X-RAY EMISSION FROM CATACLYSMIC VARIABLES

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ABSTRACT

We review X-ray observations of cataclysmic variables and theoretical work on X-ray emission from them, emphasizing recent developments.

1. INTRODUCTION

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 galactic X-ray sources, and this method promises to become increasingly important in the future. More

M. Livio and G. Shaviv (eds.), Cataclysmic Variables and Related Objects, 299–322.

than 53 of these accreting degenerate dwarf X-ray sources are now known (Cordova and Mason 1982).

The study of degenerate dwarf X-ray sources can yield many returns. For example, these sources afford a laboratory in which to explore the physics of hot, dense plasmas, often 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. 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 provide clues to the geometry of the disk and the binary system, and time delay curves yield the parameters of the binary 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 1981). 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 emission produced by accreting degenerate dwarfs. 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 (1979a) and Kylafis et al. (1980) contain earlier reviews of theoretical work.

2. OBSERVATIONAL PROPERTIES

2.1. 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 1982) but $\sim 10^3$ times brighter than ordinary stars (Linsky 1981).

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 pc)$^{-3}$ pc^{-3}. Assuming a uniform distribution of sources throughout the galaxy and a galactic volume $V \sim 1 \times 10^{12}$ pc^3, the above space density implies that the total number of sources in the galaxy is $N \sim 3 \times 10^5$ (d/ 100 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 ($L \sim 10^{36}$-10^{38} ergs s^{-1}) neutron star sources of ~ 100.

2.2. 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 1979a, Patterson and Price 1981). The remaining systems do not manifest a magnetic field. However, some of these sources will no doubt be reclassified as AM Her or DQ Her stars on the basis of future observations. Below we discuss the X-ray spectra and temporal behavior of the AM Her stars, the DQ Her stars, and the remaining cataclysmic variables in turn.

2.2.1. AM Her stars. Eleven AM Her stars are now known (EF Eri, E1114+182, VV Pup, E1405-451, E1013-447, H0139-68, PG1550+191, CW1103+254, AN UMa, AM Her, and E2003+225, in order of increasing period). These stars show strong (> 10%) circular and linear polarization of their infrared and visible light, and are believed to be accreting magnetic degenerate dwarfs (Chanmugam 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_{bb} < 100 ev and a bremsstrahlung component with T_{br} > 10 kev. The measured soft X-ray flux is greater than the hard X-ray flux, 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 ~ 7 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, due to interaction of the magnetic field of the degenerate dwarf with the companion star (Joss, Katz, and Rappaport 1979; Lamb et al. 1983). Figure 3 shows the resulting 3.1 hour "pulse profile" of AM Her in soft X-rays (Tuohy et al. 1978).

2.2.2. DQ Her stars. We have classified nine systems as DQ Her stars (AE Aqr, V533 Her, DQ Her, V1223 Sqr, H2252-035, 3A0729+103, H2215-086, EX Hya, and TV Col in order of increasing period). DQ Her, the prototype of this class, has long been 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 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. 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 the theorists), pulsed X rays have been detected from a third member of the class, AE Aqr, at the 33 second optical period (Patterson et al. 1980).

Several faint galactic X-ray sources have now been identified with systems that are optically similar to cataclysmic variables. They exhibit large amplitude optical and X-ray pulsations with periods $\gtrsim$ 1000 seconds that are believed to represent the rotation period of the accreting magnetic star The source H2252-035 was the first of these systems to be optically identified (Griffiths et al. 1980) and have its character recognized (Patterson and Price 1981; Warner, O'Donoghue, and Fairall 1981; White and Marshall 1981, Hassall et al. 1981). Figure 4 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 reprossessing of the 805 second X-ray pulse. Figures 5 and 6 show the pulse profile and the spectrum of the hard X-rays (White and Marshall 1981). The hard X-ray spectrum

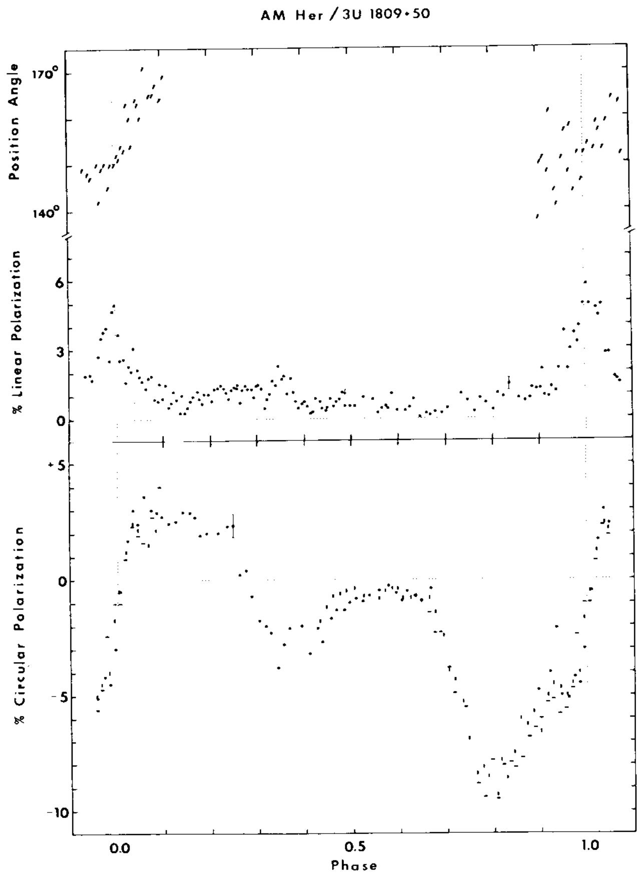

Fig. 1--Circular and linear polarization of the optical light from AM Her as a function of the phase of the 3.1 hour rotational period of the degenerate dwarf (from Tapia 1977a).

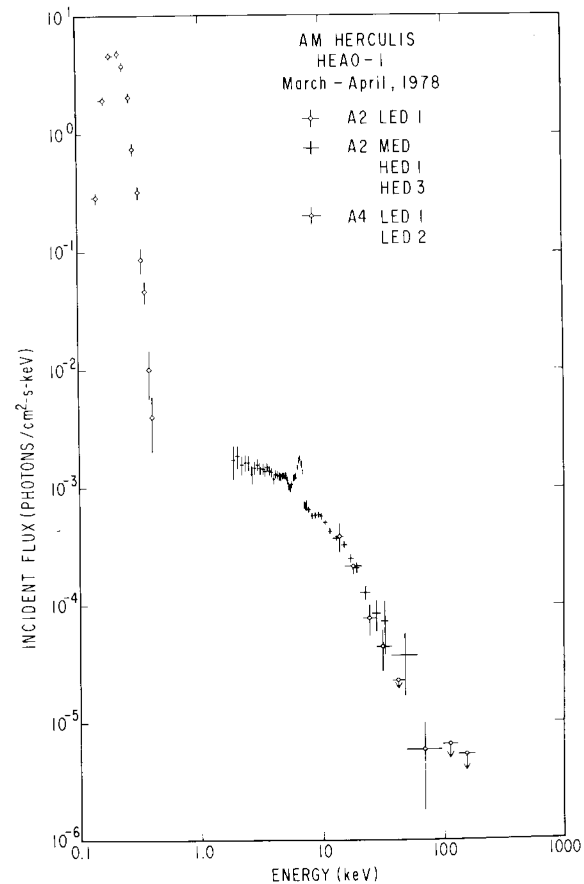

Fig. 2--Hard and soft X-ray spectrum of AM Her (from Rothschild et al. 1981). The two distinct components with T ≃ 30 keV and T < 40 eV are clearly visible. Note also the iron emission line at ≃ 7 keV.

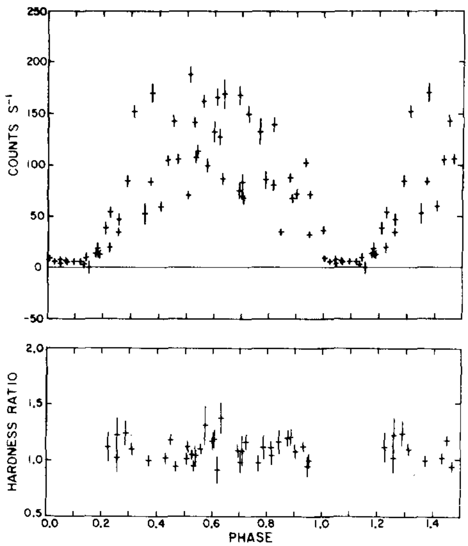

Figure 1

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).

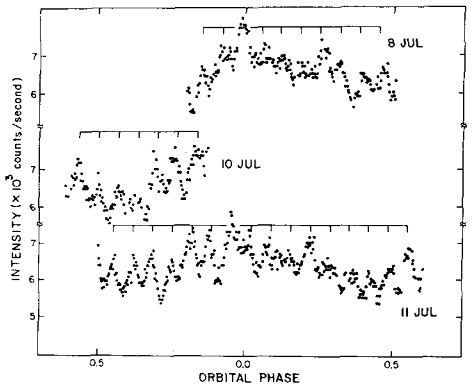

Fig. 4--Fast photometry of the optical light from H2252-035 (from Patterson and Price 1981). The 859 second pulsations, corresponding to reprocessed light from a point stationary in the rotating frame of the binary system, are clearly visible.

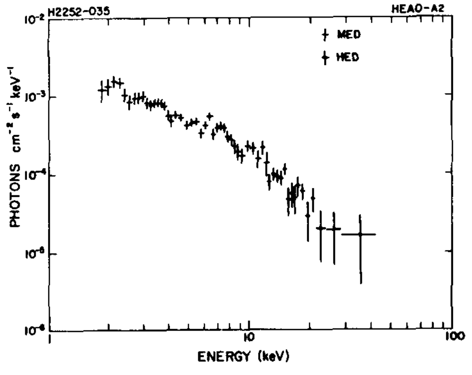

Fig. 5--Hard X-ray spectrum of H2252-035 (from White and Marshall 1981). The iron emission line at ≃ 7 keV is again clearly visible.

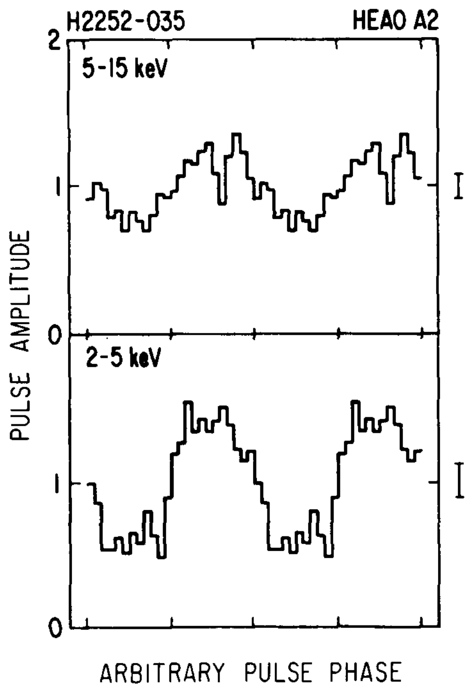

Fig. 6--Hard X-ray pulse profile of H2252-035 through the 805 second rotation period of the degenerate dwarf (from White and Marshall 1981).

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exhibits iron line emission at ~ 7 keV. Another star, now known as TV Col, had already been optically identified (Charles et al. 1979). It was recognized as possibly a similar system after photometry (Motch 1981) and spectroscopy (Hutchings et al. 1981) showed that its orbital period of 5^h11^m differed from the principal photometric period of 5^h29^m. Interestingly, a 67 minute period has also recently been found in the optical light curve of the well-studied cataclysmic variable X-ray source EX Hya (Vogt, Krzeminski, and Sterken 1980; Gilliland 1982). The period is present in soft X-rays but not in hard (Swank and White 1981). The coherence of the period over many years suggests that it is also due to rotation of a magnetic star.

2.2.3. Other cataclysmic variables. Forty-four other cataclysmic variable X-ray sources are currently known (Cordova and Mason 1982). Among these are the prototypical dwarf novae, SS Cyg and U Gem, which undergo outbursts every ~ 100 days. During quiescence, both exhibit a hard X-ray spectrum with T_{br} ~ 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). The lack of a pronounced low or high energy cutoff in the spectrum indicates that this behavior can not be due to a larger absorption or scattering optical depth during the outburst (Kylafis and Lamb 1982a), as had been earlier proposed (Ricketts, King, and Raine 1979). The origin of this behavior is therefore not yet understood.

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 them exhibit small amplitude quasi-periodic or coherent optical pulsations, usually during the onset of an outburst (Robinson 1976). Of special interest are the ~ 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).

2.3. X-Ray Emitting Cataclysmic Variables in Globular Clusters

Very recently, Hertz and Grindlay (1983) have detected faint X-ray sources in a number of globular clusters, as shown in Figure 7. In fact, several of the clusters contain multiple sources. They argue convincingly that these detections represent the "tip of the iceberg" of a large population ($\sim 10^4$ per cluster) of cataclysmic variable X-ray sources. Such a population offers exciting new prospects for studying the formation and evolution of cataclysmic variables as well as the properties of X-ray emission from degenerate dwarfs.

3. THEORY

3.1. Qualitative Picture of X-Ray Emission

The basic idea of X-ray emission from accreting degenerate dwarfs is that matter falling into the deep gravitational potential well of the star supplies a large amount of energy. The resulting rate of energy production, or luminosity, is

$$L_{acc} = \frac{GM\dot{M}}{R} = 8 \times 10^{32} \, (M/M_{\odot}) \, (R/10^9 \, cm)^{-1} \, (\dot{M}/10^{-10} \, M_{\odot} \, yr^{-1}) \, ergs \, s^{-1}, \qquad (1)$$

where M and R are the mass and radius of the star, and $\dot{M}$ is the mass accretion rate. The maximum possible shock temperature of the matter, and hence of the resulting radiation, is

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

where T_{ff} is the freefall temperature. On the other hand, if the X-ray emission region radiates as a blackbody, the temperature of the resulting radiation is

$$T_{bb} = (L/4\pi R^2 \sigma)^{1/4} = 3 \times 10^4 \, (M/M_{\odot})^{1/4} \, (R/10^9 \, cm)^{-3/4} \, (\dot{M}/10^{-10} \, M_{\odot} \, yr^{-1})^{1/4} \, K. \qquad (3)$$

Therefore, whether an accreting degenerate dwarf is an X-ray source and, if it is, whether it emits primarily soft or hard X rays depends critically on the manner in which the kinetic energy of infall is converted into radiation.

3.1.1. Disk accretion. Many cataclysmic variables show clear optical and UV evidence of accretion disks. If the disk extends down to the stellar surface, viscous dissipation in it releases approximately half of the available gravitational energy. This energy appears as blackbody radiation from the disk surfaces and produces a characteristic power law spectrum $\propto \nu^{1/3}$ in the optical and UV (cf. Shakura and Sunyaev 1973). The other half of the available gravitational energy is 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 $L_{bdry} \sim L_{acc}/2$. If the boundary layer is optically thick, the temperature of the emitted radiation is given by eq.(3), but with an appropriately smaller area. At moderate or high accretion rates, such a boundary layer is capable of producing soft X-rays by blackbody emission (Pringle 1977).

More recently, Pringle and Savonije (1979) proposed that the boundary layer might be optically thin and produce hard X-ray emission by bremsstrahlung if shocks occurred in it, thereby accounting for the hard X-rays observed from many cataclysmic variables. Since the maximum possible shock temperature is that given by eq.(2), the shocks must be strong. However, it is not obvious, as in the case of radial accretion (see below), that shocks play a dominant role in the dissipation of kinetic energy. The disk can, in principle, join onto the star without any shocks occurring. Supersonic flow is characteristic of the disk as a whole, yet in spite of that the transport of angular momentum and dissipation of energy in the disk are generally assumed to be due to subsonic turbulence rather than shocks. Of course the rate of shearing in the boundary layer is much stronger than that in the disk. However, even if shocks were to form, the geometry of the flow would tend to favor production of a large number of weak, oblique shocks. To achieve the required strong shocks, Pringle and Savonije (1979) postulate 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 (1981b), however, argues that turbulent viscosity will be a more efficient mechanism than shocks for dissipating energy in the boundary layer and suggests that this can account for the observed high temperatures without resorting to complicated flows. Unfortunately, the temperature of the boundary layer in this picture is extremely sensitive to the magnitude of the assumed turbulent viscosity, about which we know little. The temperature might approach the maximum value given by eq.(3) but could be much smaller. The situation is further clouded by the fact that, even if the Reynolds number is large, it is far from clear that the flow is turbulently unstable.

Knowledge of whether the boundary layer can produce hard X-rays and, if so, how, is important for understanding cataclymsic variable X-ray sources. But the ideas proposed have not as yet been worked out in any detail. For excellent recent discussions of disks, see the review by Pringle (1981) and the paper by Tylenda (1981).

3.1.2. Radial accretion. If the degenerate dwarf has a magnetic field,

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

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 present in them. 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 such inflow.

As accreting matter flows radially toward a 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 total luminosity is given by eq.(1). The standoff distance is

$$d \equiv r_s - R \simeq 1/4\ v_{ff}(r_s)\ t_{cool}(r_s), \quad (5)$$

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. The temperature of the bremsstrahlung radiation is approximately that given by eq.(2). Roughly half of it is emitted outward and forms a hard X-ray component. Roughly half of the cyclotron flux is also 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 luminosity of the resulting blackbody radiation is $L_{bb} \simeq L_{cyc} + L_{br}$, where L_{cyc}, and L_{br} are the luminosities in the cyclotron and bremsstrahlung components. The temperature of the blackbody radiation is approximately that given by eq.(3).

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 8. 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 8, cyclotron cooling becomes more important until eventually it dominates (Masters et al. 1977). The solid line

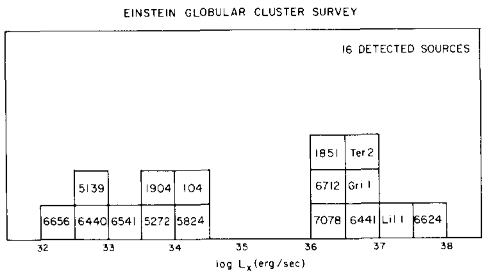

Fig. 7--Luminosity histogram of the 16 X-ray emitting globular clusters detected with Einstein (from Hertz and Grindlay 1983). Each source is identified by the NGC number or common name of the cluster. The clusters NGC 5139 and 6656 contain multiple sources, but only the source located within the core of each has been plotted for purposes of clarity.

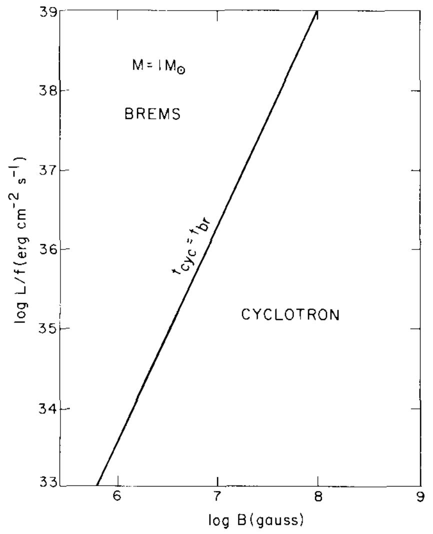

Fig. 8--Bremsstrahlung and cyclotron emission regimes in the (L/f,B)-plane for a 1 $M_\odot$ star (after Lamb and Masters 1979).

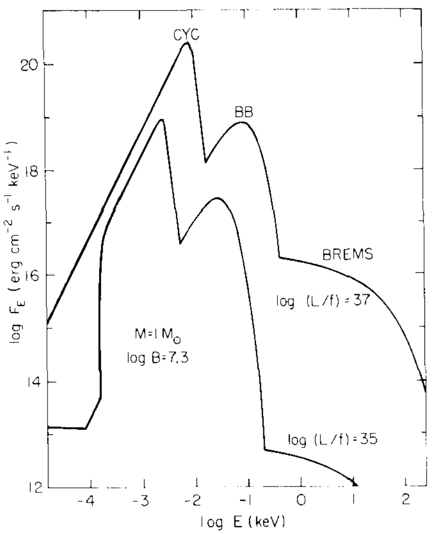

Fig. 9--X-ray and UV spectra produced by accretion at two different accretion rates onto a 1 $M_\odot$ with a magnetic field of 2 x 10^7 gauss. The spectrum with L/f = 10^{37} ergs s^{-1} is in the bremsstrahlung dominated regime, while the spectrum with L/f = 10^{35} ergs s^{-1} is in the cyclotron dominated regime (from Lamb and Masters 1979).

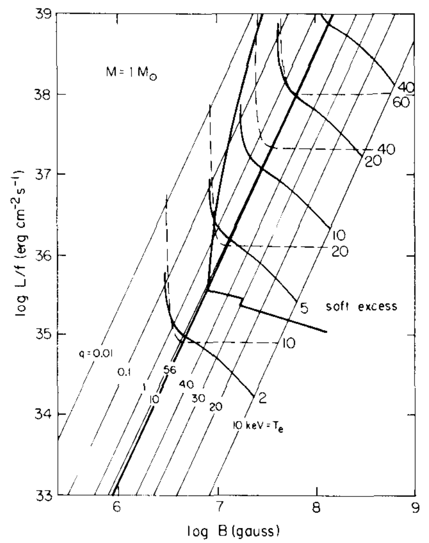

Fig. 10--Contours in the (L/f,B)-plane for a 1 $M_\odot$ star. For an explanation of the various lines, see the text.

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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

$$B = 6 \times 10^6 \, (Lf^{-1}/10^{36} \text{ ergs s}^{-1})^{2/5} \text{ gauss.} \tag{6}$$

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

3.2. 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) carried out a few calculations for the regime in which bremsstrahlung, not cyclotron emission, dominates (see Figure 7).

3.2.1. 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 9, 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 ~5 eV.

The spectra in Figure 9 illustrate 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 depend sensitively on the accretion rate. For example, the variation in accretion rate shown in Figure 9 moves the blackbody component from the UV into the soft X-ray region. Further, the luminosity of the bremsstrahlung hard X-ray component increases by nearly 4 orders of magnitude, although the total accretion luminosity increases by only 2.

3.2.2. 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, as shown in Figure 10. Bremsstrahlung and cyclotron emission dominate in the same regions as in Figure 8. The thin solid lines in the bremsstrahlung-dominated region show contours of constant $q \equiv L_{cyc}/L_{br}$, while those in the cyclotron-dominated region show contours of constant T_e, the temperature of the bremsstrahlung hard X-ray component. Contours of constant E*, the peak of the blackbody-limited cyclotron component, are shown as thick solid lines and contours of constant T_{bb}, the temperature of the blackbody component, are shown as dashed lines. To the upper right of the curve labelled "soft excess", the blackbody luminosity in soft X-rays exceeds the bremsstrahlung luminosity in hard X-rays. Figure 10 illustrates that the qualitative features of the observed X and UV spectrum determine fairly accurately the physical conditions in the emission region, including the value of the magnetic field.

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 << 1, the Eddington luminosity does not represent the stringent upper limit to the luminosity that it does in the case of nonmagnetic degenerate dwarfs. 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}, as in nonmagnetic stars (see below). Scattering and degradation affect not only the spectrum but also the pulse profile, and Imamura and Durisen (1983) have carried out a study of the resulting behavior of both.

3.3. 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 8). Thus they are relevant to the AM Her stars, such as AM Her itself, which has a magnetic field $B \sim 2 \times 10^7$ gauss (Lamb and Masters 1979; Schmidt, Stockman, and Margon 1981; Latham, Liebert, and Steiner 1981), and VV Pup, which has a magnetic field $B \sim 3 \times 10^7$ gauss (Visvanathan and Wickramasinghe 1979; Stockman, Liebert, and Bond 1979), as well as to the DQ Her stars.

3.3.1. 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 11, which shows six spectra that span the entire range of accretion rates. Figure 12 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, τ_{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 11 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.

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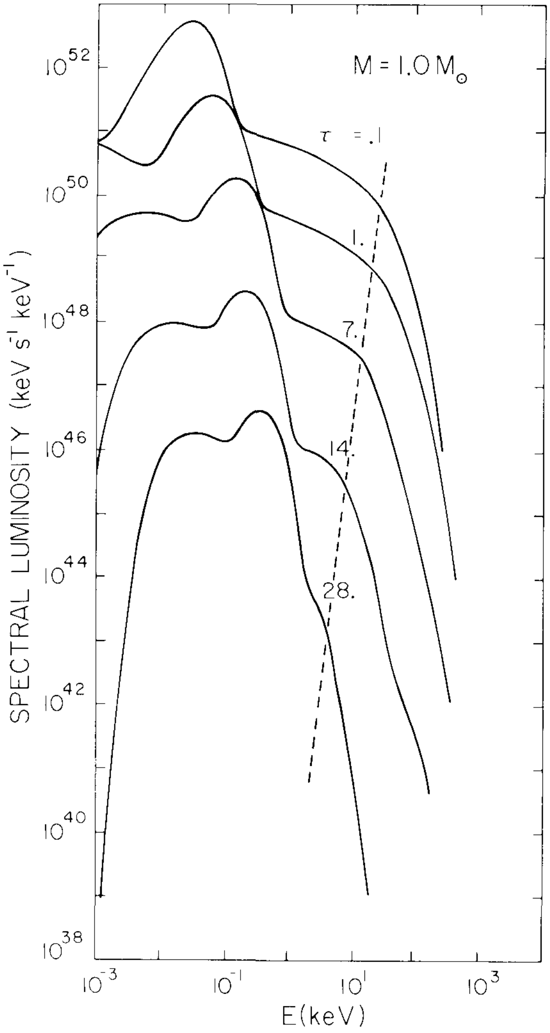

Fig. 11--X and UV spectra produced by accretion onto a 1 $M_\odot$ star for six different accretion rates (from Kylafis and Lamb 1982a). The curves are labeled by the value of the electron optical depth through the accreting matter. The dashed line shows the changing cutoff due to Compton degradation.

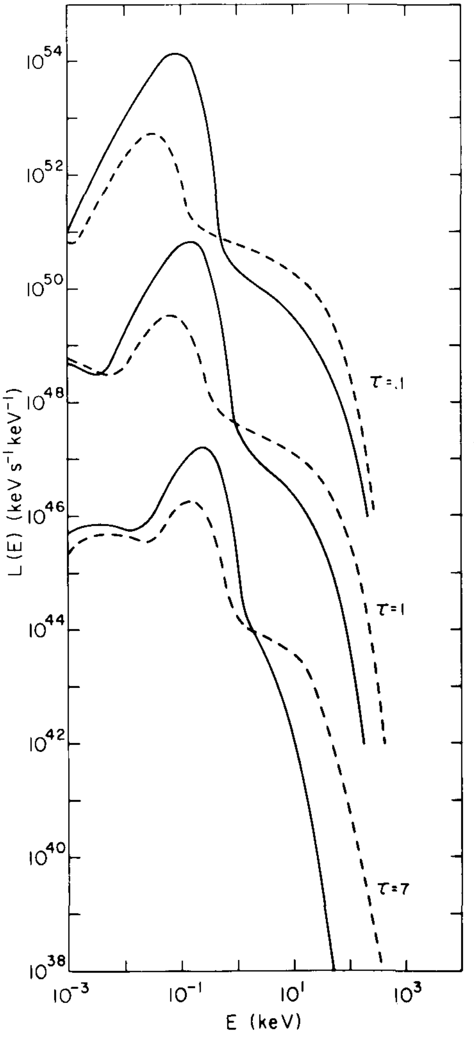

Fig. 12--Comparison of X and UV spectra produced by accretion onto a 1 $M_\odot$ star with nuclear burning at the accretion rate (solid curves) and without nuclear burning (dashed curves) (from Weast et al. 1982). The curves are again labeled by the value of the electron optical depth through the accreting matter.

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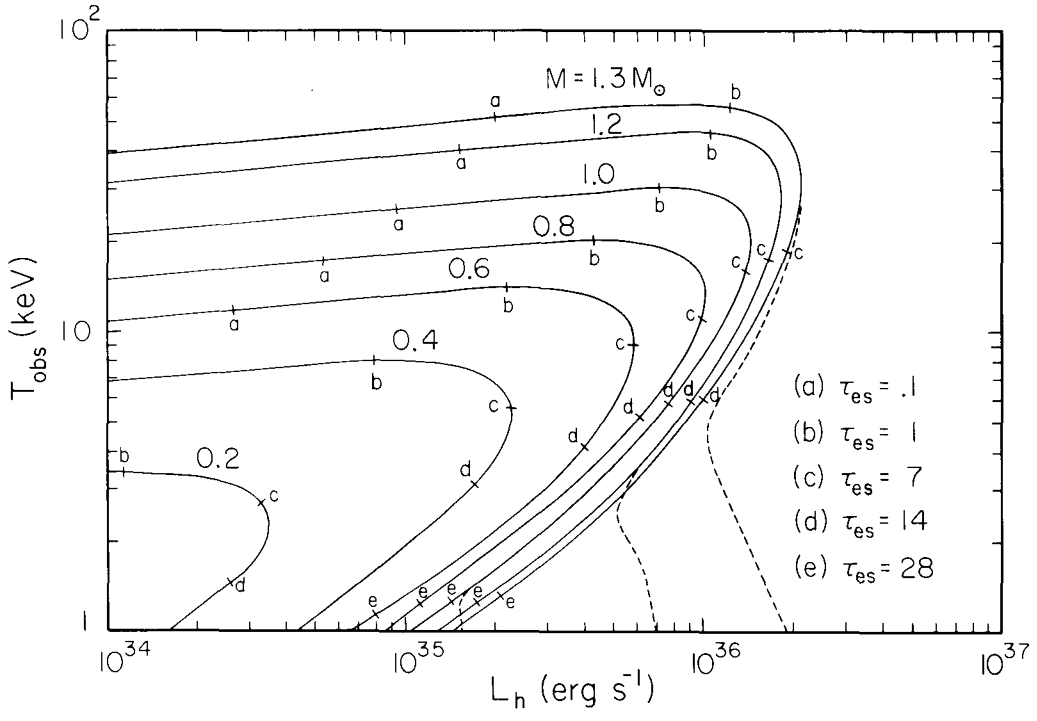

Fig. 13--Correlation between T_{obs} and L_h for stars with masses 0.2 - 1.2 $M_\odot$ (from Kylafis and Lamb 1982a). The dashed lines give the same correlation when the contribution of the blackbody component is included in L_h.

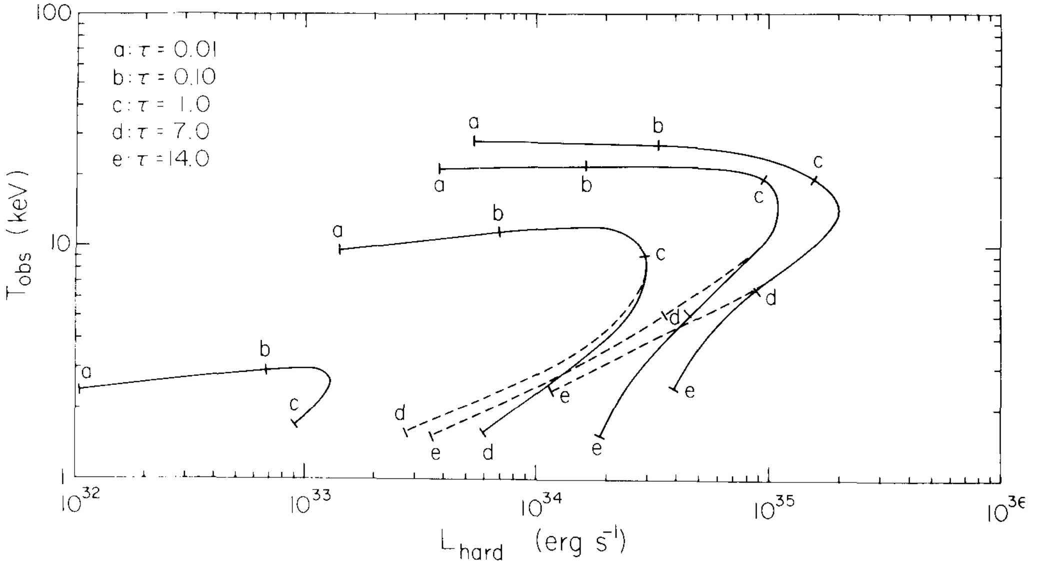

Fig. 14--Correlation between T_{obs} and L_h for stars with masses 0.2, 0.6, 1.0 and 1.2 $M_\odot$ and nuclear burning at the accretion rate (from Weast et al. 1982). The dashed lines show the correlation when the contribution of the blackbody component is omitted.

3.3.2. Correlation between spectral temperature and luminosity. Figure 13 shows the resulting dramatic variation in the spectral temperature at high accretion rates and the pronounced correlation between X-ray spectral temperature T_{obs} and luminosity L_h. Figure 14 shows for comparison this correlation when nuclear burning occurs at the accretion rate (see below). 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, an increase in T_{obs} and L_h therefore corresponds to a decrease in the accretion rate: T_{obs} and L_h increase since the smaller accretion rate lessens Compton degradation of the hard X-ray spectrum.

3.4. Ionization Structure and Line Features

3.4.1. 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 that the optical depth to absorption is small. The calculations by Kylafis and Lamb (1982b), which take self-consistent values for the hard and soft X-ray luminosities and spectral shapes based on their earlier detailed calculations, show that the blackbody soft X-ray flux ionizes H and He out to distances large compared with a typical binary separation. For high mass stars and low accretion rates, the bremsstrahlung hard X-ray flux ionizes heavy elements out to considerable distances.

3.4.2. 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 ~ 7 keV, with significant equivalent widths. Emission lines can also be produced by fluorescence in the accreting matter above the X-ray emission region. 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 thermal Doppler broadening, Compton scattering, and Doppler broadening due to bulk streaming velocities.

3.4.3. Absorption lines. According to the analytical calculations of Kylafis and Lamb (1982b), the absorption optical depth at the ionization edges of heavy elements increases rapidly when the accretion rate exceeds about 3×10^{-3} $\dot{M}_E$. These calculations also show that Compton scattering and the resulting degradation of the hard X-ray spectrum occur close to the star, while most of the absorption occurs relatively far from the star. Thus the amount of degradation is less sensitive, while the amount of absorption is more sensitive, to the distribution of accreting matter around the star.

3.4.4. Spectra. Ross and Fabian (1980) have carried out detailed numerical calculations of the emergent spectrum from a 1.0 $M_\odot$ star for three different accretion rates. These calculations treat the atomic physics carefully and are valid even for large absorption optical depths. Their results for τ_{es} = 6 and 10 are shown in Figures 15 and 16. 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 Kα lines of O VIII (0.65 keV), Si XIV (2.0 keV), and Fe XXV (6.7 keV).

3.5. Nuclear Burning

3.5.1. Nonmagnetic stars. The effects of nuclear burning on X-ray emission by nonmagnetic degenerate dwarfs were first discussed by Katz (1977) and have been

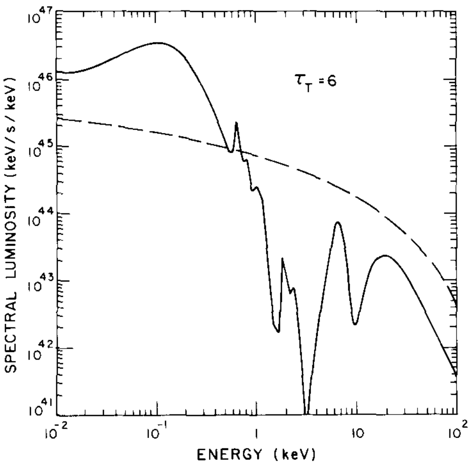

Fig. 15--X and UV spectrum produced by a 1 M star at an accretion rate 0.090 $\dot{M}_E$ (τ = 6) taking into account the effects of photoabsorption (from Ross and Fabian 1980).

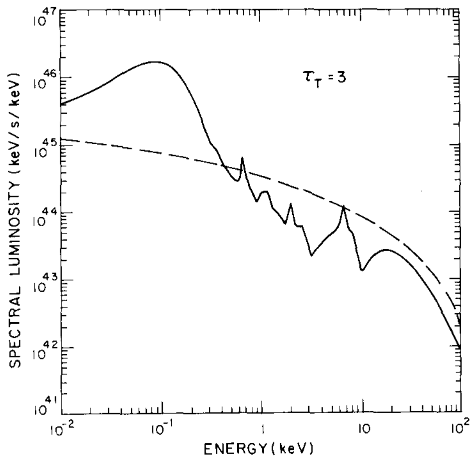

Fig. 16--Same as Figure 15 for an accretion rate 0.15 $\dot{M}_E$ (τ = 10) (from Ross and Fabian 1980).

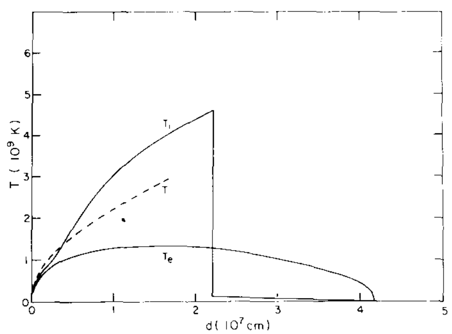

Fig. 17--Temperature structure of the emission region for a 1.4 $M_\odot$ star for an accretion rate 0.0253 $\dot{M}_E$ (τ =1) without nuclear burning (from Imamura et al. 1982). Here d is the distance above the surface of the star, and T_e and T_i are the electron and ion temperatures.

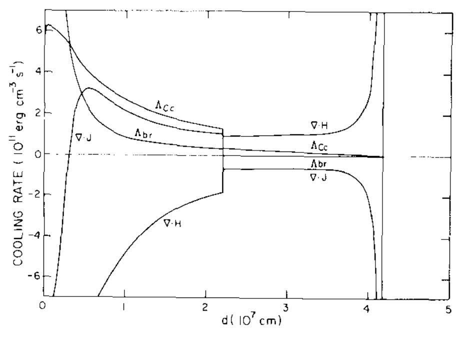

Fig. 18.--Cooling rates throughout the emission region of Figure 17. The curve labeled $\nabla \cdot H$ is the divergence of the enthalpy of the matter and corresponds to cooling (or heating) due to the flow of matter. The curves labeled Λ_{br} and Λ_{Cc} show the cooling due to bremsstrahlung and Compton cooling. The conduction curve ($\nabla \cdot J$) shows that conduction cools the region just behind the shock and heats the region near the stellar surface.

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 12 compares the X-ray spectra of a 1 $M_{\odot}$ star when the accreting matter burns at the accretion rate and the spectra when it does not. The three spectra shown span the entire range of accretion rates. Figure 14 shows the correlation between T_{obs} and L_h when nuclear burning occurs at the accretion rate. These curves should be compared with those in Figure 13, which assumes no nuclear burning.

3.5.2. Magnetic stars. 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.

3.6. Electron Conduction

Energy transport from the X-ray emission region into the star by electron conduction has been proposed (King and Lasota 1980) as a solution to the "soft X-ray puzzle" in the AM Her stars (see § 4.3 below). According to this suggestion, which is based on a one fluid (i.e. $T_e \equiv T_i$) picture of the X-ray emission region, most of the energy liberated by accretion is conducted into the star, leading to intense blackbody emission from the stellar surface and only weak bremsstrahlung hard X-ray emission from the hot, post-shock region above the surface.

The calculations of X-ray emission with nuclear burning described above entailed two-fluid (i.e. $T_e \neq T_i$) calculations incorporating electron conduction in a fully self-consistent way (Imamura et al. 1979, 1982; Weast et al. 1979; 1982). Figure 17 compares the temperature profile of the X-ray emission region in the one- and two-fluid treatments for a 1.4 $M_{\odot}$ star accreting at a rate corresponding to $\tau_{es} = 1$. Figure 18 shows the rates of heating and cooling due to mass flow (enthalpy), bremsstrahlung, Compton cooling, and electron conduction. The results show that in some cases conduction transports energy from one part of the emission region to another, but does not transport energy into the star.

Recently, Frank, King, and Lasota (1982) have confirmed this conclusion, within the approximation of a one-fluid treatment, and have gone on to propose a new mechanism of energy trasport into the star by nonthermal electrons. However, such a process is not viable in the X-ray emission regions of degenerate dwarfs, in which the mean free path of ions to Coulomb scattering is small and necessitates an ion shock and in which the diffusion approximation remains valid.

4. ISSUES

Among the important issues concerning X-ray emission from cataclysmic variables are the following.

4.1. Magnetic Fields

We have long held that magnetic fields are crucial to understanding cataclysmic variables, especially their X-ray emission (cf. Lamb 1974, 1979a,b, 1981). Recent observations have increasingly borne out our view. In AM Her stars, the strong magnetic field locks the degenerate dwarf in synchronous rotation with the binary, channels the flow of accreting matter to emission regions at the magnetic poles, and produces highly polarized light at optical wavelengths. In DQ Her stars, the magnetic field disrupts the disk, leads to more rapid spin-up of the degenerate dwarf, again channels the flow to emission regions at the magnetic poles, and is predicted (see below) to produce polarized light at infrared wavelengths. Although there is as yet no clear need to invoke magnetic fields in the other cataclysmic variables, we conjecture that smaller fields may play an important role in many, perhaps all, of them.

4.2. Origin of Hard X Rays

A crucial role in the emission of hard X rays by the AM Her and DQ Her stars is played by the magnetic field, which leads to radial inflow near the star and the formation of a strong shock. What is the origin of the hard X rays emitted by the other cataclysmic variables? Are the X rays 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 there weak magnetic fields present in these sources sufficient to disrupt the disk very near the star, producing quasi-radial inflow and a strong shock?

4.3. Soft X-Ray Puzzle in AM Her Stars

Much of the soft X-ray emission from the AM Her stars is inaccessible to observation because of interstellar absorption (cf. Tuohy et al. 1978, 1981; Rothschild et al. 1981; Patterson et al. 1983). UV observations of AM Her several years ago unexpectedly showed a turn-up at short wavelengths (Raymond et al. 1979). The most elegant explanation of the data attributed both the UV turn-up and the soft X-rays to an intense blackbody component with a temperature T_{bb} = 27 eV. However, this implied $L_{bb} \gg L_{br}$ whereas theory predicted $L_{bb} \simeq L_{br}$ (Kylafis and Lamb 1979, 1982a; Lamb and Masters 1979; King and Lasota 1979). A similar discrepancy was inferred in AN UMA (Szkody et al. 1981) and possibly for the other AM Her stars. This conflict has become known as the "soft X-ray puzzle." Ideas ranging from the transport of energy from the X-ray emission region into the star by electron conduction (King and Lasota 1980) or nonthermal electrons (Frank, King, and Lasota 1982) to nuclear burning (Fabbiano et al. 1981) have been put forward as possible explanations. Energy transport into the star by electron conduction or nonthermal electrons is not viable (recall the discussion in Section 3.6), while nuclear burning also faces difficulties (see below).

Recently, the results of nearly simultaneous observations of AM Her with the Einstein objective grating spectrometer and with IUE have become available (Kahn 1982; see also Heise and Brinkman 1982). They show that the blackbody temperature of the soft X-ray emission from AM Her is ≃ 45 eV, and that the UV and soft X-ray fluxes cannot be connnected by a blackbody. The results are consistent with $L_{bb} \simeq L_{br}$, and indicate that the turn-up in the UV flux has a separate origin. Recent Einstein soft X-ray observations of VV Pup are also consistent with $L_{bb} \simeq L_{br}$ (Patterson et al. 1982), as are earlier observations of EF Eri (Patterson et al. 1981). These results suggest that the famous "soft

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X-ray puzzle" may have gone away.

4.4. Origin of Soft X Rays

Although a soft X-ray component has not been detected in most of the other cataclysmic variables, SS Cyg and U Gem exhibit intense soft X-ray emission at outburst. Is its origin similar to the soft X-ray emission seen in the AM Her stars (which may, after all, be just reprocessed hard X-rays)? Is it emission from the hot degenerate dwarf itself? Or is it something more exotic, like nuclear burning (see below)?

4.4. 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 intense blackbody soft X-ray components inferred in the AM Her stars (Raymond et al. 1979) and in the cataclysmic variables SS Cyg and U Gem during outburst (Fabbiano et al. 1981).

Unfortunately, the conditions under which steady nuclear burning can occur are poorly understood. Detailed spherically symmetric calculations by Paczynski and Zytkow (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 novae (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 ~ 20 years or less (Sion et al. 1979) to $> 10^7$ years (Paczynski and Zytkow 1978). For a narrow range of higher accretion rates, steady nuclear burning is possible at the rate of accretion (e. g. $1.0 - 2.7 \times 10^{-7}\ M_{\odot}\ yr^{-1}$ for a $0.8\ M_{\odot}$ star; Paczynski and Zytkow 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 1982; 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.

4.5. Long-Period Pulsing Sources

Recently, several faint galactic X-ray sources have been found to pulse in both X-rays and optical light with periods $\gtrsim$ 1000 seconds (see section 2.2.2). There has been controversy about whether these objects are degenerate dwarfs or neutron stars (cf. Patterson and Price 1981, White and Marshall 1981). Their optical appearance and their X-ray to optical luminosity ratio of order unity suggest that they are degenerate dwarfs (Patterson and Price 1981). We have carried out a detailed comparison of their spin-up rate and that expected from theory (Lamb and Patterson 1983). This analysis confirms that they are indeed degenerate dwarfs. It also shows that they have magnetic fields $B \sim 3 \times 10^6$ G, an order of magnitude smaller than those of AM Her stars, and that the three previously known DQ Her stars with rotation periods < 100 seconds have still smaller fields. On this basis, we predict that the long-period sources will show significant polarization in the infrared while the short-period ones will show polarization only at longer wavelengths.

The newly discovered stars have been called "interlopers" (Patterson and Price 1981) between the previously known DQ Her stars, with rotation periods of 33 - 71 seconds, and the AM Her stars, with rotation periods synchronous with their orbital periods of 1.3 - 3.7 hours. However, spin-up theory shows that they have rotation periods appropriate to their magnetic fields and luminosities. We therefore believe that they and the DQ Her stars should be regarded as members of a single class, as are the short and long period pulsing neutron star X-ray sources.

4.6. Cyclotron-Dominated Sources

Although the AM Her stars are strongly magnetic ($B \simeq 2 \times 10^7$ G), bremsstralung, not cyclotron emission, is the dominant emission mechanism. This underscores the fact that whether bremsstrahlung or cyclotron emission dominates depends not only on the magnetic field, but also on the effective accretion rate $\dot{M}/f$ or, equivalently, the effective luminosity L/f (recall Figure 8). Bremsstrahlung dominates in AM Her stars because the accretion flow is channeled onto such a small fraction ($f \sim 10^{-3}$-10^{-6}) of the stellar surface that the effective accretion rate is very high.

Sources in which cyclotron emission dominates are characterized by weak X-ray emission and intense polarized cyclotron emission in the infrared, optical, or ultraviolet, depending on the strength of the magnetic field. We know of no reason why they cannot exist. Isolated degenerate dwarfs have magnetic fields ranging up to $\simeq 3 \times 10^8$G. If degenerate dwarfs with fields this large occur in cataclysmic variables, cyclotron emission would dominate even if the emitting area were as small as it is in the AM Her stars. Alternatively, cyclotron emission would dominate in sources with fields far smaller, provided that the area of the emission region is larger ($f \sim 10^{-1}$-10^{-2}). This could occur for magnetic degenerate dwarfs in cataclysmic variables with disks, such as the DQ Her stars, where the field lines accessible to accreting matter cover a substantial fraction of the stellar surface. So far no sources like these have been discovered, despite some searches (cf. Bond and Chanmugam 1982). Where are they? Will they be found by future UV or extreme UV surveys? Or is there some as yet unrecognized reason why they cannot occur?

4.7. *High Luminosity Sources*

Degenerate dwarfs with X-ray luminosities greater than $\simeq 10^{36}$ ergs s^{-1} cannot occur, due to Compton degradation and photoelectric absorption by the accreting matter. However, we know of no reason why sources with small X-ray luminosities but with total luminosities $L_{acc} \sim 10^{36}$ - 10^{38} ergs s^{-1} cannot occur. Such sources, whether magnetic or not, would be characterized by an intense soft X-ray component and a weak hard X-ray component, severely degraded at high energies and absorbed at low energies (cf. Figure 15 and Ross and Fabian 1980). No such X-ray source has been unequivocally identified with a degenerate dwarf. Cyg X-2 exhibited the X-ray behavior expected due to degradation (Branduardi et al. 1980) but not to absorption (Ross and Fabian 1980). And the distance, and hence luminosity, inferred from optical spectroscopy (Cowley et al. 1979) rules out a degenerate dwarf in the system. Do we not yet know how to recognize degenerate dwarf X-ray sources with high total (but not X-ray) luminosities? Or are there no such sources? And if not, why not?

4.8. Stability of Accretion Flow

Quasi-periodicities have been observed in the X-ray emission from several cataclysmic variables (cf. Patterson et al. 1981). Langer, Chanmugam, and Shaviv (1981, 1982) have considered the time dependence of accretion onto magnetized degenerate dwarfs. Their calculations show that the flow is unstable to periodic oscillations at the fundamental, and suggest that these may account for the observed quasi-periodicities. However, Chevalier and Imamura (1982) using a linear stability analysis find the fundamental to be stable, and only the overtones to be unstable. Further, such oscillations may be damped by Compton cooling and cyclotron emission, processes which have not yet been included in the calculations. Thus whether oscillations in the flow of accreting matter onto magnetic degenerate dwarfs account for the observed quasi-periodicities is not yet clear.

From the above 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 and theorists to create the ideas needed to understand them.

This research was supported in part by NASA grant NAGW 246. I also gratefully acknowledge support from the Fluid Research Fund of the Smithsonian Institution.

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DISCUSSION FOLLOWING D. LAMB'S TALK

KING: Just a clarification. The calculations with the Compton degradation are spherically symmetric, the geometry is spherically symmetric.

LAMB: That is correct.

KING: Is it then not very different if the accretion is funnelled down a column, in particular the photons will not tend to see a very large scattering optical depth, but will tend to try and escape through the sides of the column.

LAMB: That is correct, but it depends sensitively on the actual geometry.

KING: But they can escape through the sides, once they get to the sides they don't scatter back.

LAMB: In fact, the luminosities of most of these sources are surprisingly low. Even if one has a picture based on the spherically symmetric results, AM Her is on the borderline of the regime where Compton degradation would be significant. When you take into account the reduction due to the nonspherical geometry in AM Her, and almost surely in the other AM Her sources, one is not in the optically thick regime. That gives some satisfaction, in the sense that calculations don't have to deal with the complexities of degradation and of absorption, which can be rather difficult.

ROBINSON: Is the soft X-ray component seen also in the longer period rotators like 2252 and 2251?

LAMB: No. There is a lot of flux missing in the AM Her stars. In the long period DQ Her stars, even more flux is missing.

CHANMUGAM: You had a figure in which you divided the cyclotron cooling sources from the Bremsstrahlung cooling sources and you had a line which divided this. Is that line obtained by equating optically thin cyclotron cooling to optically thin Bremsstrahlung?

LAMB: No. It is obtained by taking into account that the cyclotron emission is optically thick below a certain frequency.