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X-RAY EMISSION FROM CATACLYSMIC VARIABLES WITH ACCRETION DISKS. I. HARD X-RAYS

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ABSTRACT

We address the problem of understanding the hard X-ray emission observed in cataclysmic variables which accrete through a disk. Observations show clearly that hard X-ray emission is very strong (representing about half of the total accretion luminosity) in all systems with a low accretion rate ($\dot{M} \lesssim 10^{16}$ g s^{-1}). High-$\dot{M}$ systems apparently radiate most of their accretion luminosity in the ultraviolet and extreme-ultraviolet bandpasses, with $\lesssim 1\%$ appearing as hard X-rays. From all of the available *Einstein* observations of cataclysmic variables, we show that the 0.2–4.0 keV portion of the hard X-ray flux can be predicted to within a factor of 3 by *any one* of the following quantities: accretion rate, absolute visual magnitude, and the equivalent width of the Hβ emission line.

These results can be interpreted in a simple model of the disk *boundary layer*, where accreting gas settles onto the white dwarf. At low accretion rates, this region has a low density and low optical depth; it cools itself very inefficiently, and so is heated to high temperatures ($\sim 10^8$ K) in order to radiate away its energy. At high accretion rates, this region becomes optically thick, and can radiate most of its energy at temperatures near 10^5 K. But at *any* accretion rate, there is always some gas accreting near the top of the disk, where the optical depth is low and the luminosity will emerge as hard X-rays. A simple model of the density distribution is in reasonable accord with most of the hard X-ray data, although erupting dwarf novae are apparently underluminous in hard X-rays.

Significant observable effects are expected from the reprocessing of boundary-layer radiation. In low-$\dot{M}$ systems, about half of the hard X-rays are absorbed by the white dwarf, heating it (locally) to temperatures of 10,000–60,000 K. This should produce a hot "pseudo white dwarf" component in the flux distribution, and observations of low-$\dot{M}$ systems are consistent with this possibility.

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

I. INTRODUCTION

The origin of hard X-ray emission from cataclysmic variables (CVs) remains an unsolved problem. A few of these systems (the AM Herculis stars) contain strongly magnetic white dwarfs (B $\sim 10^7$–10^8 gauss) which appear to channel the flow of accreting matter radially onto their magnetic poles (for reviews see Lamb 1983; Liebert and Stockman 1984). Radial accretion onto a white dwarf produces a standoff shock above the surface, which can efficiently convert the infall energy to hard X-rays (Hōshi 1973; Katz 1977). However, it is likely that most CVs accrete through a disk, more or less unperturbed by magnetic fields. In this case accreting matter tends to lose its energy *gradually* as it spirals inward, and the temperatures in the disk do not exceed $\sim 10^5$ K—much too low for hard X-ray emission. Where can the hard X-rays be produced?

A promising possibility is the boundary layer between the rapidly rotating disk and the (assumed) slowly rotating white dwarf. In the simplest of models, approximately half of the total accretion luminosity should be radiated away in the boundary layer (Lynden-Bell and Pringle 1974; Shakura and Sunyaev 1973). Theorists have studied in some detail the problem of X-ray emission from boundary layers assumed to be either optically thick (Pringle 1977; Tylenda 1977) or optically thin (Pringle and Savonije 1979; Tylenda 1981*a*). The general features of these models were roughly in accord with early X-ray observations of SS Cygni (Ricketts, King, and Raine 1978; Córdova *et al.* 1980), but have been severely questioned by some authors' analyses of larger data bases (e.g., Ferland *et al.* 1982*a*, *b*).

A much more detailed comparison of theory and observations is now possible, primarily because of the very extensive data base accumulated by the *Einstein Observatory* (see Giacconi *et al.* 1979 for a description of the telescope and detectors; and see Córdova and Mason 1983, 1984 for a summary and discussion of the observations). In this paper we discuss how the currently available X-ray and optical data can be used to constrain boundary-layer models for the origin of the hard X-ray emission in CVs. We shall find it useful to compare the observed and predicted dependences of the X-ray luminosity and X-ray–to–visual flux ratio F_x/F_v on accretion rate. This comparison reveals that, as suggested by the simple optically thin models, systems with a low accretion rate are invariably strong X-ray emitters, with $F_x/F_v \sim 3$. The X-ray fluxes of stars with a high accretion rate ($\dot{M} \gg 10^{16}$ g s^{-1}) are not consistent with any of the published models, but could be explained by invoking a density gradient in the boundary layer. We also discuss the effects of reprocessing boundary-layer radiation on the white dwarf surfaces, and identify this reprocessed light with the "pseudo white dwarf" components which appear in many (all?) stars with a very low accretion rate.

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TABLE 1

BASIC DATA FOR SYSTEMS OBSERVED WITH THE *Einstein* IPC

Star (1)	F_x(0.2–4.0 keV) (10^{-12} ergs cm^{-2} s^{-1}) (2)	m_v (3)[a]	EW(Hβ, λ4686, λ1640) (Å) (4)	Distance (pc) (5)[b]	log $\dot{M}$ (g s^{-1}) (6)[b]	log N_H (cm^{-2}) (7)	References[c] (8)
RX And	9.7	13.6	58, <2	200	16.2	20.7	1, 2
AE Aqr	9.3	13.5	60, <5, 12	80	15.1	20.2	3, 4
V603 Aql	22	11.6	7, 4.5, 1.0	380	18.1	21.0	2, 5, 6, 7
V794 Aql	6.8	14.5	25, 5	200	15.7	20.8	8, 9
TT Ari	21	11.5	10, 3	125	16.85	20.5	2, 10, 1
T Aur	<0.24	15.2	7, 7	800	17.4	21.4	2, 5
Z Cam	2.1	11.5	5	300	17.2	20.8	1, 2, 8, 46
SY Cnc	<0.51	12.5	7, 2	360	17.4	<20.2	2, 8, 11
YZ Cnc	1.9	(14.6)	105, 5	130	15.1	<20.4	10, 12, 13, 14
SV CMi	<0.36	(15.3)	...	...	...	...	10, 11
AM CCVn	<0.29	14.3	...	...	...	...	1
HT Cas	2.9	(16.7)	95, 1.5	190	14.65	20.8	11, 15
BV Cen	5.1	13.8	5	300	16.35	20.9	11, 16
V436 Cen	8.3	15.3	130, 4	75	14.3	19.7	11, 17
WW Cet	10.1	13.0	40, 12	130	15.9	<20.3	1, 2, 8
Z Cha	0.87	13.3	5	125	15.65	20.1	1, 18
	1.9	15.1	8	...	14.8	...	
TV Col	9.0	13.8	16, 10	160	15.8	<19.8	19
HL CMa	15	(14.8)	65, 5	100	...	<20.2	2, 20
GP Com	9.0	15.8	..., 17, 25	75	14.15	<20.0	2, 8, 21
T CrB	0.29	14.0	40, 9, 2.5	1300	18.75	20.5	7, 8, 11
EM Cyg	3.4	13.9	22, 3, 3	350	16.8	20.9	1, 22
SS Cyg	86	12.7	66, 5, 3	95	15.5	20.3	23, 24
V1500 Cyg	<0.21	17.0	...	1400	16.0	>21.0	25
AB Dra	36	12.9	16, 3	200	16.3	20.8	1, 11, 47
YY Dra	9.5	16.7	110, 8, 9	110	14.1	20.1	26, 47
HR Del	0.3	12.7	6, 5.5, 6	800	18.9	>20.8	25, 27
AH Eri	1.0	(17.5)	...	...	...	<20.3	10
U Gem	4.3	14.5	37, <1	75	14.4	<20.0	12, 22, 23
AH Her	0.48	12.0	<2	250	17.4	20.5	1, 8, 12
	<0.21	12.7	...	...	16.95	...	
DQ Her	<0.16	14.8	19, 17, 20	400	17.5	>20.5	2, 12
V446 Her	<0.29	18.8	14	...	...	21.5	8
V533 Her	<0.21	15.4	5, 6	1200	17.7	>20.8	8, 12
EX Hya	98	12.9	65, 9	110	15.5	<20.2	1, 28
VW Hyi	3.6	13.8	25	100	15.25	<20.2	12, 29, 30
WX Hyi	2.5	12.2	<4	120	16.25	<20.2	11, 29, 30
CP Lac	<0.44	(14.4)	...	1340	18.4	21.5	5
X Leo	<0.21	12.4	<3	250	17.65	<19.7	8, 11
AY Lyr	<0.27	(18.3)	29	400	14.65	>20.7	2, 11
LL Lyr	<0.27	17.1	...	...	...	>20.7	10
MV Lyr	4.1	12.6	4	320	17.1	>20.7	1, 2, 31
	1.9	(14.3)	20	...	16.1	...	
BT Mon	<0.21	15.4	30, 26	1500	19.1	21.5	2, 32
RS Oph	<0.24	13.9	70	...	...	>21.2	2, 11
V841 Oph	0.68	13.8	1.6, 3	1000		>21.2	2, 5, 33
CN Ori	<0.32	(12.7)	...	330	17.4	<20.0	1, 10
RU Peg	37	13.8	20, 3, 3	250	16.0	>20.4	7, 11, 34
GK Per	9	14.4	33, 7, 5	500	17.05	22.0	2, 5, 11
KT Per	0.61	11.7	<5	320	17.7	>20.7	8, 12
RR Pic	1.1	12.0	8, 8, 6	500	18.4	>20.7	5, 7, 35
AO Psc	12	13.5	8, 6	250	16.6	20.4	8, 36
CP Pup	2.1	15.5	8, 8	700	16.8	20.9	5, 33
T Pyx	<0.21	15.0	10, 14	...	...	>20	11, 33
WZ Sge	5.2	14.4	50	80	14.6	20.2	8, 37, 38
V1017 Sgr	0.65	15.8	...	...	...	>21.3	11
V1059 Sgr	0.51	(16.5)	...	...	18.0	>21.0	5
V1223 Sgr	20	13.3	12, 10	400	17.1	>21.0	39
V3885 Sgr	3.0	10.5	2.5	140	17.4	>20.3	11, 40
U Sco	<0.27	18.3	3, 10	...	...	21.3	8, 11
LX Ser	<0.32	14.0	25, 17, 27	220	16.7	...	10, 41
RW Sex	2.5	10.6	2	150	17.6	<20.3	11, 42
RW Tri	<0.18	13.7	10, 3	300	17.4	20.5	8, 14, 43
SU UMa	21	14.6	60, <4, 7	140	15.2	20.7	8, 11, 14
UX UMa	0.57	13.6	5, 3, <2	340	17.1	20.5	1, 2
TW Vir	2.7	15.8	80	180	15.0	~20	2, 11
CK Vul	<0.24	17	...	...	...	>20.7	5
Lanning 10	<0.15	14.5	7	700	17.6	~21	44
E1551+72	1.2	(17)	...	200	14.45	20.7	45

II. HARD X-RAY DATA FROM THE *Einstein Observatory*

Although a few CVs had been previously identified as X-ray sources, the only large and homogeneous collection of CV X-ray data is that acquired by the imaging proportional counter (IPC) over the 2.5 years of operation (1979–1981) of the *Einstein Observatory*. In Table 1 we have collected all of the available IPC data on hard X-ray emission, with other relevant data, drawn from the cited references. Since we are interested in systems with accretion disks, we have excluded the AM Herculis stars, in which the X-ray emission is probably powered by radial accretion, channeled by a strong white dwarf magnetic field. Many of the X-ray and visual fluxes have been previously reported (and compiled by Córdova and Mason 1983), but we have revised many of the published values, for two reasons: (1) In order to compare the data to theoretical predictions, we have removed the contribution of the secondary star to the visual flux. (2) We have adopted a different conversion factor between IPC count rate and X-ray flux. The most popular conversion factor used in the literature has been $C = 2.7 \times 10^{-11}$ ergs cm^{-2} s^{-1} IPC count^{-1}. As the performance of the IPC detector and the properties of the hard X-ray emission have become better known, it is now possible to improve this somewhat. For sources observed in the center of the field, we show in Figure 1 the dependence of the conversion factor on the properties of the X-ray source. This is the calibration used in the second (and presumably final) processing of the IPC data (Harnden 1983). For CVs we expect (see below) $kT_{\rm brems} \approx 5$–20 keV, $N_{\rm H} \approx 10^{19}$–$10^{21}$ cm^{-2}, suggesting $C = (2.7$–$5.0) \times 10^{-11}$ ergs cm^{-2} s^{-1} IPC count^{-1}. Because of source variability and our ignorance of the detailed shape of the spectra, no great precision is possible here; but we can probably limit our errors to within $\sim \pm 30\%$ by adopting a universal conversion factor of

$$C = 3.6 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ IPC count}^{-1} \quad (1)$$

for the *unabsorbed* 0.2–4.0 keV flux. This is the conversion used in preparing Table 1. For the *observed* X-ray flux, a conversion factor about 10% lower would be appropriate. Of course, for individual sources where kT and $N_{\rm H}$ may be known, it may be advisable to find a more accurate value from Figure 1; but for the sake of uniformity we shall adopt this conversion factor in all cases.

Except for the brightest sources, little is known about the X-ray spectra of the stars in Table 1. This is due to uncertainties in converting the IPC pulse-height spectrum to a flux spectrum, and in many sources also due to inadequate photon statistics. But comparison of the observed X-ray "colors" or "hardness ratios" to those of model spectra indicates that essentially all CVs detected by the IPC have rather hard spectra, with $kT_{\rm brems} > 2$ keV (Córdova and Mason 1983). Córdova, Mason, and Nelson (1981) suggest that the data are generally consistent with a thermal bremsstrahlung spectrum of $kT_{\rm brems} \sim 10$ keV. Because the observations require or suggest hard spectra, we will refer to the flux detected by the IPC as the "hard X-ray" flux, despite the fact that by conventional nomenclature, photons in the IPC bandpass (0.2–4.0 keV) are usually thought of as "soft" X-rays. Since we are concerned primarily with IPC data in this paper, our terms "X-ray flux" and "X-ray luminosity" L_x will refer to the *0.2–4.0 keV portion of the hard X-ray emission.* This is in order to stress the strict dichotomy between the hard X-ray emission, apparently a universal characteristic of all CVs, and the *extremely soft* ($kT < 50$ eV) X-ray emission detected in only two stars (but thought to be present, below detection limits, in many others; see Patterson and Raymond 1985, hereafter Paper II). While this simple characterization of the X-ray spectrum does not completely encompass all that is known about observed spectra, it provides a practical basis for discussing the X-ray properties of CVs, and we shall adopt it.

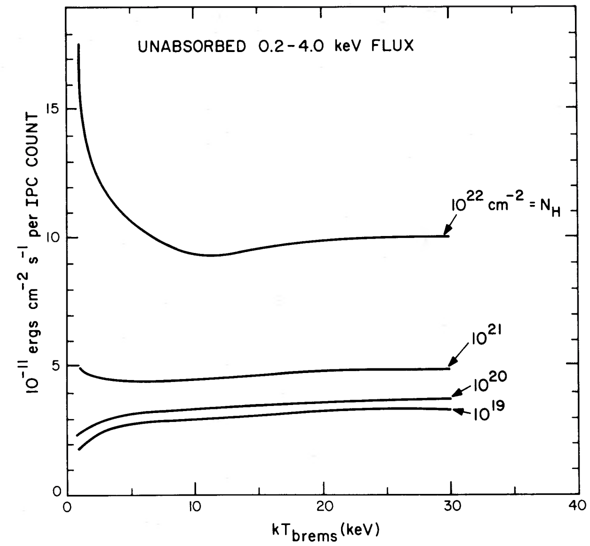

FIG. 1.—The conversion rate between unabsorbed 0.2–4.0 keV flux and IPC counts, for thermal bremsstrahlung spectra with various values of kT and $N_{\rm H}$.

In Figure 2 we have plotted for each system (individually identified on a "first-name" basis) the observed X-ray flux F_x versus the observed or estimated visual flux F_v. The two quantities are generally correlated, but the scatter is tremendous. Where should we *expect* systems to lie in this plane? Since both X-ray and visual light are thought to come from accretion, we

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[a] Drawn mostly from Cordova and Mason 1983.

[b] Drawn mostly from Patterson 1984.

[c] The sources of the X-ray and spectroscopic data, not necessarily the most complete references for the individual stars.

REFERENCES.—(1) Becker 1981; (2) Williams 1980; (3) Jameson, King, and Sherrington 1980; (4) Patterson *et al.* 1980; (5) Becker and Marshall 1981; (6) Drechsel *et al.* 1983; (7) Krautter *et al.* 1981; (8) this paper; (9) Szkody *et al.* 1981; (10) Cordova and Mason 1983; (11) Cordova and Mason 1984; (12) Cordova, Mason, and Nelson 1981; (13) Szkody 1981*b*; (14) Williams and Ferguson 1982; (15) Young, Schneider, and Schectman 1981; (16) Gilliland 1982*b*; (17) Gilliland 1982*a*; (18) Rayne and Whelan 1981; (19) Hutchings *et al.* 1981; (20) Chlebowski, Halpern, and Steiner 1981; (21) Nather, Robinson, and Stover 1981; (22) Stover 1981*a*; (23) Fabbiano *et al.* 1981; (24) Stover *et al.* 1980; (25) Hutchings 1980; (26) Patterson *et al.* 1985; (27) Rosino, Bianchini, and Rafanelli 1982; (28) Gilliland 1982*c*; (29) Hassall *et al.* 1983; (30) Schoembs and Vogt 1981; (31) Robinson *et al.* 1981; (32) Pravdo 1984; (33) Greenstein 1960; (34) Stover 1981*b*; (35) Vogt 1975; (36) Hassall *et al.* 1981; (37) Fabian *et al.* 1980; (38) Krzeminski and Smak 1971; (39) Steiner *et al.* 1981; (40) Cowley, Crampton, and Hesser 1977*b*; (41) Szkody 1981*a*; (42) Cowley, Crampton, and Hesser 1977*a*; (43) Frank and King 1981*a*; (44) Szkody and Crosa 1981; (45) Mason *et al.* 1982; (46) Szkody and Wade 1981; (47) Williams 1983.

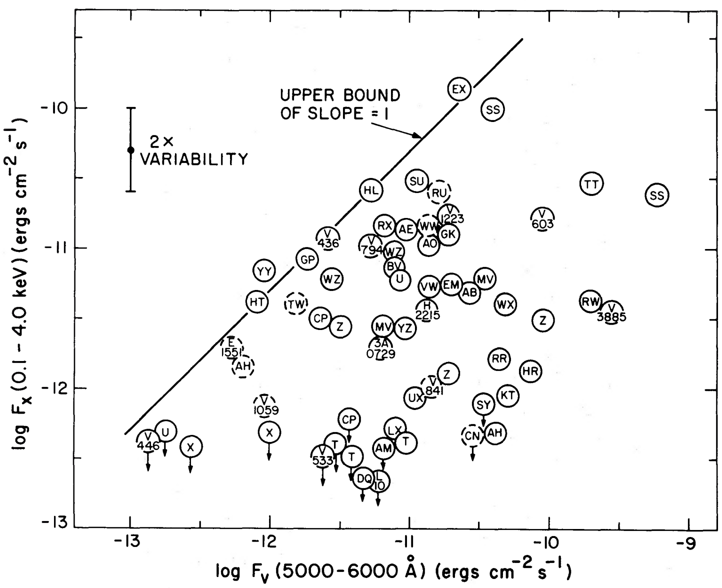

FIG. 2.—The IPC data on X-ray and visual fluxes of cataclysmic variables, drawn from Table 1. Most of the data were obtained nearly simultaneously, but the dashed circles indicate that no simultaneous visual observation was made. We note that there appears to be an upper bound of slope equal to 1, corresponding to $F_x/F_v \sim 4$.

might expect, as a first approximation, that F_x and F_v will increase or decrease equally as distance and mass transfer rate are varied. In Figure 2, this will move systems along a line of slope equal to 1, with the zero point representing the relative amount of X-ray versus visual radiation. In fact, the data do suggest an upper bound of slope 1, as seen in the figure. Furthermore, we have noticed that essentially without exception, the optical spectra of these systems which lie near the upper bound show strong emission lines, while systems far below the bound show only weak emission or absorption. This leads us to look for a correlation between F_x/F_v and some index of the strength of the emission, viz., the equivalent width of the Hβ emission line. Although spectra were not obtained simultaneously with the X-ray observations, it is easy to estimate the equivalent widths of the strongest emission lines, because essentially every known CV shows spectral variations which faithfully track the light variations (Warner 1976; Williams 1983). We feel that our estimates of Hβ equivalent width, given as the first entry in column (4) of Table 1, are trustworthy, except in cases where the visual magnitude either was not actually measured or was changing rapidly. Our primary sources of equivalent-width data are the tabulations of Williams (1983), Patterson (1984, hereafter P84), Williams and Ferguson (1982), and our own unpublished data.

We show the result in Figure 3. As suspected from a glance at Figure 2, there is a correlation, and it turns out to be

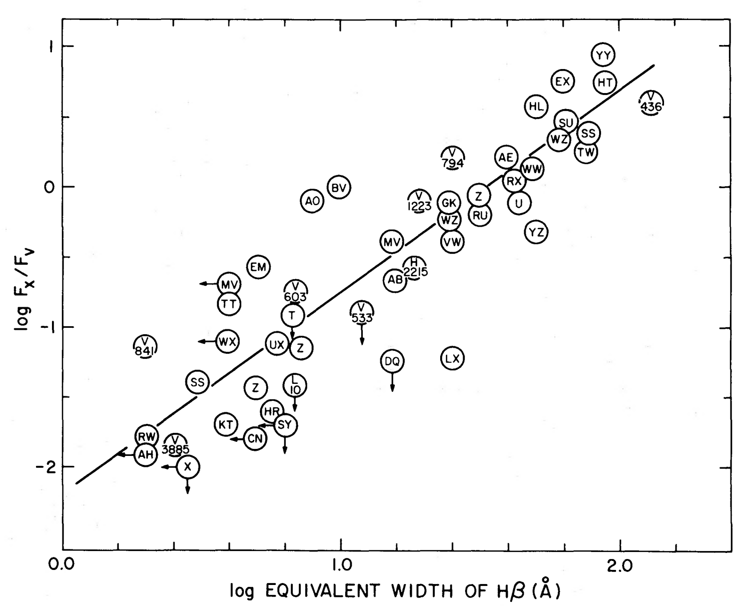

FIG. 3.—The correlation of F_x/F_v with the equivalent width of Hβ emission. The straight line indicates the best linear fit to the data in the log-log plane.

extremely good—the equivalent width EW(Hβ) essentially predicts the value of F_x/F_v to within a factor of about 3. A linear regression yields the empirical relation

$$\log F_x/F_v = -2.21 + 1.45 \log \mathrm{EW(H}\beta) . \quad (2)$$

This relation is particularly useful because the plotted quantities are *observables*—free from any assumptions about distance or spectrum (or even cloud cover!). Strong-lined systems, which must have extensive optically thin regions in their disks, radiate with $F_x/F_v \sim 3$, while the weak-lined stars, which have optically thick disks, radiate with $F_x/F_v \sim 0.03$. The variation appears to be smooth over this large range (a factor of nearly 10^3) in F_x/F_v.

We have elsewhere (P84) shown that EW(Hβ) is well correlated with the absolute visual magnitude of the disk, which is in turn correlated with the accretion rate $\dot{M}$—in the sense that low-$\dot{M}$ systems have stronger emission lines. This is qualitatively in accord with theoretical expectation, since low-$\dot{M}$ disks have lower densities and are consequently more prone to cool by line rather than continuum emission (Tylenda 1981*b*). Thus the correlation of F_x/F_v with EW(Hβ) probably reflects an underlying correlation with $\dot{M}$, the fundamental parameter determining the properties of the disk.[1] In order to probe the meaning of the correlation in Figure 3, we now seek estimates of $\dot{M}$ for each of our 65 stars.

Unfortunately, there still exist no direct methods for measuring the accretion rate in CVs. Probably the best general method is to find the absolute visual magnitude M_v of the accretion disk in each system, and use theoretical disk models to find what $\dot{M}$ is required to produce each value of M_v. This step introduces all the usual uncertainties associated with the use of models. But the most recent disk models (Tylenda 1981*b*; Williams and Ferguson 1982) are now free from assumptions about optical depth, and are perhaps sufficiently realistic to use for determining $\dot{M}$ to within a factor of a few. There is also no sure-fire technique for measuring M_v, but for many individual systems we can constrain the distance, and hence M_v, by considering (1) the observed brightness (or upper limits thereon) of the secondary, whose intrinsic brightness is approximately known, since it is, in virtually all known cases, a main-sequence star; (2) the "expansion parallax" obtained from the shells of classical novae; (3) the empirical M_v–EW(Hβ) relation, useful for systems with EW $\gtrsim$ 15 Å; (4) general information on proper motion, parallax, interstellar reddening, location in the galaxy, and other parameters; and (5) the results of fitting disk models to the dereddened 0.1–1.0 μm flux distribution. The uncertainties and relative weights of these constraints are discussed in P84. Our distance estimates, most of which are taken from P84, are given in column (5) of Table 1. From the resultant estimates of M_v, we have interpolated in Table 1 of Tylenda (1981*b*) to find the estimated $\dot{M}$. Note that we must fit the value of M_v at the time of the X-ray observation, not the time-averaged value used in P84.

The resultant values of $\dot{M}$, entered in column (6) of Table 1, yield the correlation with F_x/F_v seen in Figure 4. Clearly the two quantities are well correlated, in the sense expected from

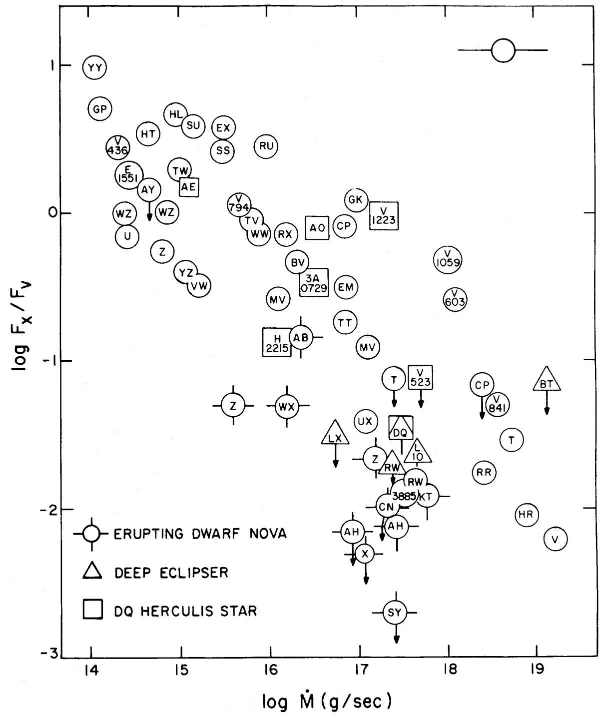

FIG. 4.—The correlation of F_x/F_v with accretion rate $\dot{M}$. Stars in crosses are erupting dwarf novae; stars in squares are DQ Herculis stars, thought to contain magnetic white dwarfs; and stars in triangles show deep optical eclipses of the optically thick disk. The effect of a 50% uncertainty in distance is shown at the upper right.

Figure 3. A linear fit to all the data yields

$$\log F_x/F_v = -0.4(\pm 0.15) - 0.55(\pm 0.12) \log \dot{M}_{16} , \quad (3)$$

where $\dot{M}_{16}$ is the accretion rate in units of 10^{16} g s^{-1}.

Of course, these uncertainties do not include the substantial and presumably systematic errors which we have introduced by the use of disk models. Nevertheless, such uncertainties do not threaten to destroy the correlation in Figure 4. We could just as easily have presented the data in the (F_x/F_v, M_v)-plane, omitting any consideration of the disk models; and since the visual luminosity L_v varies smoothly with $\dot{M}$ in the models (approximately $L_v \propto \dot{M}^{0.8}$), the plot would have looked identical. No detailed models are needed to support the idea that, in general, the visual luminosity increases as $\dot{M}$ does. Therefore, while the accuracy of the $\dot{M}$ calibration is certainly questionable, the important conclusion is secure: low-$\dot{M}$ systems radiate with a much higher F_x/F_v than high-$\dot{M}$ systems.

In column (7) of Table 1 we have made an estimate of N_{H}, obtained in some cases by dereddening the ultraviolet or hard X-ray spectra, but more commonly by using our distance estimate and a model of the galactic extinction. The latter was obtained from the data presented by Frisch and York (1983) and Paresce (1984). We do not use these estimates elsewhere in this paper, but have decided to include them for completeness, since the value of N_{H} will turn out to be of great importance when we study the constraints on *soft* X-ray emission in Paper II.

Finally, we can use our distance estimates to convert the observed X-ray fluxes to luminosities. In Figure 5 we show these luminosities plotted against $\dot{M}$. While there are system-

[1] It is also possible that F_x/F_v is well correlated with EW(Hβ) because the X-rays *produce* the emission lines—by photoionization in the disk, for example. We are suggesting that systems with low $\dot{M}$ necessarily produce strong emission lines and a large F_x/F_v ratio, but the causal relation between these is still not clear.

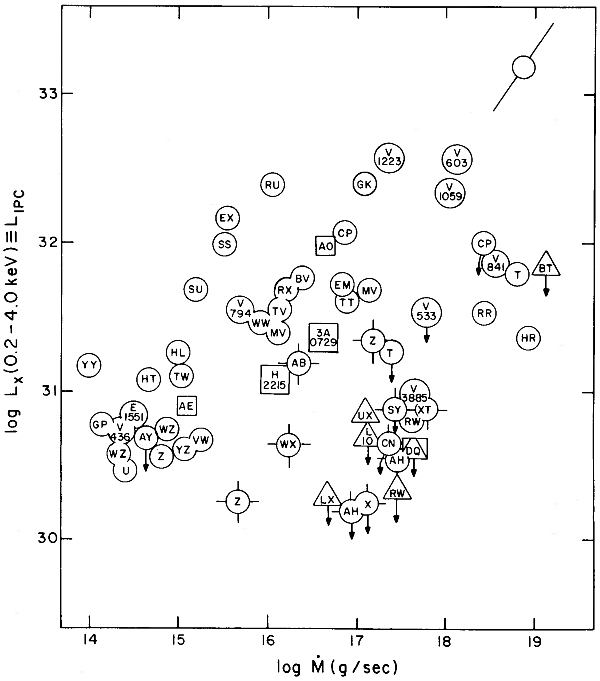

FIG. 5.—The correlation of 0.2–4.0 keV luminosity with accretion rate $\dot{M}$. The symbols have the same meaning as in Fig. 4. The effect of a 50% uncertainty in distance is shown at the upper right.

atic trends in the figure, there is no strong correlation in the entire set of data.

In Figures 4 and 5 we have separately identified known DQ Herculis stars, in which it is thought that near the white dwarf, a magnetic field channels accreting gas radially onto the white dwarf (Patterson 1979; Warner 1983). We are tempted to discard these stars, as we did the AM Herculis stars. However, because no direct observations of a magnetic field have been made (e.g., circular polarization, Zeeman-split spectral lines), we prefer to retain these stars, although with a separate label. We have also assigned separate symbols to two classes of stars which have proved to be very feeble X-ray sources: dwarf novae in eruption, and all systems with optical light curves showing deep eclipses of the accretion disk. In § III we shall discuss the dwarf nova problem in more detail, albeit without any real solution. The deep eclipsers, seven in number (DQ Her, RW Tri, LX Ser, BT Mon, Lanning 10, UX UMa, Z Cha in eruption), all lie well below the mean F_x/F_v and L_x relations for CVs, seen in Figures 4 and 5. This is especially striking because the optical spectra of the first five are all endowed with strong He II λ4686 emission, known to be a characteristic signature of strong X-ray emitters. Because all of these systems are viewed at a high binary inclination, it is quite possible that in each case the white dwarf may be partly or totally shrouded by the nearly edge-on, optically thick disk (as originally suggested by Petterson 1982 for DQ Her). This requires that matter in the disk must stray up to $\sim 15°$ from the midplane of the disk—which does not occur in the simplest disk models, but would be a plausible consequence of fairly small perturbations to the disk structure (caused, e.g., by extra heating at the rim of the disk where accreting material first strikes, or near the inner edge where the boundary layer disrupts the disk). We shall delete these eclipsing stars with optically thick disks from subsequent analysis, because it seems likely that their low X-ray fluxes are due to the accident of high inclination, not to intrinsically feeble X-ray emission.

III. THE BOUNDARY LAYER IN HARD X-RAYS

a) *Why the Boundary Layer?*

While there is no fully credible theory for the origin of hard X-rays from CVs with disks, it seems very likely that the X-rays are powered by accretion and emerge in some manner from the boundary layer (Pringle and Savonije 1979; Tylenda 1981*a*; Jensen 1984). In part this is because the other possible sources are so problematical. We briefly review other processes which have been suggested, and their most severe difficulties.

1. *Coronal X-ray emission from the mass-losing secondary* (e.g., Córdova and Mason 1984).—Because essentially all of the CV secondaries are rapidly rotating main-sequence stars of late spectral type (G, K, M), and because the coronae of such stars are known to be X-ray sources (e.g., Walter 1982 and references therein), this seems at first to be a resonable hypothesis. However, its prima facie appeal is greatly overshadowed by its problems. First, it seems that coronal emission is just too feeble to explain the X-ray luminosities observed. No rapidly rotating, cool main-sequence stars have been found with L_x(0.2–4.0 keV) as high as 10^{31} ergs s^{-1}, and very few exceed 10^{30} ergs s^{-1}. The most recent data on the $L_x(v_{\rm rot})$ relation (Walter 1982; Cruddace and Dupree 1984) suggest that for any rotational velocity, the upper limit to coronal emission on the lower main sequence is probably in the range (1–5) × 10^{30} ergs s^{-1}. Second, available information on the X-ray spectrum in CVs, while sparse, suggests higher bremsstrahlung temperatures, generally 10–30 keV (see below), compared with 0.3–3 keV for coronal sources (Schmitt 1983). Other arguments which disfavor a coronal origin can be based on (1) the fact that known coronal X-ray sources usually vary on time scales much longer than those present in the CV X-ray data (Stern 1983; Golub 1983; Córdova and Mason 1984); (2) the exceptionally low X-ray fluxes from eclipsing systems, as discussed above; (3) good covariability of simultaneous X-ray and optical light curves (AE Aqr: Patterson *et al.* 1980; TT Ari: Jensen *et al.* 1983). From these considerations we conclude that coronal emission from the secondary is only a minor contributor, at best, to hard X-ray emission in CVs.

2. *A shock (" hot spot ") at the edge of the accretion disk where the mass-transfer stream strikes the disk.*—Luminosities of $\sim 10^{31}$ ergs s^{-1} can easily be generated in the hot spot, but Pringle (1977) argued that any X-rays produced must traverse a large column density of cool matter to reach the observer—reducing the received X-ray flux to a negligible level. In addition, the observed temperatures in the X-ray–emitting region (as high as $\gtrsim 20$ keV [Drechsel *et al.* 1983]) are much higher than the maximum temperature attainable in the hot spot (~ 1 keV [Pringle 1977]).

3. *A shock above the magnetic pole of a radially accreting, magnetic white dwarf* (Rickett, King, and Raine 1978; Lamb 1979).—Since strong shocks are a natural feature of radial accretion (Hōshi 1973; Katz 1977), this hypothesis is tempting, and we think it is still viable. It is very likely appropriate for *some* stars, especially those with rapid and stable periodicities in X-ray and/or optical light (the DQ Herculis stars). But such periodicities are quite rare, yet hard X-ray emission is a characteristic of essentially *all* CVs. Therefore, it seems desirable to find a mechanism which does not require a magnetic white dwarf.

These difficulties lead us to examine, following Pringle and Savonije (1979) and Tylenda (1981*a*), the disk/star boundary layer as the most probable site for X-ray production. We shall henceforth assume that the X-rays come from this vortex of tortured gas, and will now explore more detailed models.

b) Boundary-Layer Models

i) *Optically Thin Case*

Let us first consider a maximally naive accretion model for the origin of the hard X-rays. In this model, half of the total gravitational energy of the infalling matter is liberated in an optically thin boundary layer, where the temperature is sufficiently high to produce X-rays. Only a fraction of the emergent X-ray luminosity appears in the IPC bandpass, and it is crucial to know what that fraction is.

Assuming a 10 keV thermal bremsstrahlung spectrum, this fraction should be ~ 0.5. However, detailed studies of the X-ray spectra have not been made, and we prefer to estimate this fraction empirically. We shall compare the X-ray fluxes observed in two energy bands, 0.2–4.0 keV (*Einstein* IPC) and 2–10 keV (essentially all of the pre-*Einstein* scanning experiments, and the *Einstein* MPC). The results are shown in Figure 6. When the published data permit, we have used the simultaneously observed IPC and MPC fluxes (viz., SU UMa, TT Ari, V603 Aql, GK Per, V1223 Sgr); otherwise we have adopted a 2–10 keV flux averaged over the various values reported from the hard X-ray experiments. Since all of the latter stars appear to be fairly steady X-ray sources, we do not expect that Figure 6 contains large errors due to nonsimultaneity of the measurements (although this is certainly an issue that deserves unrelenting vigilance). All stars with an IPC count rate >0.2 counts s^{-1}, plus all stars detected by the 2–10 keV experiments, are shown individually. We do not show the several dozen stars with weak IPC fluxes and 2–10 keV upper limits, but indicate their location in the shaded region labeled "most CVs." The

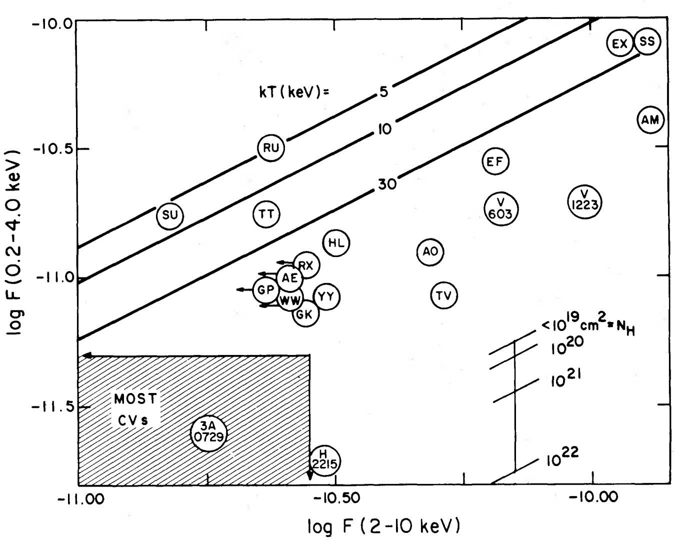

FIG. 6.—Empirical data on 0.2–4.0 keV and 2–10 keV fluxes. Stars detected by 2–10 keV experiments, as well as with IPC count rates >0.2 counts s^{-1}, are shown individually. Most CVs are in the shaded region at the lower left—which extends indefinitely to the left, since most stars are not detected by the 2–10 keV experiments. The long diagonal lines show the relations predicted from an unabsorbed thermal bremsstrahlung spectrum with various values of kT, while we show at the lower right how the 0.2–4.0 keV flux is quenched for higher values of N_H.

long diagonal lines show the relations expected for unabsorbed thermal bremsstrahlung spectra with various values of kT, and the line segments at the lower right indicate how a line should be moved vertically for other values of N_H.

Figure 6 demonstrates that the best-studied CV X-ray sources have extremely hard spectra. With light absorption ($N_H \lesssim 10^{21}$ cm^{-2}), we require temperatures in the range 10–30 keV to satisfy the data. By increasing N_H to 10^{22} cm^{-2} or more, we can satisfy the data with lower temperatures, but since a high N_H is unlikely, since (*a*) these systems are rather nearby, and therefore unlikely to be heavily absorbed, and (*b*) such large values of N_H should leave an unmistakable imprint on the low-energy spectrum, and no such imprint is generally seen (Córdova and Mason 1983, 1984). The surprisingly hard spectra present an interesting and important unsolved problem. But our purpose is merely to find an appropriate "bolometric correction" for the 0.2–4.0 keV X-rays. From the data in Figure 6 we estimate that the 2–10 keV flux exceeds the IPC flux by a factor which is typically 2–2.5, but which varies considerably from star to star. With some allowance for flux beyond 10 keV, we shall adopt a uniform factor of 0.25 to convert between total hard X-ray flux and IPC flux.

From our simple accretion model we therefore expect a 0.2–4.0 keV luminosity given by

$$L_x(0.2\text{–}4.0 \text{ keV}) = (0.5)(0.25)\,\frac{GM_* \dot{M}}{2R_*}\,, \tag{4}$$

where $\dot{M}$ is the accretion rate, M_* and R_* are the mass and radius of the white dwarf, 0.5 is the correction for the fraction of the X-rays emitted inward and absorbed by the white dwarf,[2] and 0.25 is the fraction of X-rays appearing in the IPC bandpass. For a star satisfying the white dwarf mass-radius relation [approximately $R/R_\odot = 0.007\,(M/M_\odot)^{-0.8}$ (Hamada and Salpeter 1961)], we then expect

$$L_x(0.2\text{–}4.0 \text{ keV}) = 8.7 \times 10^{31} \dot{M}_{16}^{1.0} M_{0.7}^{1.8} \text{ ergs s}^{-1}\,, \tag{5}$$

where $M_{0.7}$ is the white dwarf mass in units of 0.7 $M_\odot$, the average mass empirically determined in CVs (Shafter 1983). Of course, it is quite likely that our factor of 0.25 is itself dependent on white dwarf mass and/or accretion rate. If these dependences were known, equation (5) would change significantly. But until these questions have been more thoroughly studied, we will adopt equation (5) as our working prediction.

In Figure 7 the dashed line shows the $L_x(\dot{M})$ and the $F_x/F_v(\dot{M})$ relations predicted from equation (5), and superposed on the observational data. It is evident that our maximally naive model is in good agreement with the IPC observations for $\dot{M}_{16} < 1$, but vastly overestimates L_x for $\dot{M}_{16} \gg 1$.

ii) *Dependence on $\dot{M}$*

More realistic models suggest that hard X-ray emission should depend drastically on $\dot{M}$ (Pringle 1977; Pringle and Savonije 1979; Tylenda 1981*a*). The model of Pringle and Savonije (1979) produced X-rays via strong shocks in the boundary layer, while that of Tylenda (1981*a*) relied on turbulent viscosity. Both models predict efficient generation of hard X-rays at low accretion rates ($\dot{M} < 10^{16}$ g s^{-1}), and a fairly sudden drop at higher accretion rates as the temperature

[2] Subsequent calculations should probably account for the dependence of this fraction on X-ray energy, as discussed by Kylafis and Lamb (1982) and Felsteiner and Opher (1976).

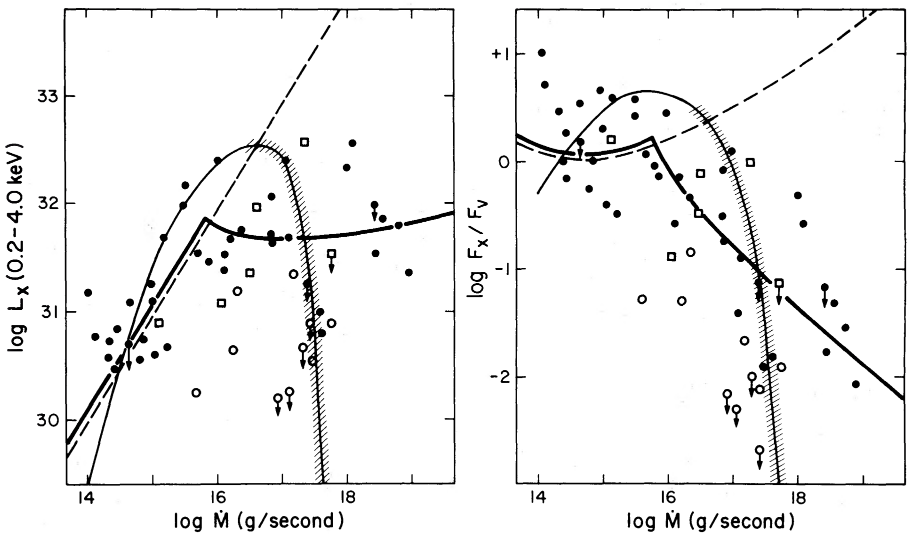

FIG. 7.—Predicted dependences of L_x and F_x/F_v on accretion rate for three boundary-layer models, superposed on the observational data. *Dashed curve:* a simple "optically thin" model. *Light solid curve:* Tylenda's (1981*a*) model (within shaded region, X-ray source is predicted to be soft, contrary to observation). *Heavy solid curve:* a model of optically thin region with density gradient. In all cases, we assume $M = 0.7\ M_\odot$, $f = 0.25$.

declines, and as the heated gas becomes unable to expand out of the plane of the disk.

Let us examine this prediction more closely in the context of Tylenda's (1981*a*) model of a turbulent boundary layer, averaged over its vertical extent. We apply his equation (24) to a standard white dwarf, and find the expected dependence of the bremsstrahlung temperature $kT_{\rm brems}$ of the boundary layer on the accretion rate $\dot{M}$:

$$kT_{\rm brems} = 1.3\,\frac{M_{0.7}^{3.6}}{\dot{M}_{16} r_e^2}\ {\rm keV}\ , \qquad (6)$$

where r_e is the Reynolds number of the turbulent region (defined in Tylenda's eq. [17]), in units of 10^3, the value favored by Tylenda (1981*a*) and by Webbink (1976). For simplicity we shall set $M_{0.7} = 1$, $r_e = 1$, in order to explore the dependence on $\dot{M}_{16}$. The calculated dependence of L_x and F_x/F_v on $\dot{M}$ are shown as the light solid curve in Figure 7. As mentioned earlier, the hard X-ray emission is very substantial for $\dot{M}_{16} < 1$, but plummets steeply when $\dot{M}_{16} \gtrsim 5$.

Obviously, the fit to the observational data is poor. And it is even worse than it looks, because the shaded portion of the theoretical curves corresponds to a regime in which the 0.2–4.0 keV bandpass is being populated by photons from a low-temperature source ($kT_{\rm brems} \lesssim 1$ keV). But the observations indicate that in general the X-rays come from a high-temperature source, with $kT_{\rm brems} > 1$ keV and in most cases $kT_{\rm brems} \gg 1$ keV. Therefore the predicted "hard component" of the X-ray emission drops almost immediately to zero when $\dot{M}_{16}$ exceeds ~ 2, while the observations show no such drop.

iii) *Adding a Density Gradient*

Qualitatively, we can see one important feature missing in these models. Only the *average* properties of the boundary layer (BL) are considered; with no allowance for any temperature gradient, the accretion luminosity is confined to a fairly narrow wavelength range. But in a real accretion disk, the local density of accreting matter almost certainly declines smoothly with increasing height in the disk. Since low density means less efficient cooling and therefore higher temperature, it seems likely that the tops of all disks will be very hot at the interface with the white dwarf—and thus able to produce hard X-rays. For high-$\dot{M}$ disks we should expect not $L_x = 0$ as in the vertically averaged model, but something like $L_x \approx$ *constant* for $\dot{M}_{16} > 1$ (since we will see X-rays from the top of the disk down to some critical height where the "effective" $\dot{M}$ is about 10^{16} g s^{-1}). This appears to be in better agreement with the data, and therefore we shall explore it in more detail.

Essentially nothing is known about the density gradient in the BL, but we require an assumption in order to proceed. Since the BL is fed by the accretion disk, we shall assume that the density gradient is determined by that in the accretion disk just beyond the BL. Assuming the viscosity parameter $\alpha = 1$ and a BL width equal to the disk scale height, the α-disk model gives a vertical density structure (Shakura and Sunyaev 1973; Pringle and Savonije 1979)

$$n = n_0 e^{-(z/z_*)^2}\ , \qquad (7)$$

where

$$n_0 = 8.1 \times 10^{16} \dot{M}_{16}^{0.65} M_{0.7}^{2.46}\ {\rm cm}^{-3}\ , \qquad (8)$$

$$z_* = 2.2 \times 10^6 \dot{M}_{16}^{0.18} M_{0.7}^{-1.18}\ {\rm cm}\ . \qquad (9)$$

Following the discussion in the preceding paragraph, let us assume that there is a critical density n_c, such that matter entering the BL with $n < n_c$ radiates its energy in hard X-rays, while matter with $n > n_c$ either remains too cool to emit hard X-rays, or remains so close to the disk plane that any hard X-rays emitted are degraded by Compton scattering or absorbed by the disk. Integrating equation (7) over the disk height, we find that the mass fraction of the BL having $n < n_c$ is

$$2\pi^{-1/2} \int_{z_c/z_*}^{\infty} e^{-(z/z_*)^2} d(z/z_*) = {\rm erfc}\,(z_c/z_*)\ , \qquad (10)$$

where

$$\frac{z_c}{z^*} = \left(\ln \frac{n_0}{n_c}\right)^{1/2}\ . \qquad (11)$$

Finally, we need an estimate for n_c. We can find one by assuming (cf. Pringle and Savonije 1979) that gas which can expand in a time less than its radiative cooling time will form a hot, easily observable layer above the disk, while gas with $t_{\rm exp} > t_{\rm cool}$ will remain close to the disk plane, where its radiation will be degraded by Compton scattering or absorbed by the disk. The criterion $t_{\rm exp} = t_{\rm cool}$ is just

$$\frac{z_*}{c_s} = \frac{2kT}{n_c \Lambda}, \tag{12}$$

where c_s is the sound speed and Λ is the radiative cooling coefficient. Since we do not know the temperature structure, we assume $T = 10^8$ K, based on the X-ray measurements. Then we have

$$c_s = (2kT/m_p)^{1/2} = 1.3 \times 10^8 \text{ cm s}^{-1}, \tag{13}$$

$$\Lambda = 3 \times 10^{-23} \text{ ergs cm}^3 \text{ s}^{-1}, \tag{14}$$

$$\frac{n_c}{n_0} = \frac{kTc_s}{\Lambda z_* n_0} \approx 0.68 \dot{M}_{16}^{-0.82} M_{0.7}^{-1.28}. \tag{15}$$

This implies that $n_c = n_0$ for $\dot{M}_{16} = 0.62$, i.e., $\dot{M} = 6 \times 10^{15}$ g s^{-1}. Consequently the theory predicts

$$L_x(0.2\text{–}4.0 \text{ keV}) = 8.7 \times 10^{31} M_{0.7}^{1.8} \dot{M}_{16}^{1.0} \times \begin{Bmatrix} 1 & \text{if } \dot{M}_{16} < 0.62 \\ \text{erfc } (z_c/z_*) & \text{if } \dot{M}_{16} > 0.62 \end{Bmatrix} \text{ ergs s}^{-1}. \tag{16}$$

The predicted dependences of L_x and F_x/F_v on $\dot{M}$ are shown as the heavy solid curves in Figure 7. L_x rises linearly with $\dot{M}$ up to 6×10^{15} g s^{-1}, and stays virtually constant thereafter. If we exclude dwarf novae in eruption, we find a reasonably good fit to the observations, with an rms dispersion of a factor of 3 in both L_x and F_x/F_v. This is comparable to the dispersion expected solely from uncertainties in accretion rate and white dwarf mass.

Of course, we have not *determined* the structure of the boundary layer. We have merely made a simple "semiempirical" assumption about the optically thin portion of the boundary layer, and noticed that it yields $L_x(\dot{M})$ and $F_x/F_v(\dot{M})$ relations which fit the data about as well as any smooth curve could. It remains to be seen whether a *self-consistent* theory of the BL structure (i.e., of the density and temperature distributions) can be devised, without destroying the agreement with the observational data. This is certainly an open and crucial question.

iv) *The Dwarf Nova Problem*

The most embarrassing feature in this model is the prediction $L_x \sim 10^{32}$ ergs s^{-1} for erupting dwarf novae. All the points substantially below the theoretical curve are either known dwarf novae in eruption, or "UX UMa" stars, commonly thought to be dwarf novae in more or less permanent eruption (Warner 1976; Bond 1978). Why should the observed values of L_x be so low in these systems?

Within the above model, the obvious possibility is that somehow the density gradient in the BL is suppressed, thereby quenching the expected hard X-ray emission. We have no detailed suggestion for how this might be accomplished. But it is interesting to note that the quenching of hard X-ray emission coincides at least roughly in time with the appearance of short-period oscillations ("dwarf nova oscillations" [Patterson 1981; Córdova *et al.* 1980]) at optical and EUV/soft X-ray wavelengths.[3] The origin of these oscillations is not yet known, but their short time scale, high luminosity, and high temperature require an origin very near the white dwarf, where a substantial fraction of the total energy is liberated. Because in these high-$\dot{M}$ systems the BL is vertically supported chiefly by radiation pressure from soft X-rays (Pringle 1977), it seems plausible that the vertical density gradient could be strongly affected by the process driving the oscillations. This possibility should be checked in future theoretical studies.

v) *A Closeup View*

In Figure 8 we show a picture, roughly to scale, of the boundary-layer structure we are suggesting. The dotted region is optically thin, and radiates an X-ray bremsstrahlung component at $\sim 10^8$ K. The shaded region is optically thick, and radiates nearly half of the accretion energy in a blackbody component at a fairly low temperature (~ 1–3×10^5 K [Pringle 1977]). Sufficiently far from the midplane of the disk, the density is too low for efficient cooling, and so even the high-$\dot{M}$ systems radiate a low-luminosity, high-temperature X-ray component.

IV. REPROCESSED CONTINUUM RADIATION

a) Theory

An inescapable feature of this theory is that all of the white dwarfs in CVs should be locally heated to high temperatures by the boundary-layer radiation. In high-$\dot{M}$ systems there are probably no observable effects from the heating of the white dwarf, because the heated region cannot be distinguished from the optically thick disk, and because the disk itself is very bright at visual and ultraviolet wavelengths. But in low-$\dot{M}$ systems the heated white dwarf should be prominent and unobscured, and the disk is relatively faint. It is straightforward to calculate the reprocessed visual luminosity of the white dwarf. From Tylenda (1981*a*) we estimate the scale height H of the optically thin boundary layer:

$$H = 3.85 \times 10^8 M_{0.7}^{0.1} \dot{M}_{15}^{-0.5} \text{ cm}. \tag{17}$$

Consequently the fraction f of the white dwarf surface that is irradiated by X-rays is found to be

$$f = 0.55 M_{0.7}^{0.9} \dot{M}_{15}^{-0.5}. \tag{18}$$

Now the luminosity incident on the white dwarf is

$$L_{Hx} = 3.4 \times 10^{31} M_{0.7}^{1.8} \dot{M}_{15}^{1.0} \text{ ergs s}^{-1}. \tag{19}$$

Let A be the irradiated area on the white dwarf, which is given by

$$\begin{aligned} A &= A_* \quad \text{if } f > 1 \\ &= fA_* \quad \text{if } f < 1, \end{aligned} \tag{20}$$

where A_* is the surface area of the white dwarf. The effective temperature T_e of the irradiated surface is then easily determined from

$$A\sigma T_e^4 = L_{Hx}, \tag{21}$$

[3] The optical dwarf nova oscillations are known to occur near the peak of an outburst (Patterson 1981; Robinson 1976). The X-ray observations are much less extensive, but suggest that the suppression of hard X-ray emission also occurs only near the peak (Bennets 1982; Córdova and Mason 1983; Figs. 3 and 4 of Ricketts, King, and Raine 1978; Fig. 2 of Swank 1979). Intensive X-ray monitoring of individual systems could greatly clarify this point.

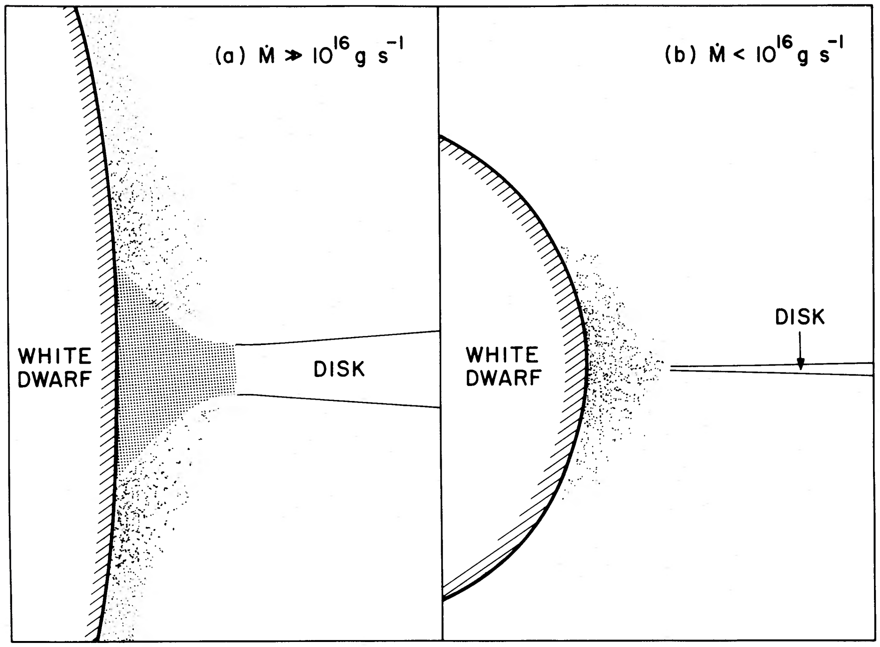

FIG. 8.—Picture of the boundary layer for (*a*) high accretion rates and (*b*) low accretion rates. The dotted region is optically thin and radiates a bremsstrahlung component at $T \sim 10^8$ K. The shaded region is optically thick and radiates a blackbody component at $T \sim (1\text{–}3) \times 10^5$ K.

and the result is

$$\begin{aligned} T_e &= 17{,}800 M_{0.7}^{0.62} \dot{M}_{15}^{0.37} f^{-0.25} \text{ K} \quad \text{if } f < 1 \\ &= 17{,}600 M_{0.7}^{0.85} \dot{M}_{15}^{0.25} \text{ K} \quad \text{if } f > 1\,. \end{aligned} \tag{22}$$

In Figure 9 we show the resultant values for T_e and M_v, using the bolometric corrections computed by Wesemael *et al.* (1980) for hot, high-gravity, pure hydrogen model atmospheres. The behavior of T_e is more or less as expected: for the range $\dot{M}_{15} \approx 0.3$–10, the heated white dwarf surface radiates at temperatures of $(1\text{–}6) \times 10^4$ K. The behavior of M_v is somewhat surprising, because for $\dot{M}_{15} \gtrsim 0.5$, the "pseudo white dwarfs" have $M_v \approx 11.1$–11.5, nearly independent of mass and accretion rate. This seems to be an accidental consequence of the way in which the scale height (set by the cooling time) declines as the accretion rate increases.

b) *Comparison with Observations*

Are there any *observations* of reprocessed boundary-layer radiation? The answer to this is not known, but there are at least fifteen stars in which photometric and/or spectroscopic signatures of a hot white dwarf have appeared during a low-$\dot{M}$ state. In Table 2 we present the basic data for these stars; we will now discuss the entries in more detail.

Col. (*2*).—Here we indicate the nature of the evidence which suggests the existence of, and constrains the temperature of, a white dwarf component. The first three stars listed are eclipsing binaries, and in quiescence the behavior of the light curve during eclipse shows that ~30%–70% of the visual light comes from a bright object at the center of the disk, with the dimensions of a white dwarf. It has usually been assumed (e.g., Bailey 1979; Smak 1979; Patterson 1981) that this object *is* the white dwarf, although this case is not easily distinguished from the case in which the light comes from the innermost portions of the accretion disk (e.g., see Fig. 2 of Bath *et al.* 1974). The next six stars listed have ultraviolet spectra showing a small, hot object with absorption lines—consistent with the spectrum of a hot white dwarf. Evidence of type 3 (see note to table) consists of broad absorption lines in the optical spectrum, again suggesting the presence of a moderately hot white

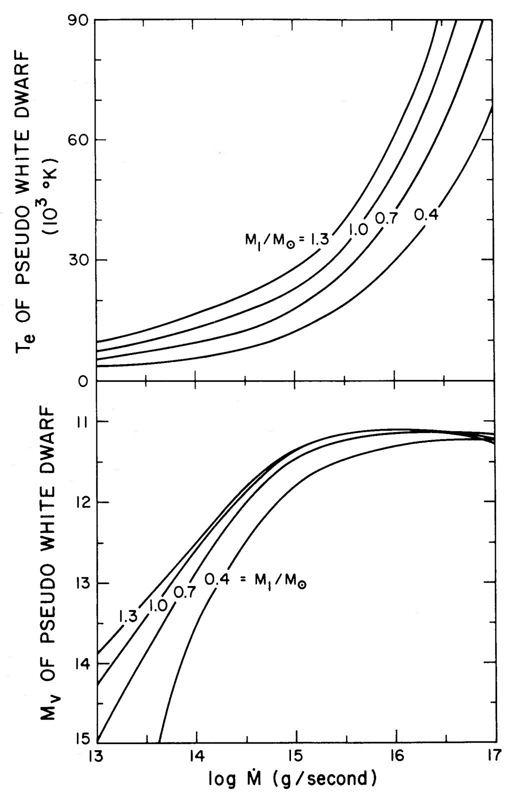

FIG. 9.—Theoretical values of effective temperature T_e and absolute visual magnitude M_v for the region on the white dwarf which reprocesses the incident hard X-ray flux into continuum light. These values are averaged over all binary inclinations.

TABLE 2

PSEUDO WHITE DWARF CANDIDATES IN SYSTEMS OBSERVED IN A LOW-$\dot{M}$ STATE

Star (1)	White Dwarf and T_e Evidence (2)	$(m_v)_{wd}$ (3)	$(M_v)_{wd}$ (4)	$T_e(\times 10^3$ K) (5)	$f = A_{em}/A_{wd}$ (6)	Data Reference (7)
HT Cas	1, 4	17.3	11.0	~50	0.2–1.0	1
Z Cha	1, 4	17.0	10.7	20–30	0.4–4.0	2, 3
OY Car	1, 3	17.1	11.7	20–30	0.2–1.5	4, 5
U Gem	2, 4	16.5	11.9	30–40	0.1–0.5	6, 7, 8
SS Cyg	2, 4	15.5	10.5	30–45	0.2–1.3	8
MV Lyr	2, 3, 4	17.8	10.4	35–50	0.2–1.1	9, 10, 11
AM Her	1, 2, 3, 4	15.9	11.5	40–60	0.1–0.5	12, 13, 14
TT Ari	2, 3, 4	16.6	10.9	~50	0.2–1.0	15, 16
VW Hyi	2, 3, 4	16.0	10.6	15–25	0.3–3.0	17
WZ Sge	3, 4	15.9	11.7	10–20	0.3–3.5	18, 19
SW UMa	3, 4	16.9	11.7	10–25	0.2–3.5	20
T Leo	3, 4	17.0	11.5	20–30	0.2–1.5	21
V436 Cen	3, 4	16.1	11.5	10–20	0.4–4.0	22
UU Aql	4	17.9	12.3	20–30	0.1–1.0	23
YY Dra	4	17.7	12.5	20–30	0.1–1.0	24

NOTE.—Code for white dwarf and T_e evidence: 1 = optical eclipse; 2 = UV absorption lines; 3 = optical absorption lines; 4 = UV/optical colors.

REFERENCES.—(1) Patterson 1981; (2) Bailey 1979; (3) Rayne and Whelan 1981; (4) Bailey and Ward 1981; (5) Gilliland 1982*a*; (6) Holm and Panek 1984; (7) Cordova and Mason 1983; (8) Fabbiano *et al.* 1981; (9) Robinson *et al.* 1981; (10) Schneider, Young, and Schectman 1981; (11) Szkody and Downes 1982; (12) Schmidt, Stockman, and Margon 1981; (13) Patterson and Price 1981; (14) Szkody, Raymond, and Capps 1982; (15) Shafter *et al.* 1982; (16) Shafter *et al.* 1984; (17) Hassall *et al.* 1983; (18) Krzeminski and Smak 1971; (19) Gilliland 1983; (20) Shafter 1983; (21) Shafter and Szkody 1984; (22) Gilliland 1982*a*; (23) Thorstensen, Stanford, and Patterson 1985; (24) Patterson *et al.* 1985.

dwarf.[4] Evidence of type 4 consists of an ultraviolet upturn in the continuum spectrum, suggesting that the UV light is dominated by a source smaller and hotter than the accretion disk.

Cols. (*3*) *and* (*4*).—From the published photometry we have estimated the apparent visual magnitude m_v of the white dwarf component, and have used the distance estimates in P84 to estimate the absolute magnitude M_v (thought to be uncertain by $\pm \sim 1$–1.5 mag).

Col. (*5*).—Here we have estimated the observational constraints on the temperature of the white dwarf component, by comparing the observed spectra with the extensive grid of model atmospheres published by Wesemael *et al.* (1980), Wesemael (1981). The best constraints come from observations of the Lyman-α and He II λ1640 absorption lines. Optical colors and absorption lines (principally Hβ, Hγ, and He II λ4686) are also useful, but are strongly contaminated by the accretion disk, which tends to dominate at visual wavelengths (see Fig. 10 below). Ultraviolet colors are less affected by disk light, but are rather insensitive to temperature: essentially all model atmospheres of white dwarfs show a large Lyman jump in absorption, which causes the flux distribution longward of 912 Å to mimic a very hot star, regardless of the actual temperature (e.g., Wesemael *et al.* 1980; Böhm and Kapranidis 1980). From these clues we have derived the tabulated estimates for T_e. These are rough estimates, not firm upper and lower bounds. In a later paper we will study the flux distributions, equivalent widths, and line profiles of these white dwarf components, and try to find full self-consistent solutions.

Col. (*6*).—Here we estimate the fraction of the white dwarf surface area that is emitting at the observed temperature; we will discuss this below.

Col. (*7*).—Finally, we give references to the papers we have used to prepare Table 2.

Let us consider the question: are these small, bright objects the "bare" white dwarfs, uncontaminated by accretion, or are they some form of accretion light? In principle, this question can be addressed by using the observed constraints on M_v and T_e to calculate how much surface area—and hence what fraction f of the white dwarf surface—is responsible for the observed light. In column (6) of Table 2 we have estimated the range of acceptable values for f, based on the estimates for M_v and T_e. For SS Cyg, U Gem, and HT Cas, we assume a white dwarf radius appropriate for the measured white dwarf mass (1.3, 1.1, and 0.7 $M_\odot$, respectively); for the others, a radius of 7×10^8 cm is assumed.

The values in column (6) suggest a surface area approximately equal to, or perhaps somewhat smaller than, the surface area of a white dwarf. The most secure values of T_e in Table 2 are provided by the simultaneous detections of Lyman-α and He II absorption lines (requiring, respectively, $T_e \lesssim 50{,}000$ K and $T_e \gtrsim 40{,}000$ K, with some dependence on gravity). Consequently the deduced values of f are most secure for AM Her, U Gem, TT Ari, and MV Lyr; it is worth noting that for these stars, we obtain tantalizing hints[5] of $f < 1$. We

[4] Of course, it is well known that in high-$\dot{M}$ systems, broad absorption lines can be produced in the accretion disk (e.g., Herter *et al.* 1979). We are doubtful that such lines can be produced in low-$\dot{M}$ disks, but in the absence of theoretical studies this must certainly be reckoned an open question.

[5] In the case of AM Her, the observed U band light curve (Szkody, Raymond, and Capps 1982; Patterson and Price 1981) shows a modulation in phase with the familiar light curve in soft and hard X-rays. This strongly suggests that the light comes not from the entire white dwarf but from a large area centered on the magnetic pole, heated by an X-ray flux from above. Of course this is a special case, since AM Her contains a magnetic white dwarf and is presumably a radial accretor. But we include the star anyway, because it gives us some extra confidence in the hypothesis we shall favor: that X-ray heating of the stellar surface really does produce a "pseudo white dwarf" component in the spectrum, primarily in the ultraviolet.

consider four hypotheses for the identification of these small, hot objects:

1. *The "bare" white dwarfs, which happen to be fairly hot.*—This has some difficulty with the (M_v, T_e) test, and is hard to accept for other reasons as well. High-speed photometry of HT Cas through eclipse (Patterson 1981) showed that (*a*) the bright object remains constant in size but varies by a factor of ~ 2 in brightness, and (*b*) the bright object is probably the source of the optical flickering. Inspection of the published light curves of Z Cha and OY Car (Bailey 1979; Schoembs and Hartmann 1983) suggests similar behavior. This cannot be reconciled with the steady luminosity expected from a bare white dwarf.

2. *The optically thick inner portions of the accretion disk.*—This is a possible identification, but it suffers from three major problems. First, the eclipse light curves of HT Cas, Z Cha, and OY Car indicate that the central object has approximately the size of a white dwarf. This argument is simple and quantitative, but is unfortunately quite sensitive to binary inclination (see Patterson 1981). Second, we note that at low accretion rates, disk models show flux distributions characteristic of a low-temperature gas (see Fig. 2 of Tylenda 1981*b* or Fig. 4 of Williams and Ferguson 1982)—contrary to observation. Third, it is somewhat doubtful that the accretion disk can produce the very deep and broad absorption lines seen in many systems. The effective gravity in the disk is less than 10^7 cm s^{-2}, and this seems to be too low for Stark broadening to be very effective (see models of Wesemael *et al.* 1980). Doppler broadening from Keplerian motion in the disk will help, but the disk models of Herter *et al.* (1979) and Mayo, Wickramasinghe, and Whelan (1980) produced lines far too weak to match the observations of these low-$\dot{M}$ systems. This argument should be checked by extending the model calculations to the low-$\dot{M}$ regime (in which the optically thick disk component is probably restricted to the inner disk, where stronger lines might be produced, due to the greater line broadening and narrower temperature range).

3. *The white dwarf surface, which is kept hot by the ongoing or the recent accretion.*—This hypothesis is viable, but would be greatly strengthened by a self-consistent theory of the heating. In the customary accretion theory, the accretion energy is promptly *radiated away.* It is not clear that the white dwarf can be maintained hot for longer than the thermal reprocessing time scale of the white dwarf's outermost layers, which is at most a few minutes.

4. *The heated white dwarf surface, which reprocesses incident X-rays emitted by the boundary layer.*—This is a plausible hypothesis which leads to straightfoward predictions. Eight of our stars (HT Cas, Z Cha, U Gem, SS Cyg, AM Her, VW Hyi, WZ Sge, and V436 Cen) have measured X-ray fluxes in their low-$\dot{M}$ states. From the X-ray luminosities and equation (5) we estimate a mean accretion rate of $\sim 7 \times 10^{14}$ g s^{-1}. At this accretion rate we expect from Figure 9 that a pseudo–white dwarf should have $M_v \sim 11$–12, $T_e \sim (1.5$–$3.0) \times 10^4$ K. This is fairly consistent with most of the data in Table 2. Higher temperatures are certainly required for TT Ari and MV Lyr, but we are unable to interpret this without an estimate of the simultaneous X-ray flux.

We can gain further insight into the relative importance of disk and pseudo white dwarfs by calculating their theoretical absolute visual magnitudes for a range of accretion rates and binary inclinations. This comparison is shown in Figure 10, where we have fixed the white dwarf mass at 0.7 $M_\odot$. For the accretion disk we have used the models of Tylenda (1981*b*). For the inclination we adopt a simple cos *i* dependence, which should be adequate for $i \lesssim 80°$. For the white dwarf we have used the reprocessing models shown in Figure 9, but now account explicitly for the effect of inclination, which is important since the reprocessed light tends to come from an equatorial band on the white dwarf.

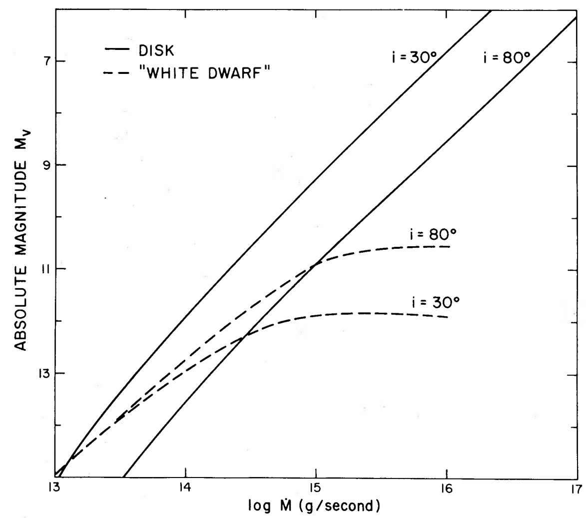

FIG. 10.—Theoretical absolute visual magnitudes for accretion disks and pseudo white dwarfs, viewed from binary inclinations of 30° and 80°. A white dwarf mass of 0.7 $M_\odot$ has been assumed. Note that for highly inclined systems, the white dwarf can actually exceed the disk in brightness, for sufficiently low $\dot{M}$.

The resultant curves in Figure 10 are more or less in accord with intuition. As long as the BL is optically thin (i.e., for $\dot{M} \lesssim 5 \times 10^{15}$ g s^{-1}), the disk and white dwarf contributions are comparable, since each of them represents $\sim 25\%$–50% of the total accretion light. But disks radiate perpendicular to their plane, while the white dwarf preferentially radiates in the disk plane; consequently there is a strong dependence on inclination. In relatively face-on systems the disk tends to dominate the white dwarf, while in relatively edge-on systems the white dwarf can be brighter. For our three systems showing deep eclipses, the binary inclination is near 80°, and the accretion rate derived above is $\sim 7 \times 10^{14}$ g s^{-1}. From Figure 10 we deduce that the pseudo white dwarf should produce about 50% of the visual light—in reasonable agreement with the observed light curves.

Finally, we can calculate the ultraviolet flux expected from the "pseudo white dwarf" theory presented above. In Figure 11 we compare the observed ratios of ultraviolet to optical flux, uncorrected for interstellar reddening, with theory. The curve labeled *DISK* gives the contribution of the accretion disk alone, taken from Tylenda (1981*b*). The curve labeled *PWD* gives the contribution of the pseudo white dwarf alone, as stated above. Stars are thus predicted to lie along the curve labeled *SUM*, maintaining a nearly constant ultraviolet-to-optical flux ratio even while $\dot{M}$ varies over four orders of magnitude. As can be seen in Figure 11, the empirical data are reasonably consistent with this description, subject to the usual worries about nonsimultaneous measurement, uncertainty in $\dot{M}$, uncertainty in reddening, and nonsteady accretion. This tends to support the pseudo white dwarf theory, and provides very strong evidence that the ultraviolet light in low-$\dot{M}$ systems comes from a source much smaller and hotter than the accretion disk.

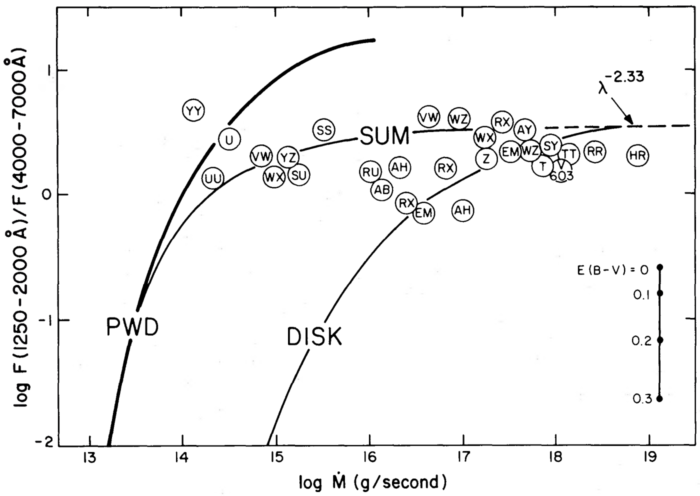

FIG. 11.—Predicted dependence of ultraviolet-to-optical flux ratio on $\dot{M}$ for the accretion disk alone (curve labeled *DISK*), the pseudo white dwarf alone (curve labeled *PWD*), and the composite (curve labeled *SUM*). The dashed line shows the predicted value for a classical "infinite disk," with $F_\lambda \propto \lambda^{-2.33}$ (Lynden-Bell and Pringle 1974). The scale at lower right shows how the theoretical curves are shifted by interstellar reddening. The empirical data are superposed, and we interpret their close agreement with the *SUM* curve as indicating support for the pseudo white dwarf theory.

Hypotheses 3 and 4 are both viable explanations of the small, hot components seen in these systems. We favor hypothesis 4, because it leads to straightforward observational tests, which it survives. However, it is true that we have constructed our arguments from available data on 8 of the 15 stars in Table 2, as if a *single* phenomenon were present. Not every argument can be made for each star, and it may be that Table 2 contains examples of several different phenomena.

V. SUMMARY, PREDICTIONS, EXHORTATIONS

1. We analyze the hard X-ray data collected by the *Einstein* IPC for systems accreting through a disk, and find that the F_x/F_v ratio appears to vary smoothly with the accretion rate $\dot{M}$. Because the absolute visual magnitude and the emission-line equivalent widths are also determined by $\dot{M}$, knowledge of any *one* of these three quantities suffices to predict the hard X-ray flux and luminosity to within a factor of ~ 3. Dwarf novae in outburst, and all systems with nearly edge-on disks, appear to be systematically underluminous in hard *X*-rays by a factor of $\gtrsim 5$.

2. Following Pringle and Savonije (1979) and Tylenda (1981*a*), we favor a boundary-layer origin for the X-rays. A simple optically thin model is quite successful for low-$\dot{M}$ systems, without exception. This presents a serious problem for the commonly held view that in dwarf novae, accretion through the disk does not occur during quiescence (see especially Paczyński and Schwarzenberg-Czerny 1980). It still may be true that matter accumulates in the outer disk between outbursts, but a way must be found to dump matter onto the white dwarf at a rate $\gtrsim 10\%$ of the mass transfer rate.

3. Systems with $\dot{M} \gg 10^{16}$ g s^{-1} show hard X-ray luminosities exceeding those predicted in the simple models. But low density is the necessary and sufficient condition for producing hard X-rays in the boundary layer, and it seems plausible that a proper accounting of the density structure could explain this discrepancy. Our estimate of this effect should be replaced by a *self-consistent* solution for the density and temperature variation.

4. It would be very desirable to study the changes in L_x and X-ray spectrum as $\dot{M}$ changes through the eruption cycle of one particular star. This would avoid the "snapshot" problem inherent in the IPC observations, and would eliminate or greatly reduce the uncertainties introduced by errors in the distance and white dwarf mass. Particularly attractive targets are SS Cyg, RU Peg, V436 Cen, and HL CMa.

5. X-rays from the boundary layer are likely to produce observable effects by the heating of nearby cooler gas, both in the white dwarf and in the disk. It is hard to predict a definite observational signature of the disk heating (emission lines?), but the heating of the white dwarf in a low-$\dot{M}$ system should produce a "pseudo white dwarf component in the spectrum, with $M_v \sim 11$–12, $T_e \sim (1$–$5) \times 10^4$ K. We identify these components as the small, bright objects seen in many, and perhaps all, systems when $\dot{M}$ is very low. Figure 11 provides a means of testing this hypothesis.

6. This interpretation of the low-$\dot{M}$ systems leads to a number of predictions. The X-ray flux F_x from the BL should be approximately equal to the bolometric flux $F_{\rm wd}$ of the white dwarf. If steady accretion is occurring, the bolometric flux F_d from the accretion disk should satisfy $F_d \approx 2F_x \approx 2F_{\rm wd}$. These predictions are strong, easily testable, and not strongly dependent on distance estimates; we shall make a detailed comparison with data in a later paper. In addition, variations in hard X-rays and optical (or UV) light should be well correlated on all time scales, if the pseudo white dwarf is a major component in optical (or UV) light. Of course, we also predict that in systems with deep optical eclipses, the X-ray source should suffer a sharp and total eclipse when the secondary occults the white dwarf. Since the optical eclipse ephemerides are known to very high precision, this can easily be tested by obtaining a long X-ray light curve of HT Cas or Z Cha (the only deep eclipsers detected in X-rays to date) in quiescence. We predict that the other low-$\dot{M}$ deep eclipsers (viz., OY Car and probably V2051 Oph), for which no *Einstein* observations are available, should also be reasonably strong X-ray sources ($F_x/F_v \sim 1$–10) and therefore suitable targets. All the high-$\dot{M}$ eclipsing systems are likely to be unsuitable targets, because of heavy obscuration of X-rays.

7. The major conclusion of this paper is that it is possible to understand the observed X-ray fluxes in terms of a more or less

conventional boundary-layer model. In the paper following, we shall deal with the complementary question: for systems in which the observed X-ray luminosity represents only a small fraction of the total expected BL radiation, can the same conventional BL models account for the *unobserved* fraction of the total (the "missing boundary layer")?

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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

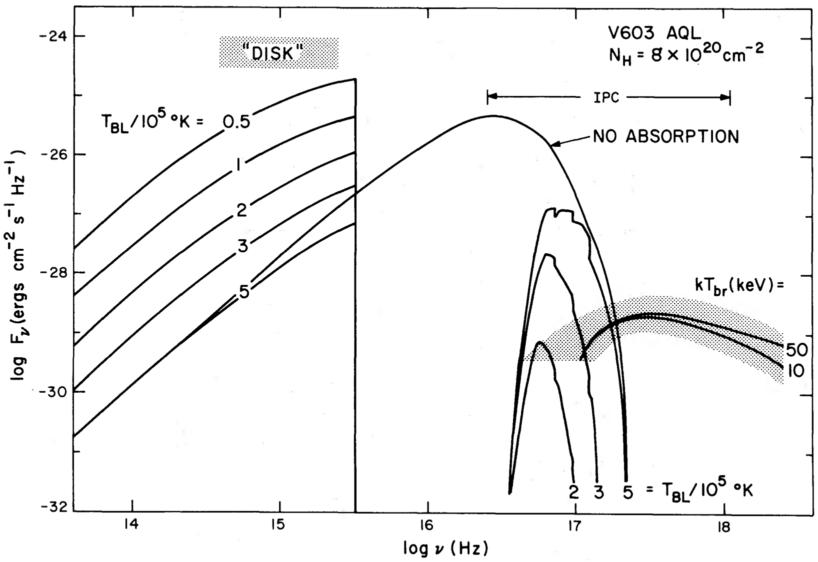

FIG. 1.—Observed flux distribution of V603 Aql. The curves labeled 0.5, 1, 2, 3, 5 are blackbody distributions of various temperatures, modified by an interstellar absorption $N_H = 8 \times 10^{20}$ cm^{-2}, and possessing a total luminosity equal to half of the disk luminosity. One of the unabsorbed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

[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).

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

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

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.

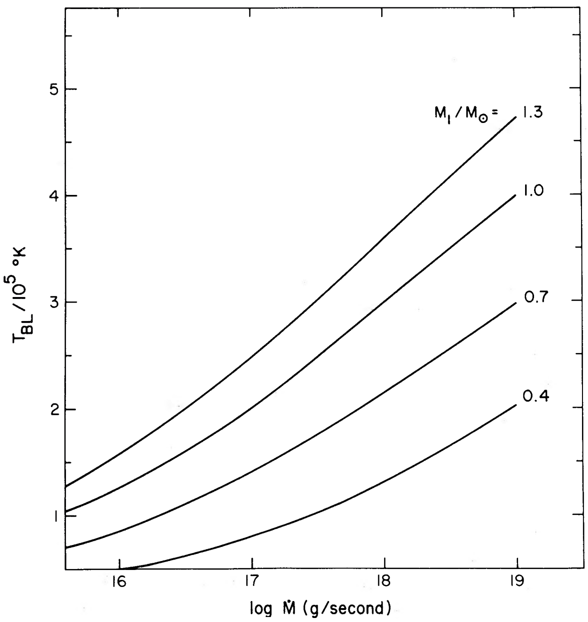

FIG. 2.—The effective temperature T_{BL} of an optically thick boundary layer, as a function of the accretion rate $\dot{M}$ and the white dwarf mass M. Note the strong dependence on white dwarf mass (approximately $\propto M^{0.86}$).

With these assumptions we find the boundary layer temperatures T_{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_{BL} and scale height H_{BL}:

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

and

$$T_{BL} = 2.16 \times 10^5 M_{0.7}^{0.86} \dot{M}_{18}^{0.18} \text{ K} . \quad (3)$$

Before proceeding further, we note that for V603 Aql, Figure 2 and the above estimates for T_{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 $p[\equiv F(0.12\text{–}1.0 \text{ keV})/F_{total}]$ on T and N_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_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_{sx} (0.12–1.0 keV)/F_v(5000–6000 Å) on $\dot{M}$, for a standard value of $N_H = 2 \times 10^{20}$ 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_H-distance relation found for stars within 1 kpc of the Sun (1.3×10^{18} cm^{-2} 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_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., $F_{sx}/F_v < 1$ 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

[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.

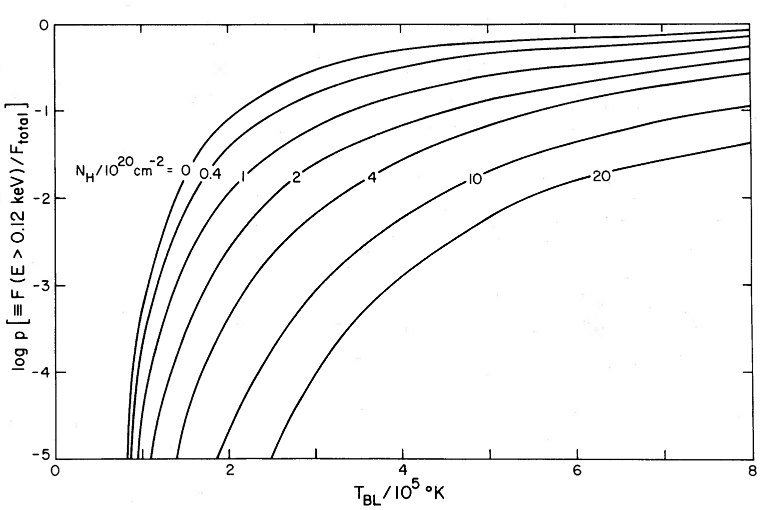

FIG. 3.—The fraction p of blackbody luminosity appearing in the soft X-ray bandpass, as a function of T and N_H

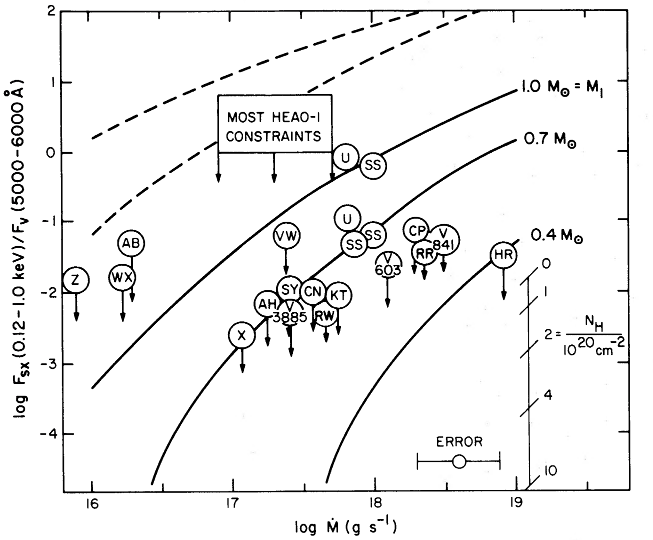

FIG. 4.—*Solid curves* show the theoretical dependence of F_{sx}(0.12–1.0 keV)/F_v(5000–6000 Å) on $\dot{M}$, for three choices of white dwarf mass M_1. An interstellar column density $N_H = 2 \times 10^{20}$ cm^{-2} has been assumed, but at lower right we show how the curves should be shifted for other 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 $M_1 = 1.0$–$1.3\ M_\odot$, $d = 100$ 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	$(m_v)_{outburst}$	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 $\lambda 4686$ 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 $\lambda 4686$ and $\lambda 1640$, which should be in the ratio $I(\lambda 1640)/I(\lambda 4686) \sim 7$ 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_{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 $\lambda 1640$ and $\lambda 4686$ 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_{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 $\lambda 4686$ 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 $\lambda 4686$ 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 $\lambda 4686$ equivalent-

[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

Quantity	$\dot{M}$ (g s^{-1}) =	10^{16}			10^{17}			10^{18}			10^{19}		
	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 $M_1 = 0.7\ M_\odot$, $EW_{4686} = 3$ 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

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

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

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

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}.

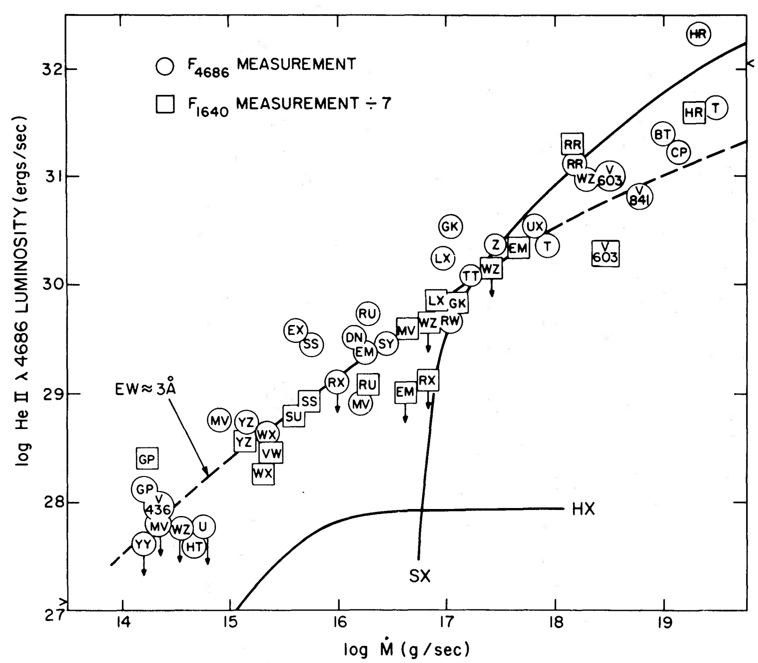

FIG. 5.—The observed He II λ4686 emission luminosities, plotted vs. accretion rate. Squares indicate that the λ4686 emission is estimated from the assumption $L(\lambda1640)/L(\lambda4686) = 7$. The carats at lower left and upper right indicate the best linear fit to the data, eq. (5). The dashed curve indicates the approximate relation expected from accretion disk systems with $M_1 = 0.7\ M_\odot$, $EW_{4686} = 3$ 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 $kT_{\rm brems} \gtrsim 0.6$ 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 $N_{\rm H} \lesssim 5 \times 10^{19}$ cm^{-2}. Hence we estimate that the existence of a component of the required luminosity is compatible with the observed hard spectra, provided that $kT_{\rm brems}$ is in the range 0.2–0.5 keV. For stars with sufficiently low $N_{\rm H}$, 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 $kT_{\rm brems} \approx 0.5$ 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 λ4686 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 $N_{\rm H}$ 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 λ1640 and λ4686 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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