

ULTRAVIOLET SPECTRA OF CATAclysmic VARIABLE ACCRETION DISKS WITH NONSTEADY $T(r)$ LAWS

JEROME A. OROSZ

Department of Astronomy, San Diego State University, 5500 Campanile Drive, San Diego, CA 92182; orosz@sciences.sdsu.edu

AND

RICHARD A. WADE

Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802-6305;
 wade@astro.psu.edu

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ABSTRACT

An extensive grid of synthetic mid- and far-ultraviolet spectra for accretion disks in cataclysmic variables has been presented by Wade & Hubeny. In those models, the disk was assumed to be in steady state; that is, $T_{\text{eff}}(r)$ is specified completely by the mass M_{WD} and radius R_{WD} of the accreting white dwarf star and the mass transfer rate $\dot{M}$, which is constant throughout the disk. In these models, $T_{\text{eff}}(r) \propto r^{-3/4}$, except as modified by a cutoff term near the white dwarf. Actual disks may vary from the steady state prescription for $T_{\text{eff}}(r)$, however, as a result of, for example, outburst cycles in dwarf novae ($\dot{M}$ not constant with radius) or irradiation (in which case T_{eff} in the outer disk is raised above T_{steady}). To show how the spectra of such disks might differ from the steady case, we present a study of the ultraviolet (UV) spectra of models in which power-law temperature profiles $T_{\text{eff}}(r) \propto r^{-\gamma}$ with $\gamma < \frac{3}{4}$ are specified. Otherwise, the construction of the models is the same as in the Wade & Hubeny grid, to allow comparison. We discuss both the UV spectral energy distributions and the appearance of the UV line spectra. We also briefly discuss the eclipse light curves of the nonstandard models. Comparison of these models with UV observations of nova-like variables suggests that better agreement may be possible with such modified $T_{\text{eff}}(r)$ profiles.

Subject headings: accretion, accretion disks — binaries: close — novae, cataclysmic variables — stars: atmospheres — ultraviolet: stars

1. INTRODUCTION

In most types of cataclysmic variable (CV) stars matter accretes onto the white dwarf (WD) via an accretion disk. In some classes of CVs, e.g., the nova-like systems or dwarf novae in outburst, the accretion disk can dominate the flux in the ultraviolet (UV) part of the spectrum. Several studies of the UV spectra of uneclipsed CV disks have shown that we do not have a confident understanding of how the photospheric spectrum is formed. The disks in nova-like variables (such as the prototype UX UMa and also V603 Aql and RW Sex) should be close to “steady state” where

$$T_{\text{eff}}(r) = T_{\text{ref}} \left(\frac{r}{R_{\text{WD}}} \right)^{-3/4} \left[1 - \left(\frac{r}{R_{\text{WD}}} \right)^{-1/2} \right]^{1/4},$$

where r is the distance from the white dwarf and R_{WD} is the radius of the white dwarf. The reference temperature T_{ref} depends on the mass of the white dwarf M_{WD} , its radius, and the mass accretion rate $\dot{M}$:

$$T_{\text{ref}} = \left(\frac{3GM_{\text{WD}}\dot{M}}{8\pi\sigma R_{\text{WD}}^3} \right)^{1/4},$$

where G and σ are the usual physical constants (Pringle 1981).

Modeling attempts that take into account the detailed vertical structure and local emitted spectra from the disk surface have so far shown considerable discrepancies between predicted and observed energy distributions or $T(r)$ structures, especially at short wavelengths (e.g., Wade 1988; Long et al. 1994; Knigge et al. 1997; Robinson, Wood, &

Wade 1999). A general feature of the failing of these models is that they predict UV spectra that are too “blue” compared with the observations.

To try to improve agreement between models and observation, the computation of the local emitted spectra can be made more sophisticated in various ways. Alternatively, additional sources of UV radiation have been proposed to be important in some cases (e.g., optically thin emission from the base of a disk wind; Knigge et al. 1998). However, it is also worth considering whether the standard $T_{\text{eff}}(r)$ formula given above should be modified. This may be because the disk is nonstationary (e.g., a dwarf nova near outburst maximum may not have relaxed to a steady state or quasi-steady state), or because additional local heating besides the viscous dissipation inside the disk may alter the energy radiated locally at the disk surface (an example would be strong irradiation of the outer disk by the central star, as considered by, e.g., Vrtilik et al. 1990 in the context of low-mass X-ray binaries), or for various other reasons.

In attempting to unravel the true structure of accretion disks, studies of the emergent line spectrum should reveal much because each absorption line is formed in a relatively narrow range of temperatures (corresponding to a narrow range of radii within the disk) and thus has a characteristic Doppler width from projected disk rotation at the characteristic radius (for illustrative examples see Wade, Diaz, & Hubeny 1996). An aspect of any study that considers an altered $T_{\text{eff}}(r)$ profile should therefore be to consider its effect on the line spectrum from the disk.

Wade & Hubeny (1998, hereafter WH98) presented a grid of detailed models for accretion disks in CVs. The WH98 models are computed self-consistently in the plane-parallel

approximation, assuming LTE and vertical hydrostatic equilibrium, by solving simultaneously the radiative transfer, hydrostatic equilibrium, and energy balance equations. Line transitions of elements from H to Ni are accounted for in the computation of the local spectra of individual disk annuli. Limb darkening (Diaz, Wade, & Hubeny 1996), Doppler broadening, and blending of lines are fully accounted for in the computation of the integrated disk spectra.

In this work we construct accretion disk models for CVs (based on the WH98 grid and its component local spectra), in which the temperature profiles $T_{\text{eff}}(r)$ are allowed to deviate in a prescribed way from the standard prescription.¹ We consider profiles that take a power-law form $T_{\text{eff}}(r) \propto r^{-\gamma}$ in the outer disk, with $\gamma < \frac{3}{4}$. This does not exhaust the possibilities of modified disks, but the choice is motivated by simplicity and the intriguing and puzzling indication (explored below) that such disks may in some sense better describe the observations of nova-like variables.

We discuss in the sections below our computational method and results, including the UV spectral energy distributions, the appearance of the UV line spectra, and briefly the UV light curves of eclipsing systems.

2. METHOD

The computation of a WH98 model spectrum involves four stages, which we summarize briefly (see WH98 for a detailed discussion). First, the disk is divided up into concentric annuli, which are treated as independent plane-parallel radiating slabs. The vertical structure of each ring is computed with the program TLUSDISK (Hubeny 1990a, 1990b). Second, the program SYNSPEC (Hubeny, Lanz, & Jeffrey 1994) is used to solve the radiative transfer equation to compute the local rest-frame spectrum for each ring. This computation includes typically thousands of lines selected from the lists of Kurucz (Kurucz 1991; Kurucz & Bell 1995). Third, the program DISKSYN5a is used to combine the rest-frame intensities and generate the integrated disk spectrum. DISKSYN5a divides each ring into a large number of azimuthal sectors and sums the individual elements with the appropriate area weighting and Doppler shifting (owing to the projected orbital motion of the gas within the disk). Finally, the program ROTINS is used to convolve the integrated disk spectrum with a Gaussian instrumental broadening function and resample the result uniformly in wavelength.

In the present study, modified temperature profiles are generated that have $T(r) \propto r^{-\gamma}$ in the outer disk and that match smoothly onto the steady state $T(r)$ profile at a tangent point. The modified models therefore share the standard model's $T(r)$ behavior in the inner disk and depart smoothly from it farther out. The dimensionless radius of the tangent point, $x_{\text{crit}} \equiv r/R_{\text{WD}}$, is given by

$$x_{\text{crit}} = \left(\frac{7 - 8\gamma}{6 - 8\gamma} \right)^2$$

(valid for $\gamma < 0.75$). Table 1 lists x_{crit} and other useful quantities for a selection of values of γ . Figure 1 illustrates a

TABLE 1
DATA FOR POWER-LAW $T(r)$ DISK MODELS

γ	x_{crit}	$T(x_{\text{crit}})/T_{\text{max}}$	$T(x=50)/T_{\text{max}}$	$T(x=100)/T_{\text{max}}$
0.7.....	12.250	0.288	0.108	0.066
0.6.....	3.361	0.678	0.134	0.088
0.5.....	2.250	0.848	0.180	0.127
0.4.....	1.842	0.929	0.248	0.188
0.3.....	1.633	0.969	0.347	0.282

NOTE.—See text for definition of x_{crit} . The dimensionless radius is $x \equiv r/R_{\text{WD}}$, where r is the radial coordinate in the disk. T_{max} is the maximum effective temperature of a steady state disk, attained at $x = 1.36$.

family of modified $T(r)$ profiles for a particular model (v) from WH98. Note that $\gamma = 0.75$ is just the steady state case (as $x_{\text{crit}} \rightarrow \infty$). We emphasize that our particular class of models is chosen because it allows a convenient parameterization for exploratory purposes that has the standard model as a limiting case. Other classes of models can be contemplated [e.g., a single power-law behavior of $T(r)$ throughout the entire disk] that would give qualitatively similar results, as well as model types that might give considerably different behavior. Since observed disks seems to differ from the standard model disks by being “redder,” our considered class of models is possibly representative of the character of plausible changes in $T(r)$ structure.

We consider modifications of the standard (i.e., steady state) WH98 models that have $M_{\text{WD}} = 1.03 M_{\odot}$, namely, models t , u , v , dd , and jj . The radius of the central WD for these models is $R_{\text{WD}} = 5.18 \times 10^8$ cm; this is also taken to be the inner edge of the accretion disk. For discussion of eclipse light curves in the UV, we make use of models based on WH98 models k and bb , which have $M_{\text{WD}} = 0.55 M_{\odot}$ and $R_{\text{WD}} = 9.05 \times 10^8$ cm. Table 2 summarizes some properties of these models. For each of these standard WH98 models we generated modified models for $\gamma = 0.7$, 0.6, 0.5, 0.4, and 0.3.

The construction of the final model spectra is the same as for the WH98 grid, except for the modified temperature

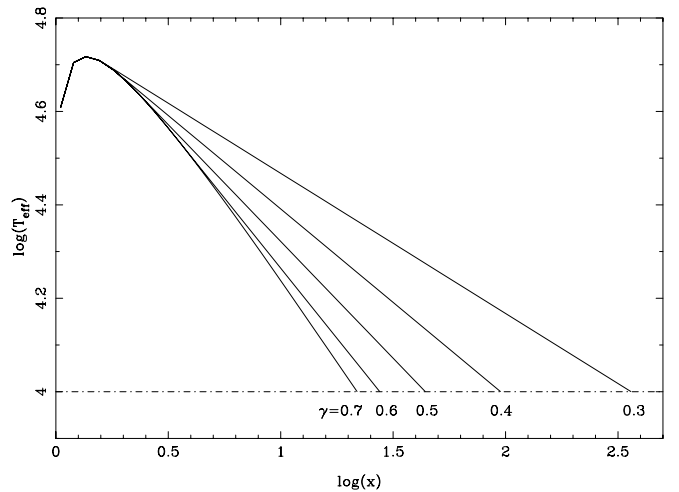


FIG. 1.—Temperature profiles for a class of nonstandard disks based on the WH98 model v . Here x is the dimensionless radius defined by $x \equiv r/R_{\text{WD}}$. The segmented appearance of the graph at small radii reflects the discrete set of radii used in constructing the models and is not a physical feature.

¹ In what follows, we usually suppress the subscript on T_{eff} , but by $T(r)$ we always mean the effective temperature.

TABLE 2
PROPERTIES OF DISK MODELS

Model Family	$\log \dot{M}$	$T_{\max}$ (K)	$x(T = 10,000 \text{ K})$	$T(x = 50)^a$ (K)	$T(x = 100)^a$ (K)
<i>t</i>	-10.0	29330	9.40	10180	(8270)
<i>u</i>	-9.5	39110	14.30	13580	11030
<i>v</i>	-9.0	52160	21.70	18100	14710
<i>dd</i>	-8.5	69560	28.80	24140	19620
<i>jj</i>	-8.0	92760	43.70	32200	26160
<i>k</i>	-9.0	29330	9.40	10180	(8270)
<i>bb</i>	-8.5	39110	14.30	13580	11030

NOTE.—For model sequences *t*, *u*, *v*, *dd*, and *jj*, $M_{\text{WD}} = 1.03 M_{\odot}$ and $R_{\text{WD}} = 5.18 \times 10^8 \text{ cm}$. For model sequences *k* and *bb*, $M_{\text{WD}} = 0.55 M_{\odot}$ and $R_{\text{WD}} = 9.05 \times 10^8 \text{ cm}$. The steady state mass transfer rate $\dot{M}$ is in units of solar masses per year; $x \equiv r/R_{\text{WD}}$, where r is the radial coordinate in the disk; and $T_{\max} = T_{\text{eff}}(x = 1.36)$. All temperatures are effective temperatures. See WH98 for further details.

^a $T(x = 50)$ and $T(x = 100)$ are shown for the case $\gamma = 0.3$. Models discussed in the text are extended to $T_{\text{eff}} = 10,000 \text{ K}$ or are truncated at $x = 50$ or 100 , if $T_{\text{eff}} = 10,000 \text{ K}$ has not been reached at that radius.

profile of the disk and the specification of the outer radius of the disk. We prescribe the outer edge of the disk in two ways. In the first case, the outer edge of the disk is where T_{eff} falls below about 10,000 K, as in WH98. Since we consider only the far- and mid-ultraviolet fluxes, the restriction to temperatures greater than about 10,000 K results in flux errors of less than a few percent. In the second case, the outer edge of the disk is defined by the tidal truncation radius appropriate to CVs. If $M_{\text{WD}} = 1.03 M_{\odot}$, the outer disk edge would be at about $50R_{\text{WD}}$ for an orbital period of $P = 1.5 \text{ hr}$ or at about $100R_{\text{WD}}$ for an orbital period of $P = 6.0 \text{ hr}$. (These limits were computed using Roche geometry and $M_{\text{sec}} = 0.1P$, where P is measured in hours and M_{sec} is the mass of the secondary star in solar units.) Table 2 shows that truncation of the disk at a temperature well above 10,000 K is likely in the case of high mass transfer rates or low values of γ .

Once the modified radii are computed, the integrated disk spectrum is computed in exactly the same way as the standard WH98 models: local spectra are generated and summed together with appropriate area weighting, taking into account Doppler shifts (owing to orbital motions of the area elements within the disk) and limb darkening. We chose inclination angles of 8° , 60° , and 76° ($\cos i = 0.99$, 0.50, and 0.25) for illustration. The fluxes presented here are given for an assumed distance of 100 pc and correctly account for limb darkening, but they do *not* include a geometrical foreshortening factor $\cos i$.

Note that in these exploratory calculations we have deviated from requiring that the local T_{eff} and photospheric gravity $\log g$ be mutually consistent: rather than compute new vertical structures and local spectra for each annulus, we have simply used the vertical structures and spectra from WH98, shifting each model annulus to a new radius according to its T_{eff} . The main results of this study of the UV spectrum should not be greatly affected by this shortcut.

3. RESULTS

3.1. Color-Magnitude Diagrams

We show color-magnitude diagrams of the resulting disk spectra in Figures 2 and 3. We use near-monochromatic

fluxes that are averages of f_{ν} over 10 Å intervals centered at 1455 and 1945 Å. These intervals are relatively line-free. Note that the flux ratio $f_{\nu}(1455 \text{ Å})/f_{\nu}(1945 \text{ Å})$ is very nearly independent of interstellar reddening (Seaton 1979). Figure 2 shows power-law disks that are viewed nearly face-on ($\cos i = 0.99$) and are not truncated (i.e., the disks extend until an effective temperature of about 10,000 K is reached). The solid lines connect sequences of models with the same maximum temperature and different γ . For $\gamma < 0.75$, the disks are hotter at each radius in the outer disk than in the corresponding standard case, the disks extend farther out in radius, and there is a larger proportion of the disk surface at relatively low temperatures. These disks are brighter and *redder*; that is, $\log[f_{\nu}(1455 \text{ Å})/f_{\nu}(1945 \text{ Å})]$ is more negative,

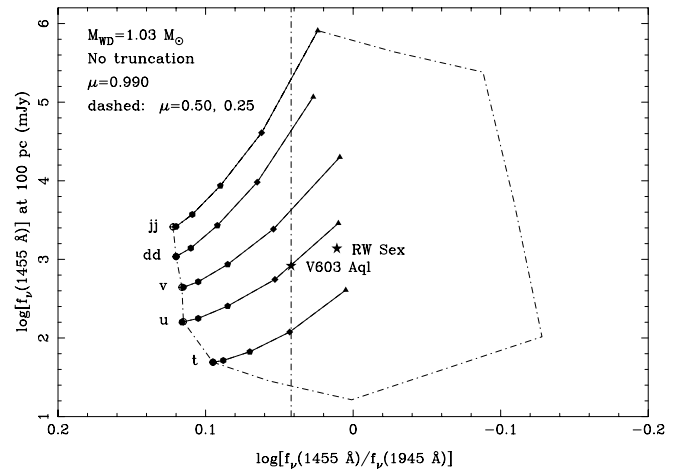


FIG. 2.—Color-magnitude diagram for the integrated disk spectra where the “color” is defined as $\log[f_{\nu}(1455 \text{ Å})/f_{\nu}(1945 \text{ Å})]$ and the “magnitude” is defined as $\log f_{\nu}(1455 \text{ Å})$ at 100 pc, with f_{ν} in mJy. The disks are viewed nearly face-on ($\cos i = 0.99$) and are allowed to extend outward until $T_{\text{eff}} \approx 10,000 \text{ K}$. The solid lines connect sequences of models with the same maximum temperature $T_{\max}$ and different γ . The dashed box outlines the region occupied by models of disks inclined to the line of sight, with limb darkening taken into account but geometrical foreshortening ignored (see text). A spectral index $\alpha = \frac{2}{3}$, where α is defined by $f_{\nu} \propto \nu^{-\alpha}$, is shown by the vertical dashed line. Points representing *IUE* observations of the nova-like variables RW Sex and V603 Aql are also shown (see text for details).

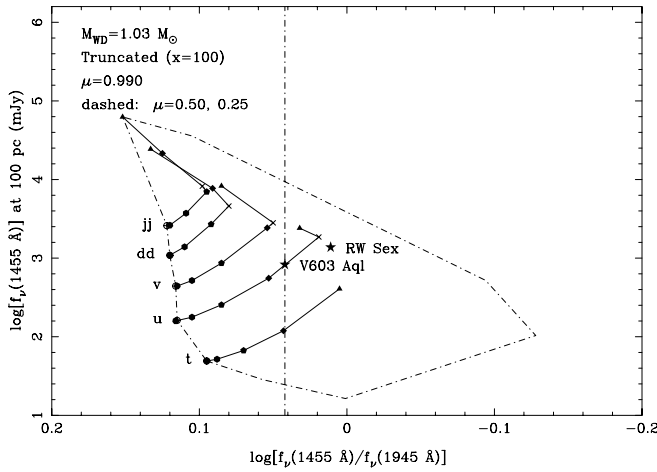


FIG. 3.—Similar to Fig. 2, except that the disks have been truncated at a dimensionless radius of $x = 100$.

displayed farther to the right in Figure 2. The dashed box outlines the region occupied by models when limb darkening is taken into account.² (Models with $\cos i = 0.50$ and 0.25 are included in defining this box. As before, the calculated fluxes are scaled to a distance of $d = 100$ pc. The purely geometrical foreshortening factor $\cos i$ is *not* included.) At high inclinations, limb darkening lowers the disk surface brightness and reddens the disk. “Cooler” models such as model *t* and models with $\gamma = 0.3$ have more pronounced limb-darkening effects in the UV (for further discussion of limb darkening in accretion disk spectra see Diaz et al. 1996).

Figure 3 shows what happens when the model disks are truncated at a dimensionless radius of $x = 100$. The dashed box again outlines the region when high-inclination angles are considered. In this case a disk becomes brighter and redder as γ declines from 0.75 , as long as the entire disk with $T_{\text{eff}}(x) > 10,000$ K fits within $x = 100$, as before. For γ less than some critical value γ_{crit} , however, the disk is no longer allowed to grow in radius, but each part of the disk within $x = 100$ continues to get hotter, so the disk gets brighter but *bluer*. At a fixed value of γ , truncated disks are fainter and bluer than nontruncated disks.

For truncation at $x = 50$, corresponding to shorter orbital periods, the result is that the disk is smaller, fainter, and bluer than the corresponding disk truncated at $x = 100$. Such disks are still brighter than the standard disks from which they were derived but may be either redder or bluer depending on γ and maximum temperature T_{max} .

² To make the meaning of this region more explicit, consider the point marked “t” in Fig. 2. This is model *t* in the case of the standard disk and for $\mu = 0.990$. The edge of the dashed box descending to the right from this point is the track of this model as μ decreases to 0.250 . The next vertex ascending to the right is model *t* with $\gamma = 0.3$ and $\mu = 0.250$. The vertex descending to the right from the point representing model *jj* (with $\gamma = 0.3$ and $\mu = 0.990$) is model *jj* with $\gamma = 0.3$ and $\mu = 0.250$. For all the other models explicitly shown (with $\mu = 0.990$), the corresponding points for $\mu = 0.500$ and 0.250 lie within the dashed box, descending to the right from the $\mu = 0.990$ case. Fig. 3 is similar, with the dashed vertex at coordinates $(-0.094, 2.717)$ representing the critical case for model *u* for $\mu = 0.250$ and the vertex at $(0.105, 4.554)$ representing the truncated model *jj* for $\mu = 0.250$.

In both Figures 2 and 3, points are plotted that represent *IUE* observations of the nova-like variables RW Sex and V603 Aql (e.g., Verbunt 1987). The data have been corrected for extinction and reddening and scaled to $d = 100$ pc and $\cos i = 0.99$ (i.e., geometrical foreshortening removed) for comparison with the models. For RW Sex, $d = 150$ pc and $\cos i = 0.73$ are used; for V603 Aql, $d = 376$ pc and $\cos i = 0.96$ are used, following Wade (1988). The orbital periods are 5.9 and 3.3 hr, respectively. The disk models for the standard cases are too blue to match the observed colors of RW Sex and V603 Aql. This point will be discussed further below.

WH98 discuss the contribution of the central WD to the light from the disk (their § 4.3). For the relatively hot disks that are considered here, the WD’s contribution does not make a qualitative difference to the discussion, as a result of its small surface area in comparison with the outer disk, and has been omitted from our exploratory calculations. This is especially true for the nonstandard disks of the kind considered here, which are more luminous than the standard disks. For realistic cases, the WD contribution to the models summarized in Figures 2 and 3 would be less than $\log f_{\nu}(1455 \text{ Å}) \approx 1$ or 1.5 (mJy at 100 pc). There will be a noticeable contribution to the (out-of-eclipse) flux of a CV only when the WD is hotter than the inner disk, and in those cases the total light will be somewhat bluer than a standard disk; in the interesting nonstandard cases, the WD contribution is even less significant. Of course, the effect of the WD might be seen during deep eclipses of the disk, and this should be modeled in detailed studies of observed systems; this does not make a qualitative or important quantitative change to the conclusions of this study in any way. Similar considerations apply to the possible contribution from a boundary layer (BL) at the inner edge of the disk, but with even more force because the BL radiating area would be smaller than the WD surface area and the UV bolometric correction would be very large, placing most of the emission in the extreme-UV or soft X-ray region.

3.2. Integrated Spectra

Figure 4 shows integrated spectra at $\cos i = 0.99$ for non-truncated γ disks derived from the standard WD98 model *u*. The disks with flatter temperature distributions (i.e., smaller γ) are brighter. Fluxes are again for a distance of $d = 100$ pc and do *not* include the foreshortening factor $\cos i$ (which is, however, the same for all spectra shown). In addition to the overall flux level and color changes, specific line features that are formed in the outer (cooler) portions of the disk are enhanced relative to features that are formed in the inner disk. For example, compare the C iv $\lambda\lambda 1548, 1550$ doublet, which is formed in the hotter regions of the disk, with the Si ii $\lambda\lambda 1527, 1533$ doublet. In the model spectrum with $\gamma = 0.7$, the Si ii feature is only slightly stronger than the C iv feature, whereas the Si ii feature is noticeably stronger in the model spectrum with $\gamma = 0.3$.

3.3. Extension to Eclipsing Systems

Wade & Orosz (1999) discuss the modifications to the WH98 models to deal with the case of a disk that is partially eclipsed by the mass-losing star. We used the Wade & Orosz codes to compute spectra and “light curves” through various partial eclipse phases for nonstandard models derived from the WH98 models *bb* ($T_{\text{max}} = 39,000$ K) and *k*

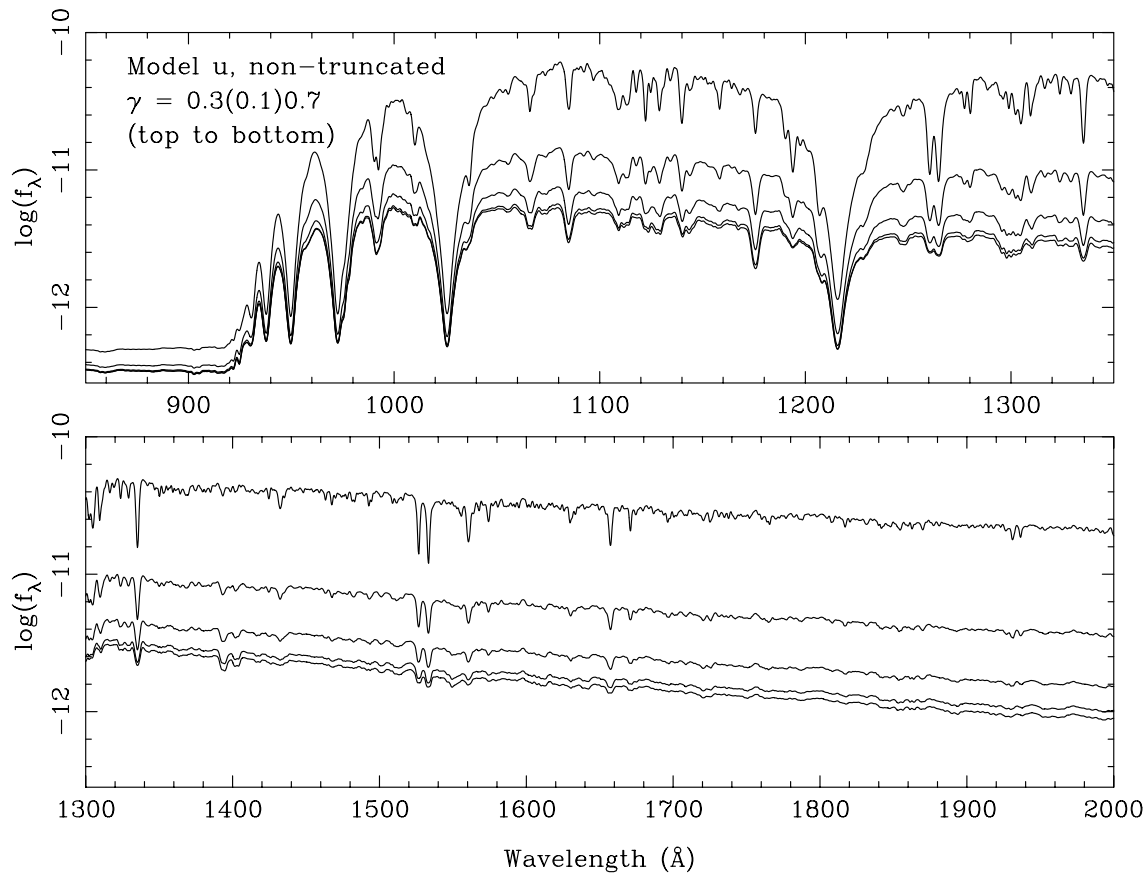


FIG. 4.—Integrated spectra at $\cos i = 0.99$ for the nontruncated γ disks derived from the WH98 model u . The fluxes are for a distance of $d = 100$ pc.

($T_{\max} = 29,000$ K). Both models have a WD mass of $M_{\text{WD}} = 0.55 M_{\odot}$. For the illustrations we choose a secondary star mass of $M_{\text{sec}} = 0.5 M_{\odot}$, an orbital period of 0.2 days, an inclination of $i = 71^{\circ}$, and an outer disk radius of $x \approx 51$. We chose two different spectral resolutions at which to sample the final model spectra: $R = 25,000$ (FWHM = $0.062 \text{ \AA}$ sampled every $0.0155 \text{ \AA}$) and $R = 2000$ (FWHM = $0.78 \text{ \AA}$ sampled every $0.195 \text{ \AA}$). The former resolving power was delivered by the G160M grating of the Goddard High Resolution Spectrograph (GHRS), which flew on the *Hubble Space Telescope*, and the latter resolving power was delivered by the G140L GHRS grating.

Figure 5 shows the eclipse geometry and predicted spectra (in the rest frame of the WD) in the region of the Si II doublet ($\lambda\lambda 1526.71, 1533.45$) for models bb ($R = 25,000$) and k ($R = 2000$) at different phases, where mideclipse is phase 0.0 (for clarity each spectrum has been normalized at $1600 \text{ \AA}$). We display only the rings in the disk that have $T_{\text{eff}} \gtrsim 10,000$ K. The integrated disk spectra for the standard models ($\gamma = 0.75$) only show weak features outside of eclipse. As the hotter inner regions of the disk are eclipsed, lines that are formed in the outer regions of the disk (for example, Si II) become apparent. As noted above, specific line features that are formed in the outer disk are enhanced relative to features that are formed in the inner disk in the models with flatter temperature profiles. Hence, the Si II feature in the uneclipsed disks with $\gamma = 0.3$ is relatively strong. Because the outer regions of the disk are relatively large in the $\gamma = 0.3$ models, the change in the line spectra of the $\gamma = 0.3$

models through eclipse is much less dramatic than in the corresponding standard model cases.

Figure 6 shows continuum light curves through eclipse for various models based on bb and k (for a mass ratio $Q \equiv M_{\text{WD}}/M_{\text{sec}} = 1.1$ and an inclination of 71°). Here the “continuum” represents the average flux between 1410 and $1530 \text{ \AA}$ in the $R = 2000$ spectra. The depth of the light curve at phase 0.0 depends on the value of γ . The disk in the standard model k is totally eclipsed at phase 0.0 for our adopted geometry, whereas the flux at phase 0.0 for the $\gamma = 0.3$ model based on k is roughly 35% of the out-of-eclipse level. Since the models with flatter temperature profiles have larger disks than the corresponding standard model, the eclipse light curves for models with low values of γ are much broader than those for the standard models. Hence, one may use the shape and depth of the eclipse light curve to help distinguish between standard models and models with much flatter temperature profiles.

4. DISCUSSION

There are several ways to compare the detailed model spectra with UV observations of disks in CVs. With the correct model, one should be able to match the overall flux, assuming that the distance and inclination of the object in question are well enough known. One should also be able to match the overall spectral shape (the “color”) over some broad wavelength range. The predicted absorption-line spectrum can be compared with high-quality observations

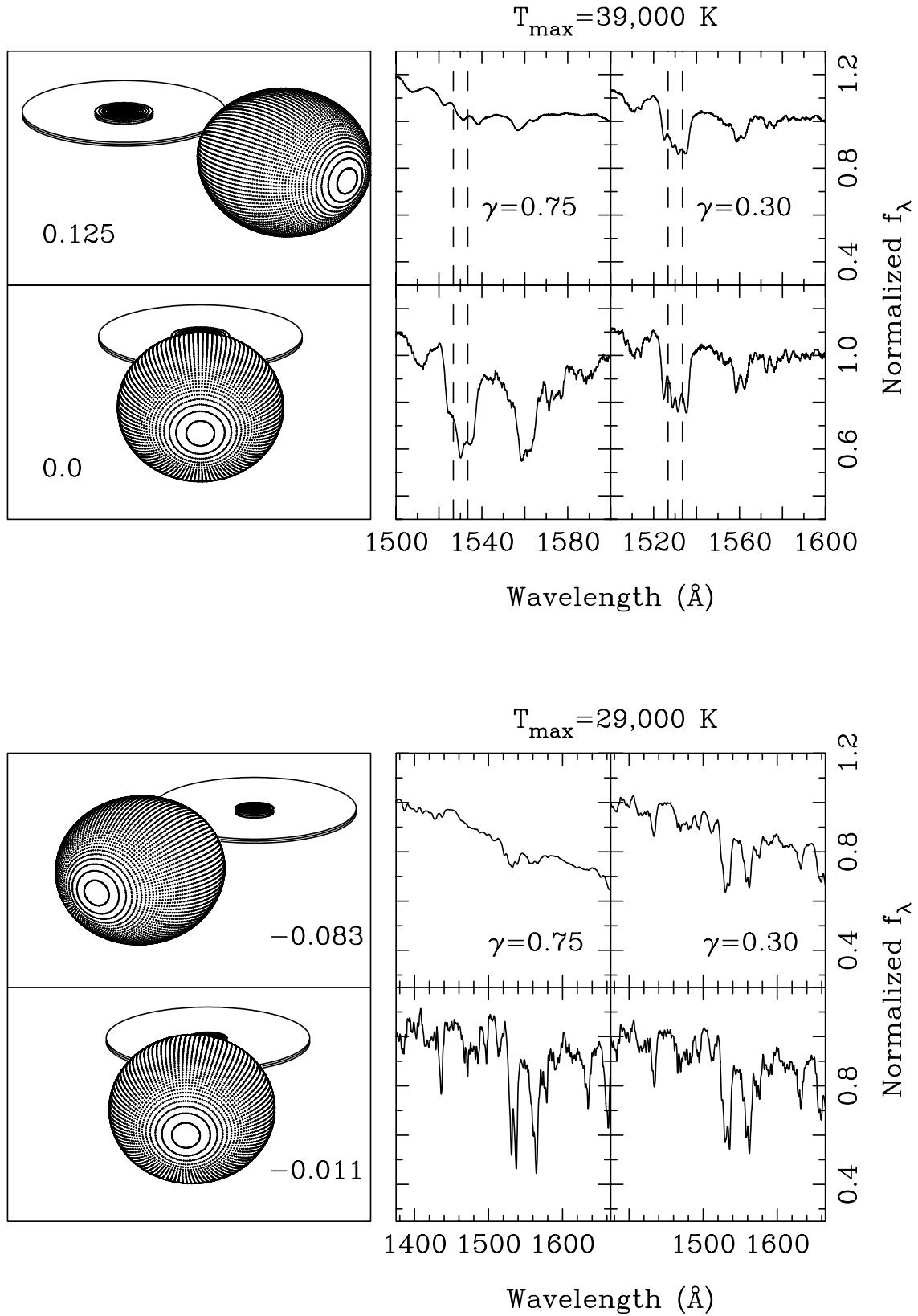


FIG. 5.—Eclipse geometry and representative spectra for models *bb* (top) and *k* (bottom). See text for model parameters. *Left panels:* Eclipse geometry, as seen by a distant observer. The orbital phase is indicated (mid-eclipse is zero phase). The dark inner regions of each disk represent the annuli of the steady state models $\gamma = 0.75$ that have $T_{\text{eff}} \gtrsim 10,000$ K. The outer rings represent the outer edge of the disks for the $\gamma = 0.3$ models (in both cases $x \approx 51$). The disk for model *k* is not truncated (i.e., the last ring has $T_{\text{eff}} \approx 10,000$ K), whereas the last ring for the *bb* model with $\gamma = 0.3$ has $T_{\text{eff}} \approx 13,500$ K. *Right panels:* Integrated spectra at $R = 25,000$ (top; *bb* models) and $R = 2000$ (bottom; *k* models) for the steady state and $\gamma = 0.3$ cases. The dashed lines in the upper plots indicate the rest wavelengths of the Si II doublet.

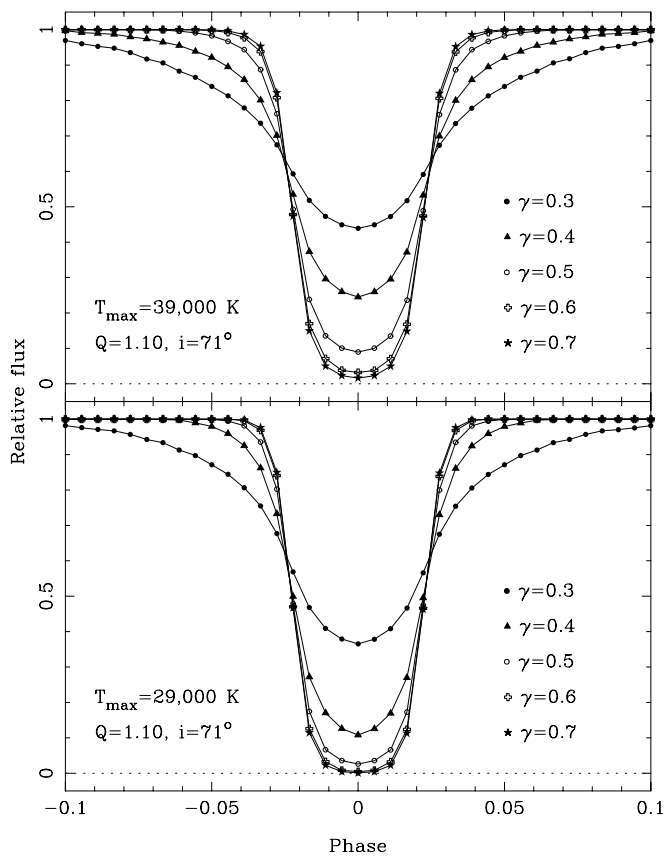


FIG. 6.—Normalized eclipse light curves for various γ models derived from models *bb* (top) and *k* (bottom).

for nearly face-on systems or for systems in partial eclipse (Wade & Orosz 1999). Finally, the predicted light curves for eclipsing systems can be compared with observations. In particular, the width and depth of the eclipse light curve are useful for distinguishing between various models.

As discussed by Wade (1988), it turns out that UV observations of nova-like variables are very difficult or impossible to fit using steady state disk models constructed from LTE stellar atmospheres; that is, one cannot match both the observed flux and color at the same time. This is still the case using the more self-consistent disk models of WH98. Indeed, this is obvious from Figures 2 and 3 (where the open circles represent the steady state disk spectra, $\gamma = 0.75$). While the standard WH98 models *dd* and *v* roughly reproduce the observed fluxes of RW Sex and V603 Aql, they fail badly in matching the colors. The present work suggests that “non-steady state” disks with a power-law $T_{\text{eff}}(r)$ distribution that is flatter than $r^{-3/4}$ might fare better. For example, V603 Aql is on the sequence of power-law disks based on the WH98 model *u* ($T_{\text{max}} = 39,000$ K) with $0.3 \lesssim \gamma \lesssim 0.4$.

There is one obvious problem associated with using non-standard $T_{\text{eff}}(r)$ profiles, either of the class described here or more generally, to model the disks in the nova-like variables: what would be the reason that the steady state $T(r)$ law is not followed in these apparently steady state disks? It is probably not reasonable to explain a nonstandard temperature profile as being due to a mass transfer rate that is constant in time but varies with radius. This would result in sources or sinks of mass density within the disk, in contra-

diction to the apparent steady state nature of these stars (see, however, Knigge 1999, who discusses how a strong wind from the *inner* disk may act as a sink of mass, angular momentum, and energy). Hence, the nonstandard temperature profile must be ascribed to some other cause. One possible suspect is irradiation of the disk by a hot central WD or BL. Vrtilek et al. (1990) showed how irradiation can lead under certain assumptions to $\gamma \approx \frac{3}{2}$ in low-mass X-ray binaries, but note that in that case radiation from the central source (a neutron star) dominates the outer disk flux, since the potential well into which the disk matter is accreted is very deep. It is far from clear that irradiation in CVs (where the central star is a WD), acting alone, will be strong enough to enforce such a flat temperature profile, and we do not claim to have shown that irradiation is the cause of a flattened $T(r)$ profile.³ However, if irradiation is the cause of the nonstandard temperature profile, then our models are incomplete: we have merely assigned the same local spectra (computed under the assumption of *no* irradiation) to different radii in the disk. A correct treatment of irradiation would include its effect in the vertical structure of the disk (e.g., Hubeny 1990a), and the emerging spectrum would differ from merely a sum of hotter “normal” spectra. An irradiated disk spectrum might even resemble to some extent a sum of Planck spectra, which Wade (1988) showed did match colors and fluxes of nova-like variables in the UV spectral range. Until detailed spectrum models incorporating a correct description of irradiation are developed, the “problem of the nova-like variables” must be considered to still be unsolved.

5. SUMMARY

We have presented a class of model spectra of accretion disks that have nonstandard power-law temperature profiles [i.e., $T_{\text{eff}}(r) \propto r^{-\gamma}$ with $\gamma < 0.75$]. When $\gamma < 0.75$, the disks are brighter and redder than disks in the corresponding standard case, assuming that the disks with the flatter temperature profiles extend outward until a temperature near 10,000 K is reached. Nonstandard disks that are truncated at some smaller radius are still brighter than the standard disks from which they were derived but may be either redder or bluer depending on γ and the maximum temperature T_{max} . For smaller values of γ (flatter temperature profiles), specific line features that are formed in the outer disk are enhanced in the integrated spectrum relative to features that are formed in the inner disk. For eclipsing systems we have illustrated how the eclipse light curves for these nonstandard disks are broader and less deep than the light curves for the corresponding standard disks. Such patterns may be useful in diagnosing whether disks in CVs do in fact have nonstandard $T(r)$ laws, or whether the failure of standard model disks to fit the data lies elsewhere.

Finally, we point out that detailed standard disk models [$T_{\text{eff}}(r) \propto r^{-3/4}$] of Wade & Hubeny (1998) cannot simultaneously match the observed UV fluxes and colors of the nova-like variables RW Sex and V603 Aql. Wade (1988)

³ Indeed, we do not even make the claim, on the basis of the limited work described here, that a flattened $T(r)$ profile is the basis of the discrepancy between standard disk models and observations of luminous CVs. We have only demonstrated consistency of such modified disks with observations of two test objects, in terms of UV colors and fluxes, along with pointing to other more sensitive tests involving spectra and eclipse light curves.

reached a similar conclusion, using disk spectra synthesized from stellar atmosphere models. Our present exploratory work suggests that a disk with a much flatter temperature profile, $T_{\text{eff}}(r) \propto r^{-\gamma}$ with $\gamma \approx 0.35$, provides a better match to both the flux and color of V603 Aql. However, the WH98 models as applied in this case are incomplete; since no mechanism is identified that results in the flatter temperature profile, we have simply constructed models as if there were a mass transfer rate that varies with radius (an apparently unphysical situation for the nova-like variables). If the flat temperature profiles that seem to be favored by this exploratory analysis are in fact due to irradiation (although for

energetic reasons this seems problematic), then further refinements to the models should include a detailed and consistent treatment of irradiation.

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