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X-RAY EMISSION FROM CATACLYSMIC VARIABLES WITH ACCRETION DISKS.
II. EUV/SOFT X-RAY RADIATION

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ABSTRACT

About half of the gravitational luminosity released by gas accreting onto a white dwarf through a disk should emerge from the star/disk *boundary layer*. For the accretion rates present in many cataclysmic variables, theory predicts that this luminosity should be in the form of an optically thick EUV/soft X-ray component, with $T_e \approx (1\text{–}3) \times 10^5$ K. We compare the theoretical predictions with presently available soft X-ray observations and find satisfactory agreement. Previous doubts on this point were based on inappropriate choices for several critical parameters: white dwarf mass, interstellar column density, and the space density of classical novae. We also attempt to constrain the boundary layer radiation by comparing observed and predicted strengths of the He II λ1640 and λ4686 emission lines, assuming that these are produced by photoionization in the upper layers of the disk. The results support the simple optically thick model for high-$\dot{M}$ systems, but may require complicated X-ray spectra in low-$\dot{M}$ systems.

Subject headings: accretion — stars: dwarf novae — X-rays: binaries

I. INTRODUCTION

In the preceding paper (Patterson and Raymond 1985, hereafter Paper I) we have discussed the observations of hard X-ray emission from cataclysmic variables (hereafter CVs) with accretion disks and found considerable support for a model in which the hard X-rays are radiated by hot gas in the optically thin portion of the star/disk boundary layer. Both theory (Pringle and Savonije 1979; Tylenda 1981*a*) and observation (Paper I) suggest that the entire boundary layer is optically thin for accretion rates $< 10^{16}$ g s^{-1}. For the much higher accretion rates present in the intrinsically bright systems ($\sim 10^{18}$ g s^{-1}), the boundary layer is expected to be optically thick, and should radiate $\sim 10^{35}$ ergs s^{-1} at EUV/soft X-ray wavelengths (Pringle 1977; Pringle and Savonije 1979). But despite intensive observation of nearly 100 of the most plausible candidates, and all-sky coverage for the possibility of serendipitous discovery, only *two* CV disk systems have been found with bright soft X-ray components which might represent the predicted radiation (SS Cyg: Córdova *et al.* 1980; U Gem: Córdova *et al.* 1984). The many nondetections have led some authors to doubt whether these observations can be reconciled with boundary layer theories (Becker 1981; Jensen 1984; and especially Ferland *et al.* 1982*a*).

In this paper we reconsider the question of how presently available soft X-ray observations can constrain models of optically thick boundary layers. In § II we show how the nondetection of the best studied system, the old nova V603 Aquilae, can be converted into an upper limit on the boundary layer *temperature*. In § III we develop a simple boundary layer model, following Pringle (1977). We compare the model's predictions with observations and find that *a simple optically thick model is fully consistent with the observations*. In § IV we suggest which stars are promising candidates for future observation at soft X-ray wavelengths. In § V we discuss, and dismiss, the problem of the lack of *serendipitous* detection of old novae at soft X-ray wavelengths. In § VI we calculate the predicted strengths of the He II emission lines, assuming that these are the result of photoionization by boundary layer radiation. In high-$\dot{M}$ systems the predictions compare favorably with observation, but in low-$\dot{M}$ systems the observed emission-line strengths are difficult to understand.

II. TEST CASE: V603 AQUILAE

For accretion disk systems with $\dot{M} > 10^{16}$ g s^{-1}, the simple gravitational models predict that the bulk of the boundary layer (BL) luminosity should appear at EUV/soft X-ray wavelengths. The most basic observer's question is this: Is it possible to locate as much as half of the total accretion luminosity in this region without violating any of the observational limits?

Before confronting this question in general, let us approach it by considering the data for the best studied high-$\dot{M}$ system, the old nova V603 Aquilae. The observed flux distribution is shown in Figure 1. The IR/optical/UV component, labeled "DISK," is taken from the data of Ferland *et al.* (1982*b*), with no correction for interstellar absorption (which is unimportant in this context). The hard X-ray component is taken from the *Einstein* IPC/MPC observation of Drechsel *et al.* (1983). They found a very hard spectrum, with a bremsstrahlung temperature $kT_{\text{brems}} \gtrsim 20$ keV, and we have displayed the observed fluxes for two extreme choices of temperature. The shading indicates an additional assumed uncertainty of a factor of 2 at every frequency in the X-ray region, in order to allow for source variability and for our ignorance of what the spectral shape really is. Thus the true X-ray flux distribution should lie wholly within the shade region.

To calculate the EUV light of the BL, we shall assume that it

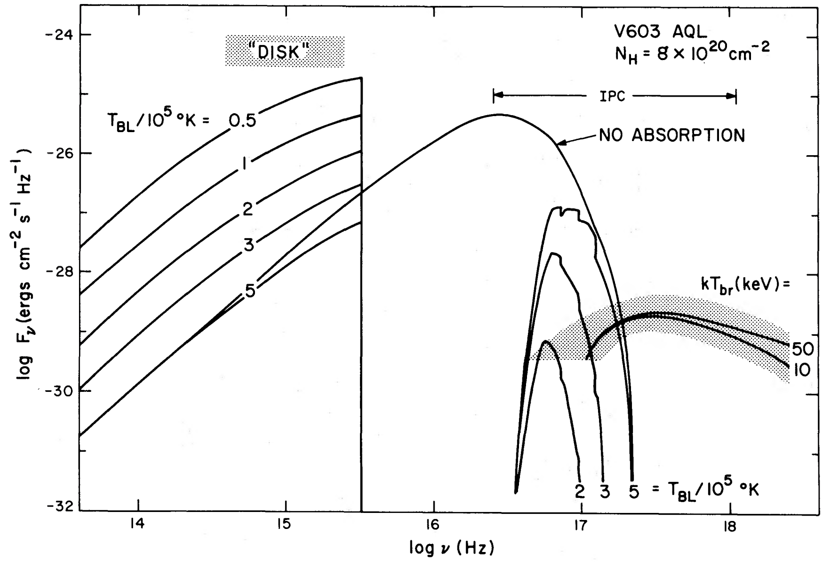

FIG. 1.—Observed flux distribution of V603 Aql. The curves labeled 0.5, 1, 2, 3, 5 are blackbody distributions of various temperatures, modified by an interstellar absorption $N_H = 8 \times 10^{20}$ cm^{-2}, and possessing a total luminosity equal to half of the disk luminosity. One of the unabsorbed blackbody curves, with $T = 5 \times 10^5$ K, is also shown for comparison.

radiates as a blackbody[1] of uniform temperature, with a luminosity equal to half of the full disk luminosity (it is likely, or at least possible, that about half of the photons from the BL will be intercepted by the white dwarf and disk, and thereby lost). If there are no severe beaming effects, we can work equally well with fluxes, which have the advantage of being observable quantities. From Figure 1 the total disk flux ($\int F_\lambda d\lambda$ from 912 Å longward) is $\sim 5.3 \times 10^{-9}$ ergs cm^{-2} s^{-1}. We have therefore calculated blackbody curves which radiate principally in the EUV and, in the absence of aborption effects, would produce a total flux of 2.7×10^{-9} ergs cm^{-2} s^{-1}. But the X-ray spectrum requires a column density $N_H = 8(\pm 2) \times 10^{20}$ cm^{-2} (Drechsel *et al.* 1983), and this is sufficient to absorb much of the expected soft X-ray flux. In Figure 1 we show the blackbody flux distributions for a range of temperatures, and modified by traversing $N_H = 8 \times 10^{20}$ cm^{-2}. For comparison, we also show the flux distribution for $T = 5 \times 10^5$ K without interstellar absorption.

By comparing theory with observation in the soft X-ray region (log $\nu \approx 17$), it appears that a blackbody boundary layer with the required luminosity could exist, as long as $T_{BL} \lesssim 2 \times 10^5$ K. The actual limit is somewhat less stringent, since the IPC observation sets a limit not on the monochromatic flux, but on the integrated flux within a bandpass, which is not well determined because of the detector's poor energy resolution at low energies (Giacconi *et al.* 1979) and the presence of a fairly strong hard X-ray component. We estimate that these effects degrade the observational limit to $T_{BL} \lesssim 3 \times 10^5$ K.

III. SOFT X-RAY FLUX FROM OPTICALLY THICK BOUNDARY LAYERS: THEORY VERSUS OBSERVATION

How does this limit compare with the *expected* temperature of the BL? This depends critically on the emitting area of the BL. A lower limit to its vertical height is given by the density scale height H_{disk} of the inner disk. Rewriting equation (2.5) of Pringle and Savonije (1979), we find

$$H_{disk} = 4.7 \times 10^6 \dot{M}_{18}^{0.18} M_{0.7}^{-1.2} \text{ cm} , \tag{1}$$

where $\dot{M}_{18}$ is the accretion rate in units of 10^{18} g s^{-1}. Here, and throughout this paper, we parameterize the white dwarf mass $M_{0.7}$ in units of 0.7 $M_\odot$, which is approximately the average value found for white dwarfs in the field (0.6 $M_\odot$, Weidemann 1979) and in CVs (0.6–0.7 $M_\odot$, Shafter 1983). The BL should be larger than H_{disk}, since (1) the extra heat released will increase its vertical extent above that provided by heating in the disk proper, and (2) the optical depth is sufficiently high ($\tau \approx 10$–100 for $\dot{M}_{18} \approx 1$) that the radiation will diffuse out over several scale heights, not just *one*.

Pringle (1977) has estimated the height of the BL by requiring that it be supported in the vertical direction by gas and radiation pressure and pointed out that it may extend outward in radius the same distance (as suggested by Fig. 8 of Paper I), since the radiation released deep in the BL must diffuse outward to escape. We have repeated his calculation under his assumptions, with two minor modifications: (1) our BL has an area which is $(2)^{1/2}$ times bigger, to allow for the possible 45° tilt of the emitting area (see Fig. 8 of Paper I); and (2) we have used the actual height of the $\tau = 1$ surface, rather than simply the density scale height of the disk. Using the expressions for optical depth given by Pringle and Savonije (1979), we find that the $\tau = 1$ surface is at 1.3–1.9 scale heights. Together these corrections lower the effective temperature by an amount ranging from 17% at $\dot{M}_{18} = 0.01$ to 27% at $\dot{M}_{18} = 10$. This representation is too crude for us to proffer these corrections with any great confidence; but in any case, our final conclusions will not depend sensitively on whether or not these corrections are applied.

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[1] Actually, the emergent flux distribution should resemble that of a model atmosphere, which will not *closely* resemble a blackbody because of the effect of: (*a*) Lyman edges of abundant elements if $T \lesssim 2 \times 10^5$ K, and (*b*) the dominant role of electron scattering in the atmosphere (see Fig. 2 of Shakura and Sunyaev 1973). We do not account for these effects, because there are no published model atmospheres of hot high-gravity stars with a solar chemical composition, and because they are probably not extremely important in what follows (since detection in soft X-rays probably requires somewhat higher temperatures).

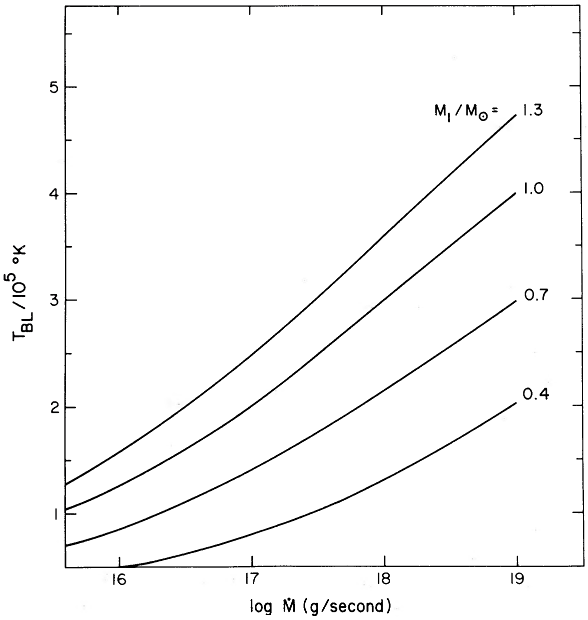

FIG. 2.—The effective temperature $T_{\rm BL}$ of an optically thick boundary layer, as a function of the accretion rate $\dot M$ and the white dwarf mass M. Note the strong dependence on white dwarf mass (approximately $\propto M^{0.86}$).

With these assumptions we find the boundary layer temperatures $T_{\rm BL}$ shown in Figure 2, as a function of accretion rate and white dwarf mass. From the numerical results we can derive approximate analytic formulae for $T_{\rm BL}$ and scale height $H_{\rm BL}$:

$$(H_{\rm BL}/R)^2 = 6.96 \times 10^{-4} M_{0.7}^{-0.85} \dot M_{18}^{0.22} + 7.29 \times 10^{-4} M_{0.7}^{0.80} \dot M_{18}^{1.0} \qquad (2)$$

and

$$T_{\rm BL} = 2.16 \times 10^5 M_{0.7}^{0.86} \dot M_{18}^{0.18}\ {\rm K}\ . \qquad (3)$$

Before proceeding further, we note that for V603 Aql, Figure 2 and the above estimates for $T_{\rm BL}$ and $\dot M$ suggest that the nondetection of a soft X-ray component implies $M_1 \lesssim 1.0\, M_\odot$.

A temperature of 2.1×10^5 K corresponds to a blackbody peak (2.7 kT) at 0.057 keV—well below the low-energy threshold for detection by the IPC. At such low temperatures, the flux transmitted into the observable soft X-ray bandpass (say 0.12–1.0 keV, which is a reasonable approximation to the *Einstein* IPC bandpass for soft sources) is quite small, and declines quite fast with decreasing temperature.[2] This is illustrated in Figure 3, where we have calculated the dependence of the transmitted fraction $p[\equiv F(0.12\text{–}1.0\ {\rm keV})/F_{\rm total}]$ on T and $N_{\rm H}$.

With the aid of Figures 2 and 3, we can calculate the expected soft X-ray flux as a function of $\dot M$, M_1, $N_{\rm H}$, and distance. In comparing with observations, it is especially convenient to calculate the ratio of soft X-ray to visual flux, since this quantity is observable and is approximately independent of distance. In Figure 4 the solid curves show the predicted dependence of $F_{\rm sx}$ (0.12–1.0 keV)/F_v(5000–6000 Å) on $\dot M$, for a standard value of $N_{\rm H} = 2 \times 10^{20}\ {\rm cm}^{-2}$. While interstellar absorption is known to be extremely patchy, this estimate is appropriate for the typical distance of the brighter systems (~150 pc) and the mean $N_{\rm H}$-distance relation found for stars within 1 kpc of the Sun ($1.3 \times 10^{18}\ {\rm cm}^{-2}\ {\rm pc}^{-1}$; Bohlin, Savage, and Drake 1978). At lower right we show the estimated error in $\dot M$, and the correction that should be applied to these theoretical curves for various values of $N_{\rm H}$. Of course, this correction depends on temperature; we have shown the correction which is valid in the domain of maximum interest, namely $\log \dot M = 17.5$ and $M_1 = 0.7\, M_\odot$.

Most of the observed points plotted individually (showing stars identified in a "first-name" basis; see Table 1 of Paper I) are derived from *Einstein* IPC observations of high-$\dot M$ systems, principally dwarf novae in eruption. A complete list of these observations has been given by Córdova and Mason (1983). We do not show stars which yield only uninteresting constraints (e.g., $F_{\rm sx}/F_v < 1$ at $\log \dot M = 16.5$). We have also used the *HEAO 1* survey of erupting dwarf novae and other high-$\dot M$ systems (Table 1 of Córdova *et al.* 1981). This survey yields constraints for 22 stars, but most of them are upper limits quite

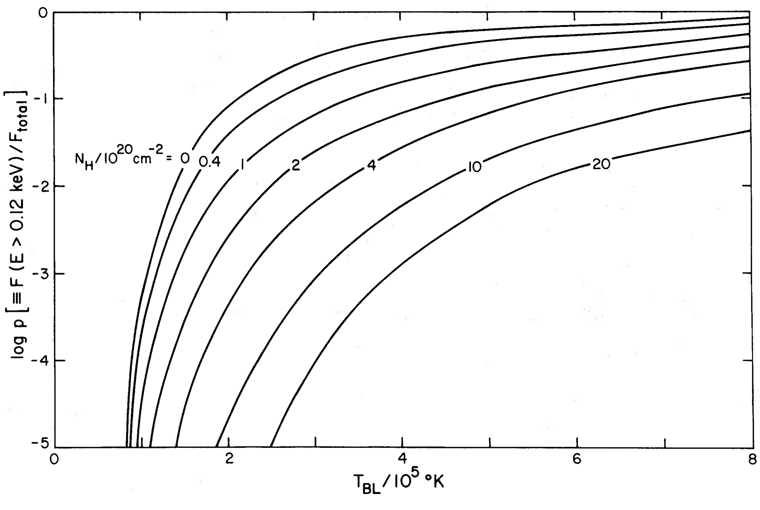

FIG. 3.—The fraction p of blackbody luminosity appearing in the soft X-ray bandpass, as a function of T and $N_{\rm H}$

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[2] Of course, this point has been made many times in the past (e.g., Pringle 1977; Córdova and Mason 1983). But since it is the critical point in the "missing boundary layer" issue, it is surely worth stressing once again.

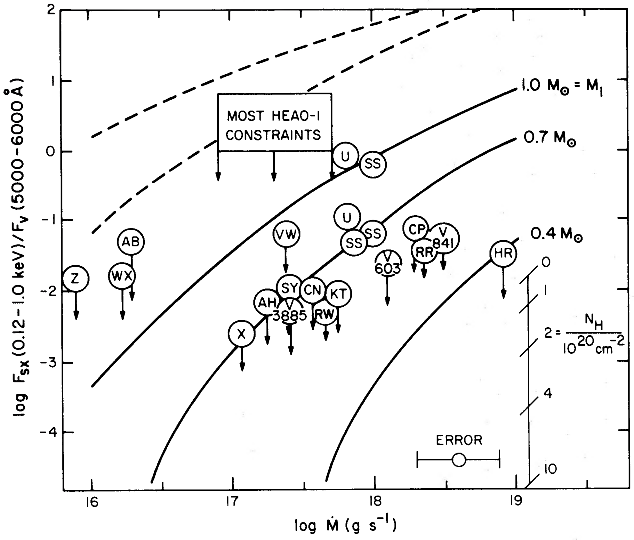

FIG. 4.—*Solid curves* show the theoretical dependence of F_{sx}(0.12–1.0 keV)/F_v(5000–6000 Å) on $\dot{M}$, for three choices of white dwarf mass M_1. An interstellar column density $N_H = 2 \times 10^{20}$ cm^{-2} has been assumed, but at lower right we show how the curves should be shifted for other values of N_H. The plotted points are *HEAO 1* and *HEAO 2* observations and limits. Approximately 19 stars have upper limits residing in or near the box labeled "most *HEAO 1* constraints." *Dashed curves* show the predicted dependence in the boundary layer of Ferland *et al.* (1982*a*), with M_1 fixed at 1 $M_\odot$ and $N_H = 0$ (*upper curve*) or 2×10^{20} cm^{-2} (*lower curve*).

near the box labeled "most *HEAO 1* constraints." To reduce clutter we do not show the individual points, except for U Gem, SS Cyg, and VW Hyi. In order to compare :with the *Einstein* observations, we have converted the 0.18–0.48 keV *HEAO 1* fluxes in Córdova *et al.* (1981) to 0.12–1.0 keV fluxes, assuming $T_{BL} = 3 \times 10^5$ K.

There are other uncertainties which may be important. The estimated error in $\dot{M}$ is probably too small if there are large deviations from steady state accretion flow, which is especially worrisome for the erupting dwarf novae. The observed F_{sx}/F_v ratio can also be somewhat uncertain due to departures from strict simultaneity, and to the inherent problems of calibrating fluxes from low-temperature sources in the proportional counter data. The presence of an outflowing wind in many systems raises the possibility that N_H may be variable (Jensen 1984), which will move points around in Figure 4 in an unpredictable way. Because of these uncertainties, no great significance should be attached to the exact location of individual points. It would not be wise, for example, to interpret the points for U Gem and SS Cyg as evidence for an intrinsic dispersion of F_{sx}/F_v at a given (M_1, $\dot{M}$) combination. In principle, a star's location in this diagram can be used—subject to the aforementioned worries—to constrain M_1, but allowance must be made for N_H. If we adopt the N_H estimates in Table 1 of Paper I and try to deduce white dwarf mass limits from the data in Figure 4, we find that the strongest constraints are $M_1 \lesssim 0.7\ M_\odot$ (for X Leo, SY Cnc, CN Ori, and RW Sex). Most of the constraints are much weaker.

The dashed curves in Figure 4 show the predicted values of F_{sx}/F_v with the temperature law adopted by Ferland *et al.* (1982*a*). As those authors remark, many of the flux limits are 2–4 orders of magnitude below their predictions. However, we believe that this conclusion follows from an inappropriate choice of parameters: 1 $M_\odot$ white dwarfs, no interstellar absorption, and adopted temperatures substantially in excess of these estimated by Pringle (1977) and by us. For the "typical" parameters we favor ($M_1 \approx 0.7\ M_\odot$, $N_H \approx 2 \times 10^{20}$ cm^{-2}, T_{BL} as given in Fig. 2). Figure 4 shows that each of these factors individually lowers the expected F_{sx}/F_v by about an order of magnitude.

We conclude that while the data are obviously insufficient for a severe test, *the observed X-ray fluxes are not inconsistent with the predictions of simple models of an optically thick boundary layer.*

IV. CANDIDATES FOR OBSERVATION

A power-law approximation to our numerical results yields an expected soft X-ray flux

$$F_{sx}(0.12\text{–}1.0\ \text{keV}) = 2.1 \times 10^{-12} \dot{M}_{17.5}^{2.1} M_{0.7}^{8.0} d_{200}^{-4.5}\ \text{ergs cm}^{-2}\ \text{s}^{-1}\ , \quad (4)$$

where d_{200} is the distance in units of 200 pc, and where we have assumed the average N_H-distance relation. Although not valid for values of $\dot{M}_{17.5}$, $M_{0.7}$, and d_{200} far from unity, this equation illustrates the great sensitivity to the three critical parameters. Thus the systems most promising for soft X-ray emission should have a massive white dwarf, a high accretion rate, and a small distance (or fairly transparent line of sight). There are only two stars known which satisfy all three criteria: SS Cygni, with $M_1 = 1.0\text{–}1.3\ M_\odot$, $d = 100$ pc, $\dot{M} \approx 10^{18}$g s^{-1} in eruption (Paper I; Stover *et al.* 1980; Cowley, Crampton, and Hutchings 1980); and U Geminorum, with $M_1 \approx 1.1\ M_\odot$, $d = 80$ pc, $\dot{M} \approx 10^{18}$ g s^{-1} in eruption (Paper I; Wade 1979, 1981; Stover 1981). Happily, these two stars are also *observed* to be the brightest in soft X-rays—in fact, they are the only stars with positive detections.

In order to guide selection of future targets for soft X-ray observation, we present in Table 1 a list of stars which are promising candidates for detection in outburst. As stated above, the selection criteria are: high visual flux, high M_1 (favoring RU Peg, Z Cam, EX Hya, but known only for a few stars), high $\dot{M}$ (generally favoring systems with long orbital periods), and location in an unobscured region in the sky. The latter favors very nearby stars, and most stars in the general direction of $l \approx 240°$, where N_H appears to be very low out to a distance of ~500 pc (Frisch and York 1983; Paresce 1983). We especially recommend CPD −48°1577, HL CMa, TTAri, BV Cen, YZ Cnc, VW Hyi, Z Cam, and RU Peg; in addition to

TABLE 1

PROMISING CANDIDATES FOR DETECTION OF EUV/SOFT X-RAY COMPONENT

Star	$(m_v)_{\text{outburst}}$	Fraction of Time in Outburst
WZ Sge	8.0	0.001
T Leo	10.5	0.004
EX Hya	11.0	0.003
VW Hyi	8.8	0.1
YZ Cnc	10.6	0.05
TT Ari	10.0	0.5
RX And	10.7	0.04
HL CMa	9.8	0.14
Z Cam	10.5	0.1
RU Peg	9.5	0.08
BV Cen	10.8	0.05
VY Aqr	9.5	0.001
CPD −48°1577	9.5	1.0

their other merits, these stars erupt sufficiently often to give a reasonable probability of successful detection.

V. THE NOVA PROBLEM

One additional remark is needed, concerning the "nova problem" discussed by Becker (1981) and Jensen (1984). We have argued that the peculiar distribution of soft X-ray fluxes of erupting dwarf novae results from an accident: two high-$\dot{M}$, high-M_1 systems are quite nearby and happened to be in outburst during observation with a sensitive soft X-ray telescope. We are satisfied with this explanation for dwarf novae, and for known classical novae, none of which appear suitably endowed for soft X-ray detection. But what about *unknown* classical novae? Since we have been certifying classical novae for only ~ 100 yr, and the interval between nova eruptions must be much longer, there must be many relatively nearby quiescent classical novae (Becker 1981; Jensen 1984)—and *none of these stars are known* (although CPD $-48°1577$, V3885 Sgr, RW Sex, and QU Car are reasonable candidates). Most old novae have high accretion rates ($\approx$ that of SS Cyg and U Gem in outburst), and one would expect that a few should contain moderately massive white dwarfs. It has been frequently argued that the failure to detect these stars *serendipitously* in soft X-rays constitutes a major problem in our understanding of accretion processes in cataclysmic variables (Becker 1981; Ferland *et al.* 1982*a*; Jensen 1984).

We do not agree that this problem exists. *Einstein* could not find these systems, because it was a *pointing* telescope and observed only $\sim 3\%$ of the sky. *HEAO 1* scanned $\sim 95\%$ of the sky, but with a vastly inferior sensitivity limit. The soft X-ray source in SS Cygni could only be detected in the *HEAO 1* scanning data out to a distance ~ 200 pc. From the estimated space density of old novae (4×10^{-7} pc^{-3}, Patterson 1984), only about five stars are expected within 200 pc; and within such a small group, there is no particular reason to expect that any member should contain an unusually massive white dwarf.

This "nova problem" arose primarily because an incorrect classical nova space density was adopted (10^{-4} pc^{-3}), and it should now be promptly forgotten.

VI. REPROCESSED EMISSION-LINE RADIATION

a) Reprocessing of EUV/Soft X-Rays

In principle it is possible to gain information about boundary layer radiation by considering the observed strengths of emission lines. Although the strongest emission lines in virtually all CVs are the Balmer lines, these are not a useful probe since they are not necessarily produced by photoionization. Williams (1980) and Tylenda (1981) show that hydrogen lines can be easily produced by the gravitational energy released *in situ* in low-density parts of the disk.

But the He II $\lambda4686$ emission line can be a very useful probe of the presence of high-energy radiation in the system. This line has long been known as a characteristic signature of X-ray binaries, and should be an extremely good diagnostic for CVs as well. As a recombination line of an ion requiring 55 eV for ionization, it cannot be produced by the gravitational heating in the disk (Williams 1980). Because of the high abundance of helium, it is reasonable to assume that most of the photons with energies between 55 and 280 eV (the carbon K-edge) which ionize low-density gas in the system produce He II recombination line photons. The two accessible emission lines are $\lambda4686$ and $\lambda1640$, which should be in the ratio $I(\lambda1640)/I(\lambda4686) \sim 7$ for optically thin, case B recombination (Seaton 1979). If we knew the system geometry, we could use the observed strengths of the lines to infer the photon flux at energies between 55 and 280 eV.

We have suggested above that in the high-$\dot{M}$ disk systems, as much as one-half of the total accretion luminosity is radiated in an EUV component, which is usually unobservable (but which barely manages to creep into the soft X-ray bandpass in the most favorable cases, viz., SS Cyg and U Gem). Some fraction of this EUV light should illuminate and ionize the upper layers of the disk, producing He II recombination line emission.

From the temperature law shown in Figure 2, we can predict the luminosities of the He II lines. We assume that all photons incident on the disk with the energies between 55 and 280 eV are absorbed by He$^+$, and that half of the recombination line photons are lost in the optically thick disk. Seaton's (1979) recombination rates and case B are assumed. The model atmospheres of Hummer and Mihalas (1970) are used for $T_{\rm BL}$ below 2×10^5 K, while a blackbody spectrum is an adequate approximation for higher temperatures. An important uncertainty lies in the fraction of the BL luminosity which strikes the disk; this depends sensitively on the geometrical shape of the BL region. We will take this fraction to be 10%, but a factor of 3 change in either direction is easily possible.[3]

With these assumptions and the disk continuum models quoted above, we can predict the luminosities and equivalent widths of the $\lambda1640$ and $\lambda4686$ lines. These predictions are shown in Table 2. As expected, the He II line strength increase drastically with $\dot{M}$ and M_1, because $T_{\rm BL}$ does.

b) Observations

It is no simple task to compare these predictions with observational data. Published optical/UV spectra of CVs are widely scattered through the literature. Useful discussions of optical spectra are presented by Elvey and Babcock (1934), Warner (1976), and Williams and Ferguson (1982). The doctoral theses of Williams (1983) and Shafter (1983) include large compilations and extensive discussion of optical spectra. No large compilations of UV spectra are yet available, but extensive descriptions of the published spectra are given by Szkody (1984) and Selvelli and Hack (1984).

We have searched the literature for quantitative estimates of He II $\lambda4686$ line emission. Using reported line fluxes, reported equivalent widths and estimated magnitudes, and distances from Paper I and the methods described by Patterson (1984), we have estimated the luminosity of He II $\lambda4686$ emission for each star (with some stars appearing more than once, if observed in different luminosity states). These luminosities are shown in Figure 5, plotted versus the estimated accretion rate. In a few cases (shown by the squares) L_{4686} is estimated from L_{1640}, assuming that the fluxes have the ratio appropriate to case B recombination. We have included the $\lambda4686$ equivalent-

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[3] A fraction of $\sim 2\%$ is commonly assumed, and would be approximately correct if the illumination comes from an isotropically radiating point source at the center of the disk, or from a flat annulus in the disk. But these geometries seem to us to be unlikely. For any value of $\dot{M}$, the high temperature gas in the BL will likely expand well above the disk plane, where a substantial fraction of the emitted light can shine down and illuminate the disk. In addition, the extra heating associated with the hot spot in the outer disk should "puff up" the outer disk, and thereby increase the solid angle subtended at the white dwarf. Our theories are still too primitive to calculate these effects in detail, but rough estimates suggest that fractions between 3% and 30% are plausible.

TABLE 2

Helium II Emission Lines from Photoionization by EUV/Soft X-Ray Component

	$\dot{M}$ (g s^{-1}) =	10^{16}			10^{17}			10^{18}			10^{19}		
Quantity	M ($M_\odot$) =	0.4	0.7	1.0	0.4	0.7	1.0	0.4	0.7	1.0	0.4	0.7	1.0
L_{BL} ($L_\odot$)		...	4.1(32)	7.9(32)	2.4(33)	6.7(33)	1.3(34)	2.4(34)	6.7(34)	1.3(35)	2.4(35)	6.7(35)	1.3(36)
T_{BL} (10^5 K)		...	0.75	1.11	0.80	1.42	2.00	1.30	2.15	2.97	2.00	2.96	3.99
L_{1640} (ergs s^{-1})		...	2.5(26)	1.1(28)	1.4(27)	2.0(30)	9.0(30)	2.5(30)	5.6(31)	1.2(32)	1.7(32)	6.2(32)	1.0(33)
EW$_{1640}$ (Å)		...	...	0.02	0.005	0.76	1.4	0.4	3.3	4.6	3.8	8.7	8.7
EW$_{4686}$ (Å)		...	...	0.02	0.001	0.71	2.0	0.3	4.4	7.4	6.1	14	14

width data in Table 1 of Paper I for the stars with IPC X-ray data available but have made use of all the relevant spectroscopic data which we could find. Not included in Figure 5 are the magnetic white dwarf systems (AM Herculis and DQ Herculis stars), which have significantly stronger He II emission. The dashed curve in the figure shows the approximate relation expected from disk systems with $M_1 = 0.7\ M_\odot$, $\mathrm{EW}_{4686} = 3$ Å.

There is one important selection effect to be considered in evaluating Figure 5. We have excluded systems showing only He II *absorption* features, which include some nova-like variables and a fair percentage ($\sim$30%–60%) of dwarf novae in outburst. If we had included these points, most would be upper limits lying on or slightly below the curved line, since a typical nondetection of a broad emission feature implies EW $\lesssim$ 2–3 Å. But in the presence of the underlying absorption, we believe that these limits are not reliable. The presence of P Cyg emission lines in many erupting dwarf novae (e.g., Córdova and Mason 1982) demonstrates that emission and absorption features can be simultaneously present. We also note regretfully that there are very few published optical spectra of erupting dwarf novae, presumably because observers have felt that nearly continuous spectra are of little interest. It is very desirable for observers to publish these spectra in some form, despite their bland appearance.

The most striking feature of Figure 5 is the extremely good correlation of L_{4686} with $\dot{M}$ over the entire range of $\dot{M}$. One must bear in mind the many upper limits, and the exclusion of systems showing obvious absorption features. These worries will affect the detailed distribution of points in the figure, but the correlation is in any case very good. A linear fit to the data in the log-log plane yields

$$L_{4686} = 1.3(\pm 0.3) \times 10^{29} \dot{M}_{16}^{0.78 \pm 0.08}\ \mathrm{ergs\ s^{-1}}\,, \tag{5}$$

which is the straight line defined by the carets at the lower left and upper right of the figure. There is another way to describe the lesson of Figure 5: He II λ4686 emission with an equivalent width of $\sim$1–10 Å seems to be a normal feature of CV spectra at all accretion rates. Systems with the highest $\dot{M}$ evidently have the strongest He II lines, but no other significant trend with $\dot{M}$ appears. In particular, the drastic dependence of equivalent width on $\dot{M}$ predicted by Table 2 is not observed.

c) Reprocessing of Hard X-rays

But it is also possible for *hard* X-rays from the central source to produce the He II emission by photoionization. In equation (16) of Paper I we have predicted the dependence of the "hard" X-ray luminosity L_x(0.2–4.0 keV) on $\dot{M}$ and found fair agreement with observation. For an optically thin thermal bremsstrahlung source with $kT \gtrsim 5$ keV, about 12% of this luminosity will be in the 0.055–0.280 keV bandpass. Hence we obtain

$$L_{\lambda 4686} = (0.26)(0.1)\left(\frac{2.65\ \mathrm{eV}}{130\ \mathrm{eV}}\right)(0.12 L_x) = 0.000064 L_x\,, \tag{6}$$

where 0.26 is the fraction of recombinations producing a λ4686 photon (Osterbrock 1974), 0.1 is the fraction of X-ray luminosity that is absorbed, 130 eV is the assumed energy of an ionizing photon, and L_x is given in equation (16) of Paper I.

d) Comparison with Observations

i) *Soft X-Rays: Yes, for $\dot{M} > 10^{17}$ g s^{-1}*

In Figure 5 the solid curve labeled "SX" shows the predicted He II λ4686 luminosities due to photoionization by soft X-rays. Evidently the SX component does a fine job of producing the He II emission for $\dot{M} > 10^{17}$ g s^{-1}.

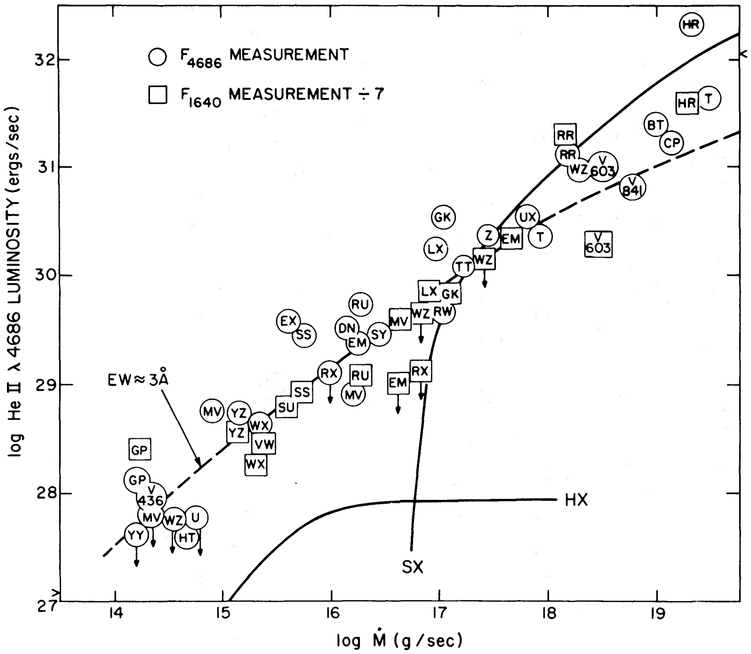

FIG. 5.—The observed He II λ4686 emission luminosities, plotted vs. accretion rate. Squares indicate that the λ4686 emission is estimated from the assumption $L(\lambda1640)/L(\lambda4686) = 7$. The carats at lower left and upper right indicate the best linear fit to the data, eq. (5). The dashed curve indicates the approximate relation expected from accretion disk systems with $M_1 = 0.7\ M_\odot$, $\mathrm{EW}_{4686} = 3$ Å. The solid curves show the predicted luminosities from reprocessing of soft X-rays (SX) and hard X-rays (HX).

ii) *Hard X-Rays: No*

For smaller $\dot{M}$, the hard X-ray contribution is much more important, but it appears to be still inadequate, by a factor of ~ 20, as shown by the "HX" curve in Figure 5. This discrepancy is probably too large, and too consistent, to attribute to uncertainties in the geometry or hard X-ray luminosity.

iii) *Medium X-rays: Yes, If They Exist*

It seems more likely that our assumption concerning the X-ray *spectrum* is at fault. In particular, we require an additional source of ionizing photons of energy 55–280 eV. In order to account for the observed He II emission, the luminosity in this component must be at least equal to the luminosity L_x detected by the IPC (or defined in eq. [16] of Paper I), and the temperature should be suitable for concentrating a large fraction of the luminosity in the 55–280 eV bandpass. It is clear that we are not free to invoke such components with abandon, *because the observed X-ray spectra are very hard* (see Fig. 6 of Paper I). Are the observed spectra consistent with the existence of such an "MX" component?

The answer seems to be yes, provided that the (bremsstrahlung) temperature is within a fairly narrow range. We can rule out the existence of any bright MX component with $kT_{\text{brems}} \gtrsim 0.6$ keV, because such a component could be easily detected by the IPC. A somewhat cooler component would be difficult to detect, because the C and N absorption edges in the polypropylene window of the IPC render the sensitivity to X-rays ranging from 0.28 to ~ 0.6 keV very low (see Fig. 9 of Giacconi *et al.* 1979). An MX component could still be observed in the 0.12–0.28 keV bandpass, but such low-energy X-rays tend not to survive a long voyage through the interstellar medium. At the expected column densities of $(1–10) \times 10^{20}$ cm^{-2}, the interstellar cutoff energies are in the range 0.25–0.60 keV, so there is not much contribution of the MX component to the observed IPC flux, except for systems with $N_{\text{H}} \lesssim 5 \times 10^{19}$ cm^{-2}. Hence we estimate that the existence of a component of the required luminosity is compatible with the observed hard spectra, provided that kT_{brems} is in the range 0.2–0.5 keV. For stars with sufficiently low N_{H}, this component should be detectable, and we note with much interest the preliminary reports of the *Einstein* Solid State Spectrometer (SSS) observations of SS Cyg and EX Hya, which suggested the existence of components with $kT_{\text{brems}} \approx 0.5$ keV (Swank 1979, 1981). These low-energy photons certainly deserve more study. The best hopes for good observational constraints are probably the following: (1) future experiments with good sensitivity and energy resolution at energies below 1 keV, and (2) more diligent study of the IPC X-ray spectrum of the most nearby systems.

Finally, we remind the reader again that a substantial number of systems (~ 15, mostly known or suspected dwarf novae in eruption) have been excluded from Figure 5, because their spectra show He II in absorption. Since the BL radiation has apparently been observed in two of these systems, SS Cyg and U Gem, it seems likely that (1) the system geometry somehow prevents the EUV photons from striking the disk; (2) the photons are absorbed in regions having such high continuum surface brightness that absorption rather then emission lines result; or (3) emission lines are lurking just below the typical observational threshold (EW $\lesssim$ 2–3 Å). Each of these possibilities is plausible and deserves investigation. Since the erupting dwarf novae are quite bright, it should be easy to obtain spectra of the $\lambda 4686$ line and surrounding continuum with good signal-to-noise ratio, and thereby improve the EW limits by a factor of ~ 5.

VII. SUMMARY

1. We assume that half of the gravitational energy released by gas spiralling through the accretion disk is radiated in a *boundary layer* at the disk/star interface. For $\dot{M} > 10^{16}$ g s^{-1}, this region is expected to be optically thick, and we calculate its temperature and soft X-ray luminosity, following Pringle (1977). We find that *most optically thick boundary layers are expected to be strong EUV sources but are probably too cool for significant soft X-ray emission.* An observable soft X-ray flux is predicted when the white dwarf mass is high and the interstellar column density N_{H} is low. We compare the predictions with available soft X-ray observations and find satisfactory agreement.

2. We consider the "nova problem" discussed by Becker (1981) and Jensen (1984): the lack of serendipitous detection of old novae at soft X-ray wavelengths. With realistic estimates of the old nova space density and the expected temperature of the boundary layer, this problem disappears.

3. We use our optically thick BL model to predict the strengths of the He II $\lambda 1640$ and $\lambda 4686$ emission lines, assuming that these are produced by recombination following photoionization by BL radiation. For high-$\dot{M}$ systems ($\dot{M} \gtrsim 10^{17}$ g s^{-1}), there is reasonable agreement with observation. For low-$\dot{M}$ systems, theory cannot reproduce the He II line strengths, unless there is an additional source of photons in the range 55–280 eV—such as that provided by the $kT \approx 0.5$ keV components reported in EX Hya and SS Cyg. A search for a similar component in other systems would be very desirable.

4. To conclude this and the preceding paper, we find that the observations of cataclysmic variables which accrete through a disk are in reasonable accord with an X-ray source located in the boundary layer, and powered strictly by the gravitational energy released there. There appears to be no pressing need for qualitatively new physics (magnetic fields, nuclear burning, disk coronae, etc.) Important problems still remain, especially the origin of hard X-rays in high-$\dot{M}$ systems, the details of the X-ray spectrum in all systems, and the origin of quasi-periodic oscillations in the soft X-ray flux (Córdova *et al.* 1984). But a diverse set of phenomena from optical through hard X-ray wavelengths is generally consistent with the quantitative predictions of the more or less "conventional" BL model we have discussed. It remains to be seen whether any other theory can achieve this degree of predictive power and consistency with observation. We eagerly await the development of alternative theories, improved BL models, and more detailed confrontations of data and theory, which should now be possible.

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