

ON THE OBSERVED PROPERTIES AND LONG-TERM STRUCTURE AND EVOLUTION OF
WHITE DWARFS IN CATAclySMIC VARIABLES

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ABSTRACT

The observed parameters of cataclysmic variable white dwarfs detected optically and in the far ultraviolet with the *International Ultraviolet Explorer* (IUE) are analyzed from the point of view of the cooling physics and time-averaged structure of the degenerate star in response to long-term accretion. Using the results of long-term, quasi-static model sequences, the cooling rates of accreting white dwarfs in the quasi-static approximation are found to be comparable to those for single stars of the Lamb and Van Horn, $1 M_{\odot}$, pure ^{12}C cooling sequence (and implications are discussed). Using the theoretical framework provided by long-term accretion studies in the quasi-static approximation, it is shown that the observed surface temperatures and luminosities of white dwarfs in low- \dot{M} cataclysmic variables are entirely consistent with those expected for white dwarfs accreting at rates 10^{-11} to $10^{-9} M_{\odot} \text{ yr}^{-1}$ over time intervals of the same order as the estimated recurrence times of classical novae. This interpretation is supported by observational constraints on the length of classical nova recurrence times and by the lower limit imposed on the effective temperatures of white dwarfs in cataclysmic variables by the long-term rate at which gravitational potential energy is liberated by a white dwarf in response to accretion. These intrinsic effective temperatures and luminosities appropriate to thermonuclear outburst cycles are compared to calculated effective temperatures and luminosities maintained either by radiating away a fraction of the accretion energy at the white dwarf surface or by localized hard X-ray heating, and implications are discussed. Observational tests are proposed that could distinguish between the intrinsic luminosity/effective temperature and that maintained by radiated accretion energy.

Subject headings: stars: accretion — stars: dwarf novae — stars: white dwarfs — ultraviolet: spectra

I. INTRODUCTION

Until very recently, direct observations of white dwarfs in cataclysmic and novalike short-period binaries had been restricted to systems without accretion disks, such as AM Her binaries where the white dwarf magnetic field disrupts a disk, or the V471 Tauri precataclysmic binaries in which there can be no accretion by Roche-lobe overflow. However, within the past year a number of authors (e.g., Panek and Holm 1984; Mateo and Szkody 1984; Shafter *et al.* 1985) have reported the detection of direct radiation from the white dwarf photosphere either during a dwarf nova minimum (Panek and Holm 1984) or during the exceptionally “low” state of a novalike variable (Shafter *et al.* 1985). The evidence from IUE and optical scans as well as indirect inferences based on colors, eclipse geometry, and emission line fluxes were summarized by Patterson (1984*b*), who adds a number of additional systems.

The effective temperatures tabulated by Patterson (1984*b*) and Smak (1984) for the white dwarfs in cataclysmic variables (CVs) lie in the range $10^{4.1} \lesssim T_e \lesssim 10^{4.7}$ with a median temperature of $\sim 30,000$ K. Thus, these objects, called “pseudo-white dwarfs” by Patterson and Raymond (1985), are considerably hotter and more luminous than field white dwarfs where the median effective temperature of a single DA white dwarf in the known (observed) sample is $T_e \approx 12,000$ K (see Sion 1984). An attempt to explain the inferred higher temperatures and luminosities of CV white dwarfs has been made by Patterson and Raymond (1985), who invoke localized heating of the white dwarf outer layers by hard X-rays from the disk boundary layer. *The principal goal of this work is to explain the observed surface temperatures and luminosities of CV white dwarfs from a different point of view: the cooling*

physics and time-averaged structure of the white dwarf in response to accretion. This requires an appeal to long-term quasi-static evolutionary studies of accreting white dwarfs (Paczynski and Zytkov 1978; Sion, Acierno, and Tomczyk 1979; Iben 1982; Sion and Starrfield 1985), none of which, unfortunately but for quite understandable practical reasons, follow the evolution through several classical nova outbursts. Nevertheless, sufficient progress has been made to address the CV white dwarf problem, particularly with the appearance of the excellent treatment by Iben (1982) which not only presents the most realistic quasi-static model sequences to date but also provides a thorough, insightful discussion of the relevant physics.

In a brief initial exploration (§ II of this paper), core cooling during the quasi-static evolution of accreting white dwarfs is considered. The evolutionary changes in core temperature and core luminosity as an accreting white dwarf is evolved quasi-statically are compared with the cooling evolution of a non-accreting, $1 M_{\odot}$, pure ^{12}C core. At core luminosities $\log(L/L_{\odot}) > -0.5$, it is found that (1) the accreting white dwarf cools at nearly the same rate as a nonaccreting, $1 M_{\odot}$, pure ^{12}C core and (2) the core cooling occurs on a time scale shorter than the estimated recurrence times of classical novae.

The major investigation and results of this paper are found in § III: the relevance of the quasi-static framework to the observed properties of white dwarfs in cataclysmic variables. Here, the evolutionary behavior of the white dwarf envelope in mass and temperature, in response to long-term accretion, is used to predict temperatures and luminosities of white dwarfs during quiescent intervals between nova outbursts. It is shown that the observed luminosities and effective temperatures of the

bare white dwarfs detected in some cataclysmic variables are the expected intrinsic values associated with classical nova thermonuclear outburst cycles. Two alternate interpretations of their observed surface temperatures and luminosities are assessed in § IIIb, and in § IIIc preliminary results of observational tests that may distinguish between the three alternatives are presented, and additional observational tests are proposed.

Finally, § IVa contains some final thoughts, and § IVb presents a summary of conclusions.

II. IMPLICATIONS FOR CORE/ENVELOPE COOLING OF AN ACCRETING WHITE DWARF IN THE QUASI-STATIC APPROXIMATION

In following the evolution of an accreting white dwarf through numerous shell flash cycles (whether dynamical or quasi-static), one expects the underlying core to have evolved into some thermally relaxed state, as shown by Iben (1982). A thermally relaxed structure (i.e., “steady state” core structure) should develop such that the rate of gravitational potential energy release in the core is in exact balance with the rate of energy loss due to neutrinos plus the rate of mean kinetic energy increase of electrons and ions in the core. An important remaining question, however, is the extent to which the white dwarf cools while undergoing long-term (time-averaged) accretion at a rate typical of classical novae (10^{-9} to $10^{-11} M_{\odot} \text{ yr}^{-1}$, Fujimoto 1982). The availability of long-term quasi-static studies of accreting (non-steady state burning) white dwarfs (see Iben 1982), which include the effects of structure changes and compressional heating due to accretion, allows an admittedly crude but illuminating comparison with the cooling evolution of $1 M_{\odot}$ pure ^{12}C white dwarfs, see Lamb and Van Horn (1975).

First, we compare the cooling of a hot, “non-steady state” C-O core at $0.964 M_{\odot}$ (Iben 1982) with Table 3 and Figure 6 of Lamb and Van Horn for a $1 M_{\odot}$ pure carbon core with no helium envelope, as far as possible given the limited evolutionary time baseline of the accreting model ($\sim 10^4$ yr). The time-averaged cooling rates ($\langle dT_c/dt \rangle$) are virtually identical ($\sim 10^3 \text{ K yr}^{-1}$) for the accreting white dwarf and a pure ^{12}C cooling core over the same luminosity range, $2.34 \leq \log(L/L_{\odot}) \leq 4.18$. Second, a model “steady state” core plus helium-rich layer with $M = 0.964 M_{\odot}$ was evolved by Iben (1982) with a static, steady-burning hydrogen envelope ($M_{\text{env}} \approx 10^{-6} M_{\odot}$) appropriate to $\dot{M} = 1.5 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$. The model was evolved quasi-statically and allowed to accrete material until $M_{\text{WD}} = 1.01 M_{\odot}$. The inference one derives from § IV, p. 254, of Iben (1982) is that the core was evolved for $3.5 \times 10^7 \text{ yr}$ ($\sim \Delta M/\dot{M}$). Detailed comparison with the Lamb and Van Horn results yields a time-averaged cooling rate nearly the same as that of a pure ^{12}C white dwarf over the same luminosity, $-0.8 \lesssim \log(L/L_{\odot}) \leq 2.34$, and time interval. The nearly identical cooling rates ($\sim 5 \text{ K yr}^{-1}$) between the accreting models (with core temperature change $\Delta T_c = 2.4 \times 10^8 \text{ K}$) and the Lamb and Van Horn sequence (with $\Delta T_c = 1.16 \times 10^8 \text{ K}$) must be due to the dominance of neutrino losses, especially photoneutrinos and plasma neutrinos at the core temperatures and densities considered here. In fact, neutrino energy losses dominate in single white dwarfs down to $\log(L/L_{\odot}) \approx -0.5$. It is not unreasonable to expect that a white dwarf core in a CV, with a core luminosity $\log(L/L_{\odot}) > -0.5$, should cool on a time scale comparable to or shorter than the estimated classical nova recurrence time scale (i.e., $\tau_{\text{cn}} \approx 10^4\text{--}10^6 \text{ yr}$, Ford 1978). If, however, the core luminosity $\log(L/L_{\odot}) < -0.5$ and if clas-

sical novae have lifetimes less than 10^8 yr (Patterson 1984a), thermal cooling of the white dwarf core will not be appreciable enough over the system’s lifetime to cause a strengthening of the shell flash at a given long-term accretion rate. Hence the shell flash properties will be dominated by accretion, as explained in § III.

III. RELEVANCE OF THE QUASI-STATIC FRAMEWORK TO OBSERVED PROPERTIES

a) Envelope Physics in Response to Long-Term Accretion

The theoretical framework provided by long-term quasi-static calculations is developed enough to make specific predictions about the long-term evolution of the white dwarf in cataclysmic variables. Naturally, the quasi-static studies have not included sequences with dynamical shell flashes (i.e., mass ejection). However, one can make a reasonably realistic assessment of the effect of dynamical mass ejection on the time evolution of an accreting white dwarf in the $\log M_e\text{--}\log T_e$ and $\log(L/L_{\odot})\text{--}\log T_e$ planes using quasi-static behavior as a guide.

The physical interpretation of quasi-static behavior in these same two planes is facilitated by using properties of models in the steady-burning approximation, which assumes that the rate at which matter is processed through nuclear burning is equal to the rate at which it accretes. The steady-burning approximation has been used extensively in exploring the envelope structure and pulsational and thermal stability of accreting white dwarfs with nuclear shell sources (Sienkiewicz 1975). The model structure solutions yield accreted envelopes whose properties are independent of the thermal state of the underlying core. If one constructs, for any given white dwarf mass, a grid of static envelopes with each model corresponding to a different value of steady-state luminosity (i.e., accretion rate), the resulting steady-burning solutions yield many properties in the luminosity versus surface temperature and envelope mass versus surface temperature planes which are morphologically similar to the properties of actual quasi-static evolution calculations (Fig. 3 in Iben 1982). Physically this is not surprising, since the quasi-static models are, in an averaged sense, steady-burning models, for if one followed the evolution of accreting white dwarfs through “dozens” of shell flashes, the underlying core would eventually achieve a “steady state” and the characteristics of the successive shell flashes would become identical and completely independent of the initial conditions.

A well-known property of the quasi-static sequences is that the accreting white dwarf evolves at nearly constant effective temperature between outbursts (Paczyński and Zytkov 1978; Sion, Acierno, and Tomczyk 1979; Iben 1982). This is true because the white dwarf envelope has simply cooled to a minimum luminosity at a point on its line of constant radius until the next thermal instability. It has been shown convincingly that the hydrogen burning runaway sets in at a luminosity level that can be estimated from steady-burning models (Iben 1982). One expects this because the luminosity of a steady-burning model is determined entirely by the accretion rate. Thus, at onset of instability the nuclear luminosity first exceeds the “steady-burning” surface luminosity, fixed by \dot{M} , in the steady-burning models.

The typical time-dependent behavior of a quasi-static accreting model in a $\log M_e$ versus $\log T_e$ diagram is shown schematically in Figure 1. The numerical range of parameters was extrapolated from the results of long-term quasi-static studies at higher accretion rates and approximately corresponds to the

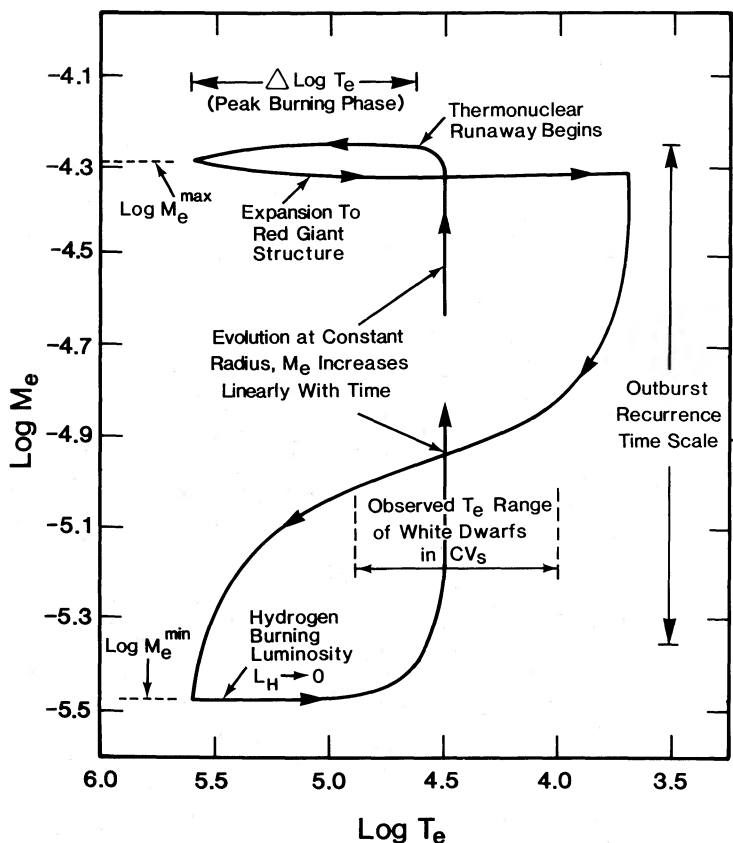


FIG. 1.—Mass M_e in the hydrogen-rich envelope as a function of effective temperature roughly corresponding to a $1 M_\odot$ white dwarf accreting at a rate $10^{-10} M_\odot \text{ yr}^{-1}$. The schematic evolution from the point where expansion to a red giant structure occurs down to where the envelope mass is reduced to M_e^{min} (by burning and mass loss) is characterized by stable hydrogen burning at roughly the plateau luminosity (Iben 1982). Subsequent evolution, after hydrogen burning is essentially extinguished, consists of the accreting white dwarf cooling along its nearly constant radius line in the H-R diagram to its minimum luminosity in the cycle (see text for details).

behavior of a $1 M_\odot$ white dwarf accreting at the rate of $10^{-10} M_\odot \text{ yr}^{-1}$. At the labeled point where the thermonuclear runaway begins, the surface luminosity is rapidly rising, but not until L_s reaches the steady-state luminosity ($L_s \approx \dot{M}/10^{-11} X_H$) corresponding to $\langle \dot{M} \rangle$ does the phase of peak burning begin and proceed to the point of maximum T_e corresponding to M_e^{max} . The quantity M_e^{max} in Figure 1 is the critical maximum envelope mass for which nuclear burning can be in a steady state with accretion.

For a given white dwarf mass and accretion rate, it is seen in Figure 1 that the surface temperatures corresponding to (1) the envelope mass at peak burning and (2) the envelope mass when hydrogen burning is essentially extinguished are nearly the same (see also Fig. 16 in Iben 1982). The white dwarf rather quickly returns, on a thermal time scale, to its effective temperature before outburst. This is expected because the behavior of the quasi-static accreting white dwarf in the $\log M_e$ versus $\log T_e$ plane is simply a relaxation oscillation in the same sense as thermal pulses in an asymptotic giant branch star. If one lowers the accretion rate, keeping the total white dwarf mass constant, a larger critical envelope mass is required to initiate a thermonuclear runaway, and a stronger flash will result. This implies that the phase of peak burning following the onset of a thermal instability must begin at a lower "steady state" luminosity (fixed by $\dot{M} = 10^{-11} L_H / X_H$, where L_H is the hydrogen-burning luminosity and X_H is the accreted hydrogen abundance). But a lower luminosity at onset of peak burning

implies a lower effective temperature at onset of instability for the accreting white dwarf and thus a lower effective temperature between outbursts. In other words, in the $\log M_e$ versus $\log T_e$ plane, for a given white dwarf total mass, if one lowers the accretion rate, a greater range in effective temperature, $\Delta \log T_e$, results between the value of T_e at the point where burning first becomes unstable and its value at the point of peak hydrogen-burning luminosity (see Fig. 1). How much lower the effective temperature must be is readily seen by examining the results of quasi-static sequences through several outbursts. For example, accretion by hot massive ($M \gtrsim 1.0 M_\odot$) white dwarfs at rates $10^{-7} > \dot{M} > 10^{-9} M_\odot \text{ yr}^{-1}$ result in degenerate stars between outburst with effective temperatures in the range 10^5 – 10^6 K (Sion, *et al.* 1979; Iben 1982; Sion and Starrfield 1985). For quasi-static sequences that are close to representing the repetitive thermonuclear outbursts in cataclysmic binaries at lower accretion rates over classical novae recurrence times, the effective temperatures are considerably lower, due to the quasi-static envelope evolution arguments stated earlier. The most realistic sequence to date (Iben 1982) is that of a $1.01 M_\odot$ white dwarf accreting at (the realistically low value of) $10^{-9} M_\odot \text{ yr}^{-1}$, resulting in a white dwarf surface temperature $\log T_e = 5.0$ over a 14,000 yr inter-outburst interval. The nuclear energy generation rate for this sequence at the peak of the flash ($2 \times 10^{13} \text{ ergs g}^{-1} \text{ s}^{-1}$) is remarkably close to the rate of order $10^{14} \text{ ergs g}^{-1} \text{ s}^{-1}$ or greater needed to achieve the Eddington luminosity and begin

mass ejection from the white dwarf. Given that in the $\log M_e$ versus $\log T_e$ plane, the physics governing the time-dependent behavior of the accreting white dwarf is the same at lower accretion rates where the hydrogen flash is more violent and where $\Delta \log T_e$ as shown in Figure 1 (and defined above), is larger, one arrives similarly at the resulting physical properties of the white dwarf between outbursts. In particular, at accretion rates of $10^{-11} \lesssim \dot{M} \lesssim 10^{-10} M_\odot \text{ yr}^{-1}$ (with outburst recurrence times of 10^4 – 10^6 yr), the effective temperature range for the resulting white dwarfs between outbursts agrees very nicely with the observed effective temperatures ($4.1 \lesssim \log T_e \lesssim 4.7$; $M_v \approx 10$ – 12) of the white dwarfs detected thus far in CVs. These intrinsic surface luminosities and effective temperatures appropriate to nova outburst cycles depend on $\langle \dot{M} \rangle$, core temperature T_c , M_{WD} , and M_e . The thermonuclear history of the white dwarf therefore determines its observed properties between outbursts, thus providing a natural explanation of the observations. Nevertheless, alternate physical interpretations have been proposed by Shafter *et al.* (1985) and Patterson and Raymond (1985).

*b) Intrinsic Luminosity in an Outburst Cycle versus
"Maintained" Accretion Luminosity and White Dwarf
Pseudo-Photospheres Induced by Localized Hard
X-Ray Heating*

One might suggest that the observed temperatures and luminosities of the white dwarfs which have been revealed during quiescence and "low" state are simply the result of radiating away immediately a fraction f of the total accretion (gravitational) energy, L_{acc} ($\approx fGM_{\text{WD}}\dot{M}/R_{\text{WD}}$) at the white dwarf surface (Shafter *et al.* 1984; Smak 1984).

In order to test this possibility, one can compute effective temperatures for the white dwarf under two assumptions: (1) $0.5L_{\text{acc}}$ is radiated away at the surface as an upper extreme, and (2) $0.17L_{\text{acc}}$ is radiated away at the surface as a lower extreme.

The choice of $0.17L_{\text{acc}}$ deserves detailed comment. It represents the fraction of the total accretion (gravitational) energy which best approximates the expected long-term average rate at which gravitational potential energy is liberated in response to accretion, regardless of the details of the accretion process or how the accreted matter is processed through nuclear shell burning. This particular value (0.17) was determined from long-term quasi-static accreting models (Iben 1982), which yield the long term release of $\langle L_g^{\text{acc}} \rangle$ due to compressional heating and changes in interior structure in response to accretion. It should hold for a range of white dwarf masses for an accretion rate of $10^{-9} M_\odot \text{ yr}^{-1}$ and was confirmed analytically by Iben (1982) through application of the virial theorem. It is expected that other accretion rates should yield similar fractions (0.17–0.25). The remainder of the total accretion energy is presumed to be radiated away via the disk.

Now, the time-averaged surface luminosity of an accreting white dwarf is given by:

$$\langle L_s \rangle = \langle L_g^{\text{acc}} \rangle + \langle L_{\text{nuc}} \rangle + L_{\text{acc}}^{\text{rad}} + \langle L_{\text{cool}} \rangle - L_{\text{v}\nu}, \quad (1)$$

where $\langle L_g^{\text{acc}} \rangle$ is the time-averaged rate of gravitational potential energy release due to structure changes and compressional heating as M_e increases due to accretion, $L_{\text{acc}}^{\text{rad}}$ is the "accretion luminosity" radiated away immediately at the surface, $\langle L_{\text{cool}} \rangle$ is the thermal cooling luminosity, $\langle L_{\text{nuc}} \rangle$ is the cycle-averaged nuclear luminosity, and $L_{\text{v}\nu}$ is the neutrino luminosity.

Suppose that we set $\langle L_s \rangle = \langle L_g^{\text{acc}} \rangle$, neglect all other luminosity source terms in equation (1), and compute an effective temperature from this luminosity alone. This resulting surface temperature will represent a *firm lower limit*, because any other luminosity source term (e.g., $\langle L_{\text{nuc}} \rangle$, $L_{\text{acc}}^{\text{rad}}$) added to that of $\langle L_g^{\text{acc}} \rangle$ will result in a *higher* surface temperature for the white dwarf provided that the white dwarf luminosity between outbursts is low enough that the neutrino luminosity is negligible.

In Table 1, effective temperatures have been computed for white dwarf masses 0.8, 1.0, and $1.2 M_\odot$ for accretion rates 10^{-9} and $10^{-10} M_\odot \text{ yr}^{-1}$ under the assumption that $0.5L_{\text{acc}}$ and $0.17L_{\text{acc}}$ are radiated away immediately upon impact of accreted material at the surface of the white dwarf. At $10^{-9} M_\odot \text{ yr}^{-1}$, the effective temperatures for both assumed fractions of L_{acc} are considerably higher than the observed range. Only at $10^{-10} M_\odot \text{ yr}^{-1}$ are the temperatures in reasonable agreement with observation, and then only if $L_{\text{WD}} \approx 0.17L_{\text{acc}}$, a firm lower limit to T_e . However, an even more serious problem with "accretion" luminosity emerges from the results in Table 1. If the underlying white dwarfs have *intrinsic* effective temperatures lower ($T_e < 20,000$ K) than the accretion-maintained values corresponding to $10^{-10} M_\odot \text{ yr}^{-1}$ in Table 1, long-term accretion rates $\langle \dot{M} \rangle < 10^{-10} M_\odot \text{ yr}^{-1}$ are implied, which would be in conflict with nova frequency statistics (i.e., unacceptably long recurrence times $\tau_{\text{cn}} \gtrsim 10^6$ yr) unless the white dwarfs are quite massive ($M_{\text{WD}} \geq 1.2 M_\odot$). There is no convincing observational evidence that a substantial fraction of CV white dwarfs are that massive (cf. Patterson 1984a, and references therein).

In a variation of the accretion luminosity idea, Patterson and Raymond (1985) argue that local heating of the white dwarf in low- \dot{M} CVs by hard X-rays from the disk boundary layer is responsible for the observed high temperatures and luminosities of what they term "pseudo-white dwarfs". Their explanation invokes reprocessing of the hard X-rays into visual luminosity. Without detailed models of localized hard X-ray heating in a white dwarf envelope, it is difficult to evaluate the validity of their scenario. However, if the hard X-rays penetrate down to a region of large optical depth, one can, by assuming global heating, estimate the Helmholtz-Kelvin thermal time scale of the affected layer:

$$\tau_K \approx \int_0^{M_e} \frac{C_v T}{L} dM, \quad (2)$$

where T is the layer temperature, L is the luminosity, and C_v the specific heat at constant volume. Upper limits to τ_K can be obtained by assuming that the *entire* nondegenerate envelope

TABLE 1
ACCRETION-"MAINTAINED" T_e

L_{acc}	$M_{\text{WD}} (M_\odot)$		
	0.8	1.0	1.2
$R_{\text{WD}} (10^8 \text{ cm})$:			
.....	8.352	5.429	3.758
$\dot{M} = 10^{-9} M_\odot \text{ yr}^{-1}$:			
0.5	53,265	77,804	107,306
0.17	40,688	59,403	81,928
$\dot{M} = 10^{-10} M_\odot \text{ yr}^{-1}$:			
0.5	29,924	43,710	60,284
0.17	22,858	33,372	46,026

is affected. For a $0.6 M_{\odot}$ at $T_e = 20,000$ K, $\tau_K \lesssim 1.5 \times 10^5$ yr. More massive white dwarfs ($1.0 < M_{\text{WD}} < 1.4$) will have shorter upper limit τ_K , because the shell source is not so deep (i.e., occurs at a smaller mass fraction closer to the surface) given the same effective temperature as a lower mass white dwarf. Recent preliminary calculations by Imamura (1984) indicate that a localized hard X-ray incident flux into the white dwarf surface layers will encounter strong Compton scattering and should be either scattered out (immediately) or absorbed down to a layer thickness of roughly 10 Compton depths. Thus, if only the upper portion of the envelope is affected, then $\tau_K \ll \tau_{\text{en}}$. It is also noteworthy that recent boundary layer calculations by Shaviv (1984) show that when $\dot{M} < 10^{-9} M_{\odot} \text{ yr}^{-1}$, the boundary layer destabilizes and expands to form a hot corona surrounding the entire white dwarf surface. The heating of the white dwarf surface layers was found to be negligible for such cases.

Despite the physical arguments presented here against either maintained accretion luminosity or localized hard X-ray heating as viable explanations of the high T_e and L_{WD} of white dwarfs in CVs, the depth of accretion heating in the outer layers remains very uncertain. Therefore specific observational tests should be carried out, examples of which are presented in § IIIc together with some preliminary results.

c) Observational Tests

Currently, observational tests are conceivable which may distinguish between “maintained” accretion luminosity (which depends on M_{WD} and \dot{M}) and the intrinsic L_{WD} and T_e appropriate to a nova outburst cycle (which depends on $\langle \dot{M} \rangle$, T_e , M_{WD} , and M_e) without requiring a Space Telescope project. Since at least four hot white dwarfs in dwarf novae (U Gem, VW Hyi, HT Cas, and SS Cyg) have been directly observed just following outburst and during quiescence, intense photometric and spectroscopic monitoring of the white dwarfs may reveal line or continuum variations or both, diagnostic of cooling. Any such variations would yield approximate thermal time scales and therefore estimates of the layer mass which underwent heating. At the present time, preliminary results by Wu and Panek (1982) indicate that the white dwarf in U Gem cools following a dwarf nova outburst, on a time scale of 10^6 – 10^7 s (Smak 1985b). Further, more intense observations of U Gem during the whole quiescent interval with the *IUE* telescope have been proposed for the Eighth Year Observing Episode of *IUE*. Simultaneous *IUE* and *Voyager* observations of U Gem and SS Cyg during decline and into quiescence when the white dwarf continuum emerges are now in progress by J. B. Holberg and R. Polidan at the Lunar and Planetary Laboratory in Tucson. In a recent *IUE* analysis of the white dwarf in VW Hyi, when the disk is virtually absent just after outburst (Szkody and Mateo 1984; Szkody 1984), the $\text{Ly}\alpha$ absorption appeared weaker, indicating that the white dwarf photosphere had been heated by the outburst. A subsequent SWP spectrum during quiescence revealed a stronger $\text{Ly}\alpha$ absorption feature which was successfully fitted with a 30,000 K, $\log g = 8$, DA model atmosphere.

The detection of white dwarf photospheres in MV Lyr and TT Ari, two members of the UX Ursae Majoris subclass, during extended “low” states (V fainter than 16.0) offer additional tests of the extent of accretion heating. In TT Ari’s previous low state ($V = 14.5$), Krautter *et al.* (1981) discovered a v^2 rise in the SWP ultraviolet continuum instead of a v^0 flat disk continuum, indicating a hot photosphere when accretion

had declined or stopped and the disk appeared to greatly shrink or vanish. A temperature determination from that observation is consistent with the effective temperature $T_e \gtrsim 50,000$ K deduced by Shafter *et al.* (1985) during the 1983–1984 low state.

In view of white dwarf detection in CVs, renewed effort toward utilization of the *IUE* archival material on dwarf novae in decline and quiescence as well as during low states of nova-like variables (including AM Her objects) is now in progress. AM Her itself contains a white dwarf which appears to exhibit two surface temperatures, one which corresponds to accretion heating at the base of its accretion column (the polar cap) and a much lower effective temperature appearing to characterize the global effective temperature of the white dwarf (Liebert and Stockman 1984).

Finally, if localized heating of the white dwarf by boundary layer hard X-rays mimics a white dwarf photosphere (Patterson and Raymond 1985) during dwarf nova quiescence, one might observe orbital phase modulation of the “pseudo—white dwarf” continuum, depending on geometry, due to the heated equatorial or polar region. The intense observations during quiescence, described earlier, provide a clear-cut test of the Patterson and Raymond scenario.

IV. CONCLUSIONS

a) Final Thoughts

One important but speculative implication of the quasi-static studies is that, insofar as an accreting CV white dwarf can evolve at nearly constant effective temperature between outbursts in response to $\langle \dot{M} \rangle$, an observation of its temperature and luminosity during an interval of low \dot{M} or no accretion could potentially yield approximate information about the mass of the white dwarf or $\langle \dot{M} \rangle$, provided that a long enough time τ_K has elapsed for the outermost layers to cool. Thus it is possible that insight into the evolutionary status of the system could be potentially acquired if either $\langle \dot{M} \rangle$ or M_{WD} is known independently. This would require a much finer grid of quasi-static (and hydrodynamic) model calculations through several outburst cycles. But in addition to greatly widening the exploration of parameter space, the difficult computational challenge of following helium runaways, including mass and energy loss, would have to be accepted.

All but two of the cataclysmic variables for which the bare underlying white dwarf has been detected are low- \dot{M} dwarf novae. Since the thermonuclear outburst cycles of low- \dot{M} CVs would have the longest nova recurrence times (for a given white dwarf total mass), it is not surprising that despite their high space density they do not appear to be as important a producer of classical nova outbursts as high- \dot{M} dwarf novae and nonruptive cataclysmic variables (e.g., UX UMa stars and other high- \dot{M} novalike variables).

b) Summary

If long-term quasi-static evolutionary models of spherically accreting degenerate stars provide a reasonable approximation to the long-term structure and evolution of white dwarfs in cataclysmic variables, several potentially far-reaching implications emerge.

These main results are summarized as follows, beginning with the primary one.

1. The observed effective temperatures and luminosities of the small bright objects detected thus far in low- \dot{M} dwarf

novae during quiescence and two UX Ursae Majoris novalike variables in very "low" states ($4.1 \lesssim \log T_e \lesssim 4.7$; $M_v \approx 10$ – 12) agree with the theoretically predicted effective temperature/luminosity range of accreting white dwarfs between nova outbursts, intrinsic to outburst cycles with accretion rates of $10^{-9} \gtrsim \langle \dot{M} \rangle \gtrsim 10^{-11} M_\odot \text{ yr}^{-1}$ over recurrence times of 10^4 – 10^6 yr. This interpretation is supported by (a) the limitation imposed by nova frequency statistics on how low the intrinsic effective temperature of the white dwarf (not maintained by a fraction of the accretion energy radiated at the surface) can be without implying unacceptably long nova recurrence times, and (b) the firm lower limit to the effective temperature of a white dwarf in a CV imposed by the long-term rate $\langle L_g^{\text{acc}} \rangle$, at which gravitational potential energy is liberated by an accreting white dwarf in response to accretion (17%–25% of the total accretion energy) regardless of the details of the accretion process.

2. At core luminosities $\log(L/L_\odot) > -0.5$, the cooling rate of accreting carbon-oxygen white dwarfs is approximately the same as that of non-accreting, $1 M_\odot$, pure ^{12}C core. At $\log(L/L_\odot) > -0.5$, the cooling time scale of the accreting white dwarf is shorter than the estimated recurrence times of classical novae. Below this luminosity, neutrino energy losses no longer dominate core cooling, and the cooling time far exceeds the classical nova recurrence times. However, in the latter case

also, the CV stage is believed to be sufficiently short ($\tau < 10^9$ yr) that the overall cooling times of white dwarfs in CVs is not significantly lengthened by their being in interacting binaries.

Further observational investigations as to the extent of accretion heating in the white dwarf envelope are crucial. While preliminary evidence cited in § IIIc points toward minimal heating, the quasi-static models with accretion may be unrealistic, in that they assume that kinetic energy of the accreted matter has completely dissipated before the matter settles onto the white dwarf with the same entropy as its outer layers. Other sources of heating (e.g., shear mixing of the accreted matter) should also be explored.

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