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The EUV Emission of Cataclysmic Variables

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ABSTRACT. Approximately half the luminosity of a typical cataclysmic variable may emerge as an optically thick component peaking in the EUV. Observations of this component are important for understanding the energetics and accretion rates of CV's in general, as well as for understanding the physics of the accretion process. The nature of the turbulent boundary layers and winds of disk accretors and the heating of the white dwarfs by accretion are among the problems which can be addressed by observations in the EUV.

INTRODUCTION

The process of accretion dominates the appearances and energetics of objects as diverse as protostars and Active Galactic Nuclei, yet the physics of accretion is poorly understood. Gas accreting by way of a disk must shed nearly all of its angular momentum. While the angular momentum transport can be successfully parameterized in the α disk models, it is variously ascribed to convective turbulence (Cannizzo and Cameron 1988) or magnetic turbulence (Coroniti 1981). Other models assume that the interaction between a large scale magnetic field and a disk wind (Blandford and Payne 1982; Pudritz and Norman 1983; Koen 1986) transports the angular momentum.

Cataclysmic variables are binary systems containing white dwarfs which accrete material from normal companions. They offer enormous possibilities for testing models of accretion physics. They are bright enough for detailed study at many wavelengths. The components of the binary systems are understood and their masses and radii can be measured. CVs also display a wide range of time variability - from quasi-periodic oscillations (QPO) at tens of seconds to flickering, outbursts, and eclipses, all of which can be used to examine the CV structure in detail. Cataclysmic variables are fascinating objects in their own right, as well. They represent late stages of binary star evolution, the outcome of a common envelope phase, and they are likely progenitors of the ever-popular Type I supernovae.

Quite a few CVs are located within 100 pc of the Sun, and the combination of modest distance with high temperature makes them promising EUV targets. Hydrogen column densities toward four systems have been obtained from IUE high resolution spectra, and they give $\tau = 1$ at 178 Å, 147 Å, 126 Å, and 108 Å (IX Vel, SS Cyg, V3885 Sgr, and RW Sex, respectively; Mauche, Raymond and Córdova 1988). VW Hyi seems to have the lowest measured column density, estimated at $10^{17.8}$ cm^{-2} (Polidan and Mauche, this volume). If one assumes equal H and He opacities, this implies optical depth one at

450 Å.

Three important questions can be addressed by EUV observations: the white dwarf temperatures call for an explanation; the physical processes in, and even the luminosities of, the boundary layers need to be determined; and, the mass loss, energetics, and dynamics of cataclysmic variable winds challenge theoretical models.

WHITE DWARF TEMPERATURES

Temperatures and luminosities of the white dwarfs in CVs are substantially larger than those of field white dwarfs. The typical temperature is around 25,000 K, but temperatures as low as 10,000 K and as high as 75,000 K have been inferred from eclipse light curves, optical or IUE spectra (e.g., Szkody, Downes, and Mateo 1988). The high temperatures have been attributed to reprocessing of hard X-rays produced just above the white dwarf surface by accretion (Patterson and Raymond 1985b), the energy released by the change in white dwarf structure with increasing mass (Sion 1985), luminosity from continuing accretion in the low state (Shafter *et al.* 1985), nuclear burning (Fabbiano *et al.* 1981), or cooling of surface layers heated during times of higher accretion rates. The last mechanism has been strongly supported by the observation that the white dwarf in the dwarf nova system U Gem cooled from about 40,000 K to about 30,000 K during 103 days between outbursts (Kiplinger, Sion and Szkody 1988).

Most of these systems are cool enough and rich enough in helium that they will be hard to observe shortward of the He II edge at 228 Å, so that only a few systems will be observable. EUV observations would be most useful not for determining a white dwarf temperature but for looking for temperature variations across the white dwarf surface. Kiplinger, Sion and Szkody (1988) found evidence for a range of temperatures on the surface of the white dwarf in U Gem from the broad range of ionization states present. Unlike DA white dwarfs, these objects have substantial metal abundances in their outer layers. Spectral resolution adequate to separate the absorption edges of many ions in various energy levels will be needed for this study. For example, Vennes *et al.* (1989) show that EXOSAT transmission grating observations of Feige 24 can be understood as a large number of weak absorption features smeared by the modest spectral resolution and statistical quality of the data. Williams, King and Booker (1987) present models of the EUV emission of a white dwarf surface illuminated by hard X-rays.

BOUNDARY LAYER EMISSION

Unless the accreting white dwarf is rotating nearly at breakup, half the accretion luminosity is liberated in a narrow region where the accretion disk encounters the white dwarf surface and the kinetic energy of the Keplerian rotation is dissipated. It has been suggested that this energy may be efficiently converted into kinetic energy of a wind or jet (Torbett 1984; Pringle 1989), though most models predict that the energy is radiated away in the form of hard X-rays at low accretion rates or blackbody emission with $kT_{bb} \sim 30$ eV at high accretion rates (Pringle 1977; Tylenda 1981; Pringle and Savonije 1979; Kley and

Hensler 1987). This accords well with the observed hard X-ray emission from dwarf novae in quiescence (Córdova *et al.* 1981; Patterson and Raymond 1985a) and the strong soft X-ray emission of a half dozen nova-like variables and dwarf novae in outburst (SS Cyg, U Gem, IX Vel, VW Hyi, OY Car, RW Sex and V3885 Sgr; see van der Woerd 1987). So far, these observations have been made either with proportional counters or with broad-band filters, so that only a combination of the blackbody temperature and the absorbing column density can be determined. Thus the luminosities of the soft X-ray components are poorly constrained.

The lack of detections of old novae in soft X-rays and difficulties in reconciling the observed ionization states of UV line emitting regions and CV winds have led to suggestions that the boundary layer emission is far weaker than expected (Jensen 1984; Ferland *et al.* 1982) or drastically attenuated by photoelectric absorption close to the white dwarf (Kallman and Jensen 1985). On the other hand, Patterson and Raymond (1985b) argue that a slightly lower boundary layer temperature and interstellar absorption explain the lack of soft X-rays from CVs more distant than those listed above, and they find that boundary layer emission at about the predicted level can explain the He II emission lines seen in the optical and UV spectra of high accretion rate CVs.

Strong quasi-periodic oscillations near 20 s with amplitudes of 15-20% are another outstanding feature of the boundary layer emission. They have been observed in soft X-rays during outbursts of the dwarf novae U Gem and SS Cyg (Córdova *et al.* 1984) and VW Hyi (van der Woerd *et al.* 1987), and it is likely that the optical QPO with similar frequencies but smaller amplitudes result from reprocessing of the soft X-rays by the accretion disk (see Patterson 1981).

No theoretical explanation for these QPO is compelling. Purely hydrodynamic instabilities near the Keplerian frequency have been demonstrated (Carroll *et al.* 1985), and the interaction of the disk with a moderate strength white dwarf magnetic field has been suggested (B. Warner and D. Lamb, private communication), but until observations reveal the basic characteristics of the oscillations, such as a correlation (or lack of same) between temperature and luminosity, it will be impossible to test theoretical ideas. EUV observations to discriminate among them will require good time resolution and enough spectral coverage to discriminate, for instance, between changes in temperature and changes in absorbing column density as causes for the oscillations. Spectral resolution capable of measuring absorption edges should suffice, as the boundary layer is believed to be very optically thick in high accretion rate systems. In low accretion rate systems (dwarf novae in quiescence), higher temperature optically thin emission dominates, and one might hope to see such features as the Fe XXIV line at 192 Å. The strength of this feature will be sensitive to photoionization, and therefore to processes such as thermal conduction which might redistribute energy between hot and cool regions in the accreting gas. Thus models such as that of King and Smith (1986) might be testable. As an example of the likely strength of the line, a calculation of simple, constant pressure cooling of gas from 30 keV with self-consistent photoionization shows a substantial shift in the temperature at which Fe XXIV occurs (Figure 1) and a luminosity in the 192 Å line of 0.0015 L_{η}. This line may be difficult to observe in most CVs ($\tau \sim 4$ for SS Cyg), but the 132 Å line of Fe XXIII should be similar in luminosity and less absorbed. The width of these lines ought to be a fair fraction of the Keplerian velocity near the white dwarf surface, so a spectral resolution of 1000 should be adequate. Variations of the line strength at the radiative cooling time scale could be expected to reveal the structure of the thermally unstable cooling gas, so time resolution of about a second is desirable.

WINDS

High velocity winds are apparent from the first IUE spectra of the dwarf nova SS Cyg in outburst (Heap *et al.* 1978). Subsequent observations (e.g., Guinan and Sion 1982; Córdova and Mason 1982) showed velocities around 5000 km/s and mass loss rates of at least $10^{-10} M_\odot \ yr^{-1}$. Theoretical models of the P Cygni profiles produced by winds illuminated by accretion disks showed that CV winds accelerate slowly relative to typical O-star winds and that they are modestly collimated (Drew and Verbunt 1985; Drew 1986; Mauche and Raymond 1987). Eclipsing systems generally show only weak orbital modulation of their C IV emission, indicating that the line is formed in a region at least as large as the accretion disk (Holm *et al.* 1982), though Drew and Verbunt (1987) find strong orbital modulation of the P Cygni profile of YZ Cnc during superoutburst. The mass loss rate in the wind and its kinetic energy are significant fractions of the accretion mass transfer rate and accretion luminosity, respectively. Thus it is important to know what part accretion disk winds play in the accretion process and the binary system evolution. In particular, if the large-scale magnetic field of the disk is strong enough to couple the disk to the wind, the angular momentum carried away by the wind may dominate over angular momentum transfer in the disk and angular momentum loss by magnetic braking of the red companion star.

The central physical question is the nature of the driving force behind the wind. While the wind velocities could be reached by a wind driven by radiation pressure in spectral lines, much like an O-star wind, the mass loss rates of the winds may be too large to be supplied by the momentum of the radiation field (Mauche and Raymond 1987; Raymond, van Ballegooijen and Mauche 1989). Magnetically driven winds (Blandford and Payne 1982; Koen 1986) may be able to drive enough mass loss, though it is hard to specify any unique magnetic wind model to test. A possible problem is that if the angular momentum lost from the disk is carried away by a wind, rather than returned to the binary orbit through tidal forces at the edge of the disk, the mass transfer may become catastrophically unstable (see Melia and Lamb 1987). Direct conversion of rotational kinetic energy to wind energy at the boundary layer (Torbett 1984) or magnetic driving of a boundary layer wind (Pringle 1989) have also been suggested, though these explanations are unlikely to predict the correct shapes for the P Cygni profiles of UV resonance lines (Drew 1987; Mauche and Raymond 1987).

A fundamental question which must be answered in order to test any of these ideas is the ionization state of the wind. IUE observations show strong C IV and N V lines, with very weak Si IV. Theoretical models of the winds show that it is very difficult to account for the presence of ions even as low as C IV in the presence of the strong EUV flux from the boundary layer (Kallman and Jensen 1985; Drew and Verbunt 1985; Mauche and Raymond 1987). Suggestions include a mass loss rate so large as to absorb out all the ionizing radiation or shocks in the wind (analogous to those presumed to generate X-rays in O-star winds) which compress the gas by a few orders of magnitude. EUV observations will be a valuable tool for examining the ionization state of the wind, thanks to the presence of strong lines of O V, O VI, Ne VI, Ne VII and Ne VIII below 200 Å. To give an idea of the line profiles to be expected, we have computed models of the 2s-3p line of O VI at 150 Å and the 173 Å 2p-3d line using the codes described in Mauche and Raymond (1987) and assuming that the 2p level population starts at 0.1 and drops off as 1/r. The radiation which must be scattered to make these lines originates in the boundary layer, rather than in the disk at around 10 white dwarf radii, as is the case for the C IV λ1550 doublet. These lines are also much less opaque than the O VI λ1034 doublet. Therefore, comparison of the EUV lines with UV lines observed by IUE or HST can reveal a great deal about the geometry and velocity structure of the wind. Figure 2 shows the profiles for inclinations of 0°, 30°, 60° and 90°. The heavy lines assume a mass loss rate of 10^{-10} $M_{\odot}$ yr^{-1}, while the dotted lines refer to an order of magnitude lower mass loss rate. Thus we predict that these lines will be easily observable during outbursts of nearby dwarf novae, such as SS Cyg.

Another interesting observation will provide a check on shocks in CV winds. A superoutburst of the eclipsing dwarf nova OY Car was observed by EXOSAT (Naylor *et al.* 1988). While the light curves at low accretion rates show that the white dwarf is eclipsed by the companion star, the X-ray emission is not eclipsed, indicating that it originates in a region at least as extended as the accretion disk. The low X-ray luminosity and the ratio of the count rates in the EXOSAT bands set OY Car apart from other CVs seen as soft X-ray sources, so it is likely that we are seeing boundary layer emission from the other systems, but in OY Car the X-rays must come from a more extended region. One possibility is that shock waves produce the X-rays just as in O stars (Lucy and White 1980). This is energetically difficult, but possible, considering the large kinetic energy of the wind and the efficiency with which that energy may be converted to X-rays by ~ 300 km/s shocks in the wind (Krolik and Raymond 1985). On the other hand, scattering of boundary layer emission by O V, O VI and other ions in the wind might also account for the observations. The edge-on model in Figure 2 indicates that each of the optically thick lines might be seen as a strong emission line with a width comparable to the wind terminal velocity. We estimate that if each of the strong lines of N V, O V and O VI (ten lines altogether) isotropically scatters 3 Å of the continuum of a 250,000 K boundary layer at the expected boundary layer luminosity, the Lexan band count rate reported by Naylor *et al.* can be matched. Provided that the hydrogen column density is fairly low (2×10^{19} cm^{-2}), the Al-Pa band count rate is also matched. Inclusion of the Ne lines at somewhat shorter wavelengths might tend to increase the count rate in the Lexan band too much compared with the Al-Pa count rate, however. The scattering hypothesis predicts very weak emission in non-resonance lines, such as the 2p-3d line in the second panel of Figure 2, while a shock emission model would predict a stronger 173 Å line than 150 Å line.

SUMMARY

Observations of cataclysmic variables between 100 and 300 Å can reveal a great deal of information about the nature of the boundary layers and winds of these objects. Dwarf novae in outburst are the most promising targets, as several are known to be bright at these wavelengths. Spectral resolution of a fraction of an Ångstrom should be adequate for most observations because of the large line widths anticipated.

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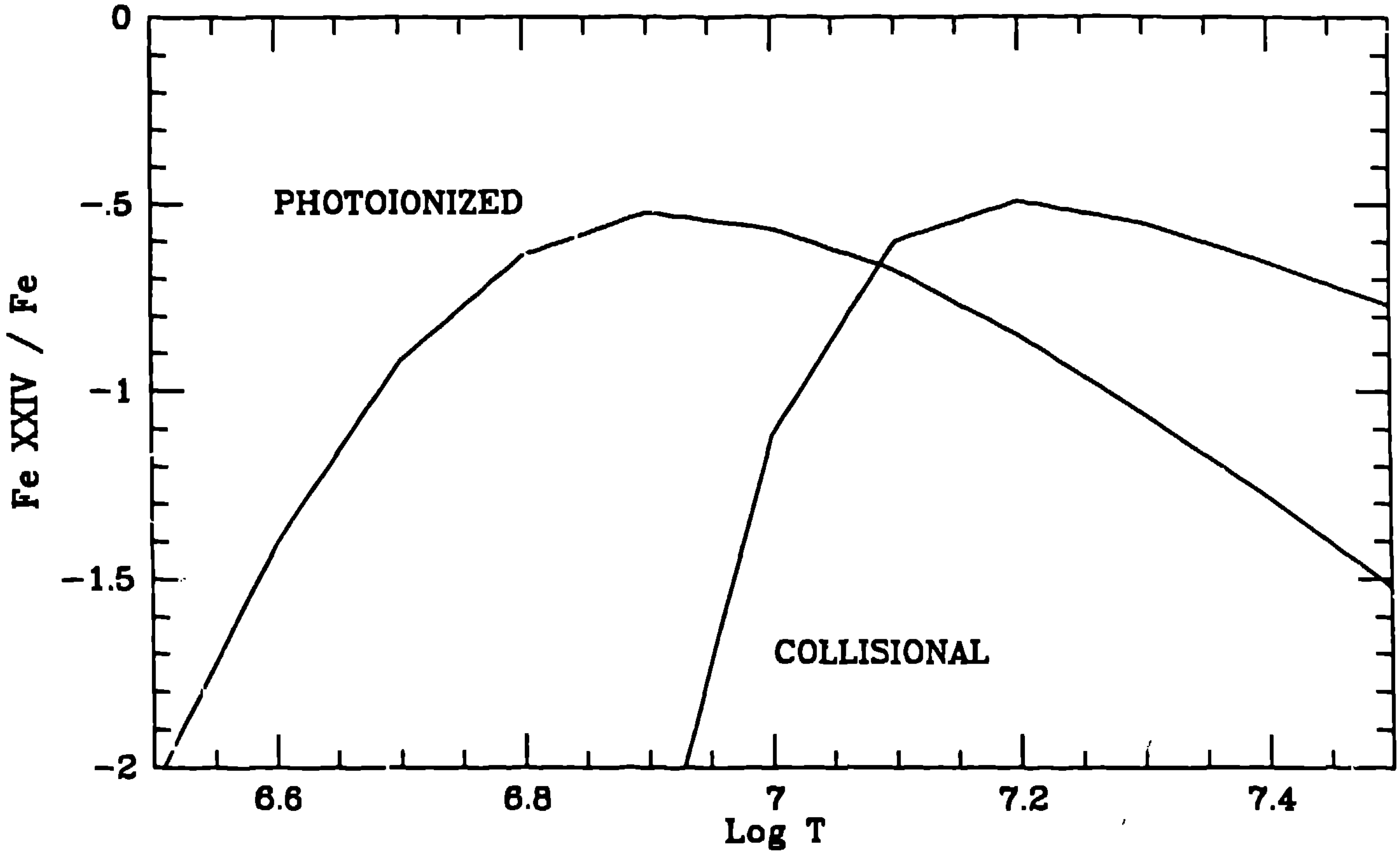
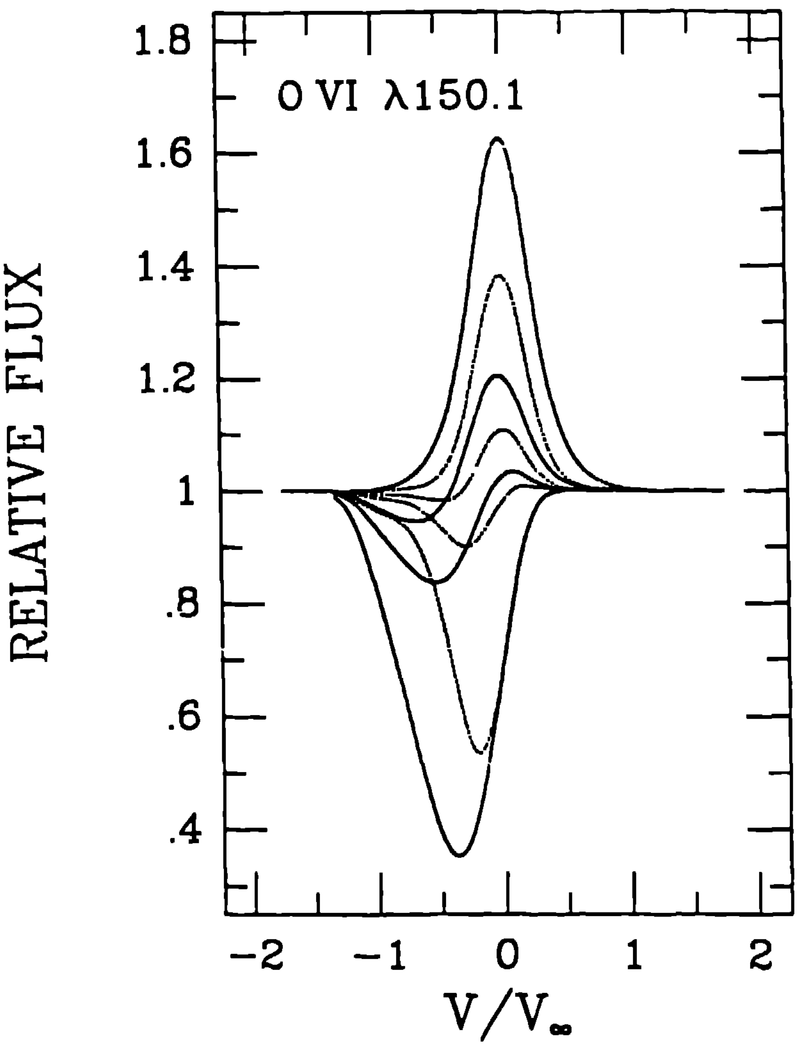
Figure Captions

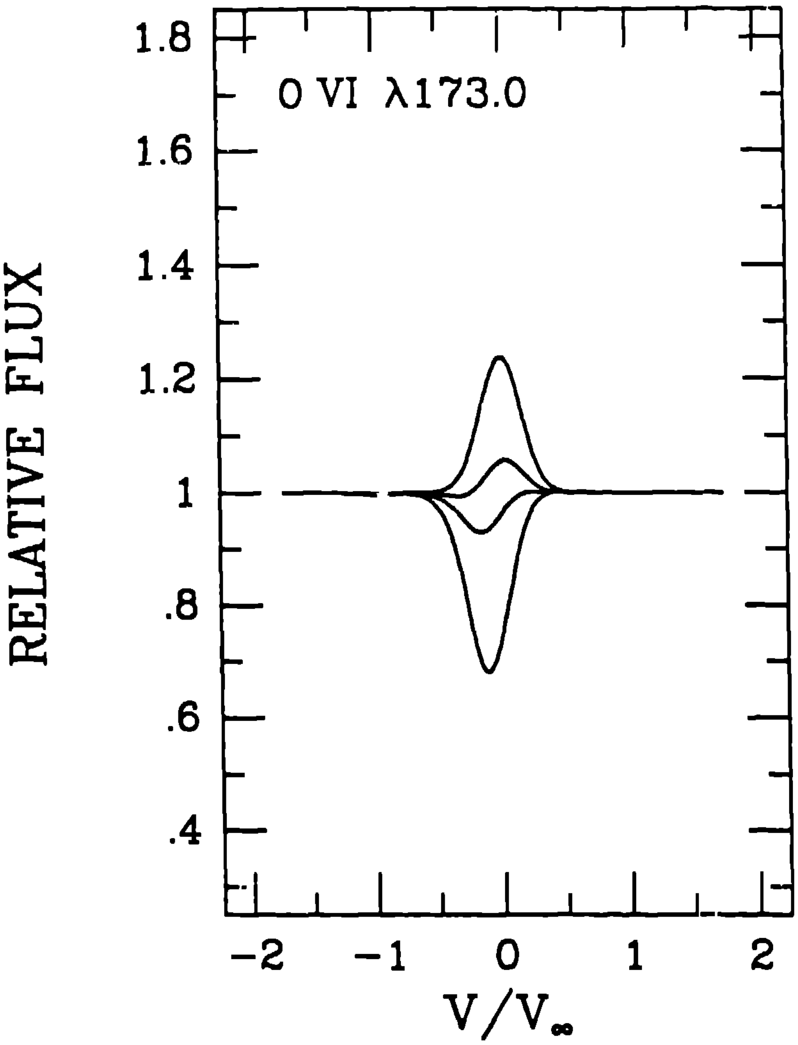
Figure 1. Fraction of iron in the lithium-like ionization state Fe XXIV as a function of temperature for collisional equilibrium and with photoionization by X-rays taken into account.

Figure 2. Predicted P Cygni profiles of the O VI 2s-3p and 2p-3d lines assuming 1 Å resolution. Highest curve is for an edge-on system, and lowest is for a face-on accretion disk.



PHOTOIONIZED
COLLISIONAL
Fe XXIV / Fe
Log T
0
-.5
−1
−1.5
−2
6.6
6.8
7
7.2
7.4


O VI λ150.1
RELATIVE FLUX
1.8
1.6
1.4
1.2
1
.8
.6
.4
−2
−1
0
1
2
V/V∞


O VI λ173.0
RELATIVE FLUX
1.8
1.6
1.4
1.2
1
.8
.6
.4
−2
−1
0
1
2
V/V∞