Hard X-ray Views of Cataclysmic Variables and Symbiotic Stars

Koji Mukai (NASA/GSFC/CRESST & UMBC)
Summary

➢ Hard X-ray surveys with INTEGRAL and Swift/BAT have expanded our view of the population of CVs and Symbiotic Stars.
   ✓ Now starting to combine with Gaia distances.
   ✓ eROSITA will expand our view of the lower L_x populations.

➢ Nova eruptions have been shown to be unexpectedly powerful particle accelerators.
   ✓ We now have the first contemporaneous detections of highly absorbed thermal X-rays from the shock responsible.
   ✓ We still do not have reliable detection of non-thermal X-rays.

➢ Accretion disk boundary layer still manages to surprise us.
   ✓ Paradigm derived from SS Cyg does not always work
   ✓ Disk instability model predicts gradual X-ray luminosity increase during interoutburst intervals - this as never been observed

➢ Reflection has become a routine ingredient of spectral fitting for these objects.
   ✓ This is both a complication and a tool.

➢ High resolution X-ray spectroscopy with XRISM and Athena will open new opportunities for the study of CVs and Symbiotic Stars.
Cataclysmic Variables (CVs) and Symbiotic Stars

- CVs: Roche-lobe filling red dwarf and an accreting white dwarf
- In about 10-20% of CVs, the WD is sufficiently magnetic to control the accretion flow.
- The majority are non-magnetic, with the disk extending down to the WD surface.

- Symbiotic stars: red giant with strong wind and an accreting white dwarf.
- Many classic symbiotic stars have shell burning as the main energy source.
- Some are purely accretion powered.
We (de Martino et al., ASR, in press) have been conducting a systematic follow-up of INTEGRAL and Swift/BAT sources proposed to be CVs using XMM-Newton.

Roughly 25% of the Galactic hard X-ray sources are CVs and Symbiotic Stars.

In particular, magnetic CVs of intermediate polar (IP) subclass is the largest subclass, other types are also found.

Combined with the Gaia DR2 distance, we can now construct reliable hard X-ray luminosity function of major subclasses.

IPs are rare and individually luminous.
Recent Examples

- Highest flux hard X-ray sources were dominated by standard IPs. We probably have a complete census of such systems to beyond 1 kpc.

- As we push our efforts to lower hard X-ray fluxes, other subtypes of CVs are showing up.

- 2PBC J0658.0-1746 is an eclipsing polar at ~200 pc; most polars are soft X-ray bright and hard X-ray faint, but this belongs to a subset (Bernardini et al. 2019, MNRAS, 489, 1044).

- Swift J0746.3-1608 has high and low states and unusual light curves, and is probably an IP (Bernardini et al. 2019, MNRAS, 484, 101).
Symbiotic Stars as hard X-ray sources

- A surprise from the early BAT survey: 4 symbiotic stars (T CrB, RT Cru, V648 Car, and CH Cyg) were detected.
- A new surprise: SU Lyn, a previously obscure red giant in an obscure constellation was also detected - a newly recognized, purely accretion-powered, symbiotic star
- A Skymapper search for similar objects under way.

**Composite UV-optical SED of SU Lyn**, a BAT-detected hard X-ray source. Low resolution optical spectroscopy cannot reveal the symbiotic nature: high resolution spectra and/or UV data are necessary.
Our current census of even the nearby (d=100-300 pc) dwarf novae are probably woefully incomplete. WZ Sge subtype has low accretion rate, faint during quiescence in the optical and in the X-rays, and outbursts are rare.

For example, TCP J21040470+4631129 was discovered in outburst this past July, and Gaia DR2 parallax puts it at 109 pc away.


Britt et al. (2015, MNRAS, 448, 3455) found correlation between outburst duty cycle and X-ray luminosity. eROSITA will discover many, many...
Nova eruptions are the consequence of violent mass ejection due to thermonuclear runaway of material accreted on the white dwarf surface.

Fermi/LAT has discovered 14 or so novae (depending on the significance threshold) as transient source of GeV gamma-rays.

In one spectacular case of V5856 Sgr, Li et al. (2017, Nature Astronomy, 1, 697) reported a striking correlation between gamma-ray and optical flux of the nova, leading to the speculation that a significant part of the nova emission may be shock-powered.

Such shocks should also emit thermal X-rays; non-thermal emission should extend down from GeV to hard X-ray energies.
X-rays from shocks in novae have been well known but previously detected with a significant delay relative to optical peak. In contrast, GeV emission is usually reported within days of optical peak, lasting for a week or two.


➢ The spectrum was highly absorbed, requiring the high energy capability of NuSTAR.

➢ Non-thermal emission has not been detected with NuSTAR, although a couple of claims exist obtained using non-imaging hard X-ray instrument. Watch out for forthcoming results on V906 Car (=ASASSN-18fv).
Hadronic or Leptonic?

❖ With the right combination of circumstances (bright, nearby novae in the right part of the sky at the right time), we may be able to detect non-thermal hard X-rays from novae while Fermi/LAT is detecting GeV gamma-rays.

❖ This is likely a good diagnostic of whether the gamma-ray emission process is leptonic or hadronic, which, so far, we have not been able to determine.

❖ In addition, the overall efficiency of particle acceleration is in question --- the NuSTAR detected thermal X-ray luminosity, if it faithfully represent the shock power, would imply an extremely high particle acceleration efficiency.
An X-ray astronomer might think that CVs and symbiotic stars are the same, since X-rays are generated in the immediate vicinity of the white dwarf. However:

- Evolutionary paths and current evolutionary drivers differ
- Symbiotic stars are embedded in the wind of the donor
- IR/optical/UV characteristics differ greatly
- Accretion disk time scales differ greatly as well

Schematic diagram of the boundary layer, the site of X-ray emission for accreting non-magnetic white dwarfs, from Patterson & Raymond (1985).
Textbook Case: SS Cyg

Note: SS Cyg is a textbook case, i.e., it’s not necessarily typical in all its aspects.

❖ SS Cyg in quiescence has an optically thin boundary layer, emitting \( \sim 10^{31} \) ergs s\(^{-1} \) of optically thin X-rays in the 0.5-\(~30\) keV range
❖ In outburst, the boundary layer switches to a mostly optically thick state, emitting blackbody-like soft (<0.5 keV) X-rays while optically thin emissions remain
❖ There is a hysteresis effect - rise and decay are not identical
❖ There is a residual, weaker and softer, optically thin component during outburst.
❖ Ishida et al. (2009, PASJ, 61, 877) proposed an accretion disk corona origin for this component.
Recent Activity of T CrB

➢ Since 2015, T CrB has gone into an optically bright state - *sign of a large, bright, disk*
➢ The hard X-ray flux dropped
➢ The *XMM-Newton* spectrum confirms the softening and dimming of hard X-rays with a dramatic soft component

Neustroev et al. (2018, A&A, 611, A13) presented an extensive Swift/XRT campaign on the WZ Sge-type dwarf nova, SSS J122221.7-311520. No soft component was detected, simply an elevated level of hard X-ray emission.

Recent snapshot Swift/XRT observations of WZ Sge-type dwarf novae in outburst similarly reveal increased hard X-ray luminosity (e.g., TCP J21040470+4631129; Sokolovsky et al. 2019, Atel 13009)
Dwarf novae are supposed to be the manifestation of disk instability.

✓ Mass transfer rate from the donor is sufficiently low to keep the disk in a low viscosity state.

✓ Mass builds up in the disk, until suddenly it transitions to a hot, viscous state (=outburst).

A general prediction of disk instability model is that, during the course of the quiescence, the accretion rate onto the central objects gradually increases.

This has never been observed in dwarf novae (SS Cyg, SU UMa, and now VW Hyi). Quite the contrary.
Reflection in IPs

- “Reflection” (really backscatter) modifies the spectrum of X-ray sources that are near cold, Compton-thick surfaces (accretion disk, white dwarf).
- Spectral shape of the reflection component is determined by the competition between photoelectric absorption (highly effective at E<10 keV) and Compton scattering (E>10 keV), and leads to continuum bump & fluorescent 6.4 keV lin.

NuSTAR legacy survey of IPs led by Shaw will produce many $M_{wd}$ estimates.
Spectral Complexities

- Given the available bandpass and S/N limitations, kTmax and reflection amplitude are correlated in the fit results.
- Reflection produces Fe edge at 7 keV - but so does the complex absorber in the case of IPs.
- The complex absorber also modifies the spectral curvature in the 1-6 keV range (see the case of TV Col, from Lopes de Oliveira & Mukai 2019, ApJ, ).
- Additional complications exist: soft, blackbody-like component from the heated surface, ionization of the complex absorber, abundances, ...
- Spin modulation can help break the degeneracy.
- Side benefit: WD mass estimate.
Reflection in Symbiotic Stars

- We detect the reflection signature in a NuSTAR observation of T CrB (similarly for RT Cru and V648 Car; inconclusive for SU Lyn)
- Reflection amplitude varies among them and is >1.0 in V648 Car
- Reflection from WD surface only or from disk only should peak at amplitude of 1.0

Combined with the high ratio of $L_{\text{UV}}$ to $L_{\text{X}}$, it’s likely that some of these symbiotic stars (at least some of the time) have a partially optically thick boundary layer, yet has hard and luminous optically thin X-ray emission. Reflection can be from both the WD surface and the disk.
XRISM and Athena will open up the power of high resolution X-ray spectroscopy for CVs and Symbiotic Stars. Possible objectives include:

➢ Density diagnostics for magnetic CVs, allowing us to measure the size of the accretion column, hence that of the magnetospheric interaction region.

➢ Density diagnostics for non-magnetic CVs, allowing us to measure the size of the boundary layer in quiescence and in outburst.

➢ Dynamical information on the post-shock regions

➢ Gravitational redshift of the 6.4 keV line from the surface of the white dwarfs.
Summary (Reprise)

➢ Hard X-ray surveys with INTEGRAL and Swift/BAT have expanded our view of the population of CVs and Symbiotic Stars.
  ✓ Now starting to combine with Gaia distances.
  ✓ eROSITA will expand our view of the lower $L_{\text{x}}$ populations.

➢ Nova eruptions have been shown to be unexpectedly powerful particle accelerators.
  ✓ We now have the first contemporaneous detections of highly absorbed thermal X-rays from the shock responsible.
  ✓ We still do not have reliable detection of non-thermal X-rays

➢ Accretion disk boundary layer still manages to surprise us.
  ✓ Paradigm derived from SS Cyg does not always work
  ✓ Disk instability model predicts gradual X-ray luminosity increase during interoutburst intervals - this as never been observed

➢ Reflection has become a routine ingredient of spectral fitting for these objects.
  ✓ This is both a complication and a tool.

➢ High resolution X-ray spectroscopy with XRISM and Athena will open new opportunities for the study of CVs and Symbiotic Stars.
Magnetism & Accretion
A conference in Cape Town, South Africa,
16 – 20 November 2020
Magnetism & Accretion

The physics of magnetically influenced accretion throughout the Universe, covering:
- compact binaries with accreting white dwarfs, neutron stars or black holes
- disk/jet connections
- AGN and blazars
- proto-stellar systems, YSOs & planets
- GRBs

Scientific Organizing Committee:
Nicholas Achilleos (UK)
Dipankar Bhattacharya (India)
Dmitry Bisikalo (Russia)
Jean-Marc Bonnet-Bidaud (France)
David Buckley (South Africa, Chair)
Dmitilla de Martino (Italy)
Jean-Francois Donati (France)
Lilia Ferrario (Australia)
Alice Harding (USA)
Theresa Lüftinger (Austria)
Pieter Meintjes (South Africa)
Carole Mundell (UK)
Marina Romanova (USA)
Axel Schwope (Germany)
Andrew Shearer (Ireland)

First announcement expected
October 2019