from expected value of 1.0) (e.g. \(1.6, 0.13, 0.6\))

\(kT_{\text{max}} = 21-35 \, \text{keV}\)

Photon index = 0.4-0.9

\(L_{\text{th}} = (0.9-5.0) \times 10^{32} \, \text{erg/s} \) (0.1-50 keV)

\(L_{\text{pow}} = (1.5-2.4) \times 10^{32} \, \text{erg/s}\)

Efficiency : \(L_x/L_{\text{disk}} \approx 0.01 - 0.001\)

WD effective \(T = 45000 - 50000 \, \text{K}\)
NL BROADBAND NOISE CHARACTERISTICS

Kepler-optical    MV Lyr

Scaringi+ 2012a

Scaringi+ 2012b
The Recurrent Nova T Pyx

F <(0.9-1.5)×10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}
L <(1.2-2.2)×10^{32} \text{ erg s}^{-1} (0.1-50 \text{ keV})
kT >37 \text{ keV (2σ)}

- T Pyx ejects about $3×10^{-5} \text{ M}_\odot$ in very eruption about 20 to 40 yr recurrence time with a 0.7-1.0 \text{ M}_\odot WD.
- Never been detected as a SSS since 1998 and final upper limits: $F_{BB} <1.5×10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2}$, $L_{BB} <2×10^{33} \text{ erg s}^{-1} (0.1-10.0 \text{ keV})$, $kT_{BB} <25 \text{ eV}$, with $\dot{M} <1×10^{-7} \text{ M}_\odot/\text{yr}$. These are not inaccordance with a BL secnario for a near-Chandrasekhar WD either.
- Optically thin BL with ADAF-like hot flows and/or accretion disk corona which heats the WD as well. $L_x/L_{\text{disk}} \sim (2-7)×10^{-4}$. T Pyx shows irradiation effects and a warped disk structure $\rightarrow$ AGNs & XRBs.
- The advective heating of the WD (0.7-1.0) \text{ M}_\odot may explain the onset of a TNR together with the high accretion rate of the system causing the RN event.

Balman 2014
MAGNETIC CVS

- Magnetic CVs constitute ~25% of the CV population
- **Polars (P) & Intermediate Polars (IP)** depending on B
  
- IPs have truncated accretion disks -- accretion curtains –
- X-ray emission from strong shock near the surface of the WD as the post-shock region is heated to 10-50 keV with
  
  \[ L_x \lesssim \text{a few} \times 10^{33} \text{ erg/s} \] (Patterson 1994, Hellier 1996, de Martino et al. 2008, Brunschweiger et al. 2009, Yuasa et al. 2010)
- X-ray spectra ➔ complex absorption partial covering, ionized warm absorption (e.g., OVII edge) / power-law like continuous absorption

- X-ray spectra ➔ multi-temperature plasma emission and/or cooling-flow (isobaric) emission model $dE/dT \sim (T/T_{max})^\alpha$ Luminous MCVs shows photoionized plasma (V1223 Sgr, GK Per, AO Psc)

- -- near the shock $T$ is high, density is low, X-ray emissivity is low. Most X-ray emission just above the WD & lines from slow plasma—line diagnostics $n_e > 10^{12}$ cm$^{-3}$
Mukai et al. 2003
See also Singh et al. 2006, Luna et al. 2010
A subclass of IPs --> soft X-ray component, blackbody emission $kT = 30\text{–}100 \text{ eV}$ (Evans & Hellier 2007) -- Heated WD surface


Asynchronous IPs with majority $P_{\text{spin}}/P_{\text{orb}} < 0.1$ (theoretical range 0.01-0.6) (Norton et al. 2004, 2007; Scaringi et al. 2009)

Polars – synchronous spin (<2 % shows asynchronicity) – mostly short orbital periods below the period gap

Cyclotron cooling vs Bremstrahlung (B dependence)

Soft blackbody component dominated --> $kT \approx 10\text{–}30 \text{ eV}$ (Mauche et al. 1999) -- about 33% Polars with no soft component
- low accretion rate Polars $L \leq 10^{30}$ erg/s $\rightarrow$ low and high states—nonuniform accretion—in any survey 50% of Polars are in low state (Ramsay et al. 2004)

- Energy dependent X-ray/UV/optical pulses
  harder/softer poles

- Power spectra—accretion mode diagnostics
  peak at $w$—disc fed
  peaks at $w$, $w-\Omega$ — stream-fed accretion
  $w$, $w-\Omega$, $\Omega$ — disc overflow

- Orbital modulations in IP s (Parker et al. 2005)
  effects of absorption on the binary plane
ORBITAL & SPIN PHASE RESOLVED PARAMETERS OF EX HYA - 2000

ORBITAL & SPIN PHASE
RESOLVED PARAMETERS OF EX HYA - 2003

Intermediate Polars and Disk Truncation radii

$R_{\text{in}} = 1.9 \times 10^9 \text{ cm}$

$f_b = 2.1 \pm 0.1 \times 10^{-2} \text{ Hz}$

Revnivtsev et al. 2011

$t = 7 \pm 1 \text{ sec}$
\[ f_b = 7 \times 10^{-2} \text{ Hz} \]

\[ R_{in} = 9 \times 10^8 \text{ cm} \]

\[ f_b = 5 \times 10^{-2} \text{ Hz} \]
WHAT IS A CLASSICAL NOVA OUTBURST?

EXPLOSIVE IGNITION OF ACCRETED MATERIAL ON THE SURFACE OF A WD IN A CATACLYSMIC VARIABLE HOSTING A WD AND A MS STAR

- Accretion phase
- TNR (T~10^8 K)
- H burning
- Initial expansion phase
- Visual maximum
- Constant bolometric luminosity phase
- Turn-off of H burning
- Cooling

**Important parameters**

- Accretion rate
- Age of the white dwarf
- Mass of the white dwarf
- Composition of the envelope over the white dwarf surface

Starrfield, Sparks, Truran 1972; Prialnik 1986, Prialnik & Kovetz 1995; Starrfield et al. 1998; Harley & Shara 2003; Yaron et al. 2005
A TYPICAL NOVA LIGHT CURVE

Time After Outburst
X-RAY EMISSION MECHANISMS IN CLASSICAL NOVA EXPLOSIONS

At the Outburst and following this, mass is expelled
Shocks in the outflowing material
≥0.5 keV X-ray emission
⇒ Bremsstrahlung + line emission

Soft X-ray Component

Hard X-ray Component
⇒ Circumstellar interaction (Contini & Priyalnik 1997; Balman 2005; Bode et al. 2006; Sokoloski et al. 2006 Drake et al. 2009)
⇒ Wind-wind interaction
⇒ Stellar wind instabilities and X-ray emission
(Owocki et al. 1992; Hillier et al. 1993)
⇒ Mass accretion
Flickering X-ray light curves, 6.4 keV Fe lines (Hernanz & Sala 2002, 2007; Page et al. 2010)

Blackbody like Stellar Atmosphere emission originating from the WD
⇒ 0.1 – 1.0 keV X-ray emission ≳ L_{edd}

Comptonized X-ray emission from the γ-rays produced in radioactive decays

Hard X-ray Component
( example: $^{22}$Na, $^{7}$Be, $^{26}$Al )
(Suzuki&Shigeyama 2010; Hernanz et al. 2002; Starrfield et al. 1992)
Gamma-ray emission from particle acceleration (Hernanz 2014, Metzger+2015)
6 Nova patlama evresinde Fermi LAT ile 100 MeV üstünde enerjilerde keşfedildi.

-- Şoklar ve rölativistik parçacık ivmelenmesi
-- Hadronik senaryo: rölativistik protonların nova atığıyla etkileşimi. Protonlar atomik Nükleuslarla etkileşimlerde pi meson üretir ve bunun bozunmasıyla gamma-ışınları üretilir. (leptonic senaryo $\rightarrow$ ters Compton ve Bremssrahlung?)

-- Uzaklıklar $< 4$-5 kpc
-- L =$(3-4) \times 10^{35}$ erk/sn ve Bütün yayımlanan enerji $(6-7) \times 10^{41}$ erk
-- Varyasyon hafta-ay bazında sürüyor.
V407 CYGNI

FERMI KEŞFI
1990 dan itibaren pozisyonda değişken kaynak bulundu (ROSAT) (Ibarra ve ark. 2008)

V=17 yılda optik bileşke (16 yıl) (Munari 2008)

Kaynak patlamadan 5 ay önce yok R<18.6 (Balman ve ark. 2008)
Region 3

Second Obs. (Region B)

Balman & Gamsızkan 2017
Two different hot absorber components from our fits with blue shifts yielding 2850-3800 km s\(^{-1}\) for the first (day 40) and 2600-3600 km s\(^{-1}\) for the second observation 50 days after outburst consistent with ejecta/wind speeds (Ness+2011) and HST-detected bipolar and equatorial outflows (Riberio+2011).

The two collisionally ionized hot absorption (in equilibrium) components have temperatures \(kT_1 \approx 1.0 - 3.6\) keV and \(kT_2 \approx 0.4 - 0.87\) keV with rms velocities \(\sigma_v_1 \approx (740 - 900)\) km/s and \(\sigma_v_2 \approx (9 - 67)\) km/s. Consistent with shock temperatures in the X-ray wavelengths for the given days after outburst \(\rightarrow 1.0-4.0\) keV (see Page+ 2010).

The equivalent hydrogen column density of the hot collisionally ionized absorbers are \((0.6-18.0)\times10^{23}\) cm\(^{-2}\) and \((2.0-5.3)\times10^{23}\) cm\(^{-2}\) on days 40 d and 50 d after outburst.

An additional photoionized absorber (third intrinsic absorber component) in the shell/ejecta improves the fits, but shows only (1-0.1)% of the absorption by the collisional-ionized hot gas \((\sigma_v \approx (31 - 170)\) km/s day 40 and \((140 - 275)\) km/s day 50. The column density is \((1.3-4.3)\times10^{20}\) cm\(^{-2}\) and \((0.5-0.7)\times10^{20}\) cm\(^{-2}\) on days 40 and 50.
THE WD, USING SPECTRAL RESULTS

• Our blackbody temperatures are in a range 61-91 eV ( (8.3-10.0)×10^5 K), slightly variable over the two observations) with 62-85 eV from the best fit value range (Table 2).

• White dwarf (WD) mass is 1.15-1.3 M☉ assuming our range is the maximum temperature achieved during the H-burning phase. WD radius → (27-30)×10^8 cm for the region 1; (17-20)×10^8 cm for the regions 2, 3 on day 40 and (2.8-4.9)×10^8 cm on day 50. A C-O WD (4.5-2.8)×10^8 cm for 1.15-1.3 M☉ (Hamada & Salpeter 1961; Panei+ 2000).

• V2491 Cyg shows signature of H-burning with underabundant carbon from our fits C/C☉ =0.3-0.5, and enhanced nitrogen N/N☉ =5-7 and oxygen O/O☉ =16-43 (Ne/Ne☉ =1.3-3.8).
CONCLUSIONS

- Optically thick disk truncation in Dwarf Novae (DN) in at least 10 systems with radii in a range $R_{tr} \approx 0.3-1.0 \times 10^{10}$ cm ($f_{br} = 1-6$ mHz). The Magnetic CVs (MCVs) show smaller truncation radii $\sim 0.9-1.9 \times 10^9$ cm. Truncation varies in quiescence and outburst.


- Detection of radio emission in DN during outburst (5 objects) --> synchrotron emission from transeint jets. NLs (3 objects) show radio emission, as well.

- Suggest that most of these systems (DN) have truncated disks with hot flows dominating in the inner disks (ie. ADAF-like). This is also true for Nova-Like CVs and even in some novae during quiescence. Outflows and jets --> from hot flows ....

- Advective hot flows will have implications on CV evolution ... WDs will be hotter .... the gravitational energy release will decrease.

- These characteristics --> CV s --> XRBs even to AGN