The Lyman-Line Region in Models of Dwarf Nova Accretion Disks

Richard A. Wade
Dept. of Astronomy & Astrophysics, Pennsylvania State University, University Park, PA 16802

Ivan Hubeny
NASA/Goddard Space Flight Center, Code 681, Greenbelt MD 20771

Ronald S. Polidan
NASA/Goddard Space Flight Center, Code 681.0, Greenbelt MD 20771

Abstract. We are constructing model spectra of accretion disks for quiescent dwarf novae. Here we present preliminary results for the Lyman-line region, 900 – 1500 Å, for a few combinations of $M_{wd}$ and $M$ chosen to illustrate various features of the spectra. The contribution of the accreting white dwarf to the spectrum is included. We point out that low-temperature disks may resemble white dwarf spectra over limited wavelength ranges, and caution that IUE spectra that show a “dip” towards Lyman-α can in principle be misinterpreted as showing evidence of a dominant white dwarf.

1. Methods

Each spectrum is the sum of a white dwarf spectrum (solar abundances), specified by $T_{eff}$ and $\log g = \log g(M_{wd}, R_{wd})$, and a steady-state accretion disk, specified by $M_{wd}$, $R_{wd}$, and $\dot{M}$ and viewed at a specified inclination angle. The effective temperature in the disk follows the usual form:

$$T_{eff}(r) = T_\ast x^{-3/4}(1 - x^{-1/2})^{1/4}$$

where $x = r/R_{wd}$ and $T_\ast = [3G/8\pi \sigma]^{1/4}[M_{wd} \dot{M} R_{wd}^{-3}]^{1/4}$.

Occultation of part of the star by the disk is taken into account, and vice versa. Doppler broadening of the disk spectrum ($v \propto r^{-1/2} \sin i$) and rotational broadening of the white dwarf ($V_{eq} \sin i = 2500$ km s$^{-1}$ adopted) are taken into account. The spectra are smoothed (3 Å FWHM Gaussian). Spectra are presented either in absolute flux units for an assumed distance of 100 pc, or normalized at a particular wavelength so that features in different models can be easily compared. Some spectra are computed with a full line list, while other spectra show continuum + H lines only.

The vertical structure of each radial zone in the accretion disk models was calculated using the program TLUSDISK, which self-consistently solves the
equations of hydrostatic equilibrium and energy balance for the geometry and boundary conditions of the disk. Viscosity was prescribed using the Reynolds number, \( Re = 5000 \). The parameter \( \zeta \), describing how the viscous dissipation is distributed with distance from the disk midplane, was given the value \( 2/3 \). (See Kriz & Hubeny 1986 for details.) LTE was assumed. Hydrogen and helium continua and line transitions were treated explicitly in computing the opacity. All species contributed to the equation of state. Irradiation of the disk was ignored.

The specific intensity from each ring of the disk was calculated for a number of emergent angles, \( \mu = \cos \iota \), using the program SYNSPEC. An integrated disk spectrum was then computed by the program DISKSYN, which sums the contributions to the received flux from many annuli, each of which is divided into many segments for the purpose of calculating the doppler shift. Occultation effects were included. Each resulting disk spectrum was then smoothed with a Gaussian filter (3 Å FWHM).

The outer edge of each computed disk model was determined by the condition \( T_{\text{eff}}(x) \sim 10000 \) K. This is sufficient to assure that more than \( \sim 97\% \) of the flux at 1400 Å is accounted for.

2. Results

At this point of our study, we can draw several interesting conclusions:

1. The Doppler broadening of line features is very noticeable in the 900 – 1500 Å region, even at modest inclination. This is because the disk emits strongly in these wavelengths only in the zones close to the white dwarf surface, where orbital speeds are very high. Strong isolated lines that are characterized by a fairly narrow temperature range, such as the 1260 Å complex of Si II, show the characteristic splitting at high inclination which is due to the Doppler effect (Fig. 1).

2. Limb darkening is very important for these disks, and must be taken into account in addition to geometrical foreshortening for inclined disks. In Figure 1, the different flux levels exhibit the effect of limb darkening for lines of sight differing from normal emergence. At 1450 Å the linear limb-darkening coefficient is \( \sim 1.0 \).

3. We computed three models for widely different \( M_{\text{wd}} \) (and \( R_{\text{wd}} \), keeping \( T_{\ast} \) fixed by varying \( \dot{M} \) as well. The models differ only in vertical structure, due to differing values of the gravity gradient \( \frac{dg}{dz} = GM_{\text{wd}}/(xR_{\text{wd}})^3 \). For \( T_{\text{eff}} = 22000 \) K, the gravity at optical depth \( \tau = 1 \) is nearly the same, \( \log g = 6.0 \pm 0.2 \) (cgs units) for the three choices of \( M_{\text{wd}} \), in spite of the huge differences in \( \frac{dg}{dz} \), because the disk is much thinner for higher \( M_{\text{wd}} \). The resulting disk spectra thus show only small differences except for a scale factor. The spectra appear nearly identical when the inclinations are chosen to give the same projected velocity \( v_{\text{ kep}}(x) \sin \iota \) for the three models. When the normalized spectra are plotted for the same inclination (Fig. 2), differences are noticeable in the higher Lyman lines. The different line shapes and the dramatic change in the spectrum near 960 Å as \( M_{\text{wd}} \) increases are due to increasing amounts of Doppler shifting in the inner disk.

4. Shortward of Lyman-\( \alpha \), high-quality spectra can easily distinguish one \( \dot{M} \) from another for a fixed \( M_{\text{wd}} \), because of the sensitivity of the higher Lyman lines
and the Balmer continuum to temperature (Fig. 3). This supposes, however, that
the spectrum is not cut up by strong absorption lines from a wind.

5. In the IUE short-wavelength region, accretion disks at low mass trans-
fer rates have spectra that are similar to solar abundance white dwarfs with
$T \sim 20000$ K. Furthermore, the fluxes from the disk and white dwarf can be
comparable for intermediate disk inclinations. Without firm constraints from
independent evidence, such as known distance or disk inclination, confusion is
possible and the inferred properties of the system are correspondingly uncertain.

For example, IUE spectrum SWP 10911 of the quiescent dwarf nova VW
H Yi, previously discussed by Mateo & Szkody (1984), shows a broad absorp-
tion feature to the red of Lyman-$\alpha$. Using our solar-abundance spectra of white
dwarfs and disks to model this observation shortward of 1500 Å, we find that
the quiescent spectrum of VW H Yi can be described equally well by a white
dwarf with $T_{\text{eff}} \sim 18000$ K and no disk, with an implied distance of 52 pc, or by
a white dwarf ($M_{\text{wd}} \sim 0.55$ M$_{\odot}$) with $T_{\text{eff}} \sim 18000$ K and an accretion disk with
$\dot{M} = 10^{-10}$ M$_{\odot}$ yr$^{-1}$, viewed at an inclination of 60°. Here the implied
distance is 80 pc, and the disk contributes about 40% of the flux at 1400 Å. Details will
be published elsewhere. We emphasize that this is a preliminary result based
only on scaling a few models already computed, rather than a systematic search
for a “best fit” over a broad wavelength range. The fit is not well constrained
by short-wavelength IUE data alone.
Figure 2. Spectra of three different disks, all having the same run of $T_{\text{eff}}$ with dimensionless radius $x = r/R_{\text{wd}}$, but with different choices of $M$ and $M_{\text{wd}}$ (hence also $R_{\text{wd}}$). The peak effective temperature in the disk is 22000 K. For $M_{\text{wd}} = 0.35$, 0.80, and 1.03 $M_\odot$, the mass transfer rates required to achieve the same $T_*$ are $1.0 \times 10^{-9}$, $1.0 \times 10^{-10}$, and $3.16 \times 10^{-11} M_\odot$ yr$^{-1}$, respectively. The viewing inclination is 60° in each case. The spectra are normalized at 1450 Å; at a fixed distance, the model with the largest $M_{\text{wd}}$ (smallest $R_{\text{wd}}$) would appear faintest. Solid line: the $M_{\text{wd}} = 0.35$ $M_\odot$ disk; dotted line: the $M_{\text{wd}} = 1.03$ $M_\odot$ disk.

3. Concluding Remarks

Our modeling is a preliminary effort in exploring the far UV spectral range accessible to HUT, ORFEUS, and other missions. It also bears on the interpretation of short wavelength IUE spectra. Certain conclusions, such as the importance of taking limb darkening into account and the relative insensitivity of the photospheric disk gravity to the particulars of $M_{\text{wd}}$ and $M$ [for fixed $T_{\text{eff}}(x)$] have already emerged. In this spectral region, hydrogen and metal lines from the disk can be useful in limiting the permissible combinations of white dwarf mass, mass transfer rate, and inclination. Further exploration is necessary to characterize the effect of changing the Reynolds number, as well as to investigate non-LTE effects.

Acknowledgments. Supported by NASA grant NAG 5-2125.
Figure 3. Two disk models for $M_{wd} = 0.80 \, M_\odot$, $i = 60^\circ$, but with $\dot{M}$ differing by $\times 10$. The curves are normalized at 1450 Å for comparison, simulating the absence of any distance information. At the same distance, the model with the higher $\dot{M}$ (upper curve) would appear 15 times brighter at 1450 Å.

References