

## CONTINUUM AND LINE SPECTRA OF DEGENERATE DWARF X-RAY SOURCES\*

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## ABSTRACT

We summarize recent observations of degenerate dwarf X-ray sources, and review theoretical work on their continuum spectra and lines. We discuss some of the important unresolved issues concerning these sources, and conclude with an outline of the kinds of X-ray observations that would best advance our understanding of them.

## I. INTRODUCTION

## a) Historical Remarks

The first degenerate dwarf X-ray source was discovered in 1974 when Rappaport et al. (1974) detected an unexpected soft X-ray source during a brief rocket flight and deduced that the source was SS Cyg in outburst.

Two years later Berg and Duthie (1976) suggested that the cataclysmic variable AM Her was the optical counterpart of the hard X-ray source 4U1814+50. This identification was confirmed by Hearn et al. (1976), who detected AM Her in soft X rays. Soon after the optical identification, Szkody and Brownlee (1977) and Cowley and Crampton (1977) found that AM Her has a binary period of 3.1 hours. More remarkably, Tapia (1977a) discovered that the optical light from AM Her is nearly 10% circularly and linearly polarized and that the degenerate dwarf is strongly magnetic. The periods of the circular and linear polarization curves, the radial velocity curves, and the optical, soft and hard X-ray light curves are identical. Thus the rotation period of the accreting magnetic degenerate dwarf is phase-locked to the binary orbital period of 3.1 hours. Within less than a year, two other similar sources, AN UMa and VV Pup, were identified from their optical emission line spectrum and confirmed by detection of linear and circular polarization (Krzeminski and Serkowski 1977, Tapia 1977b).

Soft and hard X-rays were soon also detected from the well-known cataclysmic variables U Gem (Mason et al. 1978; Swank et al. 1978), EX Hya (Watson, Sherrington, and Jameson 1978; Cordova and Riegler 1979), and GK Per (King, Ricketts, and Warwick 1979), in addition to SS Cyg (Heise et al. 1978; Mason, Cordova, and Swank 1979).

Subsequent examination of nearby cataclysmic variables turned up many more X-ray sources. A few of these were discovered by Ariel 5 and HEAO-1, but most detections required the high sensitivity of the focusing instrument on Einstein. Other cataclysmic variables have been found by looking for the optical counterparts of faint

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galactic X-ray sources, and this method promises to become increasingly important in the future. More than 53 of these accreting degenerate dwarf X-ray sources are now known (Cordova and Mason 1982).

Soft X-rays have also been detected from several hot ( $T_{\text{eff}} > 30,000 - 60,000$  K) isolated degenerate dwarfs, including Sirius B (Martin et al. 1982 and references therein) and HZ 43 (Hearn et al. 1976).

#### b) Potential

The study of degenerate dwarf X-ray sources can provide many returns. For example, these sources afford a laboratory in which to explore the physics of hot, dense plasmas in strong magnetic fields (the parameter regime is, in fact, similar to that of interest in plasma fusion reactors). We can also learn from them a great deal about the masses, internal structure, and magnetic fields of degenerate dwarfs themselves. Potentially, the pulsing sources can provide as much information as has been obtained from the pulsing neutron star X-ray sources. Noise measurements can be used to probe the accretion process, reflection and reprocessing effects give clues to the geometry of the disk and the binary system, and time delay curves yield the parameters of the binary system and thereby lend insight into its formation and evolution.

However, because most degenerate dwarf X-ray sources were found only recently, we know very little about their X-ray properties. Only three (AM Her, SS Cyg, and U Gem) have been studied in any detail. The situation is similar in this respect to that of the stellar X-ray sources also found by Einstein (Linsky 1982). Exploration of the X-ray emission from both has only begun, and future X-ray astronomy missions must provide the data with which to understand it.

In this review, we concentrate on the soft and hard X-ray spectra produced by accreting degenerate dwarfs. We first summarize the observations in §II. We then discuss the theory of formation of the continuum spectrum in §III, and of emission and absorption lines in §IV. In §V, we mention some of the important unresolved issues. Finally, in §VI we outline the kinds of X-ray observations that would best advance our understanding of these sources. For reviews of the optical properties of cataclysmic variables, see Robinson (1976) and Warner (1976); for reviews of the X-ray observations, see Garmire (1979) and Cordova and Mason (1982). Lamb (1979) and Kylafis et al. (1980) contain earlier reviews of theoretical work.

## II. OBSERVATIONAL PROPERTIES

### a) Luminosities and Space Densities

Probably all cataclysmic variables are X-ray sources. The ones detected so far have X-ray luminosities  $L \sim 10^{31} - 10^{33}$  ergs  $s^{-1}$ . None of the bright ( $L \sim 10^{36} - 10^{38}$  ergs  $s^{-1}$ ) galactic X-ray sources have been identified with degenerate dwarfs. Thus the known accreting degenerate dwarf X-ray sources are  $\sim 10^5$  times fainter than, e.g., the pulsing neutron stars (Lamb 1979) but  $\sim 10^3$  times brighter than ordinary stars (Linsky 1982).

The nearest cataclysmic variable X-ray sources lie at distances  $d$  of only 75 - 100 pc (Cordova and Mason 1982). This implies a space density  $n \sim 3 \times 10^{-7} (d/100 \text{ pc})^{-3}$   $\text{pc}^{-3}$ . Assuming a uniform distribution of sources throughout the galaxy and a galactic

volume  $V \approx 1 \times 10^{12} \text{ pc}^3$ , the above space density implies that the total number of sources in the galaxy is  $N \approx 3 \times 10^5 (d/100 \text{ pc})^{-3}$ . Thus the total number of degenerate dwarf X-ray sources in the galaxy may exceed a million. This compares with a total number of bright ( $L \approx 10^{36} - 10^{38} \text{ ergs s}^{-1}$ ) neutron star sources of  $\approx 100$ .

#### b) X-Ray Spectra and Temporal Behavior

Among accreting degenerate dwarf X-ray sources, there are two recognized classes involving magnetic degenerate dwarfs: the AM Her stars and the DQ Her stars (Lamb 1979, Patterson and Price 1981). The remaining systems show no clear-cut manifestation of a magnetic field. However, if the past is a guide, some of these sources will be reclassified as AM Her or DQ Her stars on the basis of future observations. We may even speculate that magnetic fields are endemic in degenerate dwarfs. If so, most, perhaps all, of the other systems also contain magnetic degenerate dwarfs. However, the field strengths may be less. Below we discuss the X-ray spectra and temporal behavior of the AM Her stars, the DQ Her stars, and the other cataclysmic variables.

##### i) AM Her stars

Table 1 lists the seven AM Her stars that are now known and summarizes some of their properties. These stars show strong ( $> 10\%$ ) circular and linear polarization of their infrared and visible light, and are believed to be accreting magnetic degenerate dwarfs (Chanugam and Wagner 1977, 1978; Stockman et al. 1977). The polarization (Tapia 1977a) of the visible light from AM Her, the prototype of this class, is shown in figure 1. The X-ray spectra of these stars typically have two distinct components: an apparent blackbody component with  $T_{\text{bb}} < 100 \text{ eV}$  and a bremsstrahlung component with  $T_{\text{br}} > 10 \text{ keV}$ . The inferred blackbody luminosity is greater than the bremsstrahlung luminosity, often by a factor of 10 or more (cf. Tuohy et al. 1978, 1981; Szkody et al. 1981; Patterson et al. 1982). Figure 2 shows the soft and hard X-ray spectrum of AM Her recently constructed from HEAO-1 observations by Rothschild et al. (1981). The bremsstrahlung spectra of these sources also show strong iron line emission at  $\approx 7 \text{ keV}$ , as is evident in Figure 2. In these systems, the periods of the polarized light, the optical and X-ray light, and the orbital velocity curves are all the same. Thus the rotation period of the degenerate dwarf is synchronized with the orbital period of the binary system, probably due to interaction of the magnetic field of the degenerate dwarf with the companion star (Joss, Katz, and Rappaport 1979). Figure 3 shows the resulting 3.1 hour "pulse profile" of AM Her in soft X-rays (Tuohy et al. 1978).

The source EF Eri (2A0311-227) is the second most well-studied in X-rays of the AM Her stars. Figures 4 and 5 show its 1.3 hour "pulse profile" in soft X-rays (Patterson et al. 1981) and its bremsstrahlung hard X-ray spectrum (White 1981). Note again the strong iron emission line at  $\approx 7 \text{ keV}$ .

##### ii) DQ Her stars

Table 2 lists the seven systems we have classified as DQ Her stars and summarizes some of their properties. DQ Her, the prototype of this class, is believed to be an accreting magnetic degenerate dwarf (Bath, Evans, and Pringle 1974; Lamb 1974). However, it shows little, if any, polarization of its infrared and visible light (Swedlund, Kemp, and Wolstencroft 1974). This system underwent a nova outburst in 1934 and shows coherent small amplitude optical pulsations at 71 seconds, which are believed to

TABLE 1

## AM HER STARS

STAR	$P_b$ (Hours)	d (pc) <sup>a</sup>	$L_s$ ( $10^{30}$ ergs s <sup>-1</sup> ) <sup>b</sup>	$T_{bb}$ (eV)	$L_h$ ( $10^{30}$ ergs s <sup>-1</sup> ) <sup>b</sup>	$T_{br}$ (keV)	REFERENCES
EF Eri (=2A0311-227)	1.35	[100]	24	≤80	170	18.1±3.0	8, 15, 18
VV Pup	1.67	144	160	20 <sup>+60</sup> -10	7.0	>10	2, 7, 14
E1405-451	1.69	[100]	9.7	...	...	...	6
H0139-68	1.83	[100]	72	≤300	...	...	1, 17
PG1550+191	1.89	[100]	...	...	...	...	10
AN Uma	1.91	[100]	0.86 33	≤40	...	...	3, 5, 12
AM Her	3.09	75±10	45-480 21	28-40	260 480	30.9±4.5	4, 9, 11, 13, 16, 19

<sup>a</sup> Distances in brackets are assumed.

<sup>b</sup> Luminosities assume a distance of 100 pc, except for AM Her and VV Pup.

- |                                     |                                     |                                       |
|-------------------------------------|-------------------------------------|---------------------------------------|
| (1) Agrawal <u>et al.</u> (1981)    | (8) Patterson <u>et al.</u> (1981)  | (14) Tapia (1977b)                    |
| (2) Bailey (1981)                   | (9) Rothschild <u>et al.</u> (1981) | (15) Tapia (1979)                     |
| (3) Hearn and Marshall (1979)       | (10) Stockman <u>et al.</u> (1981)  | (16) Tuohy <u>et al.</u> (1981)       |
| (4) Hearn and Richardson (1977)     | (11) Swank <u>et al.</u> (1977)     | (17) Visvanathan <u>et al.</u> (1982) |
| (5) Krzeminski and Serkowski (1977) | (12) Szkody <u>et al.</u> (1981)    | (18) White (1981)                     |
| (6) Mason <u>et al.</u> (1982)      | (13) Tapia (1977a)                  | (19) Young and Schneider (1979)       |
| (7) Patterson <u>et al.</u> (1982)  |                                     |                                       |

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AM Her / 3U 1809-50

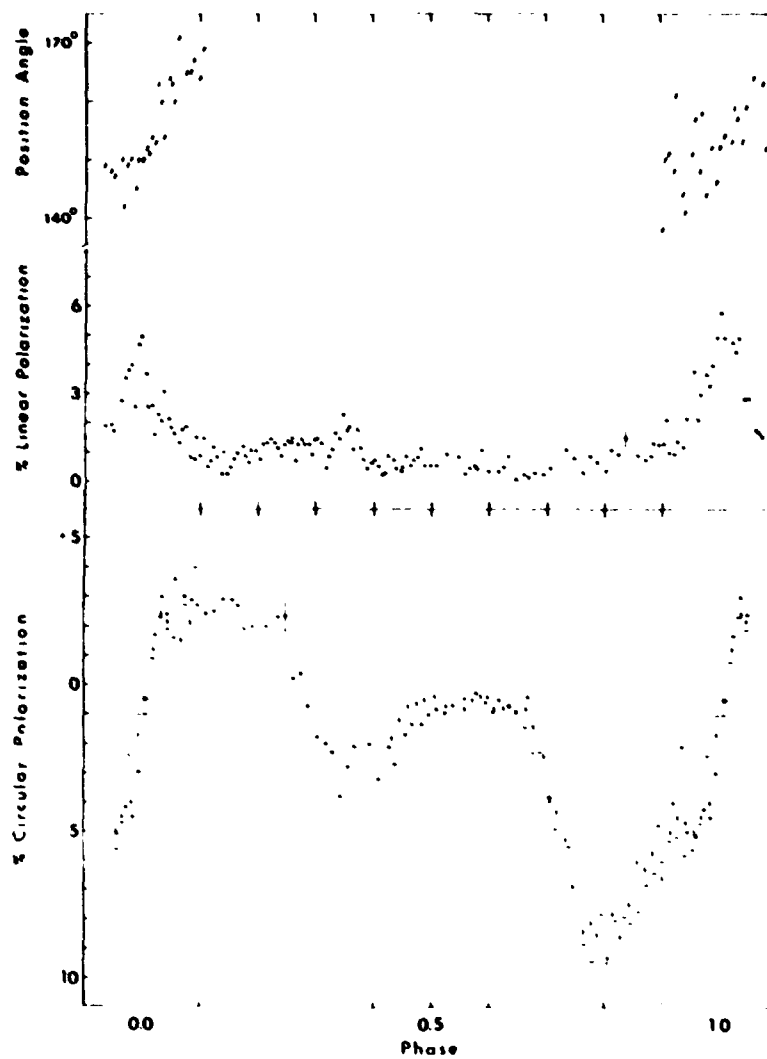


Fig. 1--Circular and linear polarization of the optical light from AM Her as a function of the phase of the 3.1 hour rotational period of the degenerate dwarf (from Tapia 1977).

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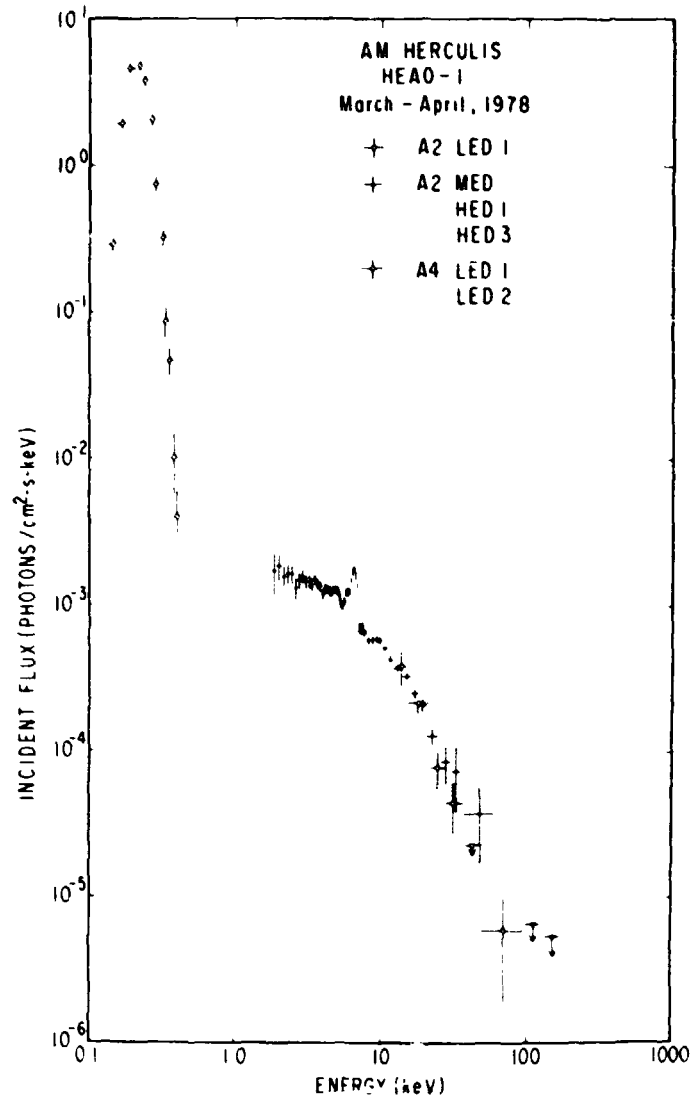


Fig. 2--Hard and soft X-ray spectrum of AM Her (from Rothschild et al. 1981). The two distinct components with  $T \approx 30$  keV and  $T < 40$  eV are clearly visible.

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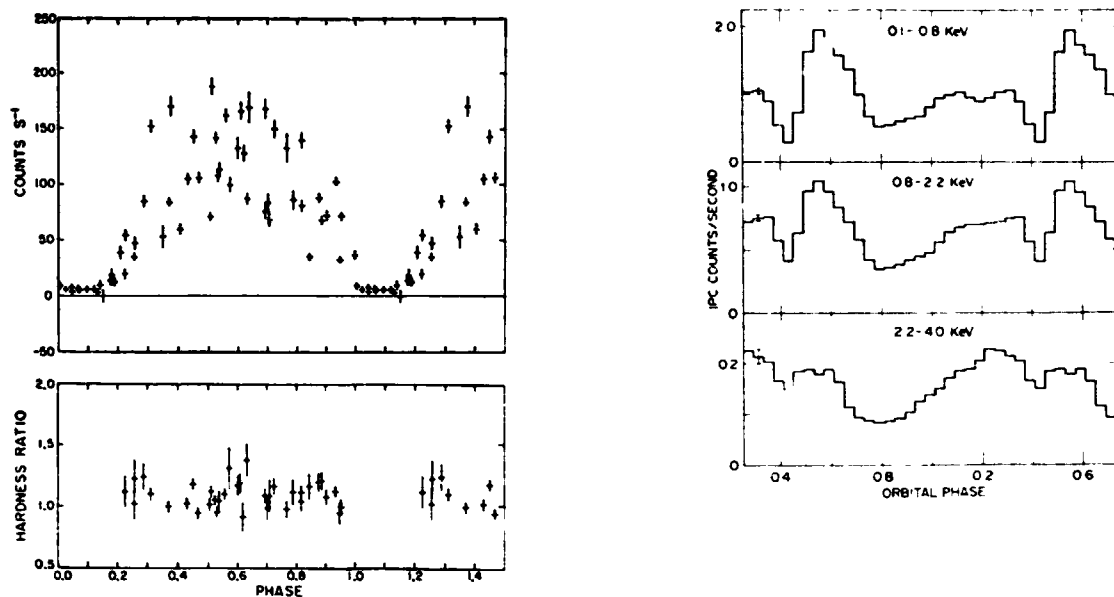


Fig. 3--Soft X-ray pulse profile and hardness ratio of AM Her as a function of the phase of the 3.1 hour rotational period of the degenerate dwarf (from Tuohy et al. 1978).

Fig. 4--X-ray pulse profile of EF Eri (2A0311-227) observed by Einstein as a function of orbital phase (or, equivalently, phase of the rotational period of the degenerate dwarf) (from Patterson et al. 1981).

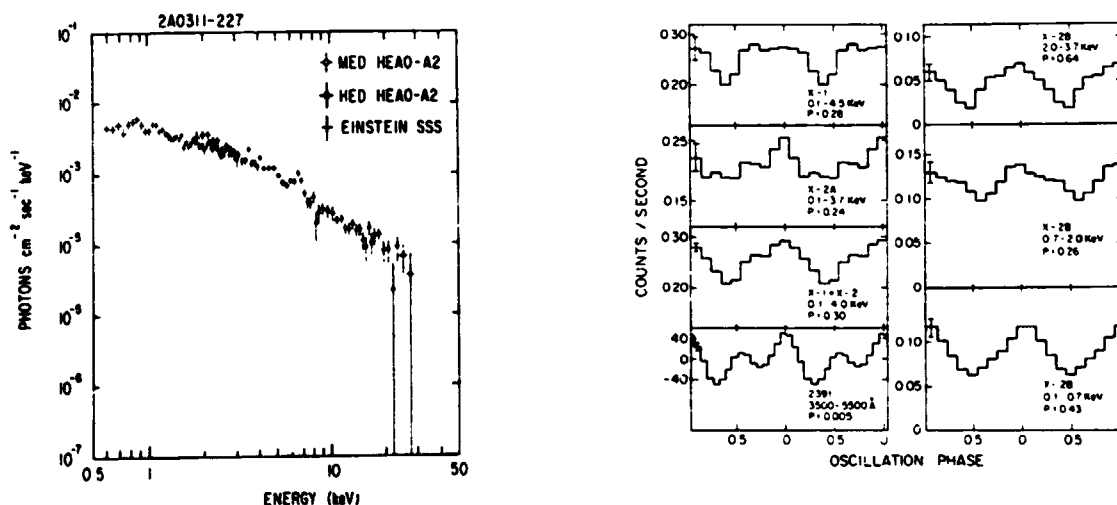


Fig. 5--Hard X-ray spectrum of EF Eri (2A0311-227) (from White et al. 1981). Note the iron emission line at  $\approx 7$  keV.

Fig. 6--Comparison of the pulse profile in soft X-rays and in optical light of AE Aqr through the 33 second rotation period of the degenerate dwarf (from Patterson et al. 1980).

TABLE 2

## DQ HER STARS

STAR	$P_b$ (Hours)	d (pc) <sup>a</sup>	P (s)	$ P ^{-1}$	$L_s$ ( $10^{30}$ ergs s <sup>-1</sup> ) <sup>b</sup>	$T_{bb}$ (eV)	$L_h$ ( $10^{30}$ ergs s <sup>-1</sup> ) <sup>b</sup>	$T_{br}$ (keV)	REFERENCES
DQ Her	4.65	420	71.0653	$1.2 \times 10^{12}$	< 2.4	...	...	...	2, 11
v533 Her	≈ 7	1000-1500	63.63307	$> 3 \times 10^{12}$	< 20-40	...	...	...	2, 5, 7
AE Aqr	9.88	84	33.076737	$2 \times 10^{13}$	5.4	...	...	...	1, 6, 7, 9
EX Hya (?)	1.64	100	4021.62	$2.2 \times 10^{10}$	14	570	60 100	≈ 5 ≈ 4.5	3, 4, 15
H2252-035	3.59	[100]	805.21	$> 5 \times 10^9$	...	...	80	> 20	8, 10, 16, 17
H2215-086	4.03	[100]	1254.5	$> 3 \times 10^8$	5	...	12 30	≥ 10 ≥ 10	12
V1223 Sgr	...	[100]	194.380	$> 5 \times 10^9$	...	...	100	≥ 10	13, 14

<sup>a</sup> Distances in brackets are assumed.

<sup>b</sup> Luminosities assume a distance of 100 pc if distance is unknown.

- |                                       |   |   |
|---------------------------------------|---|---|
| (1) Bailey (1981)                     | (7) Patterson (1982a)                       | (13) Steiner (1981)                         |
| (2) Cordova, Mason, and Nelson (1981) | (8) Patterson (1982b)                       | (14) Steiner <u>et al.</u> (1981)           |
| (3) Cordova and Riegler (1979)        | (9) Patterson <u>et al.</u> (1980)          | (15) Swank (1980)                           |
| (4) Gilliland (1982)                  | (10) Patterson and Price (1981)             | (16) Warner, O'Donoghue, and Fairall (1981) |
| (5) Patterson (1979a)                 | (11) Patterson, Robinson, and Nather (1978) | (17) White and Marshall (1981)              |
| (6) Patterson (1979b)                 | (12) Patterson and Steiner (1982)           |   |

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represent the rotation period of the degenerate dwarf (Patterson, Robinson, and Nather 1978, and references therein). Two other members of this class are V533 Her, which underwent a nova outburst in 1963 and shows coherent small amplitude optical pulsations at 63 seconds (Patterson 1979a), and AE Aqr, which shows similar pulsations at 33 seconds (Patterson 1979b). Embarrassingly, neither DQ Her nor V533 Her have been detected in X rays (see Table 2). In the case of DQ Her, it has been suggested that the X rays are blocked by the disk because we are nearly in the orbital plane of the system, while in the case of V533 it can be argued that the system is too far away, and therefore too faint, to have been detected. Thankfully (for theorists), X rays have now been detected from AE Aqr and are pulsed with the 33 second optical period (Patterson et al. 1980). Figure 6 compares the optical and soft X-ray pulse profiles of AE Aqr.

Recently, several faint galactic X-ray sources have been identified with systems that are optically similar to cataclysmic variables. They exhibit large amplitude optical and X-ray pulsations with periods  $\geq 1000$  seconds that are believed to represent the rotation period of the accreting star (Patterson and Price 1981; Warner, O'Donoghue, and Fairall 1981; White and Marshall 1981). There is controversy as to whether these X-ray sources are actually degenerate dwarfs or are neutron stars (cf. Patterson and Price 1981, White and Marshall 1981). We believe, based on their optical appearance and their X-ray to optical luminosity ratio, that they are degenerate dwarfs. They have also been called "interlopers" between the previously known DQ Her stars, with short rotation periods of 33 - 71 seconds, and the AM Her stars, with rotation synchronous with their orbital periods of 1.2 - 2.1 hours (Patterson and Price 1981). However, we believe that they should be regarded as members of the DQ Her class, in analogy with the short and long period pulsing neutron star X-ray sources, and therefore we include them in Table 2.

The source H2252-035 was the first of these systems to be optically identified (Griffiths et al. 1980). Figure 7 shows its optical light curve (Patterson and Price 1981). Clearly visible are the optical pulsations with a period of 859 seconds, which are thought to be produced by reprocessing of the 805 second X-ray pulse. Figures 8 and 9 show the pulse profile and the spectrum of the hard X-rays (White and Marshall 1981). The hard X-ray spectrum exhibits iron line emission at  $\sim 7$  keV.

Recently, a 67 minute (4022 second) periodicity has been identified in the well-studied cataclysmic variable X-ray source EX Hya (Vogt, Krzeminski, and Sterken 1980; Gilliland 1982). This period is also evident in soft X-rays but not in hard (Swank and White 1981), as shown in Figure 10. The coherence of the period over many years suggests that it may also be due to rotation of a magnetic degenerate dwarf. We have therefore included EX Hya in Table 2, but with a question mark to indicate its uncertain status.

### iii) Other cataclysmic variables

Table 3 lists 10 sources selected from the remaining 44 cataclysmic variable X-ray sources currently known (Cordova and Mason 1982). Among these are the prototypical dwarf novae, SS Cyg and U Gem, which undergo outbursts every  $\sim 100$  days. During quiescence, both exhibit a hard X-ray spectrum with  $T_{br} \sim 10 - 20$  keV (Mason, Cordova, and Swank 1979; Swank 1979). During outburst, the hard X-ray luminosity first increases and then decreases, the spectral temperature of the hard X-rays decreases, and an intense blackbody component with temperature  $T_{bb} < 100$  eV appears in soft X-rays (cf. Mason, Cordova, and Swank 1979). Figure 11 compares the hard X-ray spectrum of SS Cyg in quiescence and in outburst with the spectrum of AM Her.

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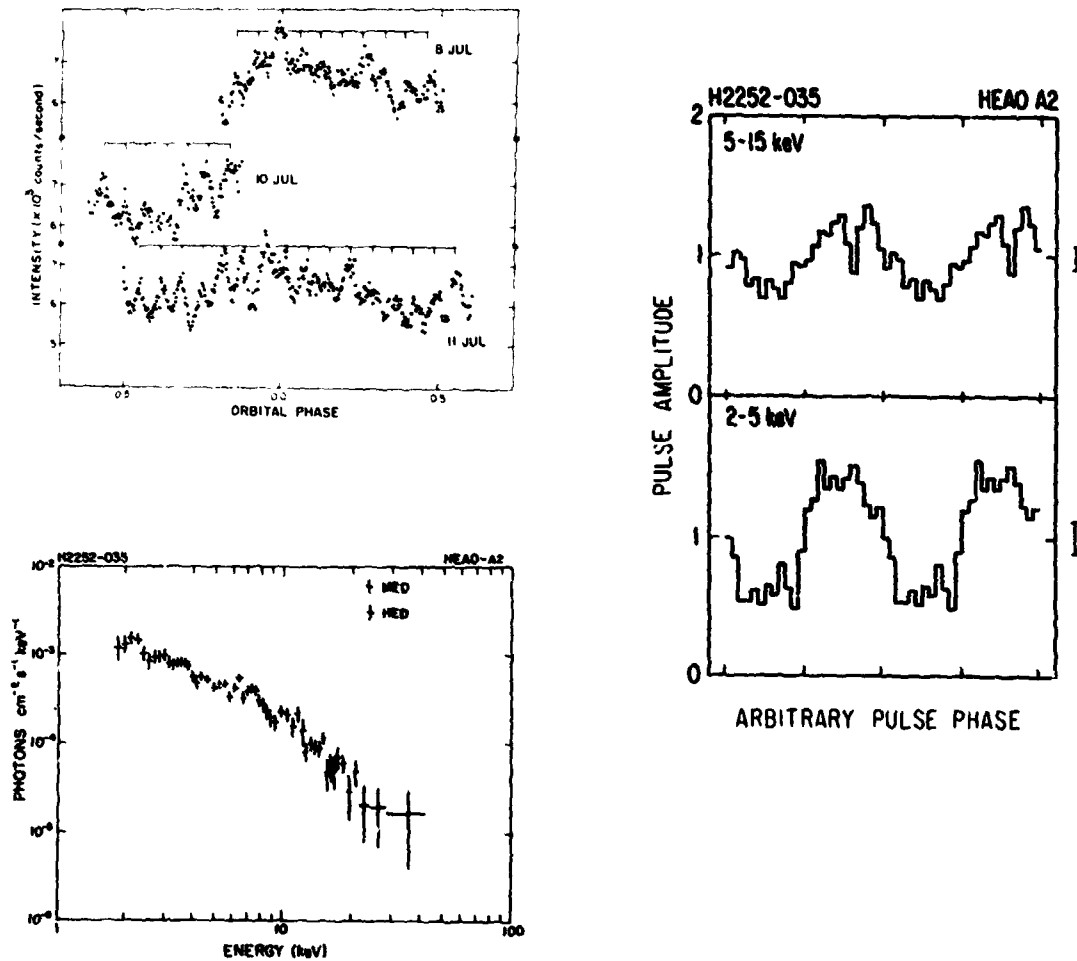


Fig. 7--Fast photometry of the optical light from H2252-035 (from Patterson and Price 1981). The 859 second pulsations, corresponding to reprocessed light from a stationary point in the binary system, are clearly visible.

Fig. 8--Hard X-ray pulse profile of H2252-035 through the 805 second rotation period of the degenerate dwarf (from White and Marshall 1981).

Fig. 9--Hard X-ray spectrum of H2252-035 (from White and Marshall 1981). The iron emission line at  $\approx 7$  keV is again clearly visible.

TABLE 3

SELECTED OTHER CATAclySMIC VARIABLES (AFTER CORDOVA AND MASON 1982)

STAR <sup>a</sup>	P <sub>b</sub> (Hours)	d (pc) <sup>b</sup>	P (s) <sup>c</sup>	L (10 <sup>30</sup> ergs s <sup>-1</sup> ) <sup>d</sup>	T <sub>br</sub> (keV) <sup>e</sup>	REFERENCES
WZ Sge	1.36	[100]	27.87, 28.97 (c)	6.0 (o)	[10]	14, 20
VW Hyi	1.78	[100]	24-32 (q) 88, 413 (q)	3.2 (q)	[10]	3, 7, 13
Z Cha	1.79	125±20	27.7 (c)	1.2 (o) 2.5 (q)	[10] [10]	1, 23
V603 Aql	3.33	430	...	160	[10]	2
U Gem	4.25	76±30	20-30 73-146	20 (o) 2 (q)	≈ 5 [10]	3, 5, 6, 19
UX UMa	4.72	214	28.5-30.0 (c)	2.0	[10]	1, 12
SS Cyg	6.60	125±25	8.5-10.9 (c, q) 32-36 (q)	100 (o) 410 (q)	≈ 8.5 = 20	1, 4, 5, 8, 9, 11, 15, 17, 19, 21
Z Cam	6.96	[100]	16.0-18.8 (c)	1.9 (s)	[10]	18, 22
RU Peg	8.90	[100]	11.6-11.8 (c) ~ 51 (q)	23 (q)	[10]	2, 3, 16, 19
GK Per	16.43	480	~ 380 (q)	5200 (o) 130-220 (q)	[10] [10]	10, 15

<sup>a</sup>All stars are dwarf novae except GK Per (classical nova) and UX UMa (nova-like).<sup>b</sup>Distances in brackets are assumed.<sup>c</sup>Symbols "c" and "q" in parentheses denote "coherent" and "quasi-periodic", respectively.<sup>d</sup>Luminosities assume a distance of 100 pc if distance is unknown; the symbols "o", "q", and "s" in parentheses denote "outburst", "quiescence", and "standstill", respectively.<sup>e</sup>Temperatures in brackets are assumed.

- |  |   |  |
|--|---|--|
| (1) Becker (1981)                            | (9) Horne and Gomer (1980)                  | (17) Patterson, Robinson, and Kiplinger (1978) |
| (2) Becker and Marshall (1981)               | (10) King, Ricketts, and Warwick (1979)     | (18) Robinson (1973)                           |
| (3) Cordova, Mason, and Nelson (1981)        | (11) Mason, Cordova, and Swank (1979)       | (19) Robinson and Nather (1979)                |
| (4) Cordova <i>et al.</i> (1980)             | (12) Nather and Robinson (1974)             | (20) Robinson, Nather, and Patterson (1978)    |
| (5) Cordova <i>et al.</i> (1981)             | (13) Patterson (1979)                       | (21) Swank (1979)                              |
| (6) Fabbiano <i>et al.</i> (1981)            | (14) Patterson (1980)                       | (22) Swank (1980)                              |
| (7) Haefner, Schoembs, and Vogt (1979)       | (15) Patterson (1981)                       | (23) Warner (1974)                             |
| (8) Hillebrand, Spiller, and Stiening (1981) | (16) Patterson, Robinson, and Nather (1977) |  |

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Fig. 10--Soft X-ray spectrum of EX Hydra measured by Einstein and showing the necessity of invoking at least two components (from Swank and White 1981).

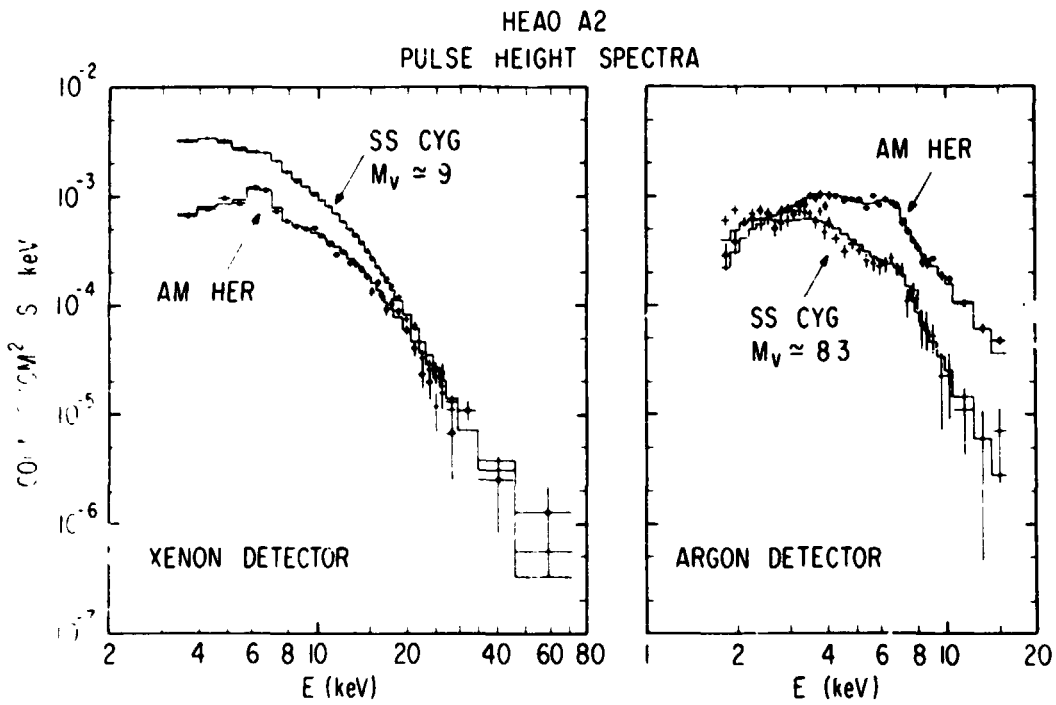
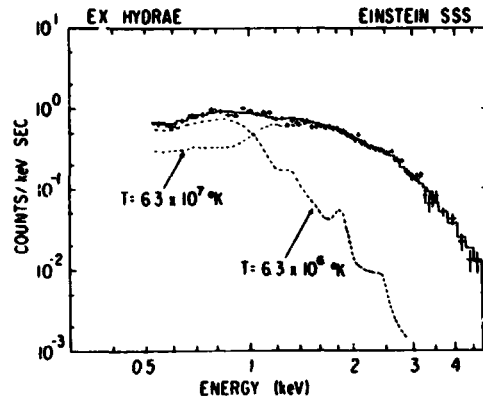


Fig. 11--Hard X-ray spectra of SS Cyg during quiescence (left panel) and during outburst (right panel) compared with the spectrum of AM Her (from Swank 1979). The presence of iron line emission at  $\approx 7$  keV in all spectra and the absence of low energy absorption in the spectrum of SS Cyg in outburst are evident.

The temporal behavior of the hard and soft X-ray luminosities of U Gem during an outburst is shown in Figure 12, while Figure 13 shows the way in which the hard X-ray spectrum of SS Cyg varies during an outburst.

Most of the remaining cataclysmic variables show only a hard X-ray component. It is not known whether the failure to detect a soft component during quiescence, or even during outburst in some sources, is due to its absence or due to the fact that it may have so low a spectral temperature that it is unobservable in soft X-rays.

Essentially all of the cataclysmic variables listed in Table 3 exhibit small amplitude quasi-periodic or coherent optical pulsations, usually during the onset of an outburst (Robinson 1976). Of special interest are the  $\sim 8 - 10$  second quasi-periodic pulsations in SS Cyg. They are strongly present in soft X-rays during outburst, yet their coherence persists for only 3-5 pulse periods (Cordova et al. 1980, 1981).

#### iv) Isolated stars

Sirius B, the first degenerate dwarf discovered, was detected as a very soft X-ray source by Mewe et al. (1975). Subsequently, very soft X rays were also detected from the hot degenerate dwarf HZ 43 (Hearn et al. 1976). Both of these degenerate dwarfs are members of binaries, but the binary separations are so large that the companions are not believed to play any role in the X-ray emission. Feige 24, another hot degenerate dwarf, has been detected in the extreme UV (Margon et al. 1976); however, it was not detected by the HEAO-1 soft X-ray survey and, unfortunately, Einstein ceased operating before observations of it were carried out. Table 4 lists these three sources and summarizes some of their properties.

The emission from Sirius B, HZ 43, and Feige 24 at optical, UV, and X-ray wavelengths can be understood as photospheric emission from a hydrogen-rich [ $n_{\text{He}}/n_{\text{H}} \sim 10^{-5}$ ] atmosphere with  $T_{\text{eff}} \sim 30,000 - 60,000$  K (Shipman 1976, Margon et al. 1976, Wesselius and Koester 1978, Martin et al. 1982). An upper limit in the extreme UV (200 - 800 Å) for Sirius B (Cash, Bowyer, and Lampton 1978) appeared to conflict with photospheric models for the X-ray emission and to lend support to coronal models. However, UV observations yielded no evidence for a corona (Bohm-Vitense, Dettmann, and Kapranidis 1979) and Martin et al. (1982) have recently demonstrated that soft X-ray data from HEAO-1, together with the optical, UV, and extreme UV data, are consistent with photospheric emission at  $\sim 28,000$  K, as shown in Figure 14. For more detailed, but earlier, reviews of extreme UV and soft X-ray emission from isolated degenerate dwarfs, see Garmire (1979) and Bowyer (1979).

### III. CONTINUUM SPECTRA

#### a) Qualitative Picture

In the remainder of this review, we shall focus on X-ray emission by accreting degenerate dwarfs.

##### i) Disk inflow near the star

Many of the cataclysmic variable X-ray sources show clear optical and UV evidence of accretion disks. If the disk extends all the way in to the stellar surface, viscous dissipation in the disk will release approximately half of the available

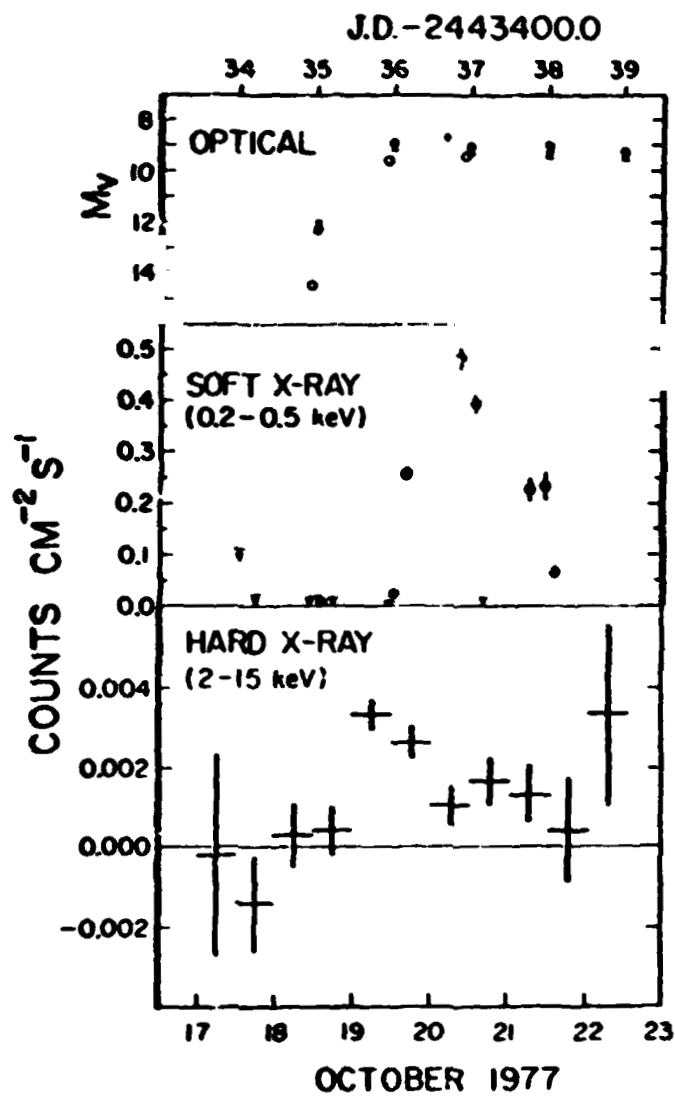
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Fig. 12--Optical, soft X-ray, and hard X-ray light curves of U Gem through an outburst (from Mason, Cordova, and Swank 1979).

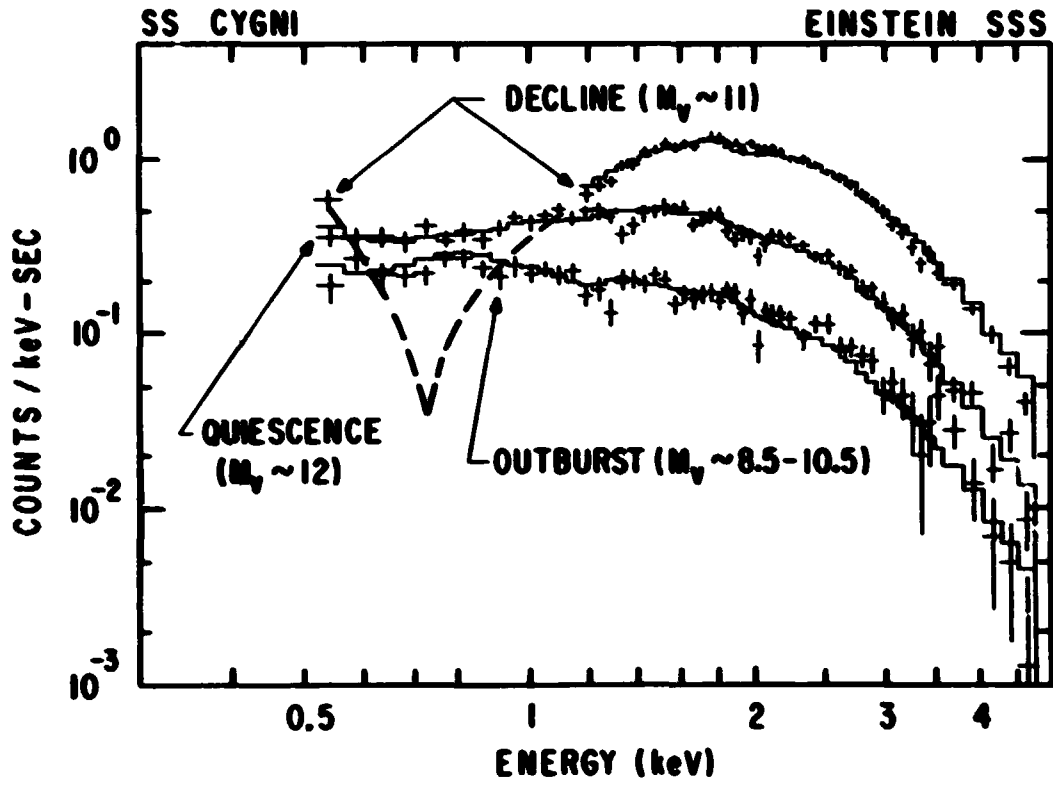


Fig. 13--Soft X-ray spectrum of SS Cyg showing the variation in the spectrum from outburst through decline to quiescence (from Swank and White 1981).

TABLE 4  
ISOLATED STARS

STAR	d (pc)	L ( $10^{30}$ ergs s $^{-1}$ )	T <sub>eff</sub> (k)	REFERENCES
Sirius B	2.7	0.06	≈ 28,000	4, 5, 6
HZ 43	65	40	≈ 60,000	2, 7
Feige 24	90	< 3	≈ 60,000	1, 3

(1) Bowyer (1979)

(2) Hearn et al. (1976)

(3) Margon et al. (1976)

(4) Martin et al. (1982)

(5) Mewe et al. (1975)

(6) Shipman (1976)

(7) Wesselius and Koester (1978)

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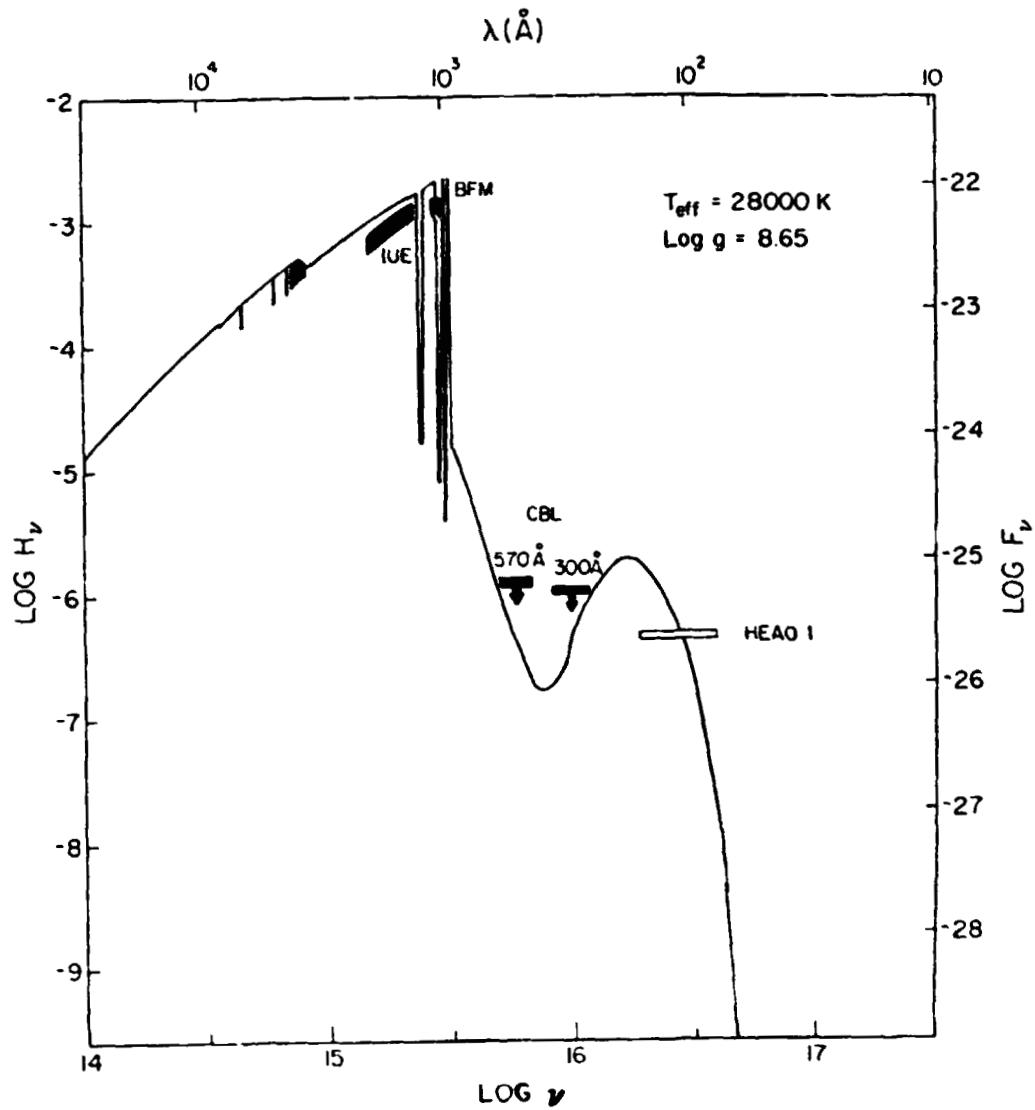


Fig. 14--Comparison of the flux from a 28,000 K hydrogen-rich model atmosphere with measurements and upper limits at UV, extreme UV, and soft X-ray wavelengths (from Martin et al. 1982).

gravitational energy, which will appear as blackbody radiation from the disk surfaces. The other half of the available gravitational energy will be released in a boundary layer at the inner edge of the disk where it encounters the surface of the star, unless the star is rotating near breakup. This luminosity is

$$L_{\text{bdry}} = \frac{1}{2} \frac{GM\dot{M}}{R} = 4 \times 10^{32} (M/M_{\odot}) (R/10^9 \text{ cm})^{-1} (\dot{M}/10^{-10} M_{\odot} \text{ yr}^{-1}) \text{ ergs s}^{-1}, \quad (1)$$

where  $M$  and  $R$  are the mass and radius of the star, and  $\dot{M}$  is the mass accretion rate. At moderate or high accretion rates, the boundary layer is capable of producing soft X-rays by blackbody emission (Pringle 1977). After it was found that most cataclysmic variables emit hard, but not soft, X rays during quiescence, Pringle and Savonije (1979) proposed that the boundary layer might produce hard X-ray emission by optically thin bremsstrahlung if shocks occurred there. The maximum possible shock temperature is

$$T_s = \frac{3}{8} T_{\text{ff}} = 2 \times 10^8 (M/M_{\odot}) (R/10^9 \text{ cm})^{-1} \text{ K}, \quad (2)$$

and thus the shocks must be strong ones. This is difficult to achieve in the strongly sheared flow of the inner disk whose geometry would tend to favor production of a large number of cooler, oblique shocks (in principle, the disk can join onto the star without the occurrence of any shocks). To attain the required strong shocks, Pringle and Savonije (1979) suggest a two-stage process in which gas that is initially mildly shocked in the boundary layer expands into the path of, and collides with, gas still circulating in the inner disk. Tylenda (1981), however, argues that turbulent viscosity will be a more efficient mechanism than shocks for dissipating energy in the boundary layer and that this mechanism can account for the observed high temperatures without resorting to complicated flow geometries.

Knowledge of whether the boundary layer can produce hard X-rays and, if so, how, is important for understanding the cataclysmic variable X-ray sources. But as yet, the ideas that have been proposed have not been worked out in any detail.

For up-to-date discussions of disks, see the review by Pringle (1981) and the paper by Tylenda (1981).

#### ii) Radial inflow near the star

If the degenerate dwarf has a magnetic field,

$$B \geq 2 \times 10^3 (10^{-10} M_{\odot} \text{ yr}^{-1})^{1/2} (R/10^9 \text{ cm})^{-5/4} (M/M_{\odot})^{1/4} \text{ gauss}, \quad (3)$$

the field will disrupt the disk and lead to approximately radial inflow near the star. This picture certainly applies to the AM Her and DQ Her stars, and may apply to other cataclysmic variables if magnetic fields are endemic in degenerate dwarfs as speculated earlier. Radial inflow may also occur if mass transfer takes place via a stellar wind rather than via Roche lobe overflow. Most theoretical work has assumed radial inflow because it is far more tractable; in the remainder of this review, we will concentrate on radial inflow.

A qualitative picture of X-ray emission by radially accreting degenerate dwarfs is shown in Figure 15. As accreting matter flows toward the star, a strong standoff shock forms far enough above the star for the hot, post-shock matter to cool and come to rest at the stellar surface (Hoshi 1973; Aizu 1973; Fabian, Pringle, and Rees 1976). The

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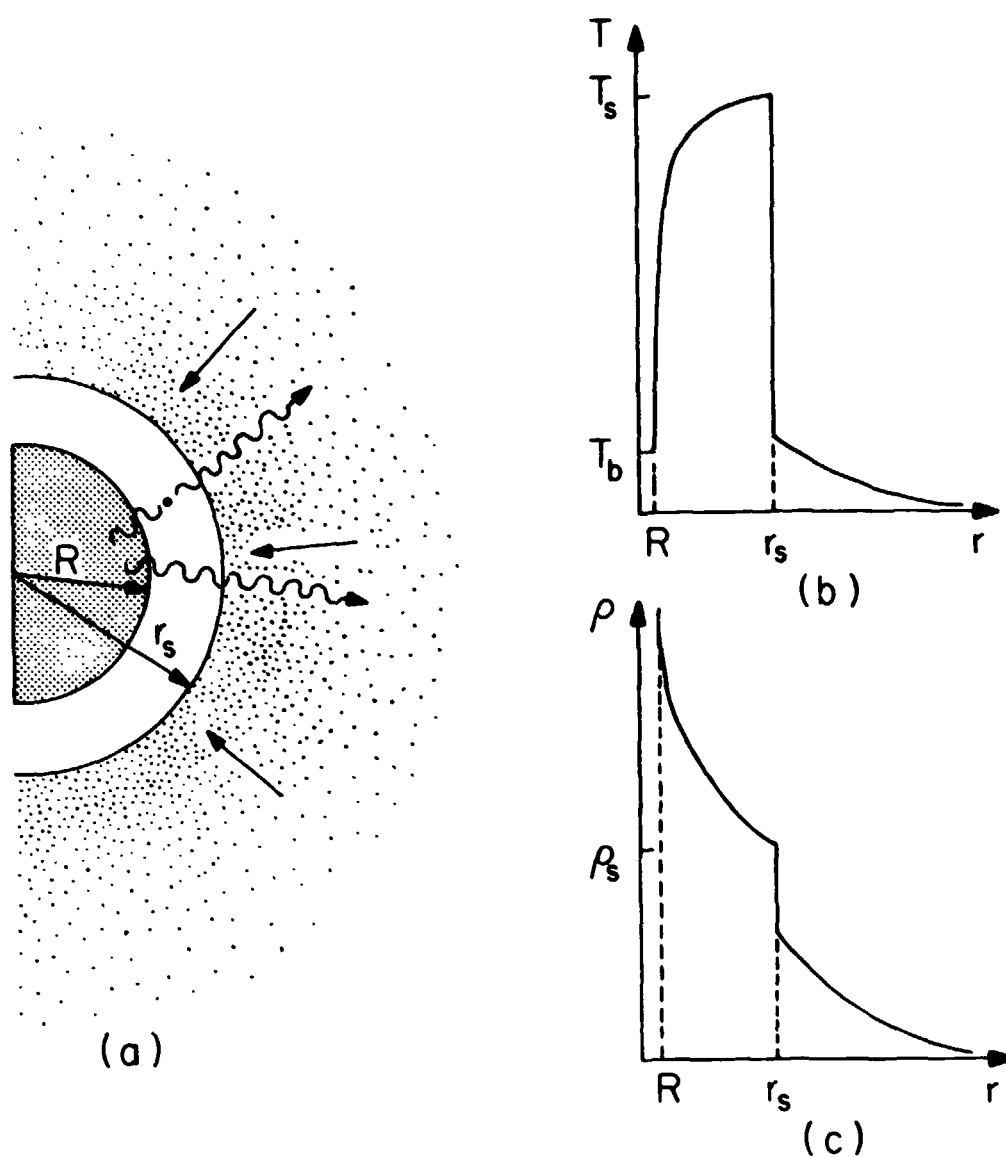


Fig. 15--Qualitative picture of X-ray emission from an accreting degenerate dwarf. a) Configuration of the star, the emission region, and the infalling matter.  $R$  is the stellar radius and  $r_s$  is the shock radius. The straight arrows indicate infalling matter, the wiggly arrows photons. b) Temperature profile of the infalling matter.  $T_s$  is the post-shock temperature and  $T_b$  is the stellar blackbody temperature. c) Density profile of the infalling matter;  $\rho_s$  is the post-shock density.

standoff distance

$$d \equiv r_s - R \approx 1/4 v_{ff}(r_s) t_{cool}(r_s), \quad (4)$$

where  $r_s$  is the shock radius,  $R$  is the stellar radius,  $v_{ff}$  is the free-fall velocity, and  $t_{cool}$  is the time scale for cooling, due to bremsstrahlung and, if a magnetic field is present, cyclotron emission. Roughly half of the bremsstrahlung flux is emitted outward and forms a hard X-ray component. Roughly half of the cyclotron flux is emitted outward and forms a blackbody-limited component in the UV. The other halves of the bremsstrahlung and cyclotron fluxes are emitted inward and are reflected or absorbed by the stellar surface. The resulting blackbody flux forms a UV or soft X-ray component with

$$L_{bb} \approx L_{cyc} + L_{br}, \quad (5)$$

where  $L_{bb}$ ,  $L_{cyc}$ , and  $L_{br}$  are the luminosities in the blackbody, cyclotron, and bremsstrahlung components. The total luminosity  $L = GM\dot{M}/R$ , or twice that given by equation (1).

If we allow for the possible presence of a magnetic field, the accreting matter may be channeled onto the magnetic poles and accretion may occur over only a fraction  $f$  of the stellar surface. The effective accretion rate of the accreting sector is  $\dot{M}/f$ , and the corresponding luminosity is  $L/f$ . X and UV radiation from magnetic degenerate dwarfs is thus a function of stellar mass  $M$ , magnetic field strength  $B$ , and effective luminosity  $L/f$ . The dependence on stellar mass is significant but is less than on the other two variables. If we specify the mass of the star, the parameter regimes encountered are conveniently displayed on a  $(B, L/f)$ -plane, as shown in Figure 16 for a  $1 M_{\odot}$ . The upper left of the plane corresponds to low magnetic field strengths and high effective luminosities (and thus high densities in the emission region). In this portion of the plane, bremsstrahlung cooling dominates cyclotron cooling in the hot, post-shock emission region, and the character of the X-ray emission is essentially the same as that of a nonmagnetic degenerate dwarf. As one increases  $B$  or lowers  $L/f$ , moving toward the lower right in Figure 16, cyclotron cooling becomes more important until eventually it dominates (Masters et al. 1977). The solid line shows the location at which this occurs, as determined from detailed numerical calculations equating  $t_{cyc}$  and  $t_{br}$ , the cyclotron and bremsstrahlung cooling time scales. This line is approximately given by

$$B = 6 \times 10^6 (L/f / 10^{36} \text{ ergs s}^{-1})^{2/5} \text{ gauss}. \quad (6)$$

To the lower right of this solid line, the magnetic field qualitatively alters the character of the X-ray emission.

#### b) Magnetic Stars

Fabian, Pringle, and Rees (1976), Masters et al. (1977), and King and Lasota (1979) have discussed the qualitative features of X-ray emission by magnetic degenerate dwarfs. Lamb and Masters (1979; see also Masters 1978) carried out detailed numerical calculations of high harmonic cyclotron emission from a hot plasma, and from them developed a self-consistent, quantitative model of the X-ray and UV emission. Wada et al. (1981) have carried out a few calculations for the regime in which bremsstrahlung,

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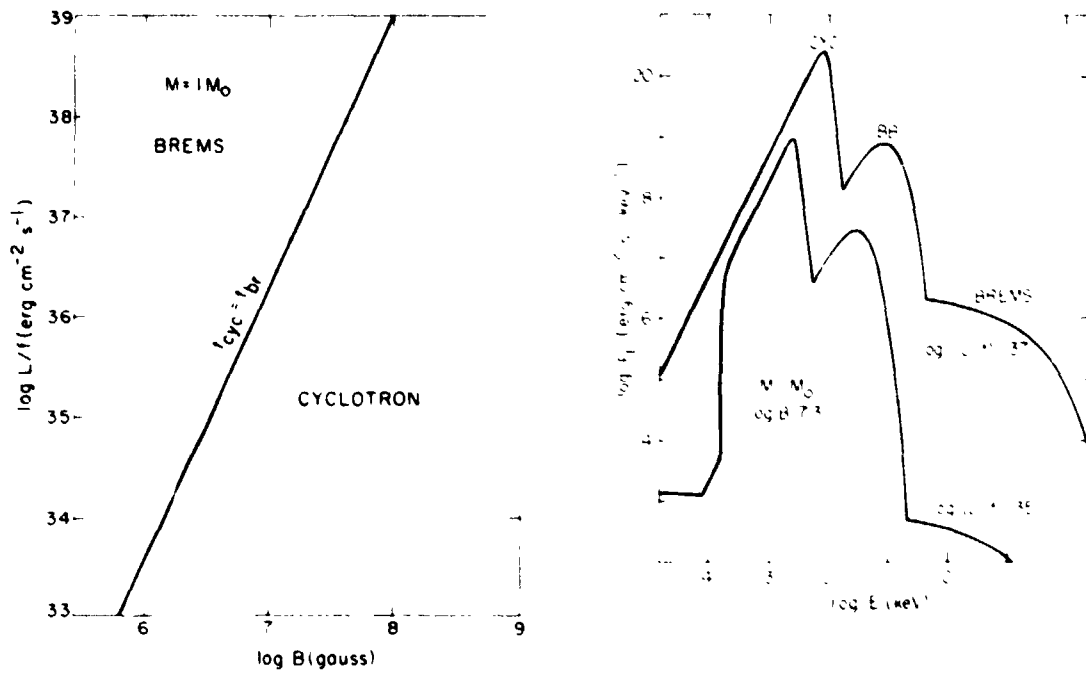


Fig. 16--Bremsstrahlung and cyclotron emission regimes in the  $(L/f, B)$ -plane for a  $1 M_{\odot}$  star (after Lamb and Masters 1979).

Fig. 17--X-ray and UV spectra produced by accretion onto a  $1 M_{\odot}$  star at two different accretion rates. The spectrum with  $L/f = 10^{37}$  ergs  $s^{-1}$  is in the bremsstrahlung dominated regime, while the spectrum with  $L/f = 10^{35}$  ergs  $s^{-1}$  is in the cyclotron dominated regime (from Lamb and Masters 1979).

not cyclotron emission, dominates (see Figure 16).

#### i) Spectra

The X and UV spectrum produced by accretion onto magnetic degenerate dwarfs generally has four components: 1) a blackbody-limited UV cyclotron component produced by the hot emission region, 2) a hard X-ray bremsstrahlung component also produced by the hot emission region, 3) a hard UV or soft X-ray blackbody component produced by cyclotron and bremsstrahlung photons that are absorbed by the stellar surface and re-emitted, and 4) secondary radiation from infalling matter above the shock or, possibly, from the stellar surface around the emission region. The first three components are clearly visible in Figure 17, which shows spectra produced by the hot, post-shock emission region alone. Since the secondary radiation is not included, the spectra do not accurately represent the observed spectrum below  $\sim 5$  eV. Figure 17 shows the X and UV spectra produced by accretion at two different rates, corresponding to  $L/f = 10^{35}$  and  $10^{37}$  erg s $^{-1}$ , onto a  $1.0 M_{\odot}$  star having a magnetic field of  $2 \times 10^7$  gauss.

The spectra illustrated in Figure 17 show two important features. First, strongly magnetic degenerate dwarfs should be intense UV sources with only a few percent of the total accretion luminosity ordinarily appearing as optical or soft and hard X-rays, and therefore easily accessible. Second, the position and relative strength of the spectral components change with variations in the accretion rate. For example, the change in accretion rate shown in Figure 17 moves the blackbody component from the UV into the soft X-ray region, and the luminosity of the bremsstrahlung hard X-ray component increases by nearly 4 orders of magnitude while the total accretion luminosity increases only by 2.

#### ii) Correlation between spectral temperature and luminosity

Variations in the shape and the strength of the spectral components are a function of both mass accretion rate and magnetic field strength. They can be conveniently displayed by plotting contours on a  $(B, L/f)$ -plane. Sets of such contours are shown in Figures 18 and 19 for a  $1.0 M_{\odot}$  star. Bremsstrahlung and cyclotron emission dominate in the same regions as in Figure 16. In Figure 18, contours of constant shock standoff distance  $d = \delta R/R$  are shown as thick solid lines. The thin solid lines in the bremsstrahlung-dominated region show contours of constant  $q = L_{\text{cyc}}/L_{\text{br}}$ , while those in the cyclotron-dominated region show contours of constant  $T_e$ , the temperature of the bremsstrahlung hard X-ray component. In Figure 19, contours of constant  $E^*$ , the peak of the blackbody-limited cyclotron component, are shown as thick solid lines while contours of constant  $T_{\text{bb}}$ , the temperature of the blackbody component, are shown as dashed lines. The thin solid lines have their same meaning as in Figure 18. To the upper right of the curve labelled "soft excess" in Figure 19, the blackbody luminosity in soft X-rays exceeds the bremsstrahlung luminosity in hard X-rays.

Near and above  $L/f = L_E = 1.4 \times 10^{38}$  erg s $^{-1}$ , radiation pressure can be important and modify the results, but because photons can easily scatter out of the accretion column if  $f \ll 1$ , the Eddington luminosity does not represent the stringent upper limit to the luminosity that it does in the case of nonmagnetic degenerate dwarfs. Below and to the left of the curve  $E^* = 2$  eV in Figure 19, the assumption  $d < R$  breaks down, as can be seen from Figure 18.

If the geometry of the hot, post-shock emission region is such that most of the flux escapes through the face rather than through the edges of the emission region (i.e.,  $d \ll \sqrt{(2f)R}$ ), then Compton degradation of the bremsstrahlung hard X-ray component will occur if  $L/f$  exceeds  $\sim 10^{37}$  erg s $^{-1}$ . Such degradation is identical to that encountered

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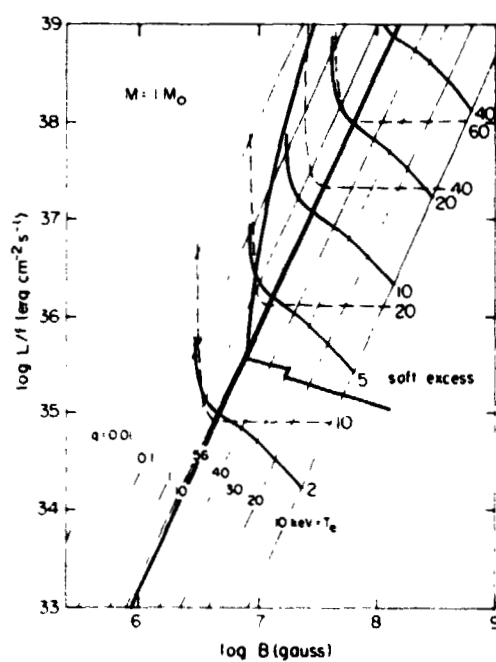
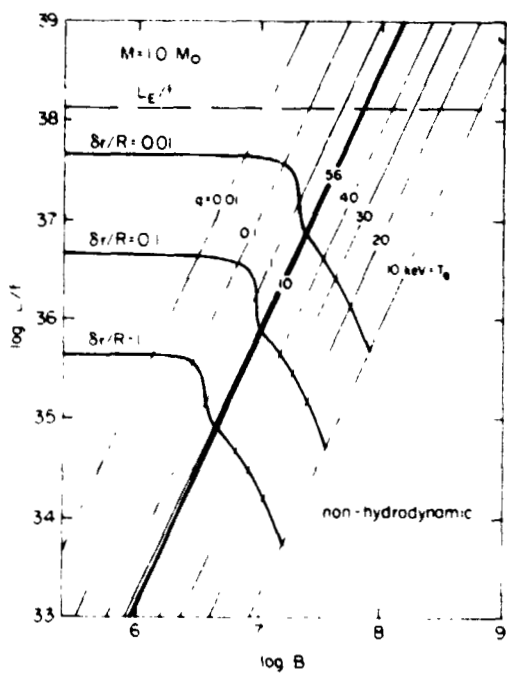


Fig. 18--Contours in the  $(L/f, B)$ -plane for a  $1 M_{\odot}$  star. For an explanation of the various lines, see the text.

Fig. 19--More contours in the  $(L/f, B)$ -plane for a  $1 M_{\odot}$  star (from Lamb and Masters 1979). For an explanation of the various lines, see the text.

in nonmagnetic degenerate dwarfs, and will be discussed below.

Figure 19 illustrates a third important feature of X-ray emission from magnetic degenerate dwarfs: observations of the qualitative features of the X and UV spectrum can determine fairly accurately the physical conditions in the emission region, including the value of the magnetic field.

### c) Nonmagnetic Stars

Studies of X-ray emission from accreting nonmagnetic degenerate dwarfs include those by Hoshi (1973), Aizu (1973), Hayakawa (1973), DeGregoria (1974), Hayakawa and Hoshi (1976), Fabian, Pringle, and Rees (1976), Katz (1977), and Kylafis and Lamb (1979, 1982a,b). These calculations are applicable, even if a magnetic field is present, as long as the accretion flow is approximately radial and bremsstrahlung cooling dominates cyclotron cooling in the X-ray emission region (recall Figure 16). Thus they are relevant to the AM Her stars, such as AM Her itself, which has a magnetic field  $B \approx 2 \times 10^7$  gauss (Lamb and Masters 1979; Schmidt, Stockman, and Margon 1981; Latham, Liebert, and Steiner 1981), and VV Pup, which has a magnetic field  $B \approx 3 \times 10^7$  gauss (Visvanathan and Wickramasinghe 1979; Stockman, Liebert, and Bond 1979), as well as to the DQ Her stars.

#### i) Spectra

The X and UV spectrum produced by accretion onto nonmagnetic degenerate dwarfs generally has three components: 1) a hard X-ray bremsstrahlung component produced by the hot, post-shock emission region, 2) a soft X-ray blackbody component produced by bremsstrahlung photons that are absorbed by the stellar surface and re-emitted, and 3) secondary radiation produced by Compton heating of infalling matter above the shock.

These components are clearly visible in Figure 20, which shows six spectra that span the entire range of accretion rates. Figure 21 shows for comparison three similar spectra when nuclear burning occurs at the accretion rate (see below). At low accretion rates,  $\tau_{es} < 1$  and the observed hard X-ray spectrum is essentially the same as that produced in the emission region. As the accretion rate is increased,  $\tau_{es}$  exceeds unity and Compton scattering begins to degrade the spectrum (Illarionov and Sunyaev 1972). The blackbody component then contains a contribution from bremsstrahlung photons which are backscattered by the accreting matter and absorbed by the stellar surface. The secondary radiation, which arises from accreting matter heated by the Compton scattering of the bremsstrahlung photons, is important only when degradation of the bremsstrahlung is substantial. As the accretion rate is increased further, this degradation becomes more severe. Finally, due to the combined effects of degradation and weakening of the shock by radiation pressure, the bremsstrahlung component disappears altogether. The star then ceases to be a hard (i.e.,  $T_{obs} > 2$  keV) X-ray source.

Figure 20 illustrates two important features of X-ray emission from nonmagnetic degenerate dwarfs. First, an intense blackbody soft X-ray component is always present. Second, at high accretion rates Compton degradation leads to low spectral temperatures even for high mass stars.

#### ii) Correlation between spectral temperature and luminosity

The resulting correlation between  $T_{obs}$  and  $L_h$  is shown in Figure 22 for stars of mass  $M = 0.2-1.2 M_{\odot}$ . Note that the accretion rate increases as one moves from upper left to lower right along the curves. For sources found in the lower right of the figure,



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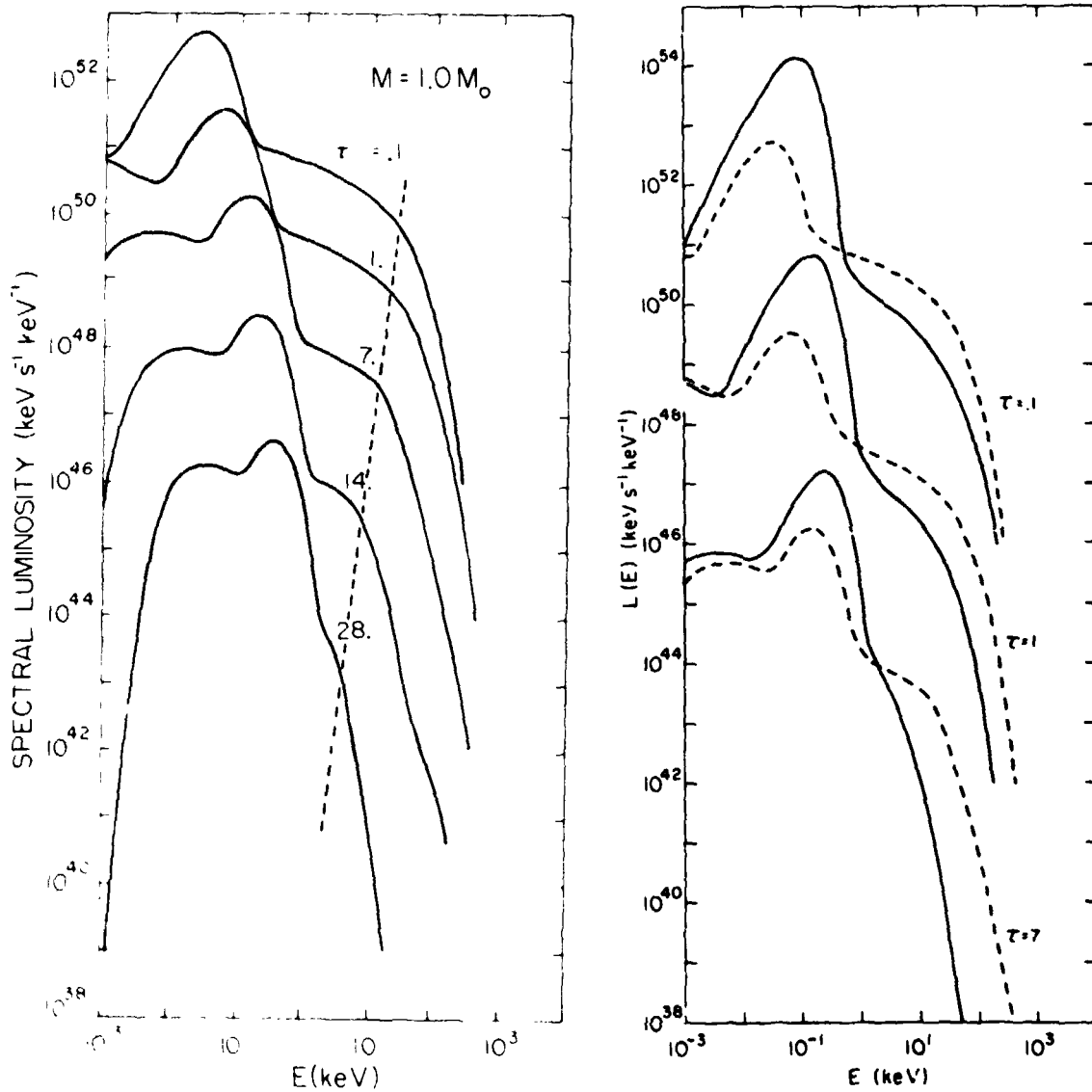


Fig. 20--X and UV spectra produced by accretion onto a  $1 M_{\odot}$  star for six different accretion rates (from Kylafis and Lamb 1982a). The dashed line shows the changing cutoff due to Compton degradation.

Fig. 21--Comparison of X and UV spectra produced by accretion onto a  $1 M_{\odot}$  star with nuclear burning at the accretion rate (solid curves) and without nuclear burning (dashed curves) (from Weast et al. 1982).

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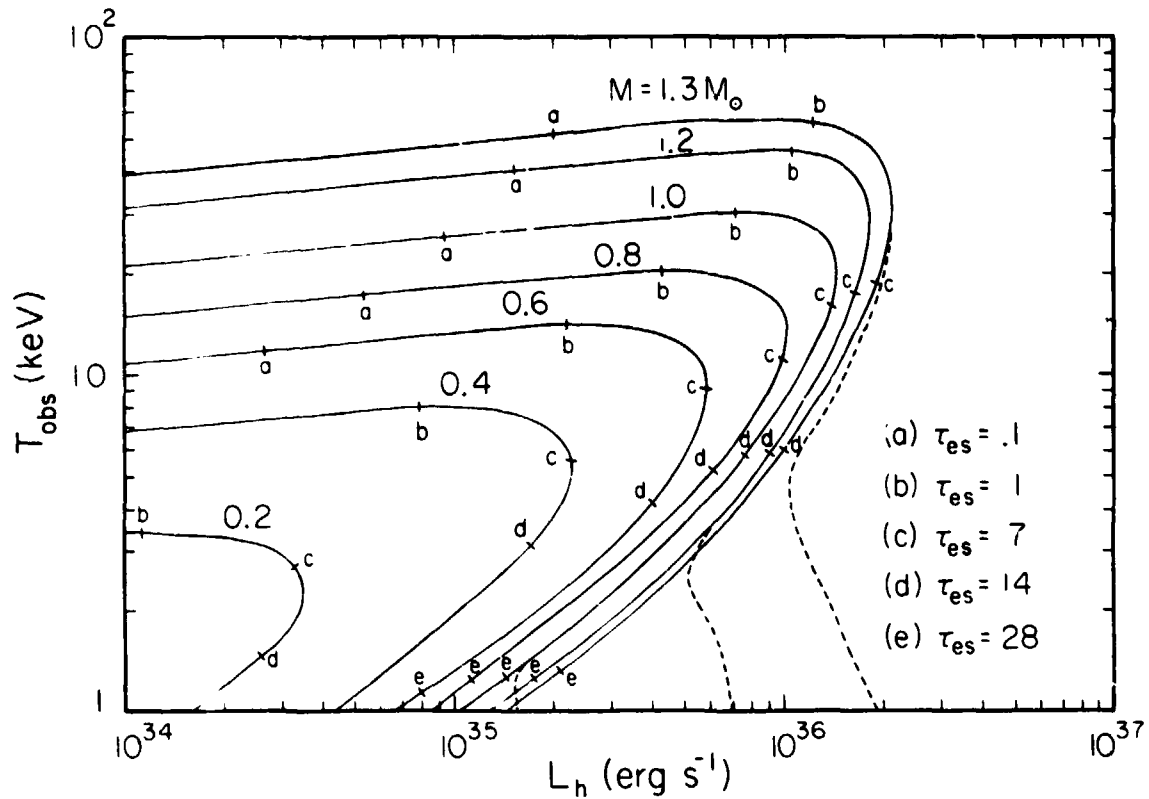


Fig. 22--Correlation between  $T_{\text{obs}}$  and  $L_h$  for stars with masses 0.2 - 1.2  $M_{\odot}$  (from Kylafis and Lamb 1982a). The dashed lines give the same correlation when the contribution of the blackbody component is included in  $L_h$ .

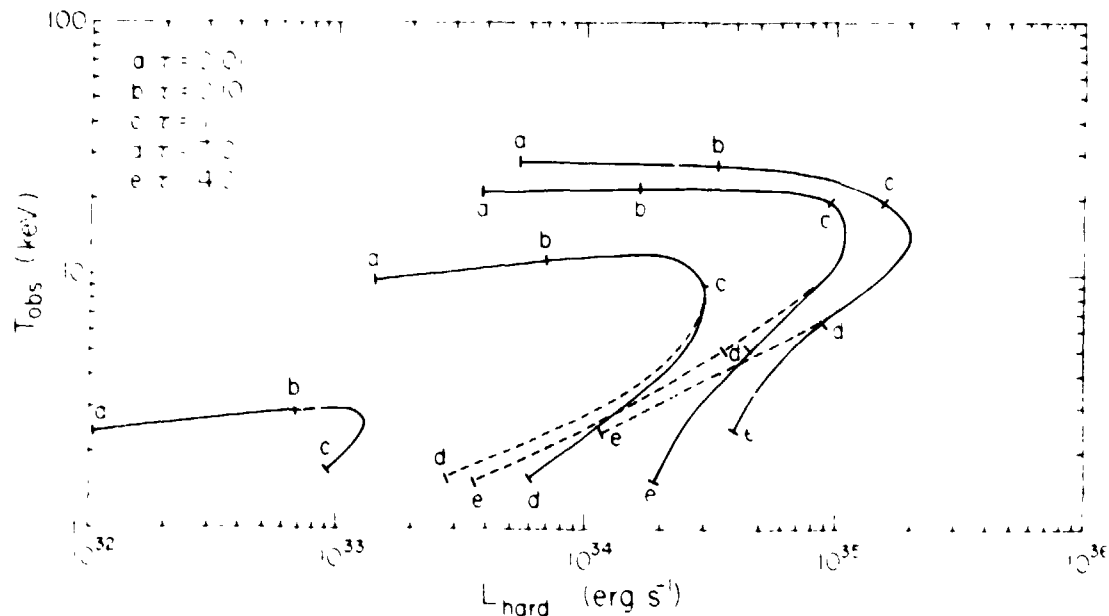


Fig. 23--Correlation between  $T_{\text{obs}}$  and  $L_h$  for stars with masses 0.2 - 1.2  $M_{\odot}$  (from Weast et al. 1982). The dashed lines give the same correlation when the contribution of the blackbody component is omitted.

an increase in  $T_{\text{obs}}$  and  $L_{\text{h}}$  therefore corresponds to a decrease in the accretion rate:  $t_{\text{obs}}$  and  $L_{\text{h}}$  increase since the smaller accretion rate lessens Compton degradation of the hard X-ray spectrum.

Figure 22 illustrates the dramatic variation in the spectral temperature at high accretion rates and the pronounced correlation between X-ray spectral temperature and luminosity.

#### d) Effects of Nuclear Burning

The energy liberated by nuclear burning of matter accreting onto degenerate dwarfs can be more than an order of magnitude greater than that available from the release of gravitational energy. If burning occurs quiescently, the resulting energy is transported to the stellar surface and produces an intense blackbody soft X-ray flux. Steady nuclear burning has therefore recently received a great deal of attention as a possible explanation of the intense blackbody soft X-ray components inferred in the AM Her stars (Raymond et al. 1979, Patterson et al. 1982) and in other cataclysmic variables, such as SS Cyg and U Gem, during outburst (Fabbiano et al. 1981).

##### i) Conditions for steady nuclear burning

Unfortunately, the conditions under which steady nuclear burning can occur are poorly understood. Detailed spherically symmetric calculations by Paczynski and Zytokow (1978), Sion, Acierno, and Turnshek (1978), and Sion, Acierno, and Tomczyk (1979) show that if the degenerate dwarf is initially cold and the accretion rate is not too high, the accreting matter becomes highly degenerate before it ignites. Electron conduction then rapidly transports energy away into the core, and it must be heated before ignition can occur. If the degenerate dwarf is hot, or if the accretion rate is high, the hydrogen in the accreting matter soon ignites due to compressional heating. In either case, eventually a violent nuclear outburst ensues. Such outbursts are believed to account for  $\approx$  ae (cf. Starrfield, Sparks, and Truran 1974).

The outbursts are separated by quiescent periods, in which nuclear burning occurs steadily at only a small fraction of the accretion rate. The quiescent periods are shorter for higher accretion rates and can last from  $\approx$  20 years or less (Sion et al. 1979) to  $> 10^7$  years (Paczynski and Zytokow 1978). For a narrow range of higher accretion rates, steady nuclear burning is possible at the rate of accretion (e. g.  $1.0 - 2.7 \times 10^{-7} M_{\odot} \text{yr}^{-1}$  for a  $0.8 M_{\odot}$  star; Paczynski and Zytokow 1978). Still higher accretion rates lead to envelope expansion and the formation of a red giant with a degenerate core.

Depletion of CNO nuclei in the accreting matter and the burning region by diffusion can lead to burning via the p-p chain rather than via the more temperature sensitive CNO-cycle (Starrfield, Truran, and Sparks 1981), and stabilize the burning at higher accretion rates. However, theoretical investigations show that such rapid depletion is unlikely (Fujimoto and Truran 1981; Papaloizou, Pringle, and MacDonald 1982).

Effects due to non-spherical geometries also warrant investigation. For example, in the AM Her and DQ Her stars a strong magnetic field channels the accreting matter onto the magnetic poles. If the matter is confined and burns over only a small fraction of the stellar surface, the burning might be stabilized by the rapid transport of energy horizontally.

##### ii) Effects on $\lambda$ -ra, emission

The effects of nuclear burning on X-ray emission by nonmagnetic degenerate dwarfs have been investigated in detail by Imamura et al. (1979, 1982) and Weast et al. (1979, 1982). The accreting matter does not burn in the hot X-ray emission region, but may do so deeper in the envelope of the star. The energy thus liberated is transported to the stellar surface and enhances the blackbody flux in soft X-rays. This flux of soft X-ray photons cools the X-ray emission region by inverse Compton scattering. As a result, the hard X-ray luminosity is often an order of magnitude less than it would be in the absence of nuclear burning, the hard X-ray spectrum is softer, and the soft X-ray luminosity can be 100 times the hard X-ray luminosity. Figure 21 compares the X-ray spectra of a  $1 M_{\odot}$  star in which nuclear burning occurs at the accretion rate to the spectra in the absence of burning. The three spectra shown span the entire range of accretion rates. Figure 23 shows the correlation between  $T_{\text{obs}}$  and  $L_{\text{h}}$  when nuclear burning occurs at the accretion rate for stars of mass  $0.2 - 1.2 M_{\odot}$ . These curves should be compared with those in Figure 22, which assumes no nuclear burning.

The effects of nuclear burning on X-ray emission by magnetic degenerate dwarfs are not expected to be as dramatic. As long as cooling by cyclotron emission dominates cooling by inverse Compton scattering of the blackbody photons, the cyclotron UV and bremsstrahlung hard X-ray luminosities will be little changed. The spectral temperatures of these components will also be little affected. The blackbody soft X-ray luminosity will, however, be much larger.

#### IV. LINE SPECTRA

##### a) Ionization Structure

The circumstellar ionization structure of degenerate dwarf X-ray sources has been calculated analytically by Hayakawa (1973) and more recently by Kylafis and Lamb (1982b). These calculations assume spherical symmetry, and assume that the optical depth to absorption is small. The degenerate dwarf X-ray sources detected so far have low luminosities and low accretion rates. Therefore, the analytical calculations are valid, provided that the accretion flow is approximately radial.

The calculations by Kylafis and Lamb (1982b) show that the blackbody soft X-ray flux ionizes H, He, and C out to distances large compared with a typical binary separation. Furthermore, for high mass stars and low accretion rates, the bremsstrahlung hard X-ray flux ionizes heavy elements out to considerable distances. These features are illustrated in Figures 24 and 25, which show  $l_Z$ , the radius at which the element with charge  $Z$  is half ionized and half neutral, as a function of mass accretion rate for a  $1.2 M_{\odot}$  star. Figure 24 shows the effect of the blackbody soft X-ray flux, while Figure 25 shows the effect of the bremsstrahlung hard X-ray flux. In both figures, the solid lines correspond to no nuclear burning and the dashed lines to nuclear burning at the accretion rate.

The absorption optical depth  $\tau^*_Z$  at the ionization edges of heavy elements remains small until the accretion rate exceeds about  $3 \times 10^{-3} M_{\odot}$  but thereafter increases rapidly, as shown in Figure 26. Compton scattering and the resulting degradation of the hard X-ray spectrum occurs primarily close to the star, while most of the absorption occurs relatively far from the star, as illustrated in Figure 27. Thus the amount of Compton degradation is less sensitive, and the amount of absorption more sensitive, to the distribution of accreting matter.

##### b) Absorption Features

Figure 28 shows the emergent hard X-ray spectrum from a  $1.2 M_{\odot}$  star for four different accretion rates as calculated analytically by Kylafis and Lamb (1982b), taking absorption into account. Ross and Fabian (1981) have carried out detailed numerical calculations of the emergent spectrum from a  $1.0 M_{\odot}$  star for three different accretion rates. The latter calculations treat the atomic physics carefully and are valid even for large absorption optical depths. The results are shown in Figures 29-31. Note both the absorption K-edges due to O VIII (0.87 keV), Si XIV (2.7 keV), and Fe XXI-XXVI (8.2 - 9.3 keV), and the emission lines, broadened by Compton scattering, due to the  $K_{\alpha}$  lines of O VIII (0.65 keV), Si XIV (2.0 keV), and Fe XXV (6.7 keV).

### c) Emission Lines

The temperatures in the X-ray emission regions of degenerate dwarf X-ray sources are high enough ( $> 10$  keV) to produce thermal emission lines, including those of Fe at  $\sim 7$  keV, with significant equivalent widths. Emission lines can also be produced by fluorescence in the accreting matter above the X-ray emission region, as seen in Figures 29-31. Fluorescent emission lines may also be produced by X-rays striking the stellar surface surrounding the emission region, the disk, and even the companion star.

The emission lines may be broadened by 1) thermal Doppler broadening, 2) Compton scattering, and 3) Doppler broadening due to bulk streaming velocities. Thermal Doppler broadening produces a relative line width,

$$\Delta v/v \sim (2kT/m_e c^2)^{1/2}. \quad (7)$$

The resulting width is  $\sim 0.5$  keV for the  $\sim 7$  keV Fe lines if they are formed in an X-ray emission region with temperature  $T_e \sim 10$  keV. Compton scattering produces a relative line width

$$\Delta v/v \sim \tau^2 \frac{hv}{m_e c^2} \sim 0.1 \tau^2 (hv / 7 \text{ keV}). \quad (8)$$

Thus the  $\sim 7$  keV Fe emission lines will be relatively broad even if the electron scattering optical depth through accreting matter is only modest. Doppler broadening due to bulk motion produces a relative line width

$$\Delta v/v \sim v/c \sim 2 \times 10^{-2} \frac{v}{v_{ff}(R)}, \quad (9)$$

where in the last step we have scaled from the freefall velocity at the surface of a  $1 M_{\odot}$  star. Doppler broadening due to bulk motion is therefore generally less than thermal Doppler broadening and Compton scattering. These results imply that the X-ray emission lines produced by degenerate dwarfs are relatively broad. However, as noted above, emission lines can be produced by recombination and fluorescence in accreting matter far from the star. In this case, the temperatures may be low, and the electron scattering optical depth small. If so, narrow emission lines can be produced.

## V. ISSUES

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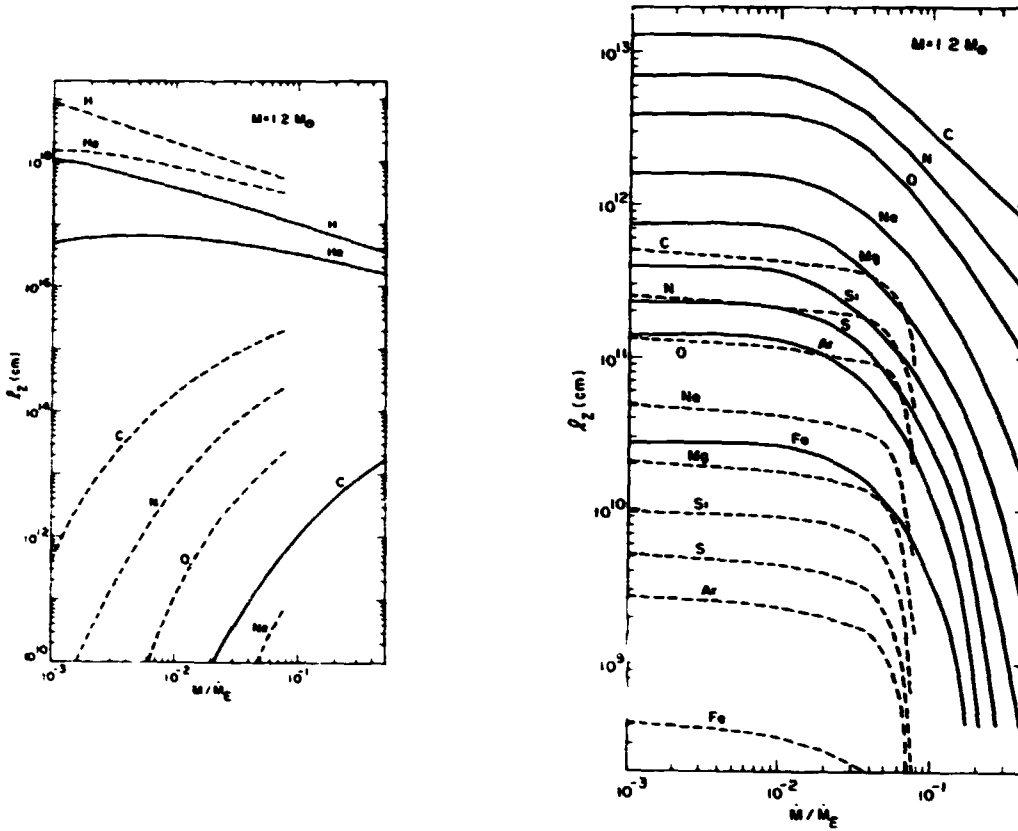


Fig. 24--Circumstellar ionization structure as a function of accretion rate produced by the blackbody soft X-ray flux of a  $1.2 M_\odot$  star (from Kylafis and Lamb 1982b). The quantity  $r_z$ , the radius at which the element with charge  $Z$  is half ionized, is shown assuming no nuclear burning (solid lines) and nuclear burning at the accretion rate (dashed lines).

Fig. 25--Circumstellar ionization structure as a function of accretion rate produced by the bremsstrahlung hard X-ray flux of a  $1.2 M_\odot$  star (from Kylafis and Lamb 1982b). The curves have the same meaning as in Fig. 24.

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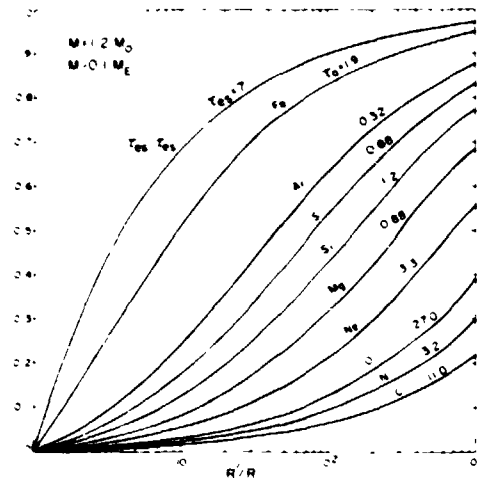
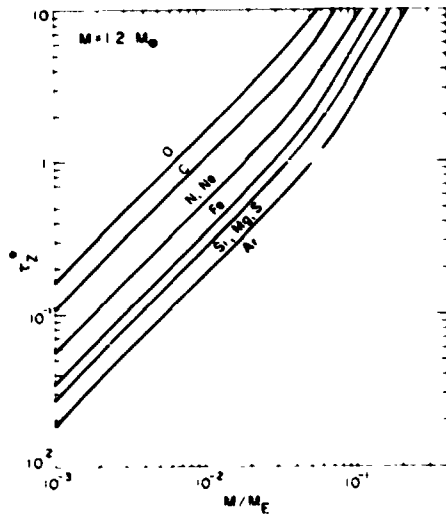


Fig. 26--Optical depth  $\tau_z^0$  at the absorption edge of a given element as a function of accretion rate for a  $1.2 M_\odot$  star without nuclear burning (from Kylafis and Lamb 1982b).

Fig. 27--Fractional electron scattering and absorption optical depths reached at a given radius for a  $1 M_\odot$  star accreting at a rate  $0.1 \dot{M}_E$  (from Kylafis and Lamb 1982b). Note that the electron scattering optical depth increases rapidly near the star, while the absorption optical depths remain small until larger radii.

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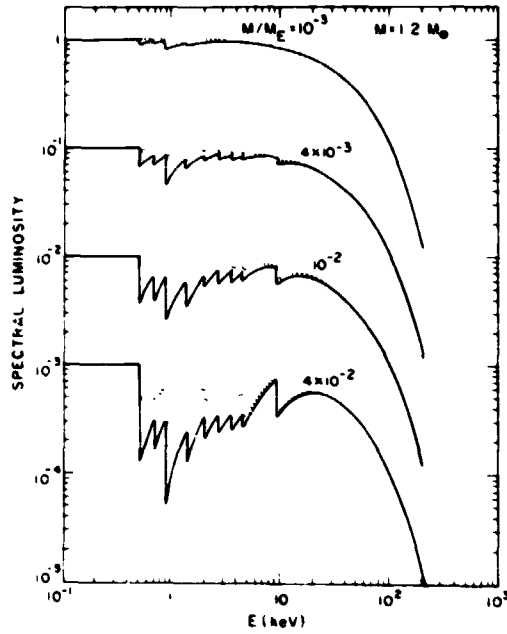


Fig. 28--Bremsstrahlung hard X-ray spectra produced by accretion onto a  $1.2 M_{\odot}$  star at 4 different accretion rates, taking into account the effects of absorption analytically (from Kylafis and Lamb 1982b).

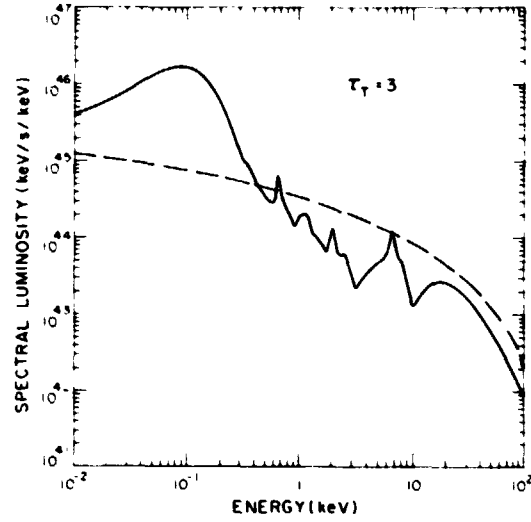


Fig. 29--X and UV spectrum produced by a  $1 M_{\odot}$  star at an accretion rate  $0.045 \dot{M}_{\odot}$  ( $\tau = 3$ ) taking into account the effects of photoabsorption through detailed numerical calculations (from Ross and Fabian 1980).

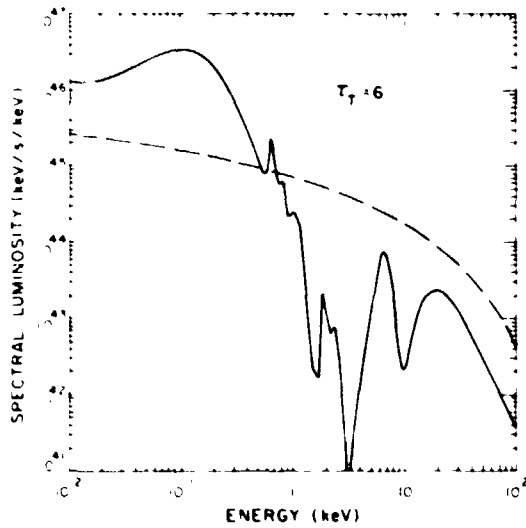


Fig. 30--Same as Fig. 29 for an accretion rate  $0.090 \dot{M}_{\odot}$  ( $\tau = 6$ ) (from Ross and Fabian 1980).

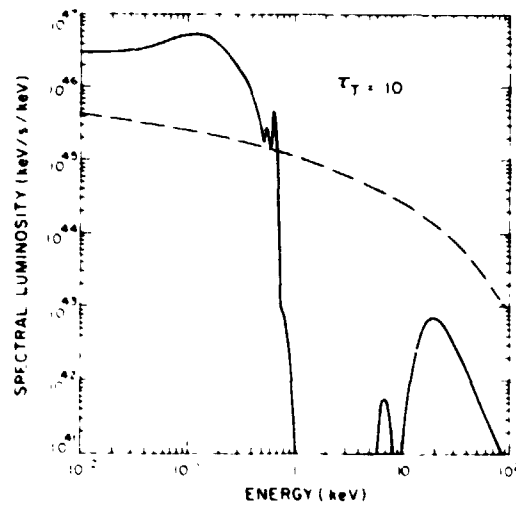


Fig. 31--Same as Fig. 29 for an accretion rate  $0.15 \dot{M}_{\odot}$  ( $\tau = 10$ ) (from Ross and Fabian 1980).



Among the important unresolved issues concerning degenerate dwarf X-ray sources are the following.

a) Magnetic Fields

Do only a few degenerate dwarfs have magnetic fields, and are the AM Her and DQ Her stars the only cataclysmic variables with magnetic fields? Or are magnetic fields endemic in degenerate dwarfs, and therefore in cataclysmic variables? If so, what are the field strengths? Are they large enough to affect the disk and the accretion flow near the stellar surface?

b) Origin of Hard X Rays

What is the origin of the hard X-rays emitted by cataclysmic variables? Are they produced by optically thin emission in the boundary layer between the disk and the star? If so, are the required high temperatures achieved by strong shocks, turbulence, or some other mechanism? Alternatively, are magnetic fields present in these sources sufficient to disrupt the disk near the star, producing quasi-radial inflow and a strong shock?

c) Origin of Soft X Rays

What is the origin of the intense blackbody soft X-ray emission inferred in the AM Her stars? How can it be so large compared to the optical and hard X-ray emission? Is its origin the same as the soft X-ray emission seen in SS Cyg and U Gem at outburst, or is it different?

d) Nuclear Burning

Under what conditions is steady nuclear burning possible? If it is generally not possible, as many calculations suggest, why are outbursts not more evident? Can steady burning occur more easily in non-spherical situations, as in the AM Her stars? If so, could it account for the intense blackbody soft X-ray emission in these stars? Could it account for the blackbody soft X-ray emission seen in cataclysmic variables like SS Cyg and U Gem?

e) Long Period Pulsing Sources

What is the nature of the long period pulsing sources? Are they actually degenerate dwarfs, or are they neutron stars? Why are they rotating so slowly; that is, why have they not been spun up more by their accretion torque? Does their rotation rate increase and then decrease with time, like the previously known pulsing neutron star X-ray sources with long periods?

f) Cyclotron-Dominated Sources

Although the AM Her stars are strongly magnetic, bremsstrahlung, not cyclotron emission, is the dominant cooling mechanism in the X-ray emission region (because the

accretion flow is channeled onto such a small fraction  $f \sim 10^{-3}$  of the stellar surface that the density in the emission region is very high). Where are the sources in which cyclotron cooling dominates? Will they be found by a UV or extreme UV survey?

#### g) High Luminosity Sources

To date no high luminosity ( $L \sim 10^{36} - 10^{38}$  ergs  $s^{-1}$ ) X-ray source has been unequivocally identified with a degenerate dwarf, and the future does not look promising. Are there no high luminosity degenerate dwarf X-ray sources? If not, why not?

From these brief remarks, it should be evident that we have only begun to explore the nature of degenerate X-ray sources. We must rely on future X-ray astronomy missions to provide the data needed to understand them. In the following section, we outline the kind of instruments that would best advance our knowledge.

## VI. OBSERVATIONAL NEEDS

### a) High Throughput

Because degenerate dwarf X-ray sources are faint, the most important attribute of any instrument designed to study them effectively is high throughput. This requirement implies that the instrument should have a large area and a low background rate. A low background rate implies, almost inevitably, the necessity of a focusing instrument. A focusing instrument is also desirable from the standpoint of source confusion, which could be a problem at lower energies.

### b) Pointing Capability and Flexibility

A central characteristic of degenerate dwarf X-ray sources, like other compact X-ray sources, is their time variability. They show quasi-periodicities on time scales ranging from several seconds to a thousand seconds, pulsing due to rotation periods ranging from 33 to as much as 4000 seconds, flaring behavior, variability correlated with the binary period, and, of course, the outbursts from which the cataclysmic variables derive their name. Pointing capability is essential for any instrument which is to study them successfully, and flexibility (so that one can move onto the source when it goes into outburst, for example) is desirable.

### c) Hard and Soft X-Ray Spectral Sensitivity

As we have seen, many, and perhaps all, degenerate dwarf X-ray sources have two distinct components, one with  $T_{br} > 10$  keV and another with  $T_{bb} < 100$  eV. As a result, a soft X-ray capability is important and should extend down to at least 0.1 - 0.25 keV. Conversely, a number of sources have hard X-ray spectra with temperatures as high as 30 keV (e.g., AM Her). Therefore a hard X-ray capability extending up to at least  $\sim 35$

keV, and possibly beyond, would be highly desirable.

#### d) Broad-Band Spectral Measurements

Correlations between the shapes and intensities of both the hard and soft X-ray components have been seen, for example, as a source declines from outburst. Although many of these correlations are not yet understood, theoretical work indicates that they are potentially a powerful source of information about the physical conditions in the X-ray emission region, such as temperature, density, magnetic field strength, and mass accretion rate. Therefore broad band spectral measurements have been, and will continue to be, very useful.

#### e) Moderate Spectral Resolution

Further studies of the iron emission lines in these sources may yield information about the X-ray emission region, the accretion flow, and the geometry of the binary system. Other emission lines, if present, could provide similar information. All of them may be broadened, either thermally or by Compton scattering. Studies of such emission lines require instruments with moderate ( $\Delta\lambda/\lambda \approx 10 - 50$ ) spectral resolution.

Table 5 summarizes the observational needs we have discussed above.

TABLE 5  
FUTURE OBSERVATIONAL NEEDS

SOURCE FEATURE	INSTRUMENTAL REQUIREMENT
Faint	<ul style="list-style-type: none"> <li>• Large area</li> <li>• Low background</li> <li>• Small field of view</li> </ul>
Variable	<ul style="list-style-type: none"> <li>• Pointing essential</li> <li>• Flexibility desirable</li> </ul>
Distinct soft X-ray and hard X-ray components	<ul style="list-style-type: none"> <li>• Soft X-ray capability important</li> <li>• Hard X-ray capability, extending up to ~40 keV desirable</li> </ul>
Continuum spectral shape correlated with luminosity	<ul style="list-style-type: none"> <li>• Low spectral resolution</li> </ul>
Iron emission line seen, broad absorption lines expected	<ul style="list-style-type: none"> <li>• Moderate spectral resolution</li> </ul>

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