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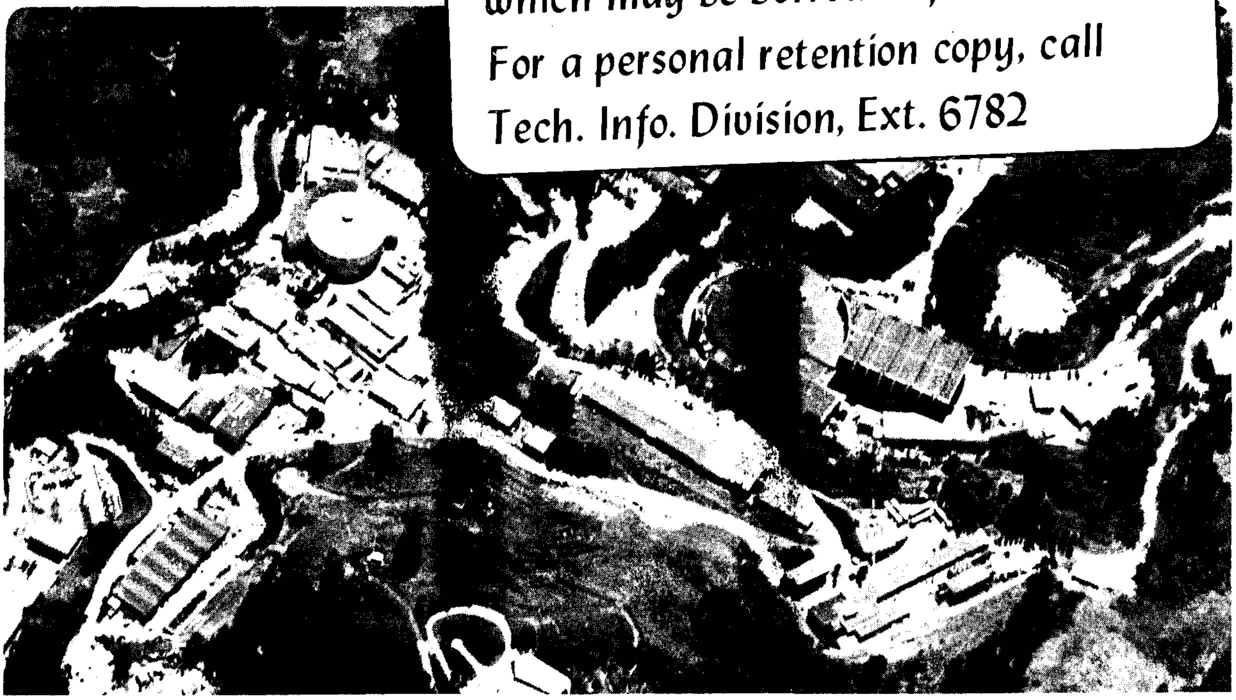

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DISCLAIMER

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} erg cm^{-2} s^{-1} in the energy interval 0.16 - 4.5 keV. The two sigma upper limits for the remaining stars, which include the so-called magnetic rotators DQ Her and V 533 Her, are $\sim 1 \times 10^{-13}$ erg cm^{-2} s^{-1}. The spectra of all the sources detected are relative hard ($kT \gtrsim 5$ keV). There is no evidence for an ultra-soft emission component ($kT \sim 50$ 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.

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 $\lesssim$ 50 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. 1980a), from magnetic cataclysmic variables such as AM Her (Hearn and Richardson 1977; Bunner 1978; Tuohy et al. 1978) AN UMa (Hearn and Marshall 1979), and 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 timescales of tens of seconds (Córdova et al. 1980a, 1980b), which is similar to the expected dynamical timescale near the surface of a degenerate dwarf. Hard X-ray emission (kT $\geq$ 5 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 V 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.

1980c; Córdova, Jensen and Nugent 1981). These observations show that the X-ray luminosity of most cataclysmic variables is less than 1×10^{31} erg 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 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 to 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 one arc minute and its field of view was approximately one 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 ~1 arc min positional uncertainty of the IPC. The brightest X-ray source detected was TT Ari, while the most sensitivie upper limit was obtained on DQ Her; these measurements are about a factor of two and five-hundred, 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 seconds. The exposure times, as well as the dates of the observations, are also 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 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 to 4.5 keV to those which encompass the range 0.16 to 0.55 keV. Allowance is made for the changing gain of the detector which can be measured with an accuracy of ~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 ultra-soft 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. 1980a,b). Simulations indicate that a source with such a spectrum would yield a hardness ratio << 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 as 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 Reigler 1979).

The variations in hardness ratio that are observed among the sources (in particular the high value found for GK Per) could well 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. 1980a). 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 ct s^{-1} from a source with this spectrum is equivalent to a flux at the Earth of 2.7×10^{-11} erg 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} erg 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 $\sim 8 \times 10^{-11}$ erg 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 factor or two (e.g. from 1.5×10^{-11} erg cm^{-2} s^{-1}/IPC count for kT = 1 keV, log N_H = 19, to 3.3×10^{-11} erg cm^{-2} s^{-1}/IPC count for kT = 20 keV, log N_H = 21). In the Einstein bandpass we are observing $\sim$ 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 $M_V \sim 7.5$ (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 respectively have been derived for TT Ari and CD-42°14462, 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 the 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 (c.f. 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 and 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, this star was variable by a factor of 2-3 on a timescale of about 200 seconds. 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 timescale in the light curve of GK Per. The remaining sources were too weak for the existence of irregular short timescale variability to be tested significantly.

DISCUSSION

Our observations show that weak hard X-ray emission is a common feature among all subgroups of cataclysmic 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 Lasoto 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; Kahn _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 correlated with the properties of the red stars 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 being accreted onto the degenerate star, a relationship between the emission in the two wavelength bands 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 1a shows the apparent 0.16-4.5 keV X-ray flux as a function of visual magnitude, while Figure 1b 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 caption. 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 Section II, the distances of individual stars are relatively uncertain. However, they are probably accurate to a factor of about two, which corresponds to an uncertainty of a factor of four in luminosity. Changing the distance estimate of a star will, to first order, move it along a 45 degree locus in Figure 1b. 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 about two, 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.

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 1b the expected locus of X-ray vs. optical flux as a function of accretion rate for a star of given mass. 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), which is normalized to the position of SS Cyg in the figure, 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 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 of order 10^{13}g s^{-1} is required to produce the observed X-ray luminosity. This accretion rate is of the same order as that derived from the brightness of the optical disk (cf. Bath *et al.* 1974; Paczynski *et al.* 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 Paczynski 1978; Paczynski *et al.* 1979). The measured X-ray flux of U Gem is thus consistent with models such as that discussed by Osaki (1974) and Paczynski (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 into 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 1b as curve (b), based on data given by Bath *et al.* (1974).

A second way in which a steep distribution of L_X vs. 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 1b 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 magnetic field strength to which curve (b) 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 (b) would be $\sim 10^6$ gauss. If $f \sim 10^{-1}$, which may be more appropriate if there is an appreciable accretion disk (King and Lasoto 1979), then $B \sim 10^4 - 10^5$ gauss is required. Differences in magnetic field strength from star to star would, of course, contribute scatter to the distribution of L_x vs. 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:

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

where M_* and r_* are the mass and radius of the degenerate dwarf in units of solar mass 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 $(\Omega/4\pi)^{1/6} \lesssim 0.5$ 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.

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, the data on which are summarized in Table 1b, 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 at the corresponding optical magnitude based on the distribution of dwarf novae in quiescence (Figure 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 0.2-4.5 keV flux from these stars. It should 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 the 0.2-4.5 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 et al. 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 some 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).

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 V 533 Her. (In contrast, the remaining nova remnant in our sample, GK Per, was detected as an X-ray source). DQ Her and V 533 Her both exhibit stable optical pulsations and are therefore thought to possess moderately strong magnetic fields that causes radiation from the stars to be emitted asymmetrically (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 of order 10^{17} g s^{-1} (Gallagher and Starrfield 1978) so that 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 V 533 Her is almost certainly not high since no evidence for eclipses has 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 V 533 Her, and the expected flux for the non-magnetic case sketched as curve (a) in Figure 1b, 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).

Conclusion

We have shown that many of the observed X-ray properties of cataclysmic variables reported here can be understood in a semi-quantitative fashion 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 a number of 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. Paczynski 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 vs. L_v to be assessed. In addition, direct evidence of cyclotron emission may be found (Lamb and Masters 1979; King and Lasoto 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 ultra-soft X-ray emission components which have so far been detected only during outbursts of SS Cyg and U Gem. Ultra-soft 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. 1980c). This may render the emission invisible to soft X-ray detectors ($\lambda < 100$ Å) although it may be observed in the EUV range where most of the energy in a spectrum with a characteristic temperature of order 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:

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 the last two years (Mattei 1980, AAVSO Circular No. 111).

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TABLE 1A. EINSTEIN OBSERVATIONS

I.D.	Source	Subclass	Obs. Date 1979	Effective Obs. Time	IPC ct s^{-1}	V	Outburst State (if dwarf nova)	Hardness Ratio (0.55-4.5) keV/(0.15-0.55) keV
1.	TT Ari	Nℓ	23 Jul	1379 s	0.512 ± 0.029	10^{m}.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	Nℓ	29 Mar	604	0.062 ±0.013	[10.4]		1.1 ± 0.4

TABLE 1B. PREVIOUS HARD X-RAY OBSERVATIONS*

I.D.	Source	Subclass	Energy Band	(erg cm^{-2} s^{-1})	Equivalent IPC ct s^{-1}	V	Outburst State	kT	Log N_H	Notes
13.	SS Cyg	dN	0.1-4.5 keV	Einstein (1)	3.0	∿11.9	quiescence			hard component
			2-25	1.6×10^{-10} (2)	3.0	11.9	quiescence	∿20	[20]	" "
			2-18	4.8×10^{-10} (3)	9.1	∿10	rise to outburst	[20]	[20]	" "
			2-25	3.2×10^{-10} (4)	6.1	8.5	rise to outburst	[20]	[20]	" "
			2-25	4×10^{-11} (4)	2.4	8.3-8.6	outburst	∿7	[20]	" "
			2-25	3.2×10^{-10} (4)	6.1	11.0	outburst decline	[20]	[20]	" "
			0.15-0.5	4.5×10^{-11}		8.5	outburst	∿0.03	20	soft component
(4.)	U Gem	dN	2-25	$2.4\text{-}3.8 \times 10^{-11}$ (5)	1.6-2.6	8.8	outburst	∿5	[< 19]	hard component
			2-25	1.5×10^{-11} (4)	1.0	10.0	outburst	∿4	[< 19]	" "
			0.15-0.5	3.2×10^{-10} (10)		9.0	outburst	∿0.03	< 19	soft component
14.	Ex Hya	dN	0.7-2 2-10	8.6×10^{-11} (6) 1.3×10^{-10} (7)	5.3	∿13.0	quiescence	∿4.5	∿21.2	hard component
(10.)	GK Per	N	2-18	$\sim 2 \times 10^{-10}$ (8)	5.6	12.6	small outburst	[10]	[20]	" "
15.	2A0526-328	?	2-6	3×10^{-11} (9)	1.7	[13.5]		[10]	[20]	" "

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(1) Fabbiano (1979), private communication

(2) Mason, Cordova and Swank (1979)

(3) Ricketts, King and Raine (1979)

(4) Swank (1979)

(5) Swank et al. (1978)

(6) Cordova and Riegler (1979)

(7) Swank (1979), private communication

(8) King, Ricketts and Warwick (1979)

(9) Schwartz et al. (1979)

(10) Mason et al. (1978)

*Values in brackets are assumed from best available data.

TABLE 2

I.D.	Source	Distance* (pc)	% light contributed by red star in V band	$M_v^{\dagger}$ (excluding red star)	$L_x^{\dagger}$ (units of 10^{30} erg s^{-1} 0.1-4.5 keV)	REF
1	TT Ari	[300]	---	3.0	140	
2	YZ Cnc	[100]	---	9.0	1.5	
3	T CrB	1500	99%	5.0	25	5,6
4	U Gem	70	∼10%	10.0	1.8	1
5	AH Her	[100]	---	7.0	0.4	
6	DQ Her	300	---	7.4	<1.3 (2σ)	3
7	V533 Her	1000	---	5.8	<18 (2σ)	4
8	VW Hyi	[100]	---	8.5	3.1	
9	EQ Mon	[100]	---	11.0	< 0.17 (2σ)	
10	GK Per	460	45%	5.8	200	2
11	KT Per	[100]	---	6.7	0.5	
12	CD-42°14462	[300]	---	3.0	17	
13	SS Cyg	150	45%	6.7	200	2,7
14	EX Hya	[100]	---	8.0	160	
15	2A0526-328	[100]	---	8.5	52	

*Values in brackets adopted as typical for subclass

†Quiescent values given only when both quiescent and outburst X-ray flux observed

References

1.	Wade (1979)	5.	Webbink (1979, private communications)
2.	Warner (1976)	6.	Kraft (1958)
3.	Mustel and Boyarchuck (1970)	7.	Kiplinger (1979)
4.	Nelson and Butcher (1980, private communication)		

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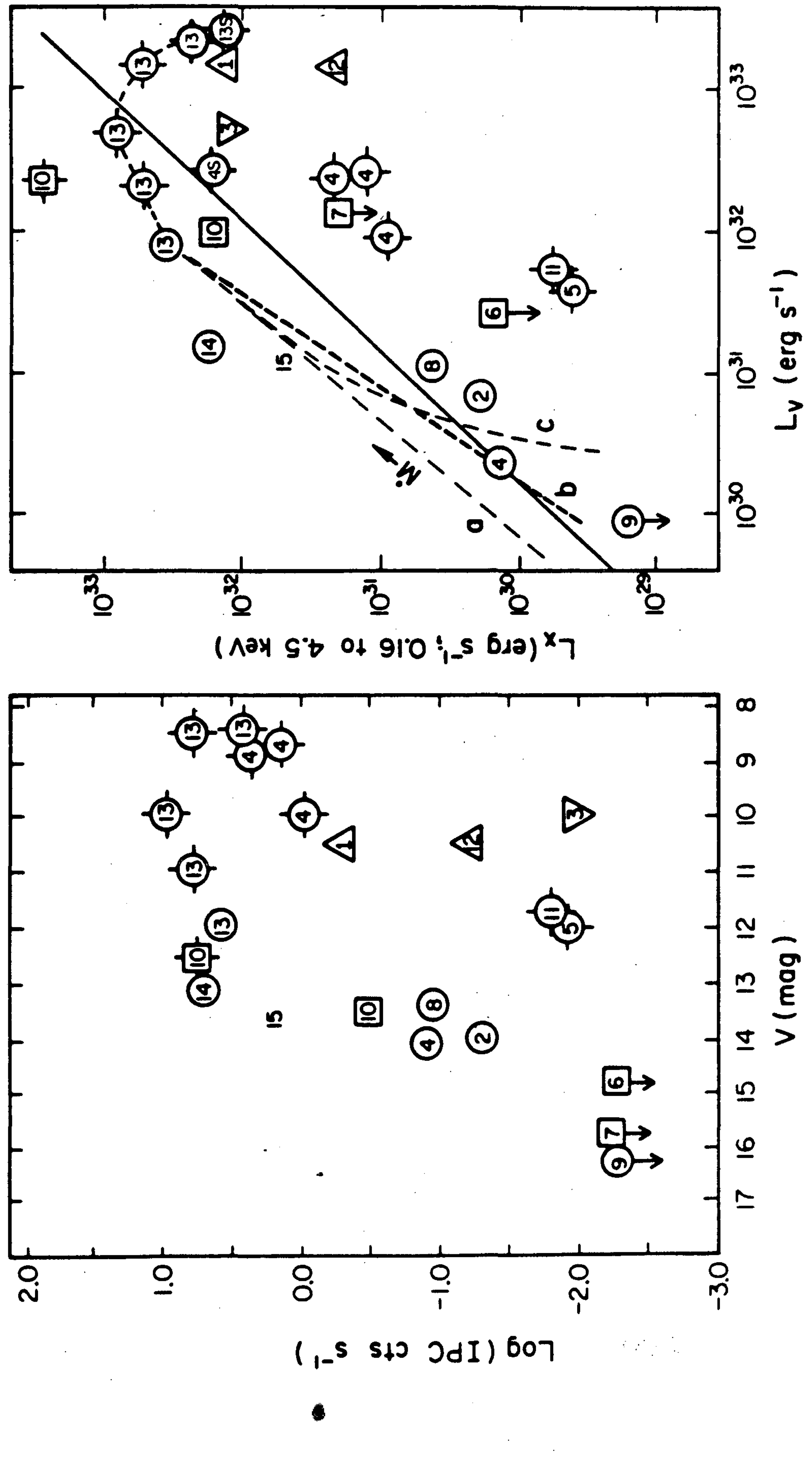
FIGURE CAPTION

Figure 1

The X-ray flux of cataclysmic variable stars as a function of their V band flux. The left hand panel (Figure 1a) illustrates the observed quantities, while in the right hand panel (Figure 1b) 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 V band luminosities of the compact components in these systems. Stars are numbered according to Table 1 and various subclasses of stars are identified as follows: open circles - dwarf novae; triangles - nova-like objects; squares - classical novae; and inverted triangles - recurrent novae. Open circles with "diffraction spikes" denote dwarf novae in some stage of optical outburst. Luminosity measurements for the ultra-soft X-ray component of SS Cyg and U Gem are annotated with the letter 'S'. Curve (a) in Figure 1b 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).


Lx (erg s⁻¹; 0.16 to 4.5 keV)
10^29
10^30
10^31
10^32
10^33
Lv (erg s⁻¹)
10^30
10^31
10^32
10^33
a
b
c
M
15
Log (IPC cts s⁻¹)
2.0
1.0
0.0
-1.0
-2.0
-3.0
V (mag)
17
16
15
14
13
12
11
10
9
8
1
2
3
4
4S
5
6
7
8
9
10
11
12
13
13S
14
15

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