Advection-Dominated Accretion Onto Weakly-Magnetized White Dwarfs

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ABSTRACT

The boundary layers of weakly-magnetized white dwarfs (WDs) accreting at rates $\lesssim 10^{16}$ g s$^{-1}$ are radially extended, hot, optically-thin, and they advect some of their internally-dissipated energy (Narayan & Popham 1993). Motivated by this, I construct here idealized spectral models of an Advection-Dominated Accretion Flow (ADAF) around a WD, for application to quiescent Dwarf Novae (DN). The Bremsstrahlung cooling of the gas in the ADAF, with temperatures ranging from a few keV to a few tens of keV, can account for the X-ray emission properties of quiescent DN. If the energy advected by the flow is thermalized in the WD atmosphere, the resulting emission from the entire stellar surface (blackbody of temperature $T_{\text{eff}} \sim 5$ eV) outshines the X-ray luminosity substantially. This extreme-UV component provides a flux in the 0.055-0.28 keV band which is sufficient to power the strong HeII $\lambda$4686 emission lines of quiescent DN by photoionization of the disk material. Reprocessing of the ADAF X-ray emission by a cold outer thin disk could also lead to an observable iron $K_\alpha$ fluorescence emission line, which can be used to probe the geometry of the accretion flow. Existing observational data indicate that the presence of ADAFs in quiescent DN is not ubiquitous, while future observations, in particular with the X-ray satellites Chandra and XMM-Newton, have the potential to detect signatures of the hot flow in promising candidates.

Subject headings: X-ray: stars – ultraviolet: stars – binaries: close – accretion, accretion disks – stars: white dwarfs

1. Introduction

Cataclysmic Variables (CVs) are binary stars in which a main-sequence donor transfers mass via Roche-lobe overflow onto a White Dwarf (WD). Many CVs are members of the subclass of transient systems called Dwarf Novae (DN). DN regularly experience luminous outbursts during which accretion onto the WD proceeds at a high rate. Most of the time, however, DN are in quiescence, a phase during which the accretion rate onto the WD (and the system luminosity) are much reduced (see Warner 1995 for a review).

DN in quiescence are well known sources of hard X-ray emission, with typical luminosities $\sim 10^{30} - 10^{32}$ erg s$^{-1}$. (Córdova & Mason 1983; Patterson & Raymond 1985a). Spectral fits to the X-ray emission of these sources suggest a Bremsstrahlung origin, from a gas with temperatures $\sim 2 - 20$ keV (Patterson & Raymond 1985a; Eracleous, Halpern & Patterson 1991; Belloni et al. 1991; Yoshida, Inoue & Osaki 1992; Mukai & Shiokawa 1993).

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The X-ray emission of quiescent DN has commonly been attributed to their boundary layer (BL), at the interface between the accreting WD and the accretion disk surrounding it. Indeed, the BL can contribute to a large fraction of the total luminosity of a system, typically half of the accretion luminosity in the case of a non-rotating star (see, e.g., Frank, King & Raine 1992). At low accretion rates (\( \lesssim 10^{16} \text{ g s}^{-1} \)), such as in quiescent DN), the gas density in the BL is low and the gas is unable to cool. This leads to a hot and optically-thin BL which is a substantial source of hard X-ray emission (Pringle & Savonije 1979; Tylenda 1981; Patterson & Raymond 1985a).

Detailed calculations by Narayan & Popham (1993) show that the optically-thin BLs of accreting WDs are also radially extended (on the order of the WD radius in their models) and that they advect part of the internally dissipated energy as a consequence of their inability to cool. Partial radial pressure support by the hot gas also results in sub-Keplerian rotation profiles in these solutions. These are all properties that optically-thin BLs and Advection-Dominated Accretion Flows (ADAFs; Ichimaru 1977; Rees et al. 1982; Narayan & Yi 1994; 1995; Abramowicz et al. 1995) have in common, and it suggests that an ADAF is a possible outcome of accretion at a low rate onto a weakly-magnetized WD. In particular, if the radially extended BLs of Narayan & Popham (1993) were to extend, not to a stellar radius or so, but to several tens of stellar radii, they would have properties similar to those of ADAFs as they have been previously discussed in the literature (see, e.g., Narayan, Mahadevan & Quataert 1998 for a review).

In this paper, I examine some consequences of the presence of an ADAF around a WD. Advection can play an important role for the overall energy budget and the emission spectrum of the accretion flow. In §2, I state the model assumptions, describe the ADAF models used for the spectral predictions and explore their dependence on various model parameters. In §3, models including a thin disk in the outer regions of the flow are constructed for application to quiescent dwarf novae. Finally, I discuss several implications and important limitations of this work in §4, before summarizing the main results in §5.

2. ADAFs around White Dwarfs

In the following, we assume for simplicity that the properties of an ADAF around a WD can be described by simply truncating the ADAF solutions that have developed for the case of accretion onto a BH. As discussed in Appendix A, it is not clear if this assumption is fully valid.

The radius of a typical WD is \( \sim 10^3 R_s \), where \( R_s = 3 \times 10^5 M_{WD}/M_\odot \text{cm} \) is the Schwarzschild radius and \( M_{WD} \) is the mass of the WD. At radii \( \gtrsim 10^4 R_s \) in an ADAF, electrons are non-relativistic (implying negligible synchrotron emission) and the flow optical thickness to infinity is \( \ll 1 \) (implying negligible Comptonization), so that Bremmstrahlung emission is the only significant cooling mechanism for the flow. At these radii, the ADAF is also essentially one-temperature because Coulomb collisions transfer more efficiently the energy between the ions and the electrons (and the non-relativistic electrons have the same adiabatic index as the protons). Contrary to the case of accretion onto a black hole, this makes the structure of the hot flow in this context independent of the uncertain assumption of preferential viscous heating of the ions (Quataert & Gruzinov 1999). Note that, in the following, we consider only accretion onto a weakly-magnetized WD, in the sense that the stellar magnetic field is neglected in the description of the accretion flow structure.
2.1. Model Specifications

The nature of the interface between the ADAF and the WD surface is important for the emission models presented here. I make two further simplifying assumptions regarding this interface: (1) the angular velocity of the gas in the ADAF nearly matches that of the WD at the stellar surface so that there is no additional shear (nor dissipation) in this region, and (2) the gas carrying the energy advected by the ADAF penetrates deep enough into the optically thick regions of the stellar atmosphere that all this energy is thermalized before being radiated away. The validity of these assumptions and the consequences of relaxing them are discussed in more detail in Appendix A.

With assumption (1), the steady-state energetics of the accretion flow is equivalent to that described in Esin, McClintock & Narayan (1997), except for the effect of the presence of the stellar surface. The rate of energy advection $L_{\text{adv}}$ at the stellar surface and an average advection parameter $f_{\text{adv}}$ for the flow are obtained from the difference between the local values of the viscous dissipation rate and the radiative cooling rate, summed over the entire radial extent of the hot flow. In cases where the ADAF describes the corona of a thin accretion disk (i.e. with an accretion rate varying with radius; see §3), the energy required to evaporate the gas from the disk to the corona is also taken into account in the energy budget as a sink for the ADAF (see Esin et al. 1997 and §3 for details).

The ADAF models used here for the spectral predictions are similar to the models described in Narayan et al. (1998; see also Quataert & Narayan 1999b), except for the emission from the stellar surface. The reemission of the energy advected by the flow is modeled as a single-temperature blackbody of temperature:

$$T_{\text{eff}} = \left( \frac{L_{\text{adv}}}{4 \pi f \sigma R_{\text{WD}}^2} \right)^{1/4},$$

(1)

where $f$ is the fraction of the stellar surface that is emitting ($f = 1$ is assumed in what follows). The interaction of this extra component of the radiation field with the gas in the ADAF is calculated self-consistently (see Menou & McClintock 2000 for details), but is found to be unimportant in all the models presented.

Unless otherwise specified, the values adopted for the ADAF parameters are $\alpha_{\text{ADAF}} = 0.2$ (viscosity parameter), $\beta = 6$ (ratio of gas to magnetic pressure), $\delta = 10^{-2}$ (fraction of direct electron viscous heating; again, the precise value of this parameter is unimportant for the present models), $\gamma = 1.636$ (adiabatic index of the fluid, including contributions from the particles, magnetic field and turbulence; see Quataert & Narayan 1999a), $\rho = 0$ (no wind) and $i = 60^\circ$ (inclination). For the accreting WD, a mass $M_{\text{WD}} = 1.2 \ M_\odot$ and a radius $R_{\text{WD}} = 5 \times 10^8 \text{cm}$ are generally assumed. Note that accretion rates are often expressed in Eddington units ($\dot{m} = \dot{M}/\dot{M}_{\text{Edd}}$, with $\dot{M}_{\text{Edd}} = 1.39 \times 10^{18} (M_{\text{WD}}/M_\odot) \text{ g s}^{-1}$). All the models described in this section have ADAFs extending from the surface of the WD up to $10^4 \ R_\odot$. The luminosities predicted by the models are calculated by numerically integrating the spectral energy distributions in the appropriate energy range. X-ray luminosities are given for the $0.1 - 3.5$ keV band; this corresponds to the energy range covered by the X-ray satellite Einstein, which has collected the most extensive X-ray data set on DN to date (see, e.g., Eracleous et al. 1991).

2.2. Emission spectrum

Figure 1 and 2 show the emission spectra of ADAFs around WDs for various values of the model parameters. All these models are characterized by a two-component spectrum. The first component,
energetically dominant in the hard X-rays, is the Bremmstrahlung emission of the hot gas in the ADAF. The second component, energetically dominant in the EUV, is the accretion-powered emission from the WD surface. This EUV component dominates the ADAF X-ray emission because of the importance of energy advection: most of the energy dissipated in the flow is radiated at the WD surface. For simplicity, we assume that the X-ray photons emitted by the flow that reach the WD surface are absorbed and reemitted in the EUV component. The energy deposited by these photons at the WD atmosphere is generally negligible compared to the energy advected by the flow. The EUV radiation from the WD surface is found to escape to infinity without significantly interacting with the gas in the ADAF.

Note that the energetics of the EUV and X-ray components in the various models described below can be simply understood as follows. In first approximation, the luminosity of the EUV component from the WD is \( L_{\text{EUV}} \propto \dot{m} \). The X-ray luminosity of the ADAF, on the other hand, is due to Bremmstrahlung emission, which scales as the gas density squared, so that \( L_X \propto \dot{m}^2/\alpha_{\text{ADAF}}^2 \) (Narayan et al. 1998). The spectral models are characterized, to first order, by the ratio

\[
\frac{L_X}{L_{\text{EUV}}} \propto \dot{m}/\alpha_{\text{ADAF}}^2. \tag{2}
\]

### 2.3. Influence of \( \alpha_{\text{ADAF}} \)

Figure 1a shows the emission spectra of two ADAF models with a same accretion rate \( \dot{m} = 7 \times 10^{-3} \) but values of the viscosity parameter \( \alpha_{\text{ADAF}} = 0.1 \) and 0.3. In the model with \( \alpha_{\text{ADAF}} = 0.1 \), the gas in the ADAF has a smaller radial velocity and a larger density (Narayan & Yi 1994), responsible for the more important X-ray Bremmstrahlung emission than in the model with \( \alpha_{\text{ADAF}} = 0.3 \). The EUV luminosity is very similar in both models because most of the dissipated energy is advected and radiated by the WD photosphere in both cases. In the model with \( \alpha_{\text{ADAF}} = 0.1 \), the advection parameter is \( f_{\text{adv}} = 0.437 \) and the X-ray luminosity (0.1-3.5 keV) is \( \simeq 2 \times 10^{31} \) erg s\(^{-1} \). In the model with \( \alpha_{\text{ADAF}} = 0.3 \), the advection parameter is \( f_{\text{adv}} = 0.937 \) and the X-ray luminosity is \( \simeq 7.5 \times 10^{30} \) erg s\(^{-1} \). In both models, the total EUV luminosity is \( \simeq 2.5 \times 10^{33} \) erg s\(^{-1} \), at a temperature \( T_{\text{eff}} \simeq 5.3 \) eV.

### 2.4. Influence of \( M_{\text{WD}} \)

Figure 1b shows the emission spectra of two ADAF models, one with a WD of mass \( M_{\text{WD}} = 1.2 M_\odot \) and radius \( R_{\text{WD}} = 5 \times 10^8 \) cm as usual, and with \( \dot{m} = 7 \times 10^{-3} \); in the second model, the WD has a mass \( M_{\text{WD}} = 0.6 M_\odot \), a radius \( R_{\text{WD}} = 8.5 \times 10^8 \) cm, and the accretion rate has been doubled to \( \dot{m} = 1.4 \times 10^{-2} \) to allow for a comparison at the same physical accretion rate \( \dot{M} = \dot{m} M_{\text{Edd}} \simeq 10^{48} \) g s\(^{-1} \). The smaller mass and compactness of the WD in the model with \( M_{\text{WD}} = 0.6 M_\odot \) are responsible for the reduced and cooler photospheric WD emission, and the softer X-ray emission (because of a smaller range of temperatures in the ADAF; see Fig. 2b). In the model with \( M_{\text{WD}} = 1.2 M_\odot \), the advection parameter is \( f_{\text{adv}} = 0.85 \), the X-ray luminosity (0.1-3.5 keV) is \( \simeq 1.1 \times 10^{31} \) erg s\(^{-1} \) and the total EUV luminosity is \( \simeq 2.5 \times 10^{33} \) erg s\(^{-1} \), at a temperature \( T_{\text{eff}} \simeq 5.3 \) eV. In the model with \( M_{\text{WD}} = 0.6 M_\odot \), the advection parameter is \( f_{\text{adv}} = 0.665 \),

\[^2\text{In the model with } \alpha_{\text{ADAF}} = 0.1, \text{the value of the parameter } \beta \text{ is 10, while } \beta = 3 \text{ in the model with } \alpha_{\text{ADAF}} = 0.3. \text{ This is to represent the larger viscosity expected when the magnetic pressure in the flow is larger, as suggested by MHD simulations of accretion disks (see Narayan et al. 1998 for details).}\]
the X-ray luminosity is \( \simeq 7.3 \times 10^{30} \) erg s\(^{-1}\) and the total EUV luminosity is \( \simeq 7.3 \times 10^{32} \) erg s\(^{-1}\), at a temperature \( T_{\text{eff}} \simeq 3 \) eV.

### 2.5. Influence of \( \dot{m} \)

Figure 2a shows three models with accretion rates \( \dot{m} = 2.1 \times 10^{-2}, \dot{m} = 7 \times 10^{-3} \) and \( \dot{m} = 3 \times 10^{-3}\). At higher accretion rates, the density in the ADAF is larger and the cooling is more efficient, so that the ratio of EUV to X-ray luminosity is reduced. The advection parameter in these models is \( f_{\text{adv}} = 0.63, 0.85 \) and 0.93, respectively. The corresponding X-ray luminosity (0.1 – 3.5 keV) for each model is \( \simeq 10^{32}, 1.1 \times 10^{31} \) and \( 2 \times 10^{30} \) erg s\(^{-1}\), respectively. The corresponding total EUV luminosity for each model is \( \simeq 7.2 \times 10^{33} \) erg s\(^{-1}\) (effective temperature \( T_{\text{eff}} \simeq 6.9 \) eV), \( 2.5 \times 10^{33} \) erg s\(^{-1}\) (\( T_{\text{eff}} \simeq 5.3 \) eV) and \( 10^{33} \) erg s\(^{-1}\) (\( T_{\text{eff}} \simeq 4.3 \) eV), respectively.

Figure 2b shows that the ion and electron temperatures in the accretion flow are almost independent of the accretion rate \( \dot{m} \) (contrary to the two-temperature case; see Esin et al. 1997). The difference in the temperature profile for the model with \( \alpha_{\text{ADAF}} = 0.3 \) can be attributed to the smaller value of \( \beta \), which modifies the relative importance of the gas and magnetic pressure in the flow. The temperature profile does not depend on \( M_{\text{WD}} \), in the sense that if one were to superpose the temperature profiles of the two models shown in Fig. 2b, they would be nearly indistinguishable. The shorter radial extent of the ADAF in the model with \( M_{\text{WD}} = 0.6 \) M\(_{\odot}\), however, implies a cooler accretion flow, with a maximum temperature \( \log[T(K)] \simeq 8.2 \) at the WD surface. The range of gas temperatures in the ADAF (from a few keV to a few tens of keV) depends therefore primarily on the radial extent of the hot flow.

### 3. Models with an Outer Thin Disk

More realistic models for quiescent DN must include the presence of a thin disk in the outer regions of the accretion flow. According to the disk instability model (DIM), this disk is responsible for the outbursts of DN, by storing mass during quiescence and accreting it suddenly during outburst under the action of a thermal-viscous instability (see Cannizzo 1993 for a review of the DIM).

Ignoring the exact structure of the transition region from the disk to the ADAF, I adopt here for simplicity the prescription of Esin et al. (1997). Beyond a transition radius \( R_{\text{trans}} \) to be defined, the mass accretion rate in the ADAF (= the disk corona) declines as \( R_{\text{trans}}/R \). This corresponds, as one goes in, to a gradual evaporation of the disk material into the corona, up to the point where, inside \( R_{\text{trans}}/R \), accretion occurs exclusively via the ADAF (Esin et al. 1997).

The disk reflection component and its iron \( K_{\alpha} \) fluorescence line are also modeled following Esin et al. (1997). Angle-averaged energy-dependent Green’s functions are used to predict the intensity of the line which depends on the supply of hard X-ray photons from the ADAF irradiating the disk (Lightman & White 1988; George & Fabian 1991). The disk is supposed to contain neutral material with a cosmic abundance of \( 3.3 \times 10^{-5} \) iron atoms per hydrogen atom (Morrison & McCammon 1983). The line profile is not modeled in detail here. However, the contribution to the line emission of each disk annulus, at a radius \( R \) from the WD, is given the proper fractional Doppler width \( \sin i/(2R/R_{\odot})^{1/2} \) (\( i \) is the disk inclination to the line of sight) and is added to the continuum emission in the proper energy bin of the computed spectrum. Note that the simple prescription used here for the variation of the accretion rate with radius.
beyond $R_{\text{trans}}$ does not necessarily guarantee that the disk material is neutral everywhere, as expected in the DIM (Wheeler 1996). It is not important for our purpose, however, because we are not interested in the disk emission properties, but instead explore the effect of varying its radial extent on the intensity of the reflection component, assuming that the disk is neutral as the DIM would predict.

### 3.1. The reflection component

Figure 3a shows the spectra predicted for a thin disk + ADAF model, under various assumptions for the accretion rate $\dot{m}$ and the disk radial extent. An inclination $i = 60^\circ$ is assumed in all four models. The solid line represents the total emission from the accretion flow, including the EUV contribution from the WD surface (dotted) and the contribution from the disk (long-dashed-dotted). The disk reflection component peaks at X-ray frequencies, while the disk intrinsic emission peaks at optical frequencies (again, this component is not supposed to represent the actual emission of a quiescent disk according to the DIM – see above). In all cases, the disk reflection component contributes only to a small fraction of the continuum X-ray flux, as expected. Depending on the geometry of the accretion flow, however, an iron $K\alpha$ emission line is present and is potentially observable on top of the X-ray continuum.

Figure 3a and b show two models with a value of the transition radius $R_{\text{trans}} = 10^4 R_\text{s}$ and a disk (+ ADAF-corona) extending up to $10^5 R_\text{s}$ (the precise value of this maximum radius is unimportant for the spectral predictions discussed here). Figure 3c and d show two models with a disk extending further in, down to $R_{\text{trans}} = 10^{3.5} R_\text{s}$. In each case, models for two values of the accretion rate $\dot{m}$ are shown.

The luminosity in the iron $K\alpha$ fluorescence line at 6.4 keV measures the amount of photons absorbed by the disk at energies $> 7.1$ keV, corresponding to the iron K-shell absorption edge seen in each of the reflection components in Fig. 3. Consequently, the line intensity mainly depends on the accretion rate in the ADAF (for the overall X-ray luminosity) and the location of the disk relative to the hottest regions of the flow (to guarantee the absorption by the disk of a large amount of hard enough photons). Fig 2b shows that temperatures above $\sim 10^8$ K in the ADAF are found only inside $R \simeq 10^4 R_\text{s}$, so that little or no $K\alpha$ line emission is expected for disks extending beyond this limit. This is confirmed by Fig. 3a and b which show rather weak line emission in the reflection component, and no significant emission on top of the continuum, for two different values of $\dot{m}$. On the other hand, Fig. 3c and d (corresponding to $R_{\text{trans}} = 10^{3.5} R_\text{s}$) show stronger iron fluorescence lines, which can be seen on top of the Bremsstrahlung continuum emission from the hot flow. Obviously, the lines would be even stronger if the disk was extending further in. The strength of this line is therefore a probe of the geometry of the accretion flow in the system. For $i = 60^\circ$ and $R = 10^{3.5} R_\text{s}$, resolving the width of the iron lines shown in Fig. 3 and d requires a spectral resolution $\simeq 92$, so that the resolving power of order 200 that can be reached with Chandra around 7 keV (with HETG) could allow detailed diagnostics of the line-emitting material if such a line is present and strong enough.

Note that ADAFs around low-mass WDs (say $<0.5 M_\odot$ or so) are not expected to be surrounded by a gas with temperatures much in excess of $10^8$ K because of the large size of the compact object (Fig. 2b). DN containing low-mass WDs are therefore not expected to show significant iron fluorescence line emission no matter how extended their disks are.
3.2. Explaining the HeII emission lines

A likely origin for the strong HeII $\lambda 4686$ emission lines shown by many DN is photoionization of the disk material by very soft X-rays in the energy range $55$–$280$ eV (Patterson & Raymond 1985b). However, there is no direct detection of these irradiating photons by either ROSAT (soft X-rays) or IUE (UV). This led Vrtilek et al. (1994) to propose that these photons could originate from an EUV component, such as blackbody emission with a temperature $\sim 10$ – $20$ eV. This makes the advection-powered EUV emission from a WD surrounded by an ADAF a good candidate for explaining the strength of the HeII emission lines in quiescent DN.

A detailed calculation of the strength of these lines for a given accretion model requires the knowledge of the amount of photons with appropriate energies which are absorbed by the disk. The result of this calculation depends on the the disk geometry (which is not described properly in the present models given the arbitrary profile assumed for $\dot{m}$ in the disk) and, more importantly in the present case, on the assumption of exact reemission as a single-temperature blackbody for the advected energy, which has a strongly peaked contribution at low energies in the $0.055$–$0.28$ keV range (see, e.g., Fig. 3). This means that even a slight deviation from the strict blackbody emission hypothesis could largely influence the predictions for the line strength. Consequently, I use here, instead of a detailed calculation, the simple argument of Patterson & Raymond (1985b; see also Vrtilek et al. 1994) to show that the spectral models of Fig. 3 can account for the observed luminosities of the HeII lines in quiescent DN.

Following Patterson & Raymond (1985b), the luminosity of a system in the HeII $\lambda 4686$ lines is estimated as

$$L_{\lambda 4686} = (0.26)(\eta) \left( \frac{2.65 \text{ eV}}{130 \text{ eV}} \right) \times L_{0.055-0.28} = 5.3 \times 10^{-4} L_{0.055-0.28},$$  \hspace{1cm} (3)

where $0.26$ is the fraction of He recombinations resulting in photons at $\lambda = 4686$ Å, $\eta = 0.1$ is a geometrical factor corresponding to the fraction of the irradiating source luminosity that is actually absorbed by the disk $3$ 130 eV is an assumed energy for a typical ionizing photon and $L_{0.055-0.28}$ is the luminosity of the irradiating source (the WD here) in the 0.055 – 0.28 keV energy range. Eq. (3) has been used by Patterson & Raymond (1985b; see also Vrtilek et al. 1994) to argue for the existence of a yet unseen soft source of ionizing photons. Note that because the EUV emission from the WD surface in the energy range 0.055-0.28 keV strongly peaks at low energies in the present models, the typical energy of ionizing photons could reasonably be estimated as being less than 130 eV. This, and possible deviations from a pure blackbody emission, could result in somewhat larger values for $L_{\lambda 4686}$ than estimated below.

For the three models shown in Fig. 3 (or, equivalently, the models with the same $\dot{m}$ in Fig. 3), the value of $L_{0.055-0.28}$ are $\simeq 1.4 \times 10^{33}$ erg s$^{-1}$ ($\dot{m} = 2.1 \times 10^{-2}$), $1.1 \times 10^{32}$ erg s$^{-1}$ ($\dot{m} = 7 \times 10^{-3}$) and $10^{31}$ erg s$^{-1}$ ($\dot{m} = 3 \times 10^{-3}$). This corresponds, according to Eq. (3), to luminosities $L_{\lambda 4686} \simeq 7.4 \times 10^{29}$ erg s$^{-1}$, $5.8 \times 10^{28}$ erg s$^{-1}$ and $5.3 \times 10^{27}$ erg s$^{-1}$, respectively. This is within the range of observed values for quiescent DN with accretion rates $\lesssim 10^{16}$ g s$^{-1}$ (Patterson & Raymond 1985b), corresponding to $\dot{m} \lesssim 10^{-2}$. The models presented here satisfy the criterion for the postulated missing soft component (Patterson & Raymond 1985b): an emission which provides a luminosity equal or superior to that in the 0.1-3.5 keV range and which is suitable for concentrating a large fraction of the luminosity in the 55-280 eV energy range. Note that for small WD masses, the contribution of the EUV component in the 55-280 eV energy

3The value $\eta = 0.1$ used by Patterson & Raymond (1985b) is based on a geometric model of the central X-ray source. The authors quoted an uncertainty of a factor 3 in either direction for $\eta$. This same value should be appropriate for the order-of-magnitude estimates made here.
band can be much reduced because $R_{\text{WD}}$ is larger and the EUV emission is then softer. This, again, depends critically on the assumption of exact reemission like a single-temperature blackbody.

The success of the proposed accretion models in providing an explanation to both the X-ray emission and the strong HeII $\lambda 4686$ emission lines of quiescent DN must be moderated, however, by noting that existing observations indicate that these models cannot be applied to the entire population of quiescent DN (see below).

4. Discussion

I have constructed idealized models of Advection-Dominated Accretion Flows (ADAFs) around WDs, for application to quiescent DN. In the more elaborate models, an ADAF is present in the inner regions of the flow, while accretion proceeds via a thin disk (plus a corona, treated as an ADAF here) in the outermost regions. According to the Disk Instability Model (DIM), the thin disk is a reservoir a mass used to power the dwarf nova outbursts (see, e.g., Cannizzo 1993). These models are inspired from the models of Narayan, Barret & McClintock (1997; see also Lasota, Narayan & Yi 1996) for quiescent Black Hole (BH) Soft X-ray Transients. If the presence of such a two-component accretion flow is established in some quiescent DN, it may be possible to interpret the various spectral states of these systems as changes in the geometry of the two-component accretion flow, by analogy with the models for BH transients (see Esin et al. 1997; 1998).

However, the models for quiescent DN differ significantly from those of BH transients for at least two reasons. First, the properties of the ADAF are different here because the radial extent of the hot flow is reduced around a WD (an object much less compact than a stellar-mass BH). As a consequence, the gas in the hot flow is one-temperature (because of efficient Coulomb coupling at lower temperatures) and the property of energy advection is independent of the assumption of preferential heating of the ions by the viscous dissipation (and poor energy exchange between the ions and the electrons) made for two-temperature ADAFs.

Second, and more importantly, while the energy advected by the flow is lost through the event horizon in the BH case, it must be reradiated from the hard surface of the WD in the DN case. Assuming that this energy is thermalized in the WD atmosphere, I have shown that the resulting EUV emission from the WD surface could explain the puzzling strength of HeII $\lambda 4686$ emission lines of quiescent DN as due to disk irradiation, while the X-ray properties of the same systems could be explained by the X-ray emission from the ADAF itself. The strong EUV component is not unique to ADAF models but could also be a consequence of substantial energy advection in the BL solutions of Narayan & Popham (1993) if, again, this energy is thermalized before being radiated away. A direct test of the existence of this strong EUV component, as a possible signature of energy advection in the flow surrounding the WD, would be quite valuable.

It may not be easy to discriminate, based on observations, between the BL solutions of Narayan & Popham (1993) and a radially extended ADAF around a WD. They are both sources of hard X-ray emission and energy advection. The BL solutions are characterized by a small radial extent compared to the ADAF models presented here and higher gas densities: $\rho \sim 10^{-10.5}$ g cm$^{-3}$ in the model d of Fig. 3, while $\rho \sim 10^{-9}$ g cm$^{-3}$ in a comparable model of Narayan & Popham (1993). The emission spectrum of the BL solutions has not been calculated by Narayan & Popham (1993), but it is clear that the higher densities counterbalance the smaller radial extent for the total X-ray emission. If the ADAFs were much less radially extended than assumed in the proposed models (say a few stellar radii at most), they could not produce
X-ray emission at the level observed in quiescent DN because of their low densities.

The proposed models for quiescent DN (with a inner hot flow replacing the traditional thin disk) share some properties with the coronal “siphon flow” model of Meyer & Meyer-Hofmeister (1994). An important difference, however, is the presence in their model of a wind from the hot flow, which is absent in the ADAF models presented here. It has been proposed that ADAFs could have winds (Narayan & Yi 1994; Blandford & Begelman 1999) able to carry away some of the dissipated energy that is not radiated by the flow. This could have consequences for the emission spectrum of a system (in particular a reduction of the EUV component originating at the WD surface) that were not considered here. Interestingly, Meyer & Meyer-Hofmeister (1994) proposed that heat conduction between the hot flow and the cold gas in the disk is responsible for the continuing “evaporation” of the cold disk material into the hot coronal flow. This process could operate equally well in the present context (ADAF + thin disk) and may be responsible for a transition from the BL solutions with a modest radial extent of Narayan & Popham (1993) to a more radially extended ADAF as considered in the present study.

The presence of an inner, extended hot flow in quiescent DN could also influence the outburst properties of these systems, as first emphasized by Meyer & Meyer-Hofmeister (1994; see also Liu, Meyer & Meyer-Hofmeister 1997). These authors pointed out that the presence of this low density region could be responsible for the well-known UV delay of DN (see, e.g., Warner 1995; Mauche 1996), by ensuring that, during the rise to outburst, the disk has to fill in the inner regions of the flow before a substantial amount of mass is accreted onto the WD (Meyer & Meyer-Hofmeister 1994; Liu et al. 1997; Hameury, Lasota & Dubus 1999). An analogous situation has been suggested for the BH X-ray transient GRO J1655-40 because of a delay of the rise of the X-ray flux relative to the optical flux during the April 1996 outburst of this system (Orosz et al. 1997); this delay has been modeled successfully by Hameury et al. (1997) with a two component, inner ADAF + outer thin disk, time-dependent accretion model.

Observations show that some quiescent DN are more likely to harbor an ADAF than others. Of the five DN observed in quiescence by the Hopkins Ultraviolet Telescope (Long 1996; spectral range $\sim 830 - 1860\,\AA$), two have shown the expected spectral UV signatures from a WD atmosphere (in particular a broad Ly$\alpha$ absorption feature and narrow metal absorption lines): U Gem and VW Hyi. However, the remaining three (WX Hyi, Yz Cnc and SS Cyg) show strong, blue continua with no evidence for the presence of a normal WD atmosphere (broad emission lines and no evidence for the expected Ly$\alpha$ absorption feature). These three sources with strong blue excesses are ideal candidates for the presence of an ADAF because a blue UV continuum is expected if the WD atmosphere is heated up to a several 10,000 K by a substantial amount of energy advection in the surrounding hot flow. That two out of the five observed quiescent DN possess the signature expected from a “naked” WD shows the large diversity of these systems and suggest that ADAF models do not apply to the entire DN population. On physical grounds, a spread in the observational properties of quiescent DN could be due, for instance, to differences in the WD rotation rate, the surface magnetic field strength or the radial extent of the hot flow for the various systems. Note that observations during quiescence suggest the existence of an “accretion belt” on the central WD in the DN VW HYi (and perhaps U Gem; see Sion 1999 for a review). This accretion belt, hotter than the rest of the WD surface, is supposedly the result of accretion at a high rate via a disk during DN outbursts (Kippenhahn & Thomas 1978). The presence of such accretion belts and of ADAFs in quiescence are not mutually exclusive.

Similarly, existing X-ray observations put strong constraints on the presence of ADAFs in some quiescent DN. X-ray eclipses during the quiescence of the dwarf novae HT Cas (Wood et al. 1995; Mukai et al. 1997) and OY Car (Pratt et al. 1999) show that the size of the X-ray emitting region is at most
comparable to the WD radius, and Szkody et al. (1996) claim that the X-ray emitting region in U Gem during quiescence is small as well. These observations appear inconsistent with the emission from a radially extended ADAF because the bulk of the Bremsstrahlung emission, with an emissivity $\propto \rho^2 T^{-1/2}$ and for the profiles $\rho \propto R^{-3/2}$ and $T \propto R^{-1}$ in an ADAF, originates from the outermost regions of the flow (see also Quataert & Narayan 1999b). This indicates, again, that ADAF models do not apply to the entire DN population, or perhaps, that if a hot flow is present in these systems, it has a structure different from an ADAF (for instance with a steeper density profile, which is contrary to what is expected for an ADAF with wind; Blandford & Begelman 1999). van Teeseling, Beurmann & Verbunt (1996) claim that the X-ray emitting region in non-magnetic CVs is close to the WD from an anticorrelation of the soft X-ray luminosity and the inclination of several of these sources. This cannot be used to strongly argue against the extended ADAF hypothesis because even a slight deviation from the assumed blackbody-type emission of the advected energy could make this component, originating close to the WD, dominate the soft X-ray flux of the system.

There are other possible consequences of the presence of an ADAF in quiescent DN which have not been considered in any detail here. The presence of such a hot flow during the long phases of quiescence could influence the time-averaged rotation rate of the weakly-magnetized WD. The star accretes from a Keplerian disk during outburst, but could also accrete from a substantially sub-Keplerian flow during quiescence. At late evolutionary stages, the star could therefore spin at an equilibrium rate which is in between the breakup value ($\Omega_K(R_{WD})$) and the rotation rate of the gas in the ADAF ($\sim 0.2 - 0.3\Omega_K$), rather than close to the breakup rate if it accretes all the time from a disk.

The presence of an ADAF in a quiescent DN can be directly tested by the detailed spectroscopic X-ray observations which have become possible with the satellites Chandra and XMM. The continuum emission of the ADAF is characteristic of a gas with temperatures in the range of a few keV to a few tens of keV, depending on the radial extent of the hot flow. The hot gas in the ADAF is also ideally suited for emitting thermal X-ray lines (Narayan & Raymond 1999). The detectability of these lines and their role as possible diagnostics of the hot flow structure (Perna, Raymond & Narayan 2000) are the subject of a separate study (Menou, Perna & Raymond, in preparation).

5. Conclusion

Motivated by the analogy between the optically-thin BL solutions of Narayan & Popham (1993) and Advection-Dominated Accretion Flows (ADAFs), I constructed idealized models of ADAFs around WDs, for application to quiescent DN. The critical assumptions made in this work are discussed in detail in Appendix A.

The Bremsstrahlung emission from the ADAF can account for the X-ray emission properties of quiescent DN. In addition, if the energy advected by the flow is thermalized in the WD atmosphere before being radiated away, the strong HeII lines of many quiescent DN could simply result from the photoionization of the disk material by the UV-luminous WD.

The presence of an ADAF in quiescent DN could have several additional interesting implications, such as offering a possible test of the accretion flow geometry by the detection of an iron $K_\alpha$ fluorescence line from the X-ray irradiated disk, or providing a possible explanation to the “UV-delay” of DN.

Although existing observational data already show a large diversity in the DN population and indicate
that ADAFs are probably not present in all quiescent DN, prospects for testing the ADAF hypothesis in promising DN candidates are good, especially with the recent advent of the powerful X-ray satellites Chandra and XMM-Newton.

Acknowledgments

I am grateful to Phil Charles, Eric Kuulkers and Tariq Shahbaz for questionning the possible role of ADAFs around WDs, and to Ann Esin, Brad Hansen, Jean-Pierre Lasota, Ramesh Narayan, Bohdan Paczynski, Rosalba Perna, John Raymond and Eliot Quataert for useful discussions. I thank R. Narayan for providing the code that he developed for studying ADAFs around neutron stars. The calculations of the disk reflection component make use of numerical routines developed by A. Esin. Support for this work was provided by NASA through Chandra Postdoctoral Fellowship grant number PF9-10006 awarded by the Chandra X-ray Center, which is operated by the Smithsonian Astrophysical Observatory for NASA under contract NAS8-39073.

REFERENCES

Abramowicz, M.A., Chen, X., Kato, S., Lasota, J.-P. & Regev, O., 1995, ApJ, 438, L37.
Belloni, T., et al., 1991, A&A, 246, L44.
Blandford, R.D. & Begelman, M.C., 1998, MNRAS, 303, L1.
Cannizzo, J.K. 1993, in Accretion Disks in Compact Stellar Systems, ed. J.C. Wheeler (Singapore: World Scientific), p. 6.
Córdova, F.A. & Mason, K.O., 1983, in Accretion Driven Stellar X-ray Sources, eds. W.H. Lewin & E. van den Heuvel (CUP), p. 147.
Cox, A.N. & Tabor, J.E., ApJS, 31, 271.
Eracleous, M., Halpern, J. & Patterson, J., ApJ, 382, 290 (1991).
Esin, A.A., McClintock, J.E., & Narayan, R., 1997, ApJ, 489, 865.
Esin, A.A., Narayan, R., Cui, W., Grove, J.E. & Zhang, S.-N., 1998, ApJ, 505, 854.
Frank, J., King, A. & Raine, D., 1992, Accretion Power in Astrophysics (Cambridge: Cambridge University Press).
Greeley, B.W., Blair, W.P., Long, K.S. & Raymond, J.C., ApJ, 513, 491.
George, I.M. & Fabian, A.C., 1991, MNRAS, 249, 352.
Hameury, J.-M., Lasota, J.-P. & Dubus, G., 1999, MNRAS, 303, 39.
Hameury, J.-M., Lasota, J.-P., McClintock, J. E. & Narayan, R., 1997, ApJ, 489, 234.
Ichimaru, S., 1977, ApJ, 214, 840.
King, A.R. & Lasota J.-P., 1979, MNRAS, 188, 653.
King, A.R. & Lasota J.-P., 1980, MNRAS, 191, 721.
Kippenhahn, R. & Thomas, H.-C., 1978, A&A, 63, 265.
Kuijpers, J. & Pringle, J.E., 1982, A&A, 114, L4.
Lasota, J.-P., Narayan, R. & Yi, I., 1996, A&A, 314, 813.
Liu, B.F., Meyer, F. & Meyer-Hofmeister, E., 1997, A&A, 328, 247.
Lightman, A.P. & White, T.R., 1988, ApJ, 335, 57.
Long, K., 1996, in IAU Colloquium 158, “Cataclysmic Variables and Related Objects”, Eds. A. Evans & J.H. Wood, p. 233.
Mauche, C.W., 1996, in Astrophysics in Extreme Ultraviolet, IAU Coll. 152, Bowyer, S. & Bowyer, R.F., eds, (Kluwer: Dordrecht), p. 317.
Menou, K. & McClintock, J.E., 2000, ApJ, submitted.
Meyer, F. & Meyer-Hofmeister, E., 1994, A&A, 288, 175.
Morrison, R. & McCammon, D., 1983, ApJ, 270, 119.
Mukai, K. & Shiozawa, K., 1993, ApJ, 418, 863.
Mukai, K., Wood, Janet H., Naylor, T., Schlegel, E.M. & Swank, J.H., 1997, ApJ, 475, 812.
Narayan, R., Barret, D. & McClintock, J.E., 1997, ApJ, 482, 448.
Narayan, R., Mahadevan, R. & Quataert, E., 1998b, in The Theory of Black Hole Accretion Discs, eds. M. A. Abramowicz, G. Bjornsson, and J. E. Pringle (Cambridge: Cambridge University Press), astro-ph/9803141.
Narayan, R., McClintock, J.E. & Yi, I., 1996, ApJ, 457, 821.
Narayan, R. & Popham, R., 1993, Nature, 362, 820.
Narayan, R. & Raymond, J.C., 1999, ApJL, 515, L69.
Narayan, R. & Yi, I., 1994, ApJ Lett., 428, L13.
Narayan, R. & Yi, I., 1995, ApJ, 444, 231.
Orosz, J.A., Remillard, R.A., Bailyn, C.D. & McClintock, J.E., 1997, ApJ, 478, L83.
Patterson, J. & Raymond, J.C., 1985a, ApJ, 292, 535.
Patterson, J. & Raymond, J.C., 1985b, ApJ, 292, 550.
Perna, R., Raymond, J.C. & Narayan, R., 2000, ApJ, in press, astro-ph/0005387.
Popham, R. & Gammie, C.F., 1998, ApJ, 504, 419.
Pratt, G.W., Hassall, B.J.M., Naylor, T. & Wood, J.H., 1999, MNRAS, 307, 413.
Pringle, J.E. & Savonije, G.J., 1979, MNRAS, 187, 777.
Quataert, E. & Gruzinov, A., 1999, ApJ, 520, 248.
Quataert, E. & Narayan, R., 1999a, ApJ, 516, 399.
Quataert, E. & Narayan, R., 1999b, ApJ, 520, 298.
Rees, M.J., Phinney, E.S., Begelman, M.C. & Blandford, R.D., 1982, Nature, 295, 17.
Sion, E.M., 1999, PASP, 111, 532.
Szkody, P., Long, K.S., Sion, E.M. & Raymond, J.C., 1996, ApJ, 469, 834.
Tylenda, R., 1981, Acta Astr., 31, 267.
van Teeseling, A., Beuermann, K. & Verbunt, F., 1996, A&A, 315, 467.
van Teeseling, A., Heise, J. & Paerels, F., 1994, A&A, 281, 119.
Vrtilek, S.D., Silber, A., Raymond, J.C. & Patterson, J., 1994, ApJ, 425, 787.
Warner, B., 1995, Cataclysmic Variable Stars, (Cambridge: Cambridge University Press).
Wheeler, J.C., 1996, in Relativistic Astrophysics, eds. B. Jones & D. Markovic (Cambridge: Cambridge University Press), p. 211.
Wood, J.H., Naylor, T., Hassall, B.J.M. & Ramseyer, T.F., 1995, MNRAS, 273, 772.
Yoshida, K., Inoue, H. & Osaki, Y., 1992, PASJ, 44, 537.

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A. Critical Assumptions

The focus of this study is put on the emission spectrum of an ADAF around a WD. In this appendix, I discuss a set of assumptions which are crucial for the results presented. The validity of these assumptions is not proven (nor obvious) and possible consequences of their invalidity are discussed. These assumptions concern the structure of the hot flow surrounding the WD, the nature of the interface between the flow and the WD, and the outcome of the energy advected by the flow when it reaches the WD surface.

A.1. The Hot Flow and the Interface with the WD

Advection onto a WD differs significantly from accretion onto a BH in that the gas does not have to cross a sonic point but, instead, it must have a radial infall speed reaching zero at the stellar surface. The neglect of this boundary condition, by using ADAF dynamical solutions initially developed for the case of accretion onto a BH (Popham & Gammie 1998), is an important weakness of the present study. This description of the hot flow around the WD therefore assumes a high radial infall speed for the gas (a fraction of its free-fall speed) and a sudden reduction of this speed to zero only in the close vicinity of the WD. Proving this assumption right or wrong by solving the dynamical equations for the flow, with the proper boundary conditions, is beyond the scope of the present work. It is worth noting, however, that this sudden reduction of the radial infall speed of the hot flow at the WD surface is found in the BL solutions of Narayan & Popham (1993).

Another region of the flow that is not described in detail in proposed the models is the interface between the hot flow and the WD, where the sudden reduction of the radial infall speed of the gas occurs. The energetics of this region can be described in the following simple terms. In a thin accretion disk, half of the gravitational potential energy available is radiated away by the disk, while the other half remains in the flow in the form of rotational kinetic energy (Frank et al. 1992). The energy budget is different in an ADAF, with three energy reservoirs: the rotational kinetic energy, the radial (infall) kinetic energy and the thermal kinetic energy of the hot gas (only a small fraction of the available energy is radiated away by the flow).

In the models presented here,

\[ \Omega_{\text{ADAF}} \simeq 0.2 \Omega_K, \]

\[ v \simeq \alpha_{\text{ADAF}} v_H \simeq \alpha_{\text{ADAF}} R \Omega_K, \]

where \( \Omega_{\text{ADAF}} \) is the rotation rate of the ADAF, \( \Omega_K \) is the Keplerian rate, \( v \) is the gas infall speed and \( v_H \) is the free-fall speed (see Narayan et al. 1998). This corresponds to rotational and kinetic energies per unit mass

\[ E_\phi \simeq \frac{1}{2} (0.2 R \Omega_K)^2, \]

\[ E_t \simeq \frac{1}{2} (\alpha_{\text{ADAF}} R \Omega_K)^2, \]

respectively. These energies are therefore comparable (for \( \alpha_{\text{ADAF}} = 0.2 \), \( \simeq 2 \times 10^{-2} R^2_{\text{WD}} \Omega^2_K (R) \)) per unit mass at the WD surface.

The total gravitational potential energy released per unit mass at the WD surface is

\[ E_{\text{pot}} = \frac{GM_{\text{WD}}}{R_{\text{WD}}} = R^2_{\text{WD}} \Omega^2_K (R_{\text{WD}}), \]
so that \( E_\phi \) and \( E_r \) are small, \( \sim 2 \times 10^{-2} E_{\text{pot}} \). The remaining part (i.e. most) of the potential energy is in the form of thermal energy in the hot gas for an ADAF.

For the spectral models presented in this study, \( E_\phi \) and \( E_r \) have been added to the advected energy \( \sim E_{\text{pot}} \) to power the EUV radiation from the WD surface. The models shown in Fig. 2a, for instance, have typical ratios of integrated EUV luminosity to integrated X-ray luminosity of a hundred or more. If the contributions \( E_\phi \) and \( E_r \) were released in optically-thin regions (at the interface between the ADAF and the WD surface), they could modify the models predictions for the X-ray emission significantly because they have magnitudes comparable to or larger than the Bremsstrahlung emission from the hot flow. Note that the non-zero rotation rate of the WD tends to reduce the importance of \( E_\phi \), especially for the values of a few \% to a few tens of \% of \( \Omega_K(R_{WD}) \) reported for the rotation rates of WDs in DN (see, e.g., Sion 1999).

### A.2. The Fate of the Advected Energy

Assuming that the properties of the ADAF surrounding the WD are those discussed above, the fate of the energy advected by the flow when it reaches the WD surface is still left unspecified. It is crucial for the spectral predictions to know if this energy is released in optically-thin or optically-thick regions at the WD surface.

There are two cooling channels for the hot gas carrying the energy: conduction and radiation. I will now show that cooling by radiation seems unlikely to result in the release of this energy in optically-thick regions at the WD surface.

#### A.2.1. Radiation

Let’s assume that the advected energy is indeed released in optically-thick regions at the WD surface. The photospheric temperature of the heated WD can then be estimated via Eq. (1), which yields

\[
T_{\text{ph}} = 3.1 \times 10^4 \dot{M}^{1/4} M_{\text{WD}}^{1/4} R_9^{-3/4} K, \tag{A6}
\]

where \( \dot{M}_{16} \) is the accretion rate onto the WD in units of \( 10^{16} \) g s\(^{-1} \) and \( R_9 \) is the WD radius in units of \( 10^9 \) cm. We will assume \( \dot{M}_{\text{WD}} = 1.2 M_\odot \) and \( R_9 = 0.5 \) in what follows. This gives

\[
T_{\text{ph}} \simeq 54,500 \text{ K}, \tag{A7}
\]

for \( \dot{M}_{16} = 1 \).

The density of the regions at the WD surface where the infalling of gas in the ADAF is stopped can be estimated by equating the kinetic pressure \( P_{\text{gas}} \) of the gas in these regions to the ram pressure \( P_{\text{ram}} \equiv \rho v^2 \) of the flow, with

\[
P_{\text{ram}} = \frac{\dot{M}}{4\pi R^2} \alpha_{\text{ADAF}} V_{\text{ff}} \tag{A8}
\]

\[
\simeq 4.1 \times 10^5 \alpha_{\text{ADAF}} \dot{M}_{16} M_{\text{WD}}^{1/2} R_9^{-5/2} \text{ dyne cm}^{-2} \tag{A9}
\]

for the ADAF, where \( V_{\text{ff}} \equiv (2GM_{\text{WD}}/R)^{1/2} \) is the free fall velocity and \( v = \alpha_{\text{ADAF}} V_{\text{ff}} \) is the radial infall speed in the ADAF (Narayan & Yi 1994).
The corresponding stopping density \( \rho_{\text{stop}} \) is therefore given by

\[
P_{\text{gas}} = \frac{\rho_{\text{stop}} k_B T_p}{\mu m_p} = P_{\text{ram}},
\tag{A10}
\]

where I adopt a value \( \frac{1}{2} \) for the mean molecular weight \( \mu \), \( k_B \) is the Boltzmann constant and \( m_p \) is the proton mass. This gives

\[
\rho_{\text{stop}} \simeq 7.9 \times 10^{-8} \alpha_{\text{ADAF}} M_{16}^{3/4} M_{\text{WD}}^{1/4} R_9^{-7/4} \text{g cm}^{-3}
\tag{A11}
\]

or

\[
\rho_{\text{stop}} \simeq 5.5 \times 10^{-8} \text{g cm}^{-3}
\tag{A12}
\]

for \( \dot{M}_{16} = 1 \) (\( M_{\text{WD}} = 1.2 M_\odot \) and \( R_9 = 0.5 \)). The Rosseland mean opacity (see, e.g., Cox & Tabor 1976) corresponding to \( \rho_{\text{stop}} \) and \( T_{\text{ph}} \) is

\[
\kappa_{\text{stop}} \simeq 13 \text{ cm}^2 \text{g}^{-1}.
\tag{A13}
\]

Again, if the advected energy is released in optically-thick regions of the WD atmosphere, the value of \( \rho_{\text{stop}} \) found above should be at least comparable to the density at the photosphere of the heated WD. For a standard Eddington atmosphere in hydrostatic equilibrium, the photospheric density is given by the relation

\[
P_{\text{ph}} \simeq \frac{2g_{\text{ph}}}{3\kappa},
\tag{A14}
\]

where \( P_{\text{ph}} \), \( g_{\text{ph}} \) and \( \kappa \) are the pressure, gravity and opacity at the photosphere, respectively. The density at the WD photosphere is therefore

\[
\rho_{\text{ph}} \simeq \frac{g_{\text{ph}} \mu m_p}{\kappa_{\text{stop}} k_B T_{\text{ph}}},
\tag{A15}
\]

For \( \mu = 0.5 \) and a WD with \( M_{\text{WD}} = 1.2 M_\odot \) and \( R_9 = 0.5 \), this yields

\[
\rho_{\text{ph}} \simeq 5.4 \times 10^{-6} \text{g cm}^{-3},
\tag{A16}
\]

with a gravity \( g_{\text{ph}} = 6.4 \times 10^8 \text{ dyne cm}^{-2} \).

The value of this photospheric density is two orders of magnitude larger than the value \( \rho_{\text{stop}} \) derived above, which suggests that the energy advected by the flow will not be released in optically-thick regions at the WD surface if radiative processes act alone.

### A.2.2. Conduction

This still leaves the possibility that conduction processes efficiently transport the advected energy deep in the WD atmosphere where it is thermalized before being radiated away. The existing literature on similar processes in the context of the post-shock settling regions of WD accretion columns shows that it is difficult to estimate the efficiency of these processes reliably. There are proposed scenarios in which a large amount of the energy carried by the hot gas behind the shock is buried deep into the WD atmosphere (King & Lasota 1979, 1980; Kuiper & Pringle 1982), but they have been challenged (see, e.g., van Teeseling, Heise & Paerels 1994; Greeley et al. 1999).

The assumption of thermalization of the energy advected by the flow is crucial to the spectral models for quiescent DN presented in this study. If a fair fraction of the advected energy were not thermalized, it would be radiated away as much harder emission from the vicinity of the WD surface. This would probably result in a soft (UV) component (corresponding to a fraction of the hard emission that is reprocessed by
the WD atmosphere) comparable in luminosity to the hard (X-ray) component itself. In that case, the strength of the HeII emission lines could not easily be explained as photoionization of the disk material by the central UV source, because it would probably be too weak given the known level of X-ray emission of quiescent DN.
Fig. 1.— The emission spectrum of an ADAF around a WD. The dotted line corresponds to the reemission of the energy advected by the flow from the photosphere of the accreting WD (assuming thermalization; see text). X-rays are due to Bremsstrahlung cooling of the hot gas in the flow. (a) Influence of the viscosity parameter $\alpha_{\text{ADAF}}$ on the model predictions ($M_{\text{WD}} = 1.2 M_\odot$). (b) Influence of the mass – and compactness – of the accreting WD on the model predictions ($\alpha_{\text{ADAF}} = 0.2$; see text for details).
Fig. 2.— (a) Same as Fig. 1, but shows the influence of the accretion rate $\dot{m}$ on the model predictions. (b) Radial temperature profiles for the ions (upper) and the electrons (lower) in three models with various parameters.
Fig. 3.— Spectral models for quiescent Dwarf Novae, including the contribution from an outer thin disk and the X-ray emission that it reprocesses (long dashed-dotted), the EUV emission resulting from the advection of energy onto the central WD (dotted) and the ADAF Bremsstrahlung emission. Models (a) and (b) have a disk extending from $10^4 R_s$ to $10^5 R_s$, while models (c) and (d) have a disk extending further in, from $10^{1.5} R_s$ to $10^5 R_s$. The iron K$_\alpha$ emission line at 6.4 keV is a probe of the geometry of the accretion flow.