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X-RAY OBSERVATIONS OF SELECTED CATACLYSMIC VARIABLE STARS USING THE *EINSTEIN* OBSERVATORY

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ABSTRACT

X-ray observations of twelve cataclysmic variable stars using the *Einstein* Observatory are reported. Nine of these stars, representing all subclasses of cataclysmic variables, were detected. Their fluxes range from 2×10^{-13} to 1×10^{-11} ergs cm^{-2} s^{-1} in the energy interval 0.16–4.5 keV. The 2 σ upper limits for the remaining stars, which include the so-called magnetic rotators DQ Her and V533 Her, are $\sim1\times10^{-13}$ ergs cm^{-2} s^{-1}. The spectra of all the sources detected are relatively hard ($kT\gtrsim5$ keV). There is no evidence for an ultrasoft emission component ($kT\sim50$ eV) such as has been observed from the dwarf novae SS Cyg and U Gem during optical outburst, even though two of the dwarf novae in the sample were in outburst when they were observed. The X-ray and optical fluxes of the objects observed can be understood in terms of differences in mass accretion rate if the accreting stars in these close binary systems possess a weak magnetic field. The X-ray data are also consistent with models of dwarf novae in which only a small portion of the matter transferred from the red star is accreted onto the degenerate dwarf during optical quiescence.

Subject headings: stars: novae — stars: U Geminorum — X-rays: binaries — X-rays: sources

I. INTRODUCTION

The recent discovery of X-ray emission from cataclysmic variable stars has provided new information on the physical processes occurring in them. Both soft and hard X-ray emission components have been observed in these stars. Soft X-ray emission ($kT\lesssim50$ eV) has been detected from the dwarf novae SS Cyg and U Gem during optical outbursts (Rappaport *et al.* 1974; Mason *et al.* 1978; Córdova 1979; Córdova *et al.* 1980*b*), from magnetic cataclysmic variables such as AM Her (Hearn and Richardson 1977; Bunner 1978; Tuohy *et al.* 1978), AN UMa (Hearn and Marshall 1979), 2A 0311−227 (Charles and Mason 1979), and the nova-like object MV Lyr (Mason, Kahn, and Bowyer 1979). A significant fraction of the soft X-ray flux from SS Cyg and U Gem occurs in the form of quasi-periodic pulses with time scales of tens of seconds (Córdova *et al.* 1980*a*, 1981), which is similar to the expected dynamical time scale near the surface of a degenerate dwarf. Hard X-ray emission ($kT\geq5$ keV) has been observed from, among others, AM Her (Swank *et al.* 1978), the dwarf novae SS Cyg, EX Hya, and U Gem (Ricketts, King, and Raine 1979; Fabbiano *et al.* 1978; Watson, Sherrington, and Jameson 1978; Córdova and Riegler 1979; Swank *et al.* 1978; Swank 1979), and the classical nova GK Per (King, Ricketts, and Warwick 1979). The observation of a line in some dwarf novae at energies close to that expected for thermal emission due to iron (Swank 1979) suggests that the hard X-ray flux is optically thin bremsstrahlung. The strength of both the hard and soft spectral components is related to the outburst state of the optical stars (Ricketts, King, and Raine 1979; Mason, Córdova, and Swank 1979).

Extensive surveys of cataclysmic variables using the *Ariel 5* and *HEAO 1* satellites have nevertheless detected only a small fraction of the total number of these stars (Watson, Sherrington, and Jameson 1978; Córdova *et al.* 1980*c*; Córdova, Jensen, and Nugent 1981). These observations show that the X-ray luminosity of most cataclysmic variables is less than 1×10^{31} ergs s^{-1}.

We have taken advantage of the much higher sensitivity of the focusing X-ray telescope on the *Einstein* Observatory to conduct a limited survey of some of the cataclysmic variables that were not detected with the

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previous experiments. This has made it possible to investigate in more detail conditions under which these objects emit X-radiation.

II. OBSERVATIONS

A description of the *Einstein* imaging proportional counter (IPC) detector used to make the observations is given by Giacconi *et al.* (1979). The data cover the energy interval 0.16–4.5 keV which, in spite of variation in the gain of the detector, was always included in the pulse height spectrum. The spatial resolution of the detector was 1′, and its field of view was approximately 1 square degree.

In Table 1A we have listed the details of the twelve objects observed, which included six dwarf novae, three classical novae, two nova-like objects, and one recurrent nova. Nine of these systems were detected. In each case the positions of the X-ray source and the optical star coincided to within the $\sim 1'$ positional uncertainty of the IPC. The brightest X-ray source detected was TT Ari, while the most sensitive upper limit was obtained on DQ Her; these measurements are about a factor of 2 and 500, respectively, below the sensitivity threshold of *HEAO 1* in a similar energy range. The exposure times for the sources (after correcting for vignetting, scattering, and deadtime) range from 600 to 4300 s. The exposure times, as well as the dates of the observations, are listed in Table 1A.

The visual magnitudes of the dwarf novae at the times of the X-ray observations also appear in Table 1. These values were obtained from data compiled by the American Association of Variable Star Observers and the Royal Astronomical Society of New Zealand Variable Star Section. All of the dwarf novae except KT Per and AH Her were in optically quiescent states. When simultaneous observations were not available, we used the usual visual magnitude of the system; these values appear in brackets in Table 1A.

The low count rate from these objects, together with the relatively poor spectral resolution of the IPC, make it difficult to measure their X-ray spectra with the exposure times used. We can, however, obtain an estimate of their relative spectral slopes by computing the ratio of counts detected in pulse height channels which encompass the energy range 0.55–4.5 keV to those which encompass the range 0.16–0.55 keV. Allowance is made for the changing gain of the detector which can be measured with an accuracy of $\sim 10\%$. This "hardness ratio" is listed in Table 1 for all but the weakest source detected, T CrB. The values obtained for the hardness ratio indicate that the X-ray spectra of these stars are comparatively hard. In particular, they are not consistent with the hardness ratio expected for an ultrasoft emission component (kT of order 0.05 keV) such as that observed from U Gem and SS Cyg during optical outburst (Mason *et al.* 1978; Córdova *et al.* 1980*a*, 1981). Simulations indicate that a source with such a spectrum would yield a hardness ratio $\ll 1.0$. Because of calibration uncertainties at low energies, it is not easy at the present time to use the IPC data to place quantitative limits on the contribution to the spectrum from a very soft component. However, it is apparent from the hardness ratios measured that such a soft component certainly does not dominate the counts received by the detector. Our data may also be compared with an IPC measurement of SS Cyg during optical quiescence, which had a hardness ratio, defined above, of 6.2 ± 0.3 (Fabbiano 1979, private communication). Measurements of the spectrum of SS Cyg using *HEAO 1* show it to be a hard X-ray source during its quiescent state, with $kT \sim 20$ keV (Swank 1979). Thus, we conclude that the IPC is detecting primarily the low-energy portion of a relatively hard spectral component similar to that observed in SS Cyg and EX Hya using *HEAO 1* (Swank 1979; Córdova and Riegler 1979).

The variations in the hardness ratios that are observed among the sources (in particular the high value found for GK Per) could be caused largely by differences in the amount of absorption by interstellar and/or circumstellar material. We can estimate the turnover in the X-ray spectrum of the brighter sources in our sample, U Gem, TT Ari, and GK Per, by comparing the shape of their pulse height spectra with that of SS Cyg (Fabbiano 1979, private communication), which is assumed to have a column density N_H, of 10^{20} cm^{-2}. This column density is derived from an analysis of the soft X-ray component that appears during outburst (Córdova *et al.* 1980*a*). In this way we find N_H values of $\lesssim 10^{19}$, $\sim 2\times 10^{20}$ and $\sim 7\times 10^{20}$ cm^{-2}, respectively, for U Gem, TT Ari, and GK Per. These values are relatively insensitive to the intrinsic spectral shape of the stars for temperatures greater than a few keV. The value of N_H required for U Gem is consistent with measurements of the soft X-ray spectral component of this star during optical outburst (Mason *et al.* 1978).

To give an estimate of the fluxes of the stars in our sample, we have folded a nominal 10 keV thermal bremsstrahlung spectrum with $N_H = 1\times 10^{20}$ cm^{-2} through the instrument response. One IPC count s^{-1} from a source with this spectrum is equivalent to a flux at the Earth of 2.7×10^{-11} ergs cm^{-2} s^{-1} in the *Einstein* bandpass. Thus, the fluxes of the objects in Table 1 range from 2.2×10^{-13} to 1.4×10^{-11} ergs cm^{-2} s^{-1}. By comparison, for the same assumed spectrum, the fluxes of SS Cyg (Fabbiano 1979, private communication) and EX Hya (using the *HEAO 1* data of Córdova and Riegler 1979) in the same energy range are both $\sim 8\times 10^{-11}$ ergs cm^{-2} s^{-1}. The conversion factor from count rate to flux is not very sensitive to kT and N_H. Varying the column density from 10^{19} to 10^{21} cm^{-2} and kT from 1 to 20 keV changes the conversion factor by only a

TABLE 1

A. *EINSTEIN* OBSERVATIONS

ID	Source	Subclass	Obs. Date 1979	Effective Obs. Time	IPC (counts s^{-1})	Visual (mag)	Outburst State (if dwarf nova)	Hardness Ratio[a]
1	TT Ari	N1	23 Jul	1379 s	0.512 ± 0.029	10.5	...	8.5 ± 1.1
2	YZ Cnc	dN	8 Apr	1779	0.050 ± 0.007	[14.0]	?	3.8 ± 1.0
3	T CrB	RN	26 Feb	2912	0.0083 ± 0.003	10.0	...	...
4	U Gem	dN	29 Apr	3078	0.120 ± 0.007	14.5	quiescence	3.4 ± 0.4
5	AH Her	dN	7 Mar	1623	0.0132 ± 0.005	12.0	outburst	4.0 ± 1.8
6	DQ Her	N	28 Mar	4329	<0.0046 (2σ)	[14.8]	...	...
7	V533 Her	N	28 Feb	2202	<0.0060 (2σ)	[15.8]	...	...
8	VW Hyi	dN	26 Feb	1336	0.101 ± 0.010	13.5	quiescence	2.7 ± 0.6
9	EQ Mon	dN	8 Mar	2221	<0.0056 (2σ)	[16.2]	quiescence	...
10	GK Per	N	25 Mar	1607	0.310 ± 0.015	13.5	quiescence	37.6 ± 11.5
11	KT Per	dN	29 Jul	2407	0.017 ± 0.004	11.7	outburst	10.0 ± 6.1
12	CD −42°14462	N1	29 Mar	604	0.062 ± 0.013	[10.4]	...	1.1 ± 0.4

[a] 0.55–4.5 keV/0.15–0.55 keV.

B. PREVIOUS HARD X-RAY OBSERVATIONS[a]

ID	Source	Subclass	Energy Band (keV)	X-Ray Flux (ergs cm^{-2} s^{-1})	Ref.[b]	Equivalent IPC (count s^{-1})	V (mag)	Outburst State	kT	Log N_H	Notes
13	SS Cyg	dN	0.1–4.5	*Einstein*	(1)	3.0	~ 11.9	quiescence	...	...	hard component
			2–25	1.6×10^{-10}	(2)	3.0	11.9	quiescence	~ 20	[20]	hard comp.
			2–18	4.8×10^{-10}	(3)	9.1	~ 10.0	rise to outburst	[20]	[20]	hard comp.
			2–25	3.2×10^{-10}	(4)	6.1	8.5	rise to outburst	[20]	[20]	hard comp.
			2–25	4×10^{-11}	(4)	2.4	8.3–8.6	outburst	~ 7	[20]	hard comp.
			2–25	3.2×10^{-10}	(4)	6.1	11.0	decline from outburst	[20]	[20]	hard comp.
			0.15–0.5	4.5×10^{-11}	...	...	8.5	outburst	~ 0.03	20	soft comp.
4	U Gem	dN	2–25	$2.4–3.8 \times 10^{-11}$	(5)	1.6–2.6	8.8	outburst	~ 5	[<19]	hard comp.
			2–25	1.5×10^{-11}	(4)	1.0	10.0	outburst	~ 4	[<19]	hard comp.
			0.15–0.5	3.2×10^{-10}	(10)	...	9.0	outburst	~ 0.03	<19	soft comp.
14	EX Hya	dN	0.7–2.0	8.6×10^{-11}	(6)	5.3	~ 13.0	quiescence	~ 4.5	~ 21.2	...
			2–10	1.3×10^{-10}	(7)	...	...	...	...	...	...
10	GK Per	N	2–18	$\sim 2 \times 10^{-10}$	(8)	5.6	12.6	outburst	[10]	[20]	...
15	2A 0526−328	?	2–6	3×10^{-11}	(9)	1.7	[13.5]	...	[10]	[20]	...

[a] Values in brackets are assumed from best available data.

[b] REFERENCES—(1) Fabbiano 1979, private communication; (2) Mason, Córdova, and Swank 1979; (3) Ricketts, King, and Raine 1979; (4) Swank 1979; (5) Swank *et al.* 1978; (6) Córdova and Riegler 1979; (7) Swank 1979, private communication; (8) King, Ricketts, and Warwick 1979; (9) Schwartz *et al.* 1979; (10) Mason *et al.* 1978.

factor of 2 (e.g., from 1.5×10^{-11} ergs cm^{-2} s^{-1}/IPC count for $kT=1$ keV, $\log N_H=19$, to 3.3×10^{-11} ergs cm^{-2} s^{-1}/IPC count for $kT=20$ keV, $\log N_H=21$). In the *Einstein* bandpass we are observing ~60% of the total X-ray flux that would be emitted by a star having a 10 keV thermal bremsstrahlung spectrum and $N_H=10^{20}$ atoms cm^{-2}.

For completeness, we have listed in Table 1B a summary of past observations of cataclysmic variable stars. The energy band and X-ray flux listed there refer to the original observations. Using the measured values for kT and N_H given in the last two columns (the values in brackets represent our best guess for the spectrum), we have converted these X-ray fluxes to the equivalent *Einstein* IPC count rates. These rates may then be compared with our own observations summarized in Table 1A.

With a few exceptions, the distances of individual cataclysmic variables, and hence their absolute luminosity, is poorly known. A typical value for the absolute magnitude of dwarf novae at minimum light is M_v ~7.5 (e.g., Warner 1976), but there is evidence for a considerable spread in values from star to star. The absolute magnitude of the nova-like stars is probably somewhat less than this. In particular, values of M_v of <6 and <5.3 have been derived for TT Ari and CD −42°14462, respectively, the two nova-like variables studied here (Cowley *et al.* 1975; Churms 1975, private communication in Warner 1976). Specific distance estimates are also available for a number of other stars that we have studied. Wade (1979) has measured the distance of U Gem to be 70±30 pc based on the spectral classification of the red star in this system, while various estimates of the distance of SS Cyg place it at about 150 pc (cf. Warner 1976). The distances of the classical novae, DQ Her, V533 Her, and GK Per, have been derived by studying the gaseous shell ejected by the nova outburst and are found to be 300 pc (Mustel and Boyarchuck 1970), 1 kpc (Nelson and Butcher 1980, private communication), and 460 pc (Warner 1976), respectively, with an accuracy of ~30%. The distance of T CrB, 1.5 kpc, has also been estimated by Webbink (1979, private communication) based on the orbital parameters of the system and the spectral type of the red star. Table 2 contains our best estimate of the distance, absolute visual magnitude, and absolute 0.16–4.5 keV X-ray luminosity of each of the stars discussed. In SS Cyg, GK Per, and T CrB, the red star is known to contribute a significant fraction of the total visual light observed. This fraction is also listed in Table 2.

The X-ray data on all the newly observed stars have been examined for temporal variability. During our observation of TT Ari, it was variable by a factor of 2–3 on a time scale of about 200 s. TT Ari's binary phase during the observation was ~0.87–0.01 according to the ephemeris of Cowley *et al.* (1975) and Hutchings and Crampton (1979, private communication). There is also some evidence for variability on a 50 s time scale in the light curve of GK Per. The remaining sources were too weak for the existence of irregular short time scale variability to be tested significantly.

III. DISCUSSION

Our observations show that weak, hard X-ray emission is a common feature among all subgroups of cata-

TABLE 2

ABSOLUTE LUMINOSITIES OF CATACLYSMIC VARIABLES

ID	Source	Distance[a] (pc)	Light from Red Star in V Band (%)	M_v [b] (excluding red star)	L_x [b] (10^{30} ergs s^{-1} 0.1–4.5 keV)	Ref.[c]
1	TT Ari	[300]	...	3.0	140.0	...
2	YZ Cnc	[100]	...	9.0	1.5	...
3	T CrB	1500	99	5.0	25.0	(5), (6)
4	U Gem	70	~10	10.4	1.8	(1)
5	AH Her	[100]	...	7.0	0.4	...
6	DQ Her	300	...	7.4	<1.3 (2 σ)	(3)
7	V533 Her	1000	...	5.8	<18.0 (2 σ)	(4)
8	VW Hyi	[100]	...	8.5	3.1	...
9	EQ Mon	[100]	...	11.0	<0.17 (2 σ)	...
10	GK Per	460	45	5.8	200.0	(2)
11	KT Per	[100]	...	6.7	0.5	...
12	CD −42°14462	[300]	...	3.0	17.0	...
13	SS Cyg	150	45	6.7	200.0	(2), (7)
14	EX Hya	[100]	...	8.0	160.0	...
15	2A 0526−328	[100]	...	8.5	52.0	...

[a] Values in brackets adopted as typical for subclass.
[b] Quiescent values given only when both quiescent and outburst X-ray flux observed.
[c] REFERENCES—(1) Wade 1979; (2) Warner 1976; (3) Mustel and Boyarchuck 1970; (4) Nelson and Butcher (1980, private communication); (5) Webbink 1979, private communications; (6) Kraft 1958; (7) Kiplinger 1979.

clysmic variable stars. This is consistent with the notion that, despite their different optical characteristics, a common mechanism is responsible for the X-radiation in all these systems.

A number of authors have considered models in which X-ray emission in cataclysmic variables arises because of the shock heating of accreting matter as it interacts with the surface of the degenerate dwarf star in the system (e.g., Pringle 1977; Pringle and Savonije 1979; Kylafis and Lamb 1979; Lamb and Masters 1979; King and Lasota 1979). While we presently believe that this is the most likely explanation for the bulk of the X-ray flux observed, X-ray emission at some level may also be produced in the corona of the companion star in a manner analogous to the X-ray emission from flare stars (e.g., Kunkell 1975; Kuhn *et al.* 1979; Haisch and Linsky 1980) or in a coronal region associated with the accretion disk (Fabbiano *et al.* 1978; Mason *et al.* 1978). The ratio of the X-ray flux to the optical flux of the red star in the cataclysmic variables studied so far is typically about two orders of magnitude higher than that found for quiescent emission from flare stars (Rosner 1979, private communication; Haisch and Linsky 1980); furthermore, the strength of the X-ray emission does not appear to be related to the properties of the red star in the cataclysmic variables. It is therefore unlikely that the red star is a major contributor to the observed X-ray flux from these systems. The situation concerning the possibility of "coronal" emission from the accretion disk is not clear. Galeev, Rosner, and Vaiana (1979) have shown that significant hard X-ray emission can be produced in a magnetically confined structured corona around an accretion disk when the disk is supported by radiation pressure (e.g., Cyg X-1). However, it remains to be shown that the requirement of convective instability is satisfied for a disk supported by gas pressure, as is likely to be the case for cataclysmic variables. It is therefore unclear whether a magnetic field permeating the disk of a cataclysmic variable could be amplified and emerge as loops above the disk, thereby giving rise to a hot X-ray emitting corona ($T \sim 10^7 - 10^8$ K).

If both the X-ray and optical emission of cataclysmic variable stars is produced primarily as a result of the release of the gravitational potential energy of matter

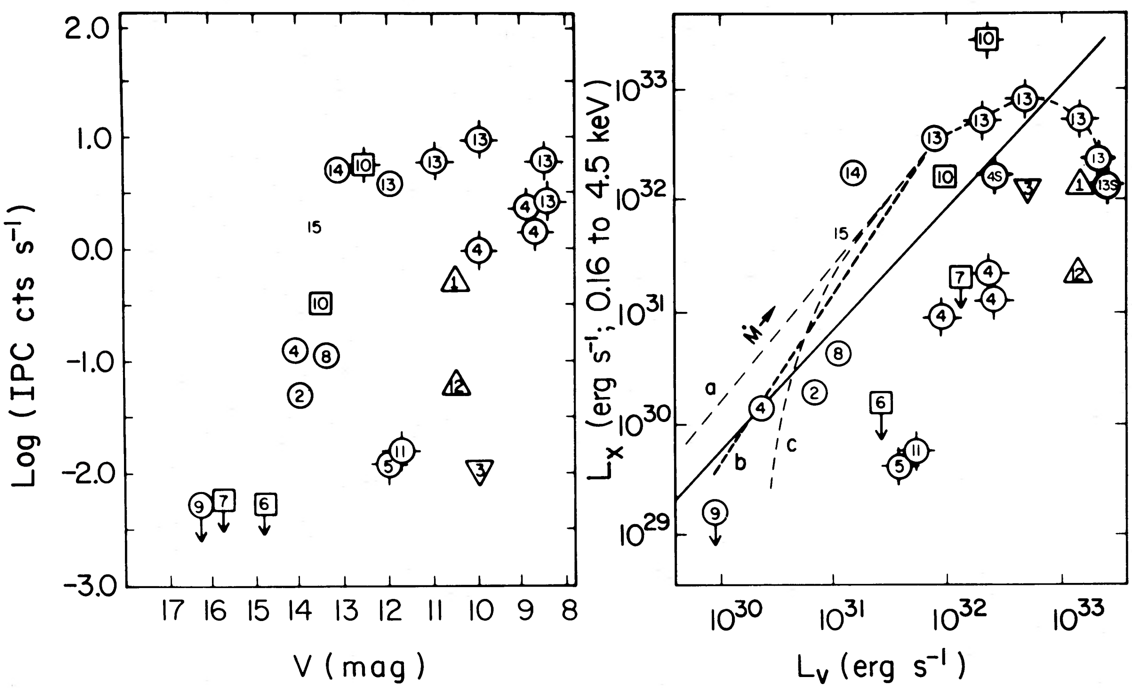

FIG. 1*a* FIG. 1*b*

FIG. 1.—The X-ray flux of cataclysmic variable stars as a function of their visual flux. The left-hand panel (Fig. 1*a*) illustrates the observed quantities, while in the right-hand panel (Fig. 1*b*) corrections for distance and the luminosity of the red star have been applied (Table 2) in order to yield an estimate of the intrinsic X-ray and visual luminosities of the compact components in these systems. Stars are numbered according to Table 1. Various subclasses of stars are identified as follows: *open circles*, dwarf novae; *triangles*, nova like objects; *squares*, classical novae; and *inverted triangles*, recurrent novae. Horizontal and vertical bars denote stars in some stage of optical outburst. Luminosity measurements for the ultrasoft X-ray component of SS Cyg and U Gem are annotated with the letter *S*. Curve (a) in Fig. 1*b* illustrates the expected distribution of X-ray and optical flux as a function of accretion rate scaled from SS Cyg (star 13) in the absence of a magnetic field. Curve (b) illustrates the distribution expected if the mass transfer between the binary components exceeds the accretion rate onto the compact star by two orders of magnitude (see text). Curve (c) shows the expected distribution if the compact star possesses a weak magnetic field (see text).

being accreted onto the degenerate star, a relationship between the emission in the two wavebands might be expected. In order to investigate this possibility, we have plotted in Figure 1 the X-ray flux of the stars observed as a function of their visual brightness. Figure 1*a* shows the apparent 0.16–4.5 keV X-ray flux as a function of visual magnitude, while Figure 1*b* shows our best estimates of the absolute X-ray luminosity versus the absolute visual luminosity of the blue component of the binary system, using the data compiled in Table 2. In Figure 1 the various subclasses of cataclysmic variables are assigned different symbols which are identified in the figure legend. In addition, we distinguish between measurements of dwarf novae in outburst and in quiescence. The contributions from the soft and hard spectral components observed in U Gem and SS Cyg during outburst are shown separately. As discussed in § II, the distances of individual stars are relatively uncertain. However, they are probably accurate to a factor of ~ 2, which corresponds to an uncertainty of a factor of 4 in luminosity. Changing the distance estimate of a star will, to first order, move it along a 45° locus in Figure 1*b*. The orbital inclination of a star might also influence the flux observed from it. The corresponding uncertainty in luminosity, however, is likely to be less than a factor of ~ 2, except for systems of very high inclination (for instance the observed emission from an optically thick accretion disk should vary as $\cos i$). To our knowledge, none of the systems we have observed has a high inclination, with the exception of DQ Her.

It is apparent from an examination of Figure 1 that the X-ray and optical luminosities of the cataclysmic variables are not simply related. Differences in the mass of the degenerate star and uncertainties in distance and orbital inclination are unlikely to account for the magnitude of the scatter observed. We therefore consider effects that might complicate the relationship between the flux in the two bands.

a) *Quiescent Emission from Dwarf Novae*

We first consider measurements made of the dwarf novae in quiescence and examine to what extent differences in accretion rate can account for the range of X-ray and optical luminosities seen in this state. We show as curve (a) in Figure 1*b* the expected locus of X-ray versus optical flux as a function of accretion rate for a star of given mass, arbitrarily scaled to the position of SS Cyg in the diagram. Curve (*a*) is drawn on the assumption that all of the optical emission is produced in an optically thick accretion disk, while the X-rays are produced in an optically thin region near the degenerate dwarf. We make use of the work of Bath *et al.* (1974) who have calculated the expected visual luminosity of an accretion disk as a function of accretion rate, $\dot{m}$. Curve (*a*) falls more rapidly with $\dot{m}$ than a line defined by $L_x \propto L_v$. This is because the effective temperature of the disk ($\sim 10^4$ K) also falls with decreasing $\dot{m}$, so that an increasing fraction of the disk luminosity is emitted in the visible band. Nevertheless, the dwarf novae for which we have data during quiescence define a distribution that is still steeper than curve (*a*).

One way in which such a steep distribution might result is suggested by a comparison of the observed X-ray luminosity of U Gem with the luminosity expected based on estimates of the rate at which mass is transferred between the components of this binary system. On the assumption that approximately half the total accretion energy is available for release near the surface of the degenerate dwarf, an accretion rate on the order of 10^{13} g s^{-1} is required to produce the observed X-ray luminosity. This accretion rate is on the same order as that derived from the brightness of the optical disk (cf. Bath *et al.* 1974; Paczyński, Schwarzenburg-Czerny, and Alcock 1979). However, it is two to three orders of magnitude less than the mass transfer rate between the binary components inferred from the luminosity of the bright spot on the accretion disk where the gas stream from the companion star impinges (see Paczyński 1978; Paczyński, Schwarzenberg-Czerny, and Alcock 1979). The measured X-ray flux of U Gem is thus consistent with models such as that discussed by Osaki (1974) and Paczyński (1978), in which only a small fraction of the matter transferred from the companion is accreted onto the degenerate dwarf during the quiescent state; according to these models most of the material transferred from the companion is stored in a torus surrounding the degenerate dwarf until it is suddenly accreted onto the compact star to produce an outburst (Smak 1971). The effect of the disparity between the rate at which mass is transferred into the disk $\dot{m}_T$, and the rate at which it is accreted onto the central star, $\dot{m}_A$, is to increase the fractional contribution of the bright spot to the total optical light of the system during quiescence. Because the bolometric correction for emission from the bright spot is different from that for the disk, inclusion of a significant luminosity from the bright spot may substantially alter the slope of curve (*a*). An example in which $\dot{m}_T = 10^2 \dot{m}_A$ is shown in Figure 1*b* as curve (*b*), based on data given by Bath *et al.* (1974).

A second way in which a steep distribution of L_x versus L_v can be understood in the context of an accretion model is to incorporate the effects of cyclotron cooling of the X-ray emitting gas in a magnetic field associated with the degenerate dwarf. When the accretion rate is high, bremsstrahlung losses dominate and the source behaves essentially as if it had no magnetic field. However, as the density in the accretion column drops, an increasing fraction of the energy in the gas is radiated as cyclotron photons below the threshold of the *Einstein* detectors. Consequently, the flux emitted at energies greater than 0.1 keV will fall more rapidly with decreasing accretion rate than it will in the absence of a magnetic field. Curve (c) in Figure 1*b* shows the expected value of L_x as a function of L_v for the magnetic case, based on the calculations of Lamb and Masters (1979) for a 1 $M_\odot$ degenerate dwarf. The precise value of the magnetic field strength to which curve (c) corresponds depends on the fraction, f, of the surface of the degenerate dwarf over which accretion is occurring, since this determines the density of the accretion flow for any given mass accretion rate. If $f \sim 10^{-3}$, as has been suggested in the case of AM Her, then the magnetic field strength, B, corresponding to the curve (c) would be $\sim 10^6$ gauss. If $f \sim 10^{-1}$, which may be more appropriate if there is an appreciable accretion disk (e.g., King and Lasota 1979) then $B \sim 10^4 - 10^5$ gauss is required. Differences in magnetic field strength from star to star would contribute scatter to the distribution of L_x versus L_v.

In considering the above scenario, we envision that the magnetic field of the degenerate dwarf disrupts the accretion disk at some critical radius, r_c, above the surface of that star, and that matter is thereafter channeled along field lines onto one or another of its magnetic poles. To test whether this is a reasonable assumption in the parameter regimes encountered, we can construct an approximate expression for r_c in the case of disk accretion by balancing magnetic pressure against the kinetic energy density of the inflowing matter following the work of Fabian, Pringle, and Rees (1976) and King and Lasota (1979). (See also Ghosh and Lamb 1979.) Thus,

$$\frac{r_c}{r_*} \approx 8.6 \left(\frac{\Omega}{4\pi} \right)^{1/6} M_*^{-1/7} r_*^{5/7} B_5^{4/7} F_{16}^{-2/7}, \quad (1)$$

where M_* and r_* are the mass and radius of the degenerate dwarf in units of solar masses and 10^9 cm, respectively, B_5 is the magnetic field strength in units of 10^5 gauss, and F_{16} is the mass accretion rate in units of 10^{16} g s^{-1}. The quantity Ω is the solid angle subtended by the accretion disk at the surface of the degenerate dwarf, so that the factor $(\Omega/4\pi)^{1/6} \approx 0.5$ for a thin disk. Thus, for a magnetic field of $\sim 10^5$ gauss, $r_c/r_* > 1$ for accretion rates below about 10^{18} g s^{-1}, which is consistent with the expected mass accretion rates of dwarf novae during quiescence.

b) *Dwarf Novae during Outburst*

We presently have available X-ray data on four dwarf novae during optical outburst. These are SS Cyg and U Gem (see data summarized in Table 1 B) and the Z Cam variables, KT Per and AH Her, which were observed in outburst during the present survey. In each case the hard X-ray flux falls below that expected if the optical brightness accurately reflects the mass accretion rate onto the central degenerate star (Fig. 1). However, inclusion of the energy in the soft X-ray emission component detected from U Gem and SS Cyg during outburst raises the total 0.1–4.5 keV flux from these stars to a level which is more consistent with the change in optical brightness. It should also be noted that the temperature of the low energy spectral component in U Gem and SS Cyg is such that only a small fraction of the total energy contained in it (e.g., $\sim 10\%$ in the case of U Gem; Mason *et al.* 1978) falls within our 0.1–4.5 keV window.

Only for SS Cyg and U Gem do we presently have measurements of the hard X-ray flux in both outburst and quiescence. These show that the hard X-ray flux of SS Cyg is higher during quiescence than it is during outburst (Ricketts, King, and Raine 1979), while for U Gem the converse appears to be true (Swank *et al.* 1978). Ricketts *et al.* (1979) have suggested that the decrease in the hard X-ray flux of SS Cyg during outburst is due to Compton degradation of the X-ray spectrum in the accretion column as the accretion rate increases and the column becomes optically thick.

Another explanation for a reduction in the hard X-ray emission during outburst is that the mode of X-ray emission changes between quiescence and outburst. One way in which this could happen is suggested by an examination of equation (1). If the accretion rate during outburst exceeds a critical value that depends on the magnetic field of the degenerate star, the accretion disk will penetrate all the way to the stellar surface (i.e., $r_c/r_* < 1$). The energy of accretion would then be dissipated in a boundary layer shock where the inner part of the accretion disk encounters the surface of the degenerate dwarf (Pringle 1977; Pringle and Savonije 1979). The latter mechanism may be less efficient in producing hard X-rays than pseudo-radial accretion along the magnetic field lines, if material in the boundary layer is heated in a number of small shocks (Pringle and Savonije 1979).

c) *Other Cataclysmic Variables*

As noted previously, there does not appear to be any marked difference between the dwarf novae and the other types of cataclysmic variables in our survey as far as their X-ray emission is concerned. This supports the idea that the energy release mechanism is essentially similar in all cataclysmic variables. The same processes that contribute to the range of X-ray and optical emission among the dwarf novae probably also operate in the stars that belong to other subclasses.

Of particular interest is our failure to detect significant X-ray emission from the two nova remnants DQ Her and V533 Her. (In contrast the remaining nova remnant in our sample, GK Per, *was* detected as an X-ray source.) DQ Her and V533 Her both exhibit stable optical pulsations and are therefore thought to possess moderately strong magnetic fields that cause radiation from the stars to be emitted asymmetrically (e.g., Chanan, Nelson, and Margon 1978 and references therein; Patterson 1979). The mass accretion rate onto the degenerate star in DQ Her has been estimated to be on the order of 10^{17} g s^{-1} (Gallagher and Starrfield 1978), so it might have been expected to emit a significant flux of hard X-rays. The high orbital inclination of DQ Her (Petterson 1980) may be a factor that contributes to its low X-ray flux; however, the orbital inclination of V533 Her is almost certainly not high, since no evidence for eclipses have been found in this system (Patterson 1979). Alternatively, the absence of hard X-ray emission in both stars may be, as discussed previously, the result of cyclotron cooling in the magnetic field of the degenerate dwarf which causes most of the accretion energy to be liberated below 0.1 keV (see also Lamb 1979). Based on our upper limits to the hard X-ray emission from DQ Her and V533 Her and the expected flux for the nonmagnetic case sketched as curve (a) in Figure 1*b*, we can constrain the ratio of bremsstrahlung to cyclotron radiation emitted in each case to be $\lesssim 0.01$. This can be interpreted as a lower limit to the magnetic field strength of the white dwarf depending on its mass and the fraction of the stellar surface over which the material is accreting (Lamb and Masters 1979).

IV. CONCLUSION

We have shown that many of the observed X-ray properties of cataclysmic variables reported here can be understood in a semiquantitative way as a consequence of differences in accretion rate, accretion geometry, and magnetic field strength among these stars. Further data, particularly on the transition of dwarf novae between outburst and quiescent states, are required to test these ideas fully.

There are other ways in which these conclusions can be tested. The inferred range in mass accretion rate among cataclysmic variables should result in corresponding differences in the effective disk temperature that should correlate with both the optical and X-ray luminosity. This could be investigated through optical and ultraviolet measurements (e.g., Bath, Pringle, and Whelan 1980), provided that the contribution from the bright spot, and possibly the outer parts of the accretion disk (cf. Paczyński 1978), can be accurately assessed. An estimate of the mass accretion rate from UV and optical measurements of the disk temperature may enable the relative importance of various mechanisms that may affect the observed distribution of L_x versus L_v to be assessed. In addition, direct evidence of cyclotron emission may be found (Lamb and Masters 1979; King and Lasota 1979). It would be of interest to extend the X-ray observations to cataclysmic variables of lower intrinsic luminosity and to test the effects of orbital inclination on the observed X-ray flux by observing more systems of high inclination. More information is required on the relationship of the hard X-ray flux to the ultrasoft X-ray emission components which have so far been detected only during outbursts of SS Cyg and U Gem. Ultrasoft X-rays may be present in all cataclysmic variables, but at a lower spectral temperature than that observed in SS Cyg and U Gem (cf. Córdova *et al.* 1980*c*). This may render the emission invisible to soft X-ray detectors ($\lambda < 100$ Å), although it may be observed in the *EUV* range ($\lambda > 100$ Å) where most of the energy in a spectrum with a characteristic temperature on the order of 10 eV will be emitted. Finally, we note that a major uncertainty in modeling cataclysmic variables remains the lack of detailed knowledge of basic data such as distance, luminosity, bright spot parameters, and orbital inclination; parameters which are known with confidence only for a few systems.

Note added in manuscript.—The classification of EQ Mon as a dwarf nova has recently been questioned because of its atypical red color (Bond 1979, private communication) and the lack of outbursts over at least the last two years (Mattei 1980, AAVSO Circ. 111). EQ Mon was not detected as an X-ray emitter in our survey.

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