Hard X-ray Cataclysmic Variables

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**CV sub-types**  \~ 1430 CVs known to date

| Magnetic Cataclysmic Variables | Non MCVs |
|-------------------------------|----------|
| \~20 % of all CVs             | \~80 % of all CVs |

| Polars                         | Intermediate Polars | Classical/Dwarf Novae |
|--------------------------------|---------------------|-----------------------|
| (Prototype AM Her)             |                     |                       |
| **Synchronous Rotation**       |                     |                       |
| $B_{\text{WD}} \sim 1 \, \text{–} \, 230 \times 10^6 \, \text{G}$ | $P_{\text{spin}} = P_{\text{orb}} \, (\text{hrs})$ | $B \ll 10^5 \text{–} 10^6 \, \text{G}$ |
| $P_{\text{spin}} (\text{mins}) \ll P_{\text{orb}} (\text{hrs})$ | $P_{\text{orb}} (P) < P_{\text{orb}} \, (\text{IP})$ | Energy Sources: |
| \~ 130 systems                | \~ 74 systems +30 candidates | CN: nuclear burning |
| **Bright in soft X-rays**      |                     | DN: through gravity   |
| ROSAT era                      |                     | (For a review see B. Warner 1995) |
| **Bright in hard X-rays**      |                     |                       |
| INTEGRAL/SWIFT era             |                     |                       |
Polars
Bright in soft X-rays
ROSAT era

Intermediate Polars
Bright in hard X-rays
INTEGRAL/SWIFT era

Bremsstrahlung

Multi temperature post-shock spectrum

Cyclotron cooling suppress the bremsstahlung high temperature emission

(Revnivtsev et al. 2008)

(Suleimanov et al. 2008)
What Cooling mechanism?

Radiative losses by **Cyclotron** & **Bremsstrahlung** for B>1MG

\[
\text{Frad} \approx \rho^a \text{T}_e^b
\]

One-fluid plasma in low B and high flow rates
(Fisher & Beuermann 2001; Beuermann 2003)

**Bremsstrahlung** is primary & **Cyclotron** is secondary

Systems with moderately low field and high dm/dt can be hard X-ray sources

\[
\begin{align*}
\text{B}=30 \text{ MG; dm/dt}=100,10,1,0.1 \text{ g/cm}^2\text{s} \\
\text{B}=100 \text{ MG; dm/dt}=1 \text{ g/cm}^2\text{s}
\end{align*}
\]

From Fisher & Beuerman 2001
The model based on Cropper et al (1999)

- Mass continuity equation

\[ \rho \frac{d}{dz}(\rho v^2 + P) = -\frac{GM_{wd}}{R_{wd}} \rho \]

- The momentum equation

\[ v \frac{dP}{dz} + \gamma P \frac{dv}{dz} = -(\gamma - 1) \Lambda \]

- The energy equation

\[ P = \frac{\rho kT}{\mu m_p} \]

- Ideal-gas law

- The cooling rate

\[ \Lambda = \left(\frac{\rho}{\mu m_p}\right)^2 \Lambda_N(T) \]

- The cooling function \( \Lambda_N(T) \) from Sutherland & Dopita (1993)
The Hard X-ray Surveys

- INTEGRAL/IBIS and SWIFT/BAT changed our view of X-ray sky
- ~ 25 % of Galactic X-ray sources are CVs
- Efficient only for some CV types

Bird et al. 2016; Krivonos et al. 2012; Cusumano et al. 2014; Oh et al. 2018
What type of hard CVs

- Novalike CVs include magnetics – many disputed to be mCVs
- IPs doubled in number with INTEGRAL/SWIFT detections!
- Still unidentified hard X-ray mCV candidates from optical spectroscopy

![Bar chart showing the distribution of CVs across different types and surveys.](chart.png)
Galactic faint X-ray source populations

• **Galactic Center:** Chandra 1Ms survey
  (Muno et al. 2004; Ruiter et al. 2006; Hong et al. 2012, 2014):
  - Thousands faint sources resolved:
  - Hard Spectra: Power law $\Gamma < 1 – 1.5$ (or $K_T \sim 25$keV) & Fe line (6.7keV) in a few
  - $L_x \sim 10^{30} - 10^{33}$ erg/s (1-8kpc)
  - Variability: Periodic ($\approx 1.3 – 3.4$hr)

• **Galactic Ridge X-ray Emission (GRXE):**
  RXTE, Chandra, INTEGRAL, Suzaku, NuSTAR, XMM-Newton
  (Revnivtsev et al. 2006, 2009; Sazonov 2006; Yuasa et al. 2012
  Warwick et al. 2014; Perez et al. 2015; Haley et al. 2016)
  - $\sim 80\%$ of diffuse X-ray emission @ 6.7keV resolved in
    discrete sources
  - $L_x \sim 10^{32} – 10^{35}$ erg/s $\rightarrow$ CVs most magnetic
  - $L_x < 10^{32}$ erg/s $\rightarrow$ coronally active binaries, non-mCVs?

MCVs purported as dominant hard low-Lx population
Is there a relation between the two types?

**Polars**

- ~130 systems
- Bright in soft X-rays
- Polarized in optical/nIR
- ROSAT era

**Intermediate Polars**

- ~74 systems +30 candidates
- Bright in hard X-rays
- Unpolarized or weakly polarized
- INTEGRAL/SWIFT era

- ➢ Different B-fields?
- ➢ Same B but evolutionary link?
Orbital Period Distribution

Binaries evolve towards short $P_{\text{orb}}$

Angular Momentum Losses via:

- Magnetic Braking above CV 2-3h “gap”
- Gravitational Radiation below “gap”

- Most IPs are above gap
- Most Polars are below gap

IPs may evolve into Polars if similar B-fields

Ritter & Kolb CV Cat. 7.24v
INTEGRAL/XMM-Newton Programme

29 CV Candidates: 23 IPs confirmed + 1 LMXB + 3 NL + 2 Polars

• X-ray Power Spectra of mCVs:
  - Accretion mode diagnostic: $\omega \approx \Omega \rightarrow \text{Polars}$
  - $\omega \rightarrow \text{Disc-fed IP}$
  - $\omega - \Omega \rightarrow \text{Stream-fed IP}$
  - $\omega$ and $\omega - \Omega \rightarrow \text{Disc-overflow (Hybrid)}$

• Energy dependent X-Ray/UV/Optical pulses:
  - Geometry and B-field complexity
  - Sites of Primary & Reprocessed radiation
  - Absorption effects

• X-Ray spectra:
  - Accretion region: Pre-Shock, Post-Shock, bulge at disc rim
  - WD irradiation and WD mass
**Hard X-ray view of MCVs**

**IPs dominate hard X-ray detected CVs**

Using Anzolin+08,09, Brunschweiger09 Tomsick 16, Hayley+16; Suleimanov+16, Bernardini+12,+13,15,17; Shaw+18, Wada+18

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**Do hard IPs host massive WDs?**

\[ kT_{\text{shock}} = \frac{3}{8} G \frac{M_{\text{WD}}}{R_{\text{WD}}} \mu m_H \]

\[ <M_{\text{IPs}}> = 0.83 \pm 0.19 \, M_\odot \]

\[ <M_{\text{Fid}}> = 0.82 \pm 0.15 \, M_\odot \]

\[ <M_{\text{CVs}}> = 0.82 \pm 0.24 \, M_\odot \]

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**K-S test give probability of 98.1% that distributions are from the same parent population**
Hard X-ray Luminosities using Gaia DR2

**Hard X-ray sample [14 – 195keV]**

\[ F_x > 7.3 \times 10^{-12} \text{ erg/cm}^2/\text{s} \]

**IPs:**
- \( \langle L_x \rangle \sim 1.3 \times 10^{33} \text{ erg/s} \) up to \( \sim 1.8 \text{kpc} \)
- High \( L_x \) IPs at \( d > 300 \text{pc} \)
- 4 IPs at \( L_x < 1 \times 10^{32} \text{ erg/s} \) within \( \sim 200 \text{ pc} \) with 3 below the 2-3h gap

**Bimodality**

**Polars:**
- \( \langle L_x \rangle \ 8 \times 10^{31} \text{ erg/s} \) up to \( \sim 520 \text{ pc} \)
- Low \( L_x \): Polars, short Porb IPs
  (see Reis et al. 2013; Pretorius & Mukai 2014)
What we still need:

Near Future:
- Census of hard X-ray CVs: population study – space density
  - Ongoing XMM-Newton identification programme
  - Searches of new systems in 3XMM (Extras project funded by EU)
- Polarimetric surveys of mCVs

Bit Far Future:
- iXPE to probe accretion geometry through X-ray polarization
- Theseus will allow monitor of large sample of CVs over a broad range
- e-ROSITA will find thousands of hard X-ray CVs: follow-ups
- eXTP will study faint mCVs over a broad-band range
- ATHENA will trace post-shock plasma (Oxygen, Fe, Si, Mg, S); warm and cool absorbers;
  WD mass via Grav. Redshift of 6.4keV fluorescent line