The EUV and X-ray Emission of Nonmagnetic Cataclysmic Variables

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Abstract. Recent results are presented and discussed regarding the EUV and X-ray emission of nonmagnetic cataclysmic variables. Emphasis is given to high accretion rate systems (novalike variables and dwarf novae in outburst), and to a number of apparent discrepancies between observations and the theory of the boundary layer between the accretion disk and the surface of the white dwarf. Discussed are EUV and X-ray light curves, dwarf nova oscillations, and spectra, with new and previously unpublished results on SS Cyg and OY Car.

1. Introduction

In 1985 Patterson & Raymond presented a simple and appealing picture of the X-ray emission of nonmagnetic CVs which for many has become the “standard model” (Patterson & Raymond 1985a; b). The essence of this model is embodied in Figure 8 of Patterson & Raymond (1985a): (1) the X-ray emission is produced in the boundary layer between the accretion disk and the surface of the white dwarf; (2) when the accretion rate $\dot{M}$ onto the white dwarf is low (e.g., dwarf novae in quiescence), the boundary layer is optically thin and quite hot; (3) when $\dot{M}$ onto the white dwarf is high (e.g., novalike variables and dwarf novae in outburst), the boundary layer is optically thick and quite cool; and (4) even when $\dot{M}$ is high, there invariably will be a hot, optically thin “atmosphere” on the otherwise cool boundary layer. At one extreme, the boundary layer can be as hot as the virial temperature $kT_{\text{vir}} = GM_{\text{wd}}\mu m_{\text{H}}/3R_{\text{wd}} \sim 50$ keV, and, at the other extreme, as cool as the blackbody temperature $kT_{\text{bl}} = k(GM_{\text{wd}}/8\pi\sigma R_{\text{wd}}^3)^{1/4} \sim 10$ eV. The boundary layer luminosity is $L_{\text{bl}} \approx 0.5 \times \zeta \times GM_{\text{wd}}\dot{M}/R_{\text{wd}} = 8 \times 10^{34} \zeta (M_{\text{wd}}/M_\odot)(\dot{M}/10^{-8} M_\odot \text{yr}^{-1})(R_{\text{wd}}/5 \times 10^8 \text{ cm})^{-1} \text{ erg s}^{-1}$, where the factor $\zeta$ accounts for the rotation of the white dwarf: $\zeta \equiv [1-(v/v_{\text{break}})^2]]^2$, where $v$ is the rotation velocity and $v_{\text{break}} = (GM_{\text{wd}}/R_{\text{wd}})^{1/2}$ is the breakup velocity of the white dwarf. The boundary layer luminosity is reduced significantly only if $v/v_{\text{break}} \gtrsim 0.3$ or $v \gtrsim 1600 (M_{\text{wd}}/M_\odot)^{1/2}(R_{\text{wd}}/5 \times 10^8 \text{ cm})^{-1/2} \text{ km s}^{-1}$, whereas $v \sin i < 200 \text{ km s}^{-1}$ for U Gem (Sion et al. 1994), $\approx 600 \text{ km s}^{-1}$ for VW Hyi (Sion et al. 1995), and possibly $\approx 300 \text{ km s}^{-1}$ for SS Cyg (Mauche 1997c).

Narayan & Popham (1993) and Popham & Narayan (1995) have recently supplied more detailed theoretical treatments of the boundary layers of CVs. In high-$\dot{M}$ systems, Popham & Narayan distinguish between the “dynamical boundary layer” very near the surface of the white dwarf where the disk mate-
rial switches from rotation to pressure support and the angular velocity deviates significantly from Keplerian, and the much more extended “thermal boundary layer” where the boundary layer luminosity is radiated. The structure of the boundary layer and the resulting radiation spectrum depend on the mass-accretion rate and the white dwarf’s mass and rotation velocity; for $M_{\text{wd}} = 0.6\text{–}1.0 \, M_\odot$ the peak effective temperatures are $kT_{\text{eff}} \approx 17\text{–}30 \, \text{eV}$, but this can be reduced further if $v/v_{\text{break}} > \sim 0.1$.

To test these and other theoretical models of the boundary layers of CVs, we present and discuss below some of the observational aspects of the EUV and X-ray emission of nonmagnetic CVs. For another recent review, see Verbunt (1996).

2. Light Curves

The physical location of the source of the X-ray emission in nonmagnetic CVs is constrained by (1) the variation of apparent emission measure with inclination (van Teeseling et al. 1996), (2) the relative strength of the line and continuum spectrum reflected off the white dwarf and accretion disk (e.g., Done & Osborne 1997), and (3) the X-ray light curves of eclipsing systems. All these constraints imply that all or most of the hard X-rays are emitted very close to the white dwarf, but the eclipse observations are the most direct and unambiguous. In Z Cha ($i \approx 82^\circ$; van Teeseling 1997a) and HT Cas ($i \approx 81^\circ$; Wood et al. 1995a; Mukai et al. 1997) in quiescence, the X-rays are fully eclipsed for $\Delta \phi \sim 0.04$, comparable to the length of the optical eclipse of the white dwarf. From the high-quality ASCA X-ray light curve of HT Cas (Fig. 1), the duration of the ingress/egress is measured to be $\Delta \phi \approx 0.004$, implying that the size of the X-ray emission region $R_X \lesssim 1.15 \, R_{\text{wd}}$. 

![ASCAX-ray_light_curve_HTCas](image-url)  

Figure 1. Folded ASCA light curve of HT Cas in quiescence (after Mukai et al. 1997).
In sharp contrast to the compact source of hard X-rays in low-\(\dot{M}\) systems, there is strong evidence for an extended source of EUV/soft X-rays in high-\(\dot{M}\) systems. *EXOSAT* light curves of OY Car (\(i \approx 83^\circ\)) in superoutburst (Naylor et al. 1988) and *ROSAT* light curves of the novalike variable UX UMa (\(i \approx 71^\circ\); Wood et al. 1995b) rule out an eclipse by the secondary of a compact source of X-rays centered on the white dwarf. In both cases, it is argued that the boundary layer is obscured from view by the accretion disk at all orbital phases, and that the observed X-rays come from a corona or wind above the disk.

The situation is far more complex in U Gem (\(i \approx 70^\circ\)). In quiescence, the hard X-rays are partially eclipsed at orbital phase \(\phi \sim 0.7\) (Szkody et al. 1996), and during outburst the EUV/soft X-rays are partially eclipsed at orbital phases \(\phi \sim 0.7\) and 0.1 (Mason et al. 1988; Long et al. 1996). These dips in the X-ray and EUV light curves are interpreted as due to partial eclipses of the boundary layer by vertical structure at the edge of the accretion disk (\(r \approx 4 \times 10^{10}\) cm) or at the circularization radius of the accretion stream (\(r \approx 5 \times 10^{9}\) cm); in either case, the heights above the orbital plane are distressingly large: \(h \approx 0.5 r\), whereas the disk thickness \(H \approx c_s/\Omega_K \ll r\). The *EUVE* spectra of U Gem in outburst supply additional diagnostic information. The phase-averaged spectrum is a melange of Ne VI–VIII, Mg VI–VII, and Fe VII–X emission lines superposed on a \(kT \approx 12\) eV blackbody continuum (Long et al. 1996). The phase-resolved spectra demonstrate that the eclipses affect the continuum more strongly than the lines (most strikingly, the Ne VIII \(\lambda 88.1\) line is nearly unaffected by the eclipses; see Mauche 1997b), implying that the lines are produced in a region of larger extent than that of the continuum, which presumably is formed in the boundary layer.

To further investigate the nature of the EUV/soft X-ray flux of OY Car, we recently obtained *EUVE* spectra (§4) and light curves of this dwarf nova in superoutburst. The observations were continuous for an interval of \(\approx 3\) days.
near the beginning of the outburst, but useful data is obtained by EUVE for only \(\approx 30\) min of every 94.9 min satellite orbit. Given the 90.9 min orbital period of OY Car, the binary phases advance by only 4% per satellite orbit, so data near the eclipse of the white dwarf is obtained for only 7–8 continuous orbits every \(\approx 40\) hrs. Nevertheless, the larger number of eclipses observed (13 vs. 2) and the higher count rate (0.8 vs. 0.02 counts s\(^{-1}\)) lead to a significant improvement over the previous EXOSAT observations. Typical EUVE Deep Survey (DS) light curves of OY Car are shown in Figure 2. As during the EXOSAT observations, no eclipses are observed in any of the EUVE light curves, implying that the EUV emission region is significantly extended: the size of the emission region must be larger than that of the secondary \((R_{\text{sec}} \approx 1 \times 10^{10}\) cm) and at least comparable to the size of the binary \((a \approx 5 \times 10^{10}\) cm).

3. Dwarf Nova Oscillations

As is well known, CVs manifest a variety of rapid periodic and aperiodic oscillations in their optical and X-ray flux (Warner 1995). The so-called “dwarf nova oscillations” (DNOs; Patterson 1981) of high-\(\dot{M}\) CVs have high coherence \((Q \approx 10^4 – 10^6)\), periods of \(\approx 10–30\) s, amplitudes of \(\approx 10–30\)% in soft X-rays and \(\lesssim 0.5\)% in the optical, and are sinusoidal to high accuracy. X-ray DNOs have been best studied in SS Cyg (Córdova et al. 1980; 1984; Jones & Watson 1992), U Gem (Córdova et al. 1984; Mason et al. 1988; Long et al. 1996), and VW Hyi (van der Woerd et al. 1987). Of these, the DNOs of SS Cyg have been studied most extensively, thanks to numerous HEAO-1, EXOSAT, and EUVE pointings of this dwarf nova in outburst. A strong anti-correlation between the oscillation period and the EUV luminosity (hence, by inference, \(\dot{M}\) onto the white dwarf) has been discovered (Mauche 1996a), the EUV spectrum of the oscillations has been measured (Mauche 1997a), and stringent limits have been placed on the amount of power in higher and lower harmonics of the fundamental (Mauche 1997c). Recently, a new and surprising property of the X-ray DNOs of SS Cyg has been discovered.

SS Cyg was observed in outburst in 1996 October and December by EUVE and ROSAT, respectively. The optical and EUV light curves of the short asymmetric 1996 October outburst are shown in the top panel of Figure 3. The figure demonstrates the well-known lag on the rise to dwarf nova outbursts between the optical and shorter wavelength flux (for additional information, see Mauche & Mattei 1997). The bottom panel of Figure 3 shows the evolution with time of the period of the EUV oscillation. During the rise to outburst, the period of the oscillation fell from 7.8 s to 6.6 s, jumped discontinuously (“tunneled”) to 2.90 s, and then fell to 2.85 s over an interval of 4.8 hr before observations with the EUVE DS were terminated. When observations with the DS instrument resumed on the decline from outburst, the period was 6.7 s and rose to 8.2 s over an interval of 2.1 days. During the ROSAT observations of the plateau phase of the subsequent long asymmetric 1996 December outburst, the period of the oscillation was observed to rise from 2.80 s to 2.92 s over an interval of 4.2 days (van Teeseling 1997b).
These observations set two precedents for DNO research: (1) periods below 7 s and (2) period doubling. While period doubling has never been observed before in the optical or X-ray wavebands, its “seeds” may have been observed in EUVE observations of the long asymmetric 1994 June/July outburst of SS Cyg (Mauche 1997c). During the optical plateau phase of the outburst, the amplitude of the first harmonic relative to the fundamental was 11%, whereas during the peak of the outburst, it was 30%. Perhaps at even higher EUV luminosities (hence, by inference, higher $\dot{M}$ onto the white dwarf), the power switches entirely into the first harmonic. That the $\sim 3$ s period is the first harmonic of the $\sim 6$ s fundamental is suggested by the smooth extrapolation of oscillation period with time shown in the lower panel of Figure 3. However, it is also possible to consider the $\sim 3$ s period the fundamental and the $\sim 6$ s period the first subharmonic. The Keplerian period at the surface of the white dwarf in SS Cyg
is \( P = 3.76 \left( \frac{R_{\text{wd}}}{3.85 \times 10^8 \text{ cm}} \right)^{3/2} \left( \frac{M_{\text{wd}}}{1.2 \text{ } M_{\odot}} \right)^{-1/2} \text{ s.} \) For the Keplerian period to equal the observed minimum period of 2.80 s, the mass of the white dwarf must be \( M_{\text{wd}} = 1.27 \text{ } M_{\odot}. \) It would be very useful to firmly confirm or exclude this value by independent means. Furthermore, it would be helpful to have data on the upward and downward transitions of the period doubling, to obtain simultaneous optical and/or UV data, and to determine if this behavior is manifested by other dwarf novae. An important question to consider is whether period doubling has never been observed in the optical simply because the typical integration times were too long.

4. Spectra

Many of the spectroscopic aspects of the X-ray emission of nonmagnetic CVs are discussed by Mauche (1997b) and consequently will not be reproduced here. We limit the discussion here to (1) the low boundary layer luminosities of high-\( \dot{M} \) systems, (2) the unique nature of the EUV/soft X-ray emission of SS Cyg, and (3) the EUV spectrum of OY Car.

One of the basic predictions of theoretical models of (thin) disk accretion onto a central object is that the ratio of the boundary layer to accretion disk luminosity is of order unity unless the central object is rotating near breakup. From §1, the ratio \( L_{\text{bl}}/L_{\text{disk}} = \left[ 1 - \left( \frac{v}{v_{\text{break}}} \right) \right]^2 \equiv \zeta. \) From the inferred white dwarf rotation rates, \( \zeta > 0.92 \) for U Gem, \( \approx 0.90 \) for SS Cyg, and \( \approx 0.64 \) for VW Hyi (Mauche 1997c). In sharp contrast, \( L_{\text{bl}}/L_{\text{disk}} \approx 0.45 \) for U Gem (Long et al. 1996), \( \lesssim 0.07 \) for SS Cyg (Mauche et al. 1995), and \( \sim 0.04 \) for VW Hyi (Mauche et al. 1991; Mauche 1996b). While we must acknowledge that our understanding of the intrinsic spectral energy distribution of the accretion disk and boundary layer is far from certain (and hence the assumed bolometric corrections are far from certain), it becomes increasingly clear that the boundary layer luminosities of high-\( \dot{M} \) CVs often fall far short of the values predicted by simple theory. While this result is seized on with relief by wind modelers (e.g., Drew 1997), it remains for boundary layer modelers a serious unsolved theoretical problem.

Another apparent discrepancy between theory and observations is the effective temperature of the boundary layer. Theory predicts \( kT_{\text{eff}} \approx 17-30 \text{ eV} \) (§1), but among the many high-\( \dot{M} \) nonmagnetic CVs detected during the ROSAT All-Sky Survey (Beuermann & Thomas 1993; Verbunt et al. 1997), only SS Cyg in outburst displayed such a soft spectral component. The boundary layer of U Gem is too soft (\( kT \approx 12 \text{ eV} \); Long et al. 1996) and that of VW Hyi is too dim and too soft (\( kT \lesssim 10 \text{ eV} \); Mauche et al. 1991; Mauche 1996b) to be detected by ROSAT. Recklessly assuming that the other high-\( \dot{M} \) nonmagnetic CVs suffer from similar inadequacies, SS Cyg in outburst stands out as unique in manifesting a relatively hard (\( kT \approx 20-30 \text{ eV} \); Mauche et al. 1995; Ponman et al. 1995) soft X-ray spectral component.

In §2 we argued that the absence of eclipses in the EXOSAT and EUVE light curves of OY Car in superoutburst evidence an extended and hence optically thin EUV/soft X-ray emission region. That this region is indeed optically thin is demonstrated by the EUV spectrum accumulated during the EUVE observations (Fig. 4). Superposed on a very weak continuum are emission lines
of such species as O V–VI, Ne V–VI, Mg IV–VI, and Fe VI–X; species which dominate in collisionally ionized gas at $T \approx 2–10 \times 10^5$ K. Of the existing EUVE spectra of high-$M$ CVs, this spectrum looks most like that of U Gem in outburst (Long et al. 1996; Mauche 1997b), but it has a significantly weaker and, with no flux shortward of $\sim 100$ Å, cooler continuum. That the emission line region of OY Car is also cooler than that of U Gem is indicated by the absence of the Ne VII $\lambda 97.5$ and Ne VIII $\lambda 88.2$ emission lines prominent in the EUV spectrum of U Gem. A Mewe et al. (1985) coronal model does a very poor job of reproducing the observed spectrum, but without additional work it cannot be completely excluded that the poor match is due simply to incomplete atomic data. A much better match is made with a model using the Verner et al. (1996) list of permitted resonance lines. If these preliminary conclusions survive detailed analysis, they argue that resonant scattering of the boundary layer continuum and not thermal emission from a shocked wind is the cause of the observed EUV flux of OY Car (Raymond & Mauche 1991).

Acknowledgments. We are grateful to K. Mukai for kindly supplying the data shown in Fig. 1. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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