Recent Advances in X-ray Observations of Cataclysmic Variables

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Abstract.

A personal selection of noteworthy X-ray results on CVs are presented, with emphasis on XMM-Newton and Chandra observations. Progressing roughly from broad-band view to narrow-band, high spectral resolution studies, I summarize: the energy balance of polars; X-ray confirmation of IPs; eclipses in non-magnetic CVs; search for magnetism in “non-magnetic” CVs; multi-temperature plasma emission from the boundary layer; complex absorption in magnetic CVs; temperature and density diagnostics; and X-ray radial velocity studies.

1. The X-ray Band

Over the past 25 years or so, X-ray observations have played a major role in the research into CVs. It would only be a slight overstatement to say that the class of magnetic CVs owes its existence to X-ray astronomy, as a high fraction of magnetic CVs are discovered and/or confirmed through X-ray observations. The role X-rays have played for non-magnetic CVs is less central, but nevertheless important. This is because, according to simple arguments, half the accretion luminosity of CVs ought to be emitted in the X-ray band. Unfortunately, this expectation has not been fulfilled observationally in most cases — we must be missing something, either theoretically or observationally.

It is an exciting era in X-ray astronomy, with the recent launches of Chandra and XMM-Newton, and the upcoming launch of Astro-E2. For example, not only is the Chandra image of the Galactic Center region breath-taking, a significant fraction of the thousands of point sources may be (magnetic) CVs (Muno et al. 2003).

In this review, I will define “X-rays” as the range 0.1–25 keV, or roughly 125–0.5Å. This is a factor of 25 in wavelength, equivalent to 1000Å (UV) to 25 µm (mid-IR). It is therefore not surprising to find several distinct spectral components that contribute to the X-ray emission from CVs. Single X-ray instruments often cover a factor of 25 in wavelength; this is a strength of X-ray astronomy. On the other hand, “high resolution spectroscopy” is a relative term. In terms of spectral resolution, ROSAT PSPC data are comparable to UBVRI photometry. CCD-based instruments (ASCA SIS, Chandra ACIS, and XMM-Newton EPIC) have typical resolution at 6 keV of 2%, and therefore may be compared to narrow-band photometry (Δλ~100Å at 5000Å, for example).
Of the existing instruments, only the Chandra and XMM-Newton gratings can deliver what optical astronomers would consider spectroscopy on a routine basis.

This review includes my personal selection of highlights from recent X-ray observations, with a natural emphasis on the Chandra and XMM-Newton results. I will emphasize magnetic CVs, but will include some results on non-magnetic CVs. I will, however, not include SSSs, novae in outburst, nova shells, or globular cluster sources. Readers are referred to other papers in this volume for these subjects.

As a starting point for discussion, I will adopt the following as the baseline models for X-ray emission in non-magnetic and magnetic CVs. In the former, the Keplerian accretion disk is connected to the white dwarf surface via a boundary layer. It is optically thin and emits hard X-rays in low accretion rate systems (Patterson & Raymond 1985a). In high accretion rate systems, the core of the boundary layer is optically thick and emits soft X-rays, while some optically thin hard X-rays remain (Patterson & Raymond 1985b). In magnetic systems, accretion is in the form of columns that are nearly vertical. Hard X-rays from the post-shock plasma is usually dominant in the IPs (Patterson 1994), while soft X-rays from the photosphere is the most prominent feature of polars (Cropper 1990).

2. Polars: Low State and Energy Balance

The XMM-Newton survey of polars have revealed the detailed pictures of X-ray emissions in a substantial number of polars. Moreover, the survey has produced two notable results on the polars as a class. One is that a large fraction (16 out of 37 surveyed) is seen to be in a low state during the XMM-Newton observations (Ramsay et al. 2004). This has an obvious impact on the efficiency of X-ray surveys to detect polars, and hence their space density.

Another result is on the soft X-ray/hard X-ray luminosity ratio of polars. There is a long history of controversy over both what ratios to expect theoretically, and what ratios observations actually indicate. In this latest contribution on this subject, Ramsay & Cropper (2004) conclude that the majority of systems have a soft to hard luminosity ratios that are consistent with a pure irradiation origin of the soft component. However, a significant minority shows a “soft excess,” indicating direct, mechanical heating of the white dwarf atmosphere. Compared to previous efforts, this study has the advantage of far superior data on the hard component: XMM-Newton is the first imaging instrument capable of producing high quality spectrum of the hard component on more than a handful of polars, over the range 0.5–10 keV. ROSAT PSPC, in contrast, could only detect the soft end of this component. Moreover, Ramsay & Cropper (2004) utilize a sophisticated spectral model to fit the hard component spectrum, rather than relying on a simple Bremsstrahlung model often with a fixed temperature.

Nevertheless, there is room for further investigation into this issue. One particular question is the true spectral shape of the soft component. As Mauche (1999) shows using EUVE data, the choice of blackbody vs. stellar atmosphere models can greatly change the inferred bolometric luminosity. Moreover, the degree of departure of the spectrum from a pure blackbody is an indicator of the origin of the soft component, since strong irradiation causes temperature
inversion and therefore weakens atmospheric features. Do the polars with no soft excess possess more blackbody-like soft component that those with strong excess? We can hope to learn a great deal on this subject over the next several years through observations and analysis of Chandra LETG data of polars.

3. IPs: X-ray Confirmations and Broad Band Spectra

Coherent X-ray pulses at periods significantly shorter than the orbital period \( P_{\text{orb}} \) is a defining characteristic of IPs. De Martino and colleagues have been conducting a systematic campaign to observe IPs and IP candidates in the BeppoSAX, RXTE, and now XMM-Newton, with the X-ray confirmation of their IP nature as an important initial objective. A latest example can be found in [de Martino et al., 2005], in which XMM-Newton observation of HT Cam \( P_{\text{orb}}=86 \text{ min} \) has revealed a coherent X-ray modulation at the optically-identified spin period of 515 s. We now have three X-ray confirmed IPs below the period gap (EX Hya, V1025 Cen, and HT Cam), while a fourth system, DW Cnc, almost certainly belongs in this group but still awaits X-ray confirmation. These systems raise an interesting evolutionary question of if and when they might synchronize to become polars.

In addition, three of the four systems (though not HT Cam) have a long \( (\gg 0.1 P_{\text{orb}}) \) spin period and should not be able to form a true Keplerian accretion disk, yet there are observational signatures of axisymmetric, disk-like structures. This conundrum may have been solved by the recent numerical simulations, in which a new regime of diamagnetic blob accretion has been found (Norton et al. 2004). In this regime, accretion is fed from a ring-like structure near the outer edge of the white dwarf Roche-lobe, and the predicted equilibrium spin period is indeed long \( (\gg 0.1 P_{\text{orb}}) \).

Returning to HT Cam, there is little sign of significant photoelectric absorption in its X-ray spectrum, both in the average and in the phase resolved spectra (de Martino et al., 2003). In this, HT Cam is similar to EX Hya, V1025 Cen, and YY Dra. It is possible that this is the hallmark of a low accretion rate IPs.

The case of WX Pyx illustrates the potential of pointed X-ray observations for serendipitous discoveries. This hydrogen rich CV was discovered serendipitously in the Einstein observation of the nearby galaxy, NGC 2613. The discovery of a stable 26 min period (O'Donoghue et al., 1996), combined with the presence of hydrogen (therefore \( P_{\text{orb}} > 70 \text{ min} \)), indicated this system is an IP. The X-ray confirmation of this classification has been obtained through XMM-Newton observations of NGC 2613 (Mukai, de Martino et al., in preparation). Among the operational X-ray satellites of today, XMM-Newton has a relatively large field of view, and so has a great potential for serendipitous discoveries (many CVs among them, one hopes), particularly because the project has a heavy investment in the XMM-Newton serendipitous X-ray sky survey.

4. Eclipses in Non-magnetic CVs

XMM-Newton is making important contributions to the studies of X-ray eclipses in non-magnetic CVs, because it has the largest effective area among imaging X-ray telescopes. In quiescent dwarf novae, the existence of X-ray eclipses has been
Mukai established through ROSAT and ASCA observations (see, e.g., Mukai et al. 1997), and the X-ray emission region has been known to be compact. However, how compact, and is it really consistent with a boundary layer? The recent re-analysis of XMM-Newton observation of OY Car (Wheatley & West 2003) show that, surprisingly, the X-ray eclipse is narrower than in the optical. Since the second and the third contacts align between the optical and X-ray data, while the first and the fourth contacts do not, a vertical displacement between the emitting regions is required. Can this be accommodated within the boundary layer picture? Or does this require a significant magnetic field in OY Car? If the latter is the case, the magnetic poles cannot have a significant optical emission, even though the upper pole must dominate the observed X-rays. This subject is likely to see further developments in the near future based on XMM-Newton observations of Z Cha and HT Cas.

![Figure 1. Folded X-ray light curves of UX UMa in two energy band. There is a hard X-ray eclipse, but not in the soft X-rays. Taken from Pratt et al. (2004).](image)

In contrast, in high accretion rate systems (dwarf novae in outburst and in nova-like systems), soft X-ray eclipses have never been observed. This includes the bright nova-like system, UX UMa, which is deeply eclipsing in the optical and the UV. It has now been shown that there is an X-ray eclipse, but only
above \( \sim 2 \) keV (Figure 1; Pratt et al. 2004). Spectrally, the hard component is strongly absorbed, and contributes few counts below 2 keV. This presumably originates in the boundary layer. The origin of the soft component is more problematic. Pratt et al. (2004) have speculated that this component may be due to scattering in the accretion disk wind. This certainly has the right size scale, but are there enough \( E \sim 1 \) keV photons that can be scattered? Wheatley (2005) explores a possible alternative origin in connection with the outburst observations of WZ Sge.

5. WZ Sge and Friends: More Magnetic CVs?

As is well known, WZ Sge is a dwarf nova with an extremely long recurrence period. The standard version of the disk instability model has difficulties explaining this system (Lasota et al. 1999), and additions and/or modifications have been sought to remedy this. Another well known puzzle regarding WZ Sge is the rapid oscillations seen in the optical and the UV. If it were not for the fact that there are two stable periods, one at 27.87 s and the other at 28.96 s, the magnetic CV interpretation would have been accepted universally. Even with the multiple periods, the magnetic CV interpretation remains an attractive explanation for the unusual outburst properties of WZ Sge.

Mukai & Patterson (2004) present the results from 2003 May XMM-Newton observation of WZ Sge. The spectrum can be fit with a multi-temperature plasma emission model with low absorption; it is similar to those of non-magnetic CVs and low accretion rate IPs. The X-ray luminosity is \( \sim 2.5 \times 10^{30} \) ergs s\(^{-1}\), requiring an accretion rate of \( \sim 5 \times 10^{13} \) g s\(^{-1}\). Even though these values are modest, they still exceed the expectations from the standard disk instability model. Most importantly, the 27.87 s signal is not present in the XMM-Newton data (see Figure 2; the detection of this periods was claimed in an earlier ASCA data). The 28.96 s signal is definitely present in the contemporaneous optical data, and may also be present at a low level in the XMM-Newton data (Figure 2). Thus, the quiescent XMM-Newton data fail to resolve the issue of the origin of these periods.

It is important to consider what would qualify a CV as a magnetic system. Conceptually, any CV in which the magnetic field of the white dwarf is strong enough to control the accretion flow is a magnetic CV\(^1\). It is quite possible that systems traditionally considered “non-magnetic” are in fact magnetic. Observers must then ask what constitutes strong evidence for this.

As an example, Baskill et al. (2004) have analyzed the complete sample of ASCA observations of “non-magnetic” CVs (29 in all), looking for periodic modulations and spectra that are indicative of magnetic CVs. They find 3 candidate magnetic CVs: LS Peg, EI UMa, and V426 Oph. Homer et al. (2004) also revived the magnetic interpretation for V426 Oph based on the Chandra HETG spectroscopy as well as their re-analysis of the archival X-ray data. V426 Oph typifies the difficulties sometimes encountered in searching for new magnetic

\(^1\)An interesting complication is that accretion may lead to the evolution of the magnetic field of the white dwarf (Cumming 2002).
CVs using X-ray data. As Homer et al. (2004) note, previously reported X-ray periods appear to be transient and quasi-periodic. The periods identified by Baskill et al. (2004) (29.2 min) and Homer et al. (2004) (4.2 hr) do not agree with each other. In summary, while there are good reasons to propose V426 Oph as an IP candidate, there does not yet appear to be a compelling evidence for its magnetic nature, either.

Baskill et al. (2004) do not find evidence for OY Car or WZ Sge being magnetic in the ASCA data. In the XMM-Newton data on OY Car, in addition to the eclipse timing which may favor a magnetic interpretation, the presence of a 2240 s period has been found (Ramsay et al. 2001; Hakala & Ramsay 2004). If this really is the spin period, and the system is in spin equilibrium, this almost certainly excludes the presence of a normal, Keplerian accretion disk. Yet OY Car is a bona fide dwarf nova. If more dwarf novae than just WZ Sge

Figure 2. Power spectra of WZ Sge in quiescence in 4 energy bands, from the 2003 May XMM-Newton observation. Marked frequencies corresponds to 28.96 s, 27.87 s, and their first harmonics.
are to be interpreted as magnetic CVs, it will be necessary to apply the disk instability model with a white dwarf magnetic field to a wide range of system parameters to conduct a systematic study of the predicted outburst properties. This must be compared with the known outburst properties of WZ Sge, OY Car, V426 Oph, as well as the bona fide IPs.

Until this is done, it is prudent to be cautious of magnetic CV interpretation of dwarf novae, unless the spin period is detected convincingly in multiple datasets. In addition, X-ray spectra that are affected heavily by intrinsic absorption may also be taken as suggestive of magnetic CVs, but this again is not definitive.

6. Chandra HETG Spectra

Although high resolution X-ray spectroscopy is also possible using XMM-Newton RGS and Chandra LETG, Chandra HETG has been the most productive instrument thus far for CVs. Here, then, are some highlights from the HETG.

6.1. Cooling Flow Type Spectrum in CVs

Mukai et al. (2003) have compared Chandra HETG spectra of seven CVs, and found two types. One type (EX Hya, V603 Aql, U Gem in quiescence, and SS Cyg in quiescence) is found to be consistent with the cooling flow model, originally developed for clusters of galaxies (see Figure 3 for an example). This is a specific version of multi-temperature plasma model with a simple physical interpretation. There is little doubt that such multi-temperature, cooling plasma model is necessary to fit the high resolution, high quality X-ray spectra of these CVs. What is less clear is whether the cooling flow model fit is correct or unique among all the multi-temperature plasma models. In fact, physical considerations suggest there may be subtle differences between real CVs and the cooling flow model, primarily near both extremes of temperature distribution due to boundary conditions. In the case of non-magnetic CVs, Perna et al. (2003) contains a comparison of several physical models in the context of Chandra HETG data on WX Hyi. The great strength of the cooling flow model, however, is that it is readily available in spectral fitting package, xspec, and one can obtain estimates of the global accretion rate and other parameters of interest. More recently, Mukai & Orio (2005) have attempted to derive the emission measure distribution as a function of temperature from Chandra HETG data on V603 Aql. Although only partially successful, this approach, which combines global model fits with individual line fits, may prove fruitful in the future.

It is important to stress that the boundary layer emissions are expected to be multi-temperature in nature. Some earlier works treat the boundary layer emission as that of a single temperature plasma. While a theoretical plot of the plasma temperature versus the height above the white dwarf surface of a boundary layer shows a large volume of near constant temperature, this is because this region is low density, cools only very inefficiently, and is advection-dominated (Narayan & Popham 1993). The actual X-ray emission mostly comes from a small volume near the white dwarf surface where the temperature plot is almost vertical. In this region, the temperature drops because energy is radiated away, which in turn is because of the high density. Single temperature treatments
Figure 3. *Chandra* HETG spectrum of V603 Aql, an example of a cooling flow type spectrum.
worked well with lower quality X-ray data, but are completely inadequate for Chandra HETG data.

Note that [Mukai et al. (2003)] did not discuss the spectra of U Gem and SS Cyg in outburst. There are drastic changes from quiescence to outburst, and also differences between U Gem and SS Cyg [Mauche et al. (2005)]. One clear difference is the greatly increased line width in outburst. It will be interesting to investigate whether a cooling flow model, with large line widths, can be applied to Chandra HETG data of dwarf novae in outburst or not.

6.2. Photoionized Spectrum in CVs

[Mukai et al. (2003)] have fitted the Chandra HETG spectra of V1223 Sgr, AO Psc, and GK Per using a photoionized plasma model originally developed for active galactic nuclei. It is important to note that this is a phenomenological model, in that a power law continuum is assumed without physical justification. The main strength of their result is the use of a physically sophisticated model of photoionized line emission. The reasons for adopting this model over the cooling flow model for the low energy emission lines have been articulated by [Mukai et al. (2003)].

So why the power law continuum? The reason [Mukai et al. (2003)] have adopted the power law prescription is that the observed continua are too hard to be from a cooling flow. The cooling flow continuum is a superposition of thermal Bremsstrahlung of many different temperatures, and resembles a power law of photon index $\sim 1.4$. In contrast, these three magnetic CVs have a much harder (photon index $\sim 0.5$ or harder) continuum in the Chandra HETG range.

However, from higher energy observation (e.g., with Ginga and RXTE) we know that these magnetic CVs have thermal Bremsstrahlung like continua above 10 keV [Ishida (1991)]. Complex, phase-dependent absorption is an essential ingredient in our understanding of the X-ray spectrum of magnetic CVs [Norton & Watson (1989)]. So, one expects to see absorbed Bremsstrahlung continua in these systems below 10 keV.

A simple absorber, however, produces an exponential cut-off at low energies. A superposition of a few discrete partial covering absorbers only produces a series of exponential cut-offs at different energies. These will not produce hard power laws as observed in V1223 Sgr, AO Psc, and GK Per with Chandra HETG. However, the real absorber in magnetic CVs can be more complex than a few discrete partial covering absorbers. [Done & Magdziarz (1998)] have explored the absorption expected from the pre-shock flow. Our lines of sight to different parts of the post-shock region pass through different amounts of pre-shock flow. Although a full numerical model is the most accurate, they have also developed an approximation in which the covering fraction is a power law function of $N_H$. This has been implemented as the `pwab` model in `xspec`. Interestingly, this results in a power-law low energy cut-off, just as required if we are to explain the Chandra HETG continuum as a cooling flow continuum with complex absorption.

So, the full physical model for V1223 Sgr, AO Psc, and GK Per is likely to be a hybrid. There is an underlying cooling flow emission from the post-shock region. We observe this through a complex absorber that is the immediate pre-shock flow. Given the physical parameters of these CVs, it would be difficult
to produce Fe Kα lines through photoionization; they are far more likely to be intrinsic to the cooling flow. However, low energy emission lines are likely to be produced as a result of photoionization of the pre-shock flow (Mukai et al. 2003).

Note that, according to Done & Magdziarz (1998) and to Rainger (unpublished work), the varying geometry of the pre-shock complex absorber is the likely cause of X-ray orbital (=spin) modulation in polars. Presumably the same model can be applied to the spin modulation in IPs. This is distinct from the “accretion curtain” absorber which is much further away, which affects the entire post-shock emission region simultaneously and hence is likely to produce a strongly energy dependent dip.

6.3. Plasma Diagnostics

A high density is expected in the X-ray emission regions in magnetic CVs. For a fiducial local accretion rate of 1 g cm$^{-2}$s$^{-1}$, decelerating by a factor of 4 from a free-fall velocity of 3,000 km s$^{-1}$, the expected density is of order 10$^{16}$ cm$^{-3}$ just below the shock, and higher lower down. There is far greater uncertainties for non-magnetic CVs, but somewhat lower densities might be expected. X-ray spectroscopy has the potential to provide strong constraints on the density, via determinations of line ratios. As the He-like triplet ratios are also affected by UV photo-excitation, Mauche and colleagues have turned their attention to potential Fe L line diagnostics, as applied to the high quality Chandra HETG spectrum of EX Hya.

Mauche et al. (2001) have used the ratio of Fe XVII lines at 17.10 ˚A and at 17.05 ˚A. However, this ratio can also be affected by UV photoexcitation. Mauche et al. (2003) have used the ratio of Fe XXII lines at 11.92 ˚A and at 11.77 ˚A. They find this ratio to be insensitive to photoexcitation, and to have a critical density of $\sim 5 \times 10^{13}$ cm$^{-3}$. The ratio observed in the Chandra HETG spectrum of EX Hya then implies a density near $1 \times 10^{14}$ cm$^{-3}$ for a 12 million degree plasma. These Fe L diagnostics require a high signal-to-noise data, and also requires the source to be relatively unabsorbed. Thus application has so far been limited just to EX Hya. However, these and other diagnostics have the potential to allow direct measurements of the plasma density and confront the physical models of the X-ray emitting regions in CVs.

The Fe Kα lines merit particular attention, not least because these have been the longest studied X-ray emission lines, due to a combination of astrophysical and technological reasons. A couple of developments merit mention here. First, Hellier & Mukai (2004) have analyzed the Chandra HETG data on five magnetic CVs. They do not confirm the earlier result based on ASCA data that the H-like and He-like lines of AO Psc is Compton broadened. There are, however, hints of structures within these components. Second, Terada et al. (2004) have studied the spin modulations of Kα line intensities in polars and in IPs. They found significant modulations in polars, but not in IPs, and explain their findings in terms of resonant scattering of line photons.

6.4. X-ray Radial Velocity Studies

Perhaps the most exciting new result is the detection of X-ray radial velocity motion in EX Hya (Hoogerwerf et al. 2004). One could say that X-ray spec-
X-ray Observations

X-rays Observations of CVs has finally come of age. Astrophysically, this is exciting, since optical spectroscopy generally does not allow an unambiguous measurement of the radial velocity motion of the white dwarf. The measured amplitude of $\sim 58$ km s$^{-1}$ in EX Hya implies a white dwarf mass of $\sim 0.5 M_\odot$. Another important result is the lack of significant spin modulation of radial velocities.

7. Conclusions and Future Prospects

Recent X-ray observations of CVs have been very fruitful, as I hope the preceding sections have shown. The large effective area of XMM-Newton EPIC allows moderate resolution spectroscopy of relatively faint CVs, and provides the best X-ray eclipse light curves of magnetic and non-magnetic CVs. X-ray confirmations of IP nature and serendipitous discoveries are other strong areas for XMM-Newton. Chandra HETG has allowed us to study the temperature distribution and the densities in some of the X-ray brightest CVs, and even an X-ray radial velocity study!

What are some of the unanswered questions?

1. What is the true spectral shape and the true luminosity of the soft component in polars?

2. What is the origin of the uneclipsed $\sim 1$ keV X-rays in UX UMa? It is likely this component exists in other high accretion rate non-magnetic CVs as well.

3. What is the geometry of hard X-ray emitting regions in quiescent dwarf novae? Is OY Car typical, if so is there such a thing as the boundary layer?

4. Is WZ Sge magnetic or not? Are there many magnetic CVs hiding among dwarf novae?

5. Why are X-ray lines often narrow in CVs, and only appear broad in dwarf novae in outburst?

Both Chandra and XMM-Newton will continue to provide high quality data on CVs. Astro-E2 is expected to join these observatories in 2005. It is particularly suited to the study of the Fe Kα lines, with a resolution of $\sim 6$ eV and an effective area of $> 100$ cm$^2$. Since the Fe Kα lines arise from the hottest, least dense, and least decelerated part of the post-shock region in both magnetic and non-magnetic CVs, there is rich potential for kinematic studies of X-ray emitting regions in CVs using Astro-E2 data in the Fe Kα region.

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