**ABSTRACT.** We carry out a spectral analysis of the archival FUSE spectrum of the VY Scl novalike cataclysmic variable MV Lyrae obtained in the high state. We find that standard disk models fail to fit the flux in the shorter wavelengths of FUSE ($\lambda < 950$ Å). An improved fit is obtained by including a modeling of the boundary layer at the inner edge of the disk. The result of the modeling shows that in the high state the disk has a moderate accretion rate $\dot{M} \approx 2 \times 10^{-9}$ $M_\odot$ yr$^{-1}$, a low inclination, a boundary layer with a temperature of $\sim$100,000 K, and size $\sim$0.20 $R_{wd}$, and the white dwarf is possibly heated up to a temperature $T \approx 50,000$ K or higher.

1. INTRODUCTION

1.1. The VY Scl Nova-like System MV Lyrae

Cataclysmic variables (CVs) are evolved compact binaries in which the primary, a white dwarf (WD), accretes matter and angular momentum from the secondary, a star approximately on the main sequence filling its Roche lobe. In dwarf nova (DN) and nonmagnetic novalike (NL) systems (two classes of CVs), the matter is transferred by means of an accretion disk around the WD. DN systems are found mostly in a faint, quiescent state with a low mass transfer rate ($\dot{M} \sim 10^{-12}$--$10^{-11}$ $M_\odot$ yr$^{-1}$), and every few weeks to months they transit into a bright, outburst state lasting days to weeks, as the mass transfer suddenly increases by several orders of magnitude ($\dot{M} \sim 10^{-8}$--$10^{-7}$ $M_\odot$ yr$^{-1}$). The transition to outburst in DNe is believed to be due to a disk instability (Shafter et al. 1986; Cannizzo 1988, 1998). NL systems are found mainly in a high-state phase, characterized by a large mass accretion rate, and from time to time the mass accretion rate suddenly drops by several orders of magnitude. The transition from high state to low state in NL systems is caused by a throttling of the mass transfer, possibly due to magnetic activity of the secondary star (see Warner [1995] for a review of CVs). With time, the accreted matter in CV systems forms a hydrogen-rich layer that covers the surface of the WD. When enough material is accreted (every few thousand years), the hydrogen-rich material undergoes a thermonuclear runaway and the system forms a classical nova event.

MV Lyr is a VY Scl novalike system, spending most of its time in the high state and occasionally undergoing short-duration drops in brightness. When this happens, the magnitude of MV Lyr drops from $V \approx 12$--13 to $V \approx 16$--18 (Hoard et al. 2004). From the American Association of Variable Star Observers online data\(^1\), it appears that MV Lyr can stay in the high state for up to $\sim$5 yr, and then for a period of a few years to $\sim$10 yr it spends its time alternating between high state and low state on a timescale of a few months to a year. The orbital period of the binary in MV Lyr is $P = 3.19$ hr and the mass ratio was found to be $q = M_{2nd}/M_{wd} = 0.4$ (Schneider et al. 1981; Skillman et al. 1995). Because of the small radial velocity amplitudes and the lack of eclipses, the inclination is constrained to be in the range $i = 10^\circ$--$13^\circ$, though it has been remarked (Linnell et al. 2005) that the inclination could be as low as $i = 7^\circ$. The parameters are given in Table 1.

Observations of MV Lyr during a low state with the International Ultraviolet Explorer (IUE) indicated a hot WD possibly reaching 50,000 K (Szkody & Downes 1982) or higher (Chiappetti et al. 1982). These observations were later confirmed when MV Lyr was observed with FUSE on 2002 July 7, during a low state that lasted for about 8 months. Hoard et al. (2004) carried out a spectral analysis of the FUSE spectrum and found that the WD must have a temperature of 47,000 K, a gravity log $g = 8.25$, a projected rotational velocity $V_\text{rot} \sin i = 200$ km s$^{-1}$, subsolar abundances $Z = 0.3 \times Z_\odot$, and a distance of 505 ± 50 pc. At the time of the observations, the magnitude of MV Lyr was possibly as low as $V \approx 18$ with a mass accretion rate no more than $\dot{M} \approx 3 \times 10^{-13}$ $M_\odot$ yr$^{-1}$ (Hoard et al. 2004). A follow-up analysis (Linnell et al. 2005) was carried out to study the different states of MV Lyr and its secondary, based on archival IUE spectra, a Hubble Space Telescope (HST)/STIS snapshot, and optical spectra. Using the parameters they derived in Hoard et al. (2004), Linnell et al.

\(^{1}\)See http://www.aavso.org/.
spectral models. More than two decades ago, Wade (1988) used IUE spectra to show that CV NL systems (high-state systems) systematically disagree with the standard disk model when either blackbody spectra or Kurucz stellar model spectra were used to represent the accretion disk. A much-improved version was developed by Hubeny (1990) for modeling annuli of accretion disks that explicitly included calculation of synthetic spectra using the standard disk model (the codes TLDISK/TLUSTY, SYNSPEC, and DISKSYN), and spectra of disks were computed (Wade & Hubeny 1998 assuming the standard disk model (Shakura & Sunyaev 1973; Lynden-Bell & Pringle 1974; Pringle 1981). UV spectra (HST, Hopkins Ultraviolet Telescope, IUE, FUSE) of DNe in outburst and high brightness states of NL systems were successfully modeled for a number of systems with synthetic spectra of optically thick disks (Knigge & Long 2002; Hamilton et al. 2007).

However, with time, it became clear that a significant number of systems still could not be fitted using the standard disk model (Long et al. 1994; Knigge et al. 1997; Robinson et al. 1999), as first shown by Wade (1988). Orosz & Wade (2003) suggested a disk temperature profile \( T(\rho) \) flatter than the standard disk model, to at least partially remediate the problem, invoking a possible nonsteady mass accretion rate and/or irradiation in the outer part of the disk. More recently, the UV spectra of RW Sex, V3885 Sgr, and UX UMa (Linnell et al. 2008, 2009, 2010) were also modeled using a modified temperature profile, and it was suggested that the outer disk temperature might increase due to its interaction with the impacting L1 stream. Maybe the most significant of all is the statistical study of Puebla et al. (2007) of 33 disk systems, which indicates that a revision of the standard model temperature profile, at least in the innermost part of the disk, is required.

These studies concentrated mainly on using UV spectra (e.g., IUE, HST/STIS, and FUSE), and the contribution to the UV continuum comes mainly from regions in the system where the temperature ranges roughly between \( \sim 10,000 \text{ K} \) and \( \sim 100,000 \text{ K} \). Lower temperatures peak in the optical, while higher temperatures peak in the extreme UV. The WD star and the disk are the main contributors to the UV flux, while the secondary star and the bright spot (the edge of the disk impacted by the incoming stream of matter) peak in the optical and near-UV, respectively. For disks in CVs with mass accretion rate \( \sim 10^{-8} \text{ M}_\odot \text{ yr}^{-1} \), the inner disk reaches a temperature higher than 50,000 K. These disk models therefore have a significant UV flux contribution from the inner region of the disk.

That same innermost part of the disk is the region where the matter in the disk has to decelerate from its Keplerian motion in order to be accreted onto the more slowly rotating stellar surface, as the centrifugal force keeps the matter from accreting. This region is known as the boundary layer (BL) and up to half the accretion luminosity can be released in this final phase of the accretion process. Therefore, the emission and heating of the BL have to be taken into account when modeling an accretion disk around a nonmagnetic (or weakly magnetic) star (Lynden-Bell & Pringle 1974; Pringle 1981). It has now become clear that the temperature profile in the inner disk is affected by the heating from the BL. Most importantly, BLs in high state have a temperature of the order of 100,000 K–200,000 K (Popham & Narayan 1995; Godon et al. 1995; Piro & Bildsten 2004), which is much lower than the first analytical estimates of \( \sim 500,000 \text{ K} \) (Pringle 1977; Pringle & Savonije 1979). Consequently, the BL of CV disk systems in the high state contributes significantly to the UV, even though it was predicted to emit only in the soft X-ray range (see also next section). Therefore, the BL has to be included in the disk modeling, and the inner disk temperature profile has to be modified accordingly.

It is the purpose of the present work to include an elementary (and preliminary) model of the BL in the spectral modeling of the FUSE spectrum of MV Lyr taken during its high state. Since the BL has an elevated temperature, its contribution will be more pronounced in the shorter wavelengths of the spectral range of FUSE.

In the next section a brief review of the standard disk and BL models is given, and it is shown that the theory does indeed predict a BL contributing a nonnegligible flux in the far-UV. The FUSE spectrum of MV Lyr and the details of the synthetic spectral modeling are presented in § 3. The results follow in § 4, and are discussed in the concluding section.
2. THE STAR-DISK BOUNDARY LAYER

2.1. The Standard Disk Model

The total luminosity available through accretion is given by

\[ L_{\text{acc}} = \frac{GM_\ast \dot{M}}{R_\ast}, \]  

where \( G \) is the gravitational constant, \( \dot{M} \) is the mass accretion rate, \( M_\ast \) is the mass of the accreting star, and \( R_\ast \) is its radius. This expression simply reflects the release of gravitational potential energy of the material brought onto the surface of the star \((r = R_\ast)\) from infinity \((r \to \infty)\) at a rate \( \dot{M} \) (mass/time).

In the standard disk theory (Shakura & Sunyaev 1973; Lynden-Bell & Pringle 1974), the accretion disk is axisymmetric, and geometrically thin in the vertical dimension: it has a vertical thickness \( H \) such that \( H/r \ll 1 \). The disk is treated with a one-dimensional radial approximation, in which the radial pressure is negligible and the matter in the disk is assumed to be rotating at Keplerian speed. The energy dissipated by viscous processes between adjacent rings of matter is instantaneously radiated locally in the vertical \( z \)-direction. The disk total luminosity \( L_{\text{disk}} \) is half the accretion luminosity,

\[ L_{\text{disk}} = \frac{L_{\text{acc}}}{2} = \frac{GM_\ast \dot{M}}{2R_\ast}, \]

and each face of the disk radiates \( L_{\text{disk}}/2 \). This occurs because the matter at the inner edge of the disk \((r \approx R_\ast)\) retains the remaining accretion energy in the form of kinetic energy, as it rotates at Keplerian speed. The effective surface temperature of such a disk is given by Shakura & Sunyaev (1973), Lynden-Bell & Pringle (1974), and Pringle (1981):

\[ T_{\text{eff}}(r) = T_0 x^{-3/4}(1 - x^{1/2})^{1/4}, \]

where \( x = r/R_\ast \),

\[ \sigma T_0^4 = \frac{3GM_\ast \dot{M}}{8\pi R_\ast^3}, \]

and \( \sigma \) the Stefan-Boltzmann constant. For practical purposes, the last relation is usually written

\[ T_0 = 64,800 \text{ K} \times \left[ \left( \frac{M_\ast}{1 M_\odot} \right) \left( \frac{\dot{M}}{10^{-9} M_\odot \text{ yr}^{-1}} \right) \left( \frac{R_\ast}{10^9 \text{ cm}} \right) \right]^{-3/4}. \]

From this it is seen that accretion disks around WD stars emit their energy in the optical and UV. The preceding relation is obtained by assuming a no-shear boundary condition, \( \partial \Omega / \partial r = 0 \), at the stellar surface \( r = R_\ast \) (Pringle 1981). Therefore, this model does not take into account the relatively slow rotation of the WD, and it gives a disk temperature \( T = 0 \) K at the stellar surface \((r = R_\ast)\) and a maximum temperature \( T_{\text{max}} = 0.488T_0 \) at \( x = 1.36 \). This model also neglects the spin-up of the star by the disk.

This relation, however, gives a good approximation of the effective surface temperature in the disk at larger radii \((r \gg R_\ast)\). For a typical high mass accretion rate of \( \dot{M} = 1 \times 10^{-8} M_\odot \text{ yr}^{-1}\), the maximum temperature in the inner disk reaches about 50,000 K–100,000 K, and the inner disk becomes the strongest emission source of the system in the UV. During the low state of NL systems (or quiescent state of DNe) the mass accretion rate decreases down to \( \dot{M} \approx 10^{-12} M_\odot \text{ yr}^{-1}\), while the maximum temperature drops to less than \( \approx 10,000 \) K, making the disk peak in the optical and barely emit any flux in the UV. The standard disk model is a good approximation for \( r \gg R_\ast \), but in the inner disk region, one needs to model the BL between the slowly rotating stellar surface and its Keplerian accretion disk. We would like also to note here that contrary to accreting neutron stars, the irradiation of the disk by the heated WD and BL is negligible in accreting WDs (van Paradijs & McClintock 1994; Shahbaz & Kuulkers 1998; King 1998), and one does not need to take it into account when modeling accretion disks in CVs.

2.2. The Boundary Layer

Accreting WDs in CVs have stellar rotational velocities of the order of a few hundred kilometers per second (Sion 1998) or about 10% of the Keplerian velocity at one stellar radius (a few thousand kilometers per second). Consequently, the theory (Lynden-Bell & Pringle 1974; Pringle 1981) predicts that the material at the inner edge of the disk rotating at Keplerian speed has to adjust itself to the slowly rotating stellar surface and, therefore, dissipates its remaining rotational kinetic energy. The remaining rotational kinetic energy liberated in the BL \( (L_{\text{BL}}) \) is nearly equal to half of the total gravitational energy of the accreting matter \( (L_{\text{acc}}/2 = L_{\text{disk}}) \), namely (Kluźniak 1987),

\[ L_{\text{BL}} = L_{\text{disk}} \left( 1 - \frac{\Omega_s}{\Omega_K(R_\ast)} \right)^2. \]

Because of its small radial extent and the large amount of energy dissipated there, the BL was expected to emit only in the X-ray bands. At high mass accretion rates \( (\dot{M} \approx 10^{-9}–10^{-8} M_\odot \text{ yr}^{-1}) \) the BL should be optically thick, and its temperature was predicted to be in the range of 200,000 K to 500,000 K (Pringle 1977; Pringle & Savonije 1979). At low mass accretion rates, the BL should be optically thin and emit in the hard X-ray (20 keV), due to either strong...
shocks or the formation of a X-ray-emitting corona around the WD (Pringle & Savonije 1979; King & Shaviv 1984).

The first one-dimensional computations of the BL (Regev 1983; Papaloizou & Stanley 1986; Stanley & Papaloizou 1987; Regev & Hougerat 1988) were carried out by assuming the “slim disk equations” (Szuszkiewicz et al. 1988): the equations are written and solved for vertically averaged quantities but also include the transport of energy (radiation and advection) in the radial dimension. The results from these one-dimensional computations were in general agreement with the predictions and showed that the BL should be narrow with a temperature increasing rapidly inward. However, more realistic one-dimensional simulations (Popham & Narayan 1995; Godon et al. 1995; Collins 1997; Collins et al. 1998a, 1998b, 2000a, 2000b) showed that the BL extends radially and vertically more than expected. The result was that at high accretion rates the BL is not as hot as expected, with a temperature of around 125,000 K (Godon et al. 1995) to 300,000 K (Popham & Narayan 1995).

Numerical works in 2D (Robertson & Frank 1986; Kley & Hensler 1987; Kley 1989a, 1989b, 1991) did not clearly reveal whether the accreting material accumulates in an equatorial belt (e.g., as claimed by Durisen 1977 and Kippenhahn & Thomas 1978) or spreads quickly over the entire WD surface (MacDonald 1983; Livio & Truran 1987). But more recently, using the semianalytical shallow-water approximation developed by Inogamov & Sunyaev (1999) for accreting neutron stars, Piro & Bildsten (2004) found that at high mass accretion rate (\( M > 10^{18} \text{ g s}^{-1} \approx 1.6 \times 10^{-8} \text{ \( M_\odot \) yr}^{-1} \)) the combined effect of centrifugal force and pressure gives rise to two latitudinal rings of enhanced brightness above and below the WD’s equator: the “spread layer” (Inogamov & Sunyaev 1999). At lower mass accretion rate (\( M < 10^{18} \text{ g s}^{-1} \approx 1.6 \times 10^{-8} \text{ \( M_\odot \) yr}^{-1} \)) the spreading is negligible, and most of the dissipated energy is radiated back into the accretion disk. The effective temperature (\( 2 \times 10^4 \text{ K} \)–\( 5 \times 10^5 \text{ K} \)) and rotational velocity (\( 1 \times 10^8 \text{ cm s}^{-1} \–\( 3 \times 10^8 \text{ cm s}^{-1} \)) of the spread BL are similar to those of the one-dimensional BL models (at least where they overlap in the parameter space). Some more recent simulations have been carried out to study the spread layer (Fisker & Balsara 2005; Balsara et al. 2009); however, these two-dimensional simulations do not yet include radiation hydrodynamics.

The significance of a cooler BL means that its emission in the UV band is stronger and cannot be neglected when computing the luminosity of the disk and WD. In the next subsection (§ 2.3) we summarize the BL emission that one may expect to observe in the UV at different mass accretion rates based on the aforementioned investigations.

### 2.3. The Emission of the Boundary Layer

For \( \dot{M} \approx 2 \times 10^{-8} \text{ \( M_\odot \) yr}^{-1} \) and higher, one expects the BL to spread onto the stellar surface, with a temperature of the order of \( 2 \times 10^5 \text{ K} \–\( 5 \times 10^7 \text{ K} \), with a velocity of the order of \( 0.3 \–\( 1 \times V_K(R_e) \). The spread layer should be observable above and below the disk (Piro & Bildsten 2004). At such temperatures the BL emits mainly in the soft X-ray with some emission in the extreme UV, and possibly also far-UV. The remaining part of the WD not covered by the spread layer emits in the UV and is likely to have an elevated temperature. The disk itself emits in the UV (far-UV to near-UV as the radius increases) and optical (outer disk). As the mass accretion rate increases, the thickness of the boundary/spread layer increases and the matter becomes advection-dominated as the heating rate surpasses the cooling rate. In this extreme case, which is achieved when the mass accretion rate approaches its Eddington limit (Godon 1997), the flow becomes spherically symmetric and the slim disk approximation for a one-dimensional BL becomes inaccurate. Instead, the vertically averaged quantities represent the spherically symmetric quantities (Narayan & Yi 1995). This implies that the results of the one-dimensional advective BL in the plane of the disk represent a massive spread layer engulfing the entire surface of the star. Such simulations have only been carried out for BL around FU Ori stars (e.g., in one dimension [Popham et al. 1993; Godon 1996b] and in 2D [Kley & Lin 1996] and symbiotics [Godon 1996a]).

For an accretion rate in the range of \( 3 \times 10^{-10} \text{ \( M_\odot \) yr}^{-1} \approx 10^{-6} \leq \dot{M} \leq 2 \times 10^{-8} \text{ \( M_\odot \) yr}^{-1} \), the matter does not spread far from the WD equator and most of the dissipated energy radiates back into the accretion disk. The BL remains confined to the plane of the disk, and one can expect the one-dimensional simulations to accurately represent the BL between the star and disk. In this case, the exact temperature, size, and rotation rate of the BL are given in Popham & Narayan (1995) and Godon et al. (1995). The temperature is in the range of \( \approx 150,000 \text{ K} \) (Godon et al. 1995) to a few 100,000 K (Popham & Narayan 1995). A modeling of the extreme UV (Chandra) spectra of some CVs (e.g., OY Car, SS Cyg, and WZ Sge) in this regime of \( \dot{M} \) leads to such temperatures (Mauche & Raymond 2000; Mauche 2004). Here, too, the BL emits in the soft X-ray regime with relatively more contribution to the extreme UV and far-UV as the temperature decreases. The WD and the inner disk emit in the UV, and the outer disk emits in the optical. The modeling we carry out in the present work is the modeling of such a BL.

For \( \dot{M} < 3 \times 10^{-10} \text{ \( M_\odot \) yr}^{-1} \), the BL is optically thin and the only UV emission is coming from the inner disk edge irradiated by the optically thin BL. That inner edge forms a ring at a radius \( r \approx 1.2 R_e \–\( 1.6 R_e \), rotating at Keplerian speed, with an effective temperature \( T_{\text{eff}} \approx 100,000 \text{ K} \–\( 500,000 \text{ K} \) (Narayan & Popham 1993; Popham 1999) for an accretion rate of \( 3 \times 10^{-10} \text{ \( M_\odot \) yr}^{-1} \) and \( 3 \times 10^{-11} \text{ \( M_\odot \) yr}^{-1} \), respectively. As the mass accretion rate decreases, the ring radius increases and its effective temperature decreases. The BL emits in the hard X-ray range and the disk’s inner edge ring emits in the UV if its temperature is high enough. Such UV emission from the inner
edge of the disk/BL was identified in VW Hyi (Pandel et al. 2003) and in other dwarf novae in quiescence (Pandel et al. 2005). This UV contribution from the BL has to be taken into account when modeling the UV spectra of accreting WDs in quiescence (Godon & Sion 2005). The WD emits in the UV, as does the very inner disk. The rest of the disk emits in the optical. As the mass accretion rate decreases further, the disk eventually ceases to emit in the UV.

As a consequence, the standard disk model is roughly correct for (say) $r \approx 2R_c$ and larger, at both high and low mass accretion rates. The exact value of $r$ for which the standard disk model breaks down depends on the mass accretion rate and mass of the WD. At smaller radii the temperature in the disk-BL region increases rapidly compared with the standard model prediction.

### 3. DATA ANALYSIS

#### 3.1. The FUSE Archival Data

MV Lyr was observed with FUSE on 2003 May 6 (at 20:07:23 UT), just after it climbed into a high state that lasted for about 4 yr. The FUSE exposure (D9050901) consists of 7637 s of good exposure time. The data were processed with the latest and final version of CalFUSE (Dixon et al. 2007) following the same procedure as in previous works (for details, see Godon et al. 2009).

The FUSE spectrum of MV Lyr (Fig. 1) is characterized by broad and deep absorption lines from highly ionized species and the absence of hydrogen Lyman lines (except for sharp lines from the interstellar medium). These absorption lines are $\text{N IV} \lambda\lambda 923$, $\text{S VI} \lambda\lambda 933.5$ and 944.5; $\text{O VI} \lambda\lambda 1131.6$ and $\lambda 1038$.

---

**Fig. 1.**—The FUSE spectrum of MV Lyr in its high state is modeled with a 44,000 K WD (dotted line), with a mass $0.8 \, M_\odot$ and a standard accretion disk (dashed line) with $\dot{M} = 3.5 \times 10^{-9} \, M_\odot \, \text{yr}^{-1}$ and $i = 10^\circ$. The combined model WD + disk is the solid black line. This gives a matching distance of 557 pc. The model cannot match the flux level in the short-wavelength range ($\lambda < 950 \, \text{Å}$). In order to fit that region, the mass accretion rate has to be increased, and this increases the distance to twice the distance of MV Lyr.
1137.3; Si IV λ1062.6 and 1073; Si III \sim λ1108; P V \lambda 1118; Si IV \lambda 1122.5 and 1128.3; and C III \lambda 1175. Such deep and broad absorption lines are often observed in CVs in high state, even in systems with a large inclination where the Keplerian velocity broadening is expected to produce a rather smooth continuum (e.g., see the FUSE spectrum of V3885 Sgr in Linnell et al. [2009]). These broad and deep absorption lines most likely form in a hot corona above the heated stellar surface, BL or disk. Additional transition wavelengths have been marked on the spectrum in Figure 1 and can be associated with some spectral features; however, they are not clearly detected.

There are a few sharp absorption lines from the interstellar medium, such as Si II λ1020, C II λ1036, Ar I λ1048.2 and 1066.7, and Fe II λ1145. The sharp emission lines are artifacts due to airglow or direct reflection of sunlight inside the telescope (e.g., such as the C III λ977 and He II λ1168 lines).

3.2. TLUSTY and SYNSPEC Codes

The modeling of the FUSE spectrum is carried out in steps. First, spherically symmetric stellar atmosphere structure and the vertical structure of disk rings are computed using the code TLUSTY (Hubeny 1988). For the stellar structure the input parameters are the surface gravity, effective temperature, and surface composition of the star. For the composition it is often enough to take hydrogen and helium and neglect the metals as long their abundance is low (say, similar to solar composition); in most cases, this does not affect the computed atmospheric structure. For high temperatures we use the non-LTE option. For the disk rings the input is the local mass accretion rate, mass of the accreting star, radius of the star, and radius of the ring and solar composition. Alternatively, one can input for each ring the effective temperature, effective vertical gravity, and column mass at midplane.

Second, the code SYNSPEC is used to derive the detailed radiation and flux distribution of continuum and lines (Hubeny & Lanz 1995). SYNSPEC generates the output spectrum of the stellar atmosphere structure and disk vertical structure computed by TLUSTY. The input for SYNSPEC is the same as for TLUSTY and it uses the structure computed by TLUSTY as an input. Composition is specified here with an additional input file and can include species up to iron or even zinc. In the present modeling we included only H, He, C, N, O, Si, P, and S.

In the next step the code ROTIN is used to account for rotational and instrumental broadening of the lines for the stellar synthetic spectrum, while the code DISKSYN (Wade & Hubeny 1998) is used to combine the disk rings together (where we substitute the inner rings with hot BL rings if a BL is computed) and account for rotational broadening due to Keplerian motion. Limb darkening is also included in the codes DISKSYN and ROTIN.

Boundary-layer synthetic spectra are generated by computing inner disk rings with an elevated temperature matching the BL temperature obtained from theoretical estimates. The rings of the BL are then substituted to the inner disk rings. We then use a reduced \( \chi^2 \) fitting technique to find the best fit to the observed spectrum. During the \( \chi^2 \) fitting process of the FUSE spectrum taken in the high state, the mass of the WD, the inclination of the system, and the composition are kept constant because they have been firmly established from previous observations. The remaining parameters (i.e., the temperature of the WD, the mass accretion rate, the number of BL rings included, and the temperature of the BL rings) are allowed to vary, as they are unknown. The distance to the system is obtained a posteriori from the spectral fitting as an output parameter; resulting models with a distance that does not agreed with the assumed distance are rejected (see the next section).

In the present work we use the following versions of the software: TLUSTY202, SYNSPEC48, and ROTIN4 for WD photospheric spectra running on a Linux platform (Cygwin-X) with a GNU FORTRAN 77 compiler; TLDISK195 (a previous variant of TLUSTY), SYNSPEC43, and ROTIN3 and DISKSYN7 for disk and BL spectra running on a Unix machine also using a GNU FORTRAN 77 compiler (the GNU FORTRAN 77 compiler runs slightly differently under Unix and Linux operating systems). The software packages and user’s guides are available online.

### Table 1: System Parameters for MV Lyr

| Parameter      | Value          | Reference                                      |
|----------------|----------------|-----------------------------------------------|
| \( M_{\text{wd}} \) | 0.73–0.8 \( M_\odot \) | This work; Hoard et al. (2004)                |
| \( R_{\text{wd}} \) | 7440 km       | Based on models of Wood (1995)                |
| \( M_{\text{bd}} \) | 0.3 \( M_\odot \) | Hoard et al. (2004)                           |
| \( i \)           | 10° ± 3°      | Schneider et al. (1981); Skillman et al.      |
|                 |                | (1995) Linnell et al. (2005)                  |
| \( E(B–V) \)      | 0             | Bruch & Engel (1994)                          |
| \( P \)           | 3.19 hr        | Skillman et al. (1995)                        |
| \( d \)          | \sim 500–550 pc | This work; Hoard et al. (2004)                |
| \( M \)          | 2 \times 10^{-9} \( M_\odot \) yr\(^{-1} \) | This work; Linnell et al. (2005)               |

Boundary-layer synthetic spectra are generated by computing inner disk rings with an elevated temperature matching the BL temperature obtained from theoretical estimates. The rings of the BL are then substituted to the inner disk rings. We then use a reduced \( \chi^2 \) fitting technique to find the best fit to the observed spectrum. During the \( \chi^2 \) fitting process of the FUSE spectrum taken in the high state, the mass of the WD, the inclination of the system, and the composition are kept constant because they have been firmly established from previous observations. The remaining parameters (i.e., the temperature of the WD, the mass accretion rate, the number of BL rings included, and the temperature of the BL rings) are allowed to vary, as they are unknown. The distance to the system is obtained a posteriori from the spectral fitting as an output parameter; resulting models with a distance that does not agreed with the assumed distance are rejected (see the next section).

In the present work we use the following versions of the software: TLUSTY202, SYNSPEC48, and ROTIN4 for WD photospheric spectra running on a Linux platform (Cygwin-X) with a GNU FORTRAN 77 compiler; TLDISK195 (a previous variant of TLUSTY), SYNSPEC43, and ROTIN3 and DISKSYN7 for disk and BL spectra running on a Unix machine also using a GNU FORTRAN 77 compiler (the GNU FORTRAN 77 compiler runs slightly differently under Unix and Linux operating systems). The software packages and user’s guides are available online.

### 4. RESULTS

In the following spectral modeling of the FUSE spectrum of MV Lyr in its high state, as we derive the mass accretion rate and characterize the BL of the system, we wish to use the mass of the WD and the distance to the system as given. These parameters were derived from the FUSE spectrum of the system in the low state by Hoard et al. (2004), who obtained a WD surface temperature \( T = 47,000 \text{ K} \), a gravity \( \log g = 8.25 \), nonsolar

---

2 Free download available at http://nova.astro.umd.edu/.
composition $Z \approx 0.3 Z_{\odot}$, and a distance $d \approx 505 \pm 50$ pc. Since these parameters are extremely important, we decided to confirm the results of Hoard et al. (2004), and we carried out a modeling of the FUSE spectrum of MV Lyr obtained in the low state. We obtained a WD surface temperature $T = 44,000$ K, a gravity $\log g = 8.1$, a projected stellar rotational velocity $V_{\text{rot}} \sin i = 200$ km s$^{-1}$, nonsolar composition $Z \approx 0.5 Z_{\odot}$, and a distance $d \approx 550 \pm 50$ pc. The small difference in the parameters derived is due to the facts that (1) Hoard et al. (2004) did not include rotational broadening; and (2) Hoard et al. (2004) used the mass-radius relation of Hamada & Salpeter (1961) for zero-temperature WDs (giving $M_{\text{wd}} = 0.73 M_{\odot}$ for $\log g = 8.25$), while we used the C/O-core WD model of Wood (1995) for a $\sim 45,000$ K WD (giving $M_{\text{wd}} = 0.73 M_{\odot}$ for $\log g = 8.1$, but $M_{\text{wd}} \sim 0.8 M_{\odot}$ for $\log g = 8.25$). We note, however, that our results are in complete agreement with the modeling carried out by E. M. S. within Hoard et al.’s (2004) work. Therefore, in the following we use the following parameters: $M_{\text{wd}} = 0.8 M_{\odot}$, $d \sim 500$–$550$ pc, and $T_{\text{wd}} = 44,000$ K and above. The abundances and stellar rotational velocity have no effects on the fitting to the FUSE spectrum in the high state, as it is dominated by emission from the solar composition disk with a large Keplerian velocity broadening.

In the fitting of the high-state spectrum, no attempt is made to model the broad and deep absorption lines. These lines form in a hot corona above the disk/BL and cannot be modeled with the synthetic spectral code TLUSTY/SYNSPEC. The code models

| Table 2: Accretion Disk and Boundary-Layer Synthetic Spectral Model Fits |
|-----------------------------|-----|-----|-----|-----|-----|-----|
| Model                      | $M \times 10^5$ ($M_{\odot}$ yr$^{-1}$) | $T_{\text{wd}}$ (10$^3$ K) | $d$ (pc) | $T_1$ (10$^3$ K) | $T_2$ (10$^3$ K) | WD/disk % | $\chi^2$   | Figure |
| Disk                       | 1.0 | 44  | 301 | 25.9 | 32.2 | 19/81 | 3.066 |
| Disk                       | 2.0 | 44  | 428 | 30.7 | 38.3 | 10/90 | 1.923 |
| Disk                       | 3.5 | 44  | 557 | 35.4 | 44.1 | 6/94  | 1.379 |
| Disk                       | 5.0 | 44  | 666 | 38.7 | 48.2 | 4/96  | 1.270 |
| Disk+BL d                  | 1.0 | 44  | 370 | 175  | 32.2 | 13/87 | 0.856 |
| Disk+BL 1                  | 1.0 | 44  | 349 | 150  | 32.2 | 14/86 | 1.083 |
| Disk+BL 2                  | 1.0 | 44  | 336 | 125  | 32.2 | 16/84 | 1.376 |
| Disk+BL 3                  | 1.0 | 44  | 327 | 100  | 32.2 | 16/84 | 1.376 |
| Disk+BL 4                  | 1.0 | 44  | 448 | 150  | 150  | 9/91  | 1.302 |
| Disk+BL d                  | 2.0 | 44  | 480 | 175  | 38.3 | 8/92  | 1.019 |
| Disk+BL 1                  | 2.0 | 44  | 464 | 150  | 38.3 | 8/92  | 1.203 |
| Disk+BL 2                  | 2.0 | 44  | 454 | 125  | 38.3 | 9/91  | 1.358 |
| Disk+BL 3                  | 2.0 | 44  | 447 | 100  | 38.3 | 9/91  | 1.485 |
| Disk+BL 4                  | 2.0 | 44  | 538 | 150  | 150  | 6/94  | 1.058 |
| Disk+BL 5                  | 2.0 | 44  | 507 | 125  | 125  | 7/93  | 0.993 |
| Disk+BL 6                  | 2.0 | 44  | 484 | 100  | 100  | 8/92  | 1.056 |
| Disk+BL da                 | 2.0 | 44  | 516 | 175  | 100  | 7/93  | 0.985 |
| Disk+BL 7                  | 2.0 | 44  | 500 | 150  | 100  | 7/93  | 1.000 |
| Disk+BL 8                  | 2.0 | 44  | 491 | 125  | 100  | 7/93  | 1.025 |
| Disk+BL da                 | 2.0 | 44  | 516 | 175  | 100  | 7/93  | 0.985 |
| Disk+BL da                 | 2.0 | 50  | 521 | 175  | 100  | 8/92  | 0.995 |
| Disk+BL 4                  | 2.0 | 44  | 538 | 150  | 150  | 6/94  | 1.058 |
| Disk+BL 4                  | 2.0 | 50  | 542 | 150  | 150  | 8/92  | 1.078 |
| Disk+BL 4                  | 2.0 | 60  | 548 | 150  | 150  | 10/90 | 1.082 |
| Disk+BL 4                  | 2.0 | 70  | 555 | 150  | 150  | 12/88 | 1.090 |
| Disk+BL 6                  | 2.0 | 44  | 484 | 100  | 100  | 8/92  | 1.056 |
| Disk+BL 6                  | 2.0 | 50  | 489 | 100  | 100  | 9/91  | 1.030 |
| Disk+BL 6                  | 2.0 | 60  | 496 | 100  | 100  | 12/88 | 1.012 |
| Disk+BL 6                  | 2.0 | 70  | 503 | 100  | 100  | 14/86 | 0.989 |
| Disk+BL 6                  | 2.7 | 50  | 545 | 100  | 100  | 8/92  | 1.068 |
the lines created in the disk itself, but not in a hot corona above it. As a consequence, only the observed continuum is considered and the broad absorption lines are masked.

The WD model used initially in the combined BL + disk + WD fits to the FUSE spectrum of MV Lyr in the high state has $T = 44,000$ K. In the high state the WD temperature could be elevated due to continuing accretion. Therefore, models with larger WD temperature are also computed (50,000 K and up), but they give very similar results. This is due to the fact that the WD is not the main emitting component of the UV spectrum. The details are given subsequently. We assume here that $i = 10^\circ \pm 3^\circ$ (Schneider et al. 1981; Skillman et al. 1995; Linnell et al. 2005).

The first four models presented in Table 2 are the 44,000 K WD+ standard disk models with increasing mass accretion rate. All these models do not have enough flux in the shorter-wavelength range to fit the FUSE spectrum. The model with $\dot{M} = 5 \times 10^{-9} M_\odot$ yr$^{-1}$ gives a distance of 666 pc, too large to be acceptable, and with $\dot{M} = 1 \times 10^{-8} M_\odot$ yr$^{-1}$ the distance becomes twice the value found in the low state. As an example, a model with $\dot{M} = 3.5 \times 10^{-9} M_\odot$ yr$^{-1}$ is shown in Figure 1, giving a distance of 557 pc. The flux deficiency in the shorter wavelengths is clearly seen. The inclusion of a hotter WD does not provide a significant improvement of the model fit.

In order to increase the flux in the shorter wavelengths, the temperatures of the two inner rings of the standard disk model are modified to represent the BL. The first ring is located at $r_1 = 1.05R_*$ and the second is at $r_2 = 1.20R_*$. The temperatures of the rings ($T_1$ and $T_2$, respectively) are listed in Table 2. In the standard disk model these temperatures are below 50,000 K for the accretion rate considered here. For the modeling of the BL, rings are computed with temperatures between 100,000 K and 175,000 K, in agreement with the BL models of Godon et al. (1995) ($\sim 125,000$ K) and Popham & Narayan.

![Image](image-url)

**Fig. 2.**—The FUSE spectrum of MV Lyr in its high state is modeled with a composite WD + disk model, which includes the BL. The WD model (dotted line) has a temperature of 44,000 K and a mass 0.8 $M_\odot$, the accretion disk model (dashed line) has a mass accretion rate of $\dot{M} = 2.0 \times 10^{-9} M_\odot$ yr$^{-1}$ and $i = 10^\circ$. The BL is modeled as the two inner rings of the disk with a temperature of 150,000 K. The combined model WD + disk is the solid black line. This gives a distance of 538 pc. The WD contributes only 6% of the flux in the FUSE spectral range.
(1995) (∼180,000 K) for the mass accretion rates considered here. In doing so, one is able to construct two models of BL: thin (first ring only) and extended (first two rings).

The standard disk model with a mass accretion rate of $3 \times 10^{-9} M_\odot\;\text{yr}^{-1}$ fits the long-wavelength end of the FUSE spectrum using the assumed distance to MV Lyr. For this reason, models with $M \geq 3 \times 10^{-9} M_\odot\;\text{yr}^{-1}$ are not considered when including the BL, since the BL increases the flux of the model and therefore its distance becomes too large. Also, since MV Lyr is in a high state, mass accretion rates below $1 \times 10^{-9} M_\odot\;\text{yr}^{-1}$ are not considered (these points are discussed in § 5).

First, an accretion disk with a mass accretion rate of $1 \times 10^{-9} M_\odot\;\text{yr}^{-1}$ is considered, and the BL temperature and size are then varied. It is found that the best model fits lead to a distance of only 350 pc–400 pc. Since the mass accretion rate is fixed to $1 \times 10^{-9} M_\odot\;\text{yr}^{-1}$, the only way to increase the distance is to increase the contribution of the BL, by increasing its temperature and/or size. In doing so, the models that give an acceptable distance (of, say, at least ∼430 pc) actually have too much flux in the shorter wavelengths, which is a sign that the BL contributes too much flux. Only a few of these models are listed in Table 2. These models are not better than the standard disk models: their $\chi^2$ is as large and/or their distance is too short. The best-fit models are obtained for a thin (one-ring) BL with a temperature of ∼150,000 K–175,000 K. The distance for these models is, however, far too short. The inclusion of a heated WD does not improve the models and produces only a small increase in the distance.

Next, to obtain models with a larger distance, the mass accretion rate is increased to $2 \times 10^{-9} M_\odot\;\text{yr}^{-1}$. This has the effect of decreasing the relative flux contributed by the BL. These models agree with the assumed distance and have a lower $\chi^2$, especially the two-ring BL models. The best one-ring model is

![Graph](https://via.placeholder.com/150)

**Fig. 3.**—The FUSE spectrum of MV Lyr in its high state is modeled with a composite WD + disk model, which includes the BL. The WD model (dotted line) has a temperature of 50,000 K and a mass of 0.8 $M_\odot$, the accretion disk model (dashed line) has a mass accretion rate of $M = 2.0 \times 10^{-9} M_\odot\;\text{yr}^{-1}$ and $i = 10^\circ$. The BL is modeled as the two inner rings of the disk with a temperature of 100,000 K. The combined model WD + disk is the solid black line. This gives a distance of 489 pc. The WD contributes 9% of the flux in the FUSE spectral range.

2011 PASP, 123:903–913
for a BL temperature of 175,000 K. This model has a relatively low \( \chi^2 \) and agrees well with the distance. For the two-ring BL models, there is little difference (in terms of \( \chi^2 \)) between a temperature of 100,000 K, 125,000 K, and 150,000 K (or any combination of those), as they produce \( \chi^2 \approx 1 \) with \( d \approx 500 \pm 50 \) pc. A 150,000 K extended (two-ring) BL model with disk and WD is shown in Figure 2. This model fits the flux in the shorter-wavelength range very well (\( \lambda < 970 \) Å, ignoring the broad absorptions of N iv and S vi) but produces too much flux around 980–1010 Å. Extended BL models with a lower temperature (e.g., 100,000 K) do not fit the shorter wavelengths as well, but on the other hand, they better fit the 970–1010 Å region and, consequently, they have the same \( \chi^2 \). In a last effort to improve the modeling, the temperature of the WD is increased to see how it affects the results. As the WD temperature increases, the hotter BL models deteriorate slightly, while the cooler BL models improve slightly. These models are listed in the lower part of Table 2 A fit with a 50,000 K WD, an extended 100,000 K BL, and a \( 2 \times 10^{-9} M_\odot \) yr\(^{-1} \) accretion disk model is shown in Figure 3.

5. DISCUSSION AND CONCLUSIONS

Overall, the best fit to the FUSE spectrum of MV Lyr in its high state consists of a composite WD + disk + BL model with a mass accretion rate \( \dot{M} = 2 \times 10^{-9} M_\odot \) yr\(^{-1} \). There are two equally acceptable BL solutions, either a broad extended (two-ring) BL with a rather low temperature (in the range of 100,000 K–150,000 K), or a thin (one-ring) BL with a higher temperature (175,000 K). The WD temperature is probably higher than the 44,000 K found in the low state, due to ongoing accretion, but it only slightly affects the quality of the fitting of the models, and we discuss this further at the end of this section.

Since the modeling of the FUSE spectrum generates more than one solution over a finite spectral range, one must consider the bolometric luminosity of each component for comparison with equations (2) and (6). For each model, the total luminosity of the BL is computed assuming that it radiates as a blackbody. This is a reasonable assumption, as in this regime the BL is most probably optically thick (Godon et al. 1995; Popham & Narayan 1995). The two components of temperature \( T_1 \) and \( T_2 \) (given in Table 2), with radii \( r_1 = 1.05 R_\star \), and \( r_2 = 1.2 R_\star \), are added. One then simply uses the Stefan-Boltzmann law and area of each ring to find the total BL luminosity. The bolometric luminosity obtained is then compared with the theoretical expectation in equation (6) using equation (2). For almost all the disk + BL models listed in Table 2 it is found that the computed bolometric BL luminosity is larger than the disk luminosity. The discrepancy is even larger for the model with \( \dot{M} = 1 \times 10^{-9} M_\odot \) yr\(^{-1} \). The only models for which the BL bolometric luminosity is smaller than the disk luminosity (eq. [6]) is for an extended BL (two-ring model) with a temperature as low as 100,000 K. For that model the bolometric BL luminosity is 93% of the disk luminosity, implying a rotational velocity (eq. [6]) of less than 4% of its Keplerian value, or about 135 km s\(^{-1} \).

With an inclination \( i = 10^\circ \pm 3^\circ \) and a projected rotational velocity of 200 ± 50 km s\(^{-1} \) (as derived in the low state), the (nonprojected) rotational velocity should be in the range of 667 km s\(^{-1} \) < \( V_{\text{rot}} < 2050 \) km s\(^{-1} \), or 0.18 < \( \Omega/L_\odot \) < 0.54 (the lower limit is for a velocity of 150 km s\(^{-1} \) and \( i = 13^\circ \), while the upper limit is for 250 km s\(^{-1} \) and \( i = 7^\circ \)). This produces a BL luminosity in the range of 0.68 > \( L_{\text{BL}}/L_{\text{disk}} > 0.21 \). For the BL model to agree with the upper limit, one could reduce the BL temperature (by 10,000 K) or increase the mass accretion rate (by one-third; such a model is listed at the end of Table 2) or both. However, one notes that the error in the WD mass of \( 0.1 M_\odot \) (~0.2 in log \( g \)) produces a computed \( L_{BL}/L_{disk} \) between 0.55 (for a 0.9 \( M_\odot \) WD mass) and ~1.5 (for a 0.7 \( M_\odot \) WD mass).

Since the BL model used here is rather simplistic, a perfect agreement between the computed bolometric luminosity of the BL and that computed from equation 6 is not expected. However, within the limits of the errors, the results of the BL model are consistent with a broad BL (of size \( \sim 2 R_\star \)) with a rather low temperature (~100,000 K or slightly less) and a mass accretion rate of the order of \( \sim 2 \times 10^{-9} M_\odot \) yr\(^{-1} \) (or slightly larger). These models are located in the lower part of Table 2, and the fit improves (lower \( \chi^2 \) and better distance) as the temperature of the WD increases, reaching a best fit for \( T = 70,000 \) K. Though the temperature of the WD is certainly not that high, this certainly points to the fact that the temperature of the WD is elevated during the high state, reaching ~50,000 K or a little higher.

This work was supported by the National Aeronautics and Space Administration (NASA) under grant NNX08AI39G issued through the Office of Astrophysics Data Analysis Program (ADP) to Villanova University. We have used some of the online data from the American Association of Variable Star Observers (AAVSO), and we are thankful to the AAVSO and its members worldwide for making these data public and for their constant monitoring of cataclysmic variables.

REFERENCES

Balsara, D. S., Fisker, J. L., Godon, P., & Sion, E. M. 2009, ApJ, 702, 1536
Bruch, A., & Engel, A. 1994, A&AS, 104, 79
Cannizzo, J. K. 1988, ApJ, 333, 227
———. 1998, ApJ, 493, 426
Chiappetti, L., Maraschi, L., Treves, A., & Tanzi, E. G. 1982, ApJ, 258, 236
Collins, T. J. B. 1997, ApJ, 478, 417
Collins, T. J. B., Helfer, H. L., & van Horn, H. M. 1998a, ApJ, 502, 730
———. 1998b, ApJ, 508, 159
———. 2000a, ApJ, 534, 934
———. 2000b, ApJ, 534, 944
Dixon, W. V., et al. 2007, PASP, 119, 527
Durisen, R. 1977, ApJ, 213, 145

2011 PASP, 123:903–913
