THE ANOMALOUS ACCRETION DISK OF THE CATACLYSMIC VARIABLE RW SEXANTI*  

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ABSTRACT

Synthetic spectra covering the wavelength range 900–3000 Å provide an accurate fit, established by a χ² analysis, to a combined observed spectrum of RW Sextantis. Two separately calibrated distances to the system establish the synthetic spectrum comparison on an absolute flux basis but with two alternative scaling factors, requiring alternative values of M for final models. Based on comparisons for a range of M values, the observed spectrum does not follow the standard model. Rather than the exponent 0.25 in the expression for the radial temperature profile, a value close to 0.125 produces a synthetic spectrum with an accurate fit to the combined spectrum. A study of time-series Far Ultraviolet Spectroscopic Explorer spectra shows that a proposed warped or tilted disk is not supported by the data; an alternative proposal is that an observed non-axisymmetric wind results from an interaction with the mass transfer stream debris.

Key words: novae, cataclysmic variables – stars: individual (constellation name: RW Sextantis) – white dwarfs

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1. INTRODUCTION

Cataclysmic variables (CVs) are semi-detached binary stars in which a late main-sequence star loses mass onto a white dwarf (WD) by Roche lobe overflow (Warner 1995). In non-magnetic systems, the mass transfer stream produces an accretion disk with mass transport inward and angular momentum transport outward, driven by viscous processes. The accretion disk may extend inward to the WD, the outer boundary extends to a tidal cutoff limit imposed by the secondary star in the steady state case. If the mass transfer rate is below a certain limit, the accretion disk is unstable and undergoes brightness cycles (outbursts), and if above the limit, the accretion disk is stable against outbursts (Osaki 1996). The latter objects (which have no recorded outburst of any type) are called nova-like (NL) systems. As shown by Cowley et al. (1977), Beuermann et al. (1992, hereafter BEU), and Prinja et al. (2003), RW Sex is an NL system (see Warner 1995 and Lasota 2001 for a detailed discussion). RW Sex has a Hipparcos (Perryman et al. 1997) parallax and a separately calibrated distance (BEU), of importance in constraining the mass transfer rate M. BEU provide estimates of the component stellar masses and the orbital inclination; Greenstein & Oke (1982) provide an estimate of $M = 1.0 \times 10^{-9} M_\odot$ yr⁻¹ while Wade (1988) quotes a value of $M = 3.0 \times 10^{-9} M_\odot$ yr⁻¹ from Patterson (1984). A Far Ultraviolet Spectroscopic Explorer (FUSE) spectrum of RW Sex is available, as well as Hubble Space Telescope (HST) and IUE spectra. FUSE spectra are important in constraining the WD $T_{\text{eff}}$ as well as $M$ since the peaks of the radiation curves fall in the FUSE spectral range.

NL systems are of special interest because they are expected to have an accretion disk radial temperature profile given by an analytic expression (Frank et al. 1992, hereafter FKR, Equation (5.41); cf. Equation (2) below) that defines the so-called standard model; the expression includes the mass transfer rate $M$ as an explicit variable. In NL systems which are above the period gap (Howell et al. 2001), the accretion disk dominates the system spectrum (with the exception of BK Lyn; Zellem et al. 2009). Fitting a synthetic spectrum based on the analytic model (a proxy of the accretion disk temperature profile) to an observed spectrum potentially determines $M$. This physical parameter is of basic importance since it controls the evolution of CV systems (Howell et al. 2001). But the analytic expression also is an explicit function of the WD mass, $M_{\text{wd}}$, and the mass must be determined independently. Wade (1988), using IUE spectra, showed that NL systems systematically disagree with the standard model when either black body spectra or Kurucz stellar model spectra are used to represent the accretion disk. The Kurucz spectra were too “blue,” i.e., had too large a spectral gradient as compared with the IUE spectra; this was specifically true of RW Sex. Wade concluded that the problem was with use of Kurucz spectra; they are not suited to representation of accretion disks. Hubeny (1990) has developed a procedure for modeling annuli of accretion disks that explicitly includes calculation of synthetic spectra using the standard model. In this paper, we apply the Hubeny model to determine system parameters for RW Sex and to test whether the system conforms to the standard model.

2. THE FUSE AND HST/GHRS SPECTRA

Table 1 presents the observations log. This is the same observation set studied by Prinja et al. (2003) and discussed by those authors.

2.1. The FUSE Spectrum

The FUSE spectrum of RW Sex consists of 25 exposures (spacecraft orbits) totaling more than 25 ks of calibrated (good) exposure time. The FUSE spectrum (flux and errors) were extracted using the CalFUSE software, initially binned
Figure 1. FUSE spectrum of RW Sex. The ordinate is flux in erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. (A color version of this figure is available in the online journal.)

Table 1
FUV Observations of RW Sex: FUSE and HST Spectra

| Instrument | Date (dd/mm/yy) | Time (hh:mm:ss) | Exp. Time (s) | Data Set | Aperture or Grating | Operation Mode | Wavelengths (Å) |
|------------|-----------------|-----------------|---------------|----------|---------------------|----------------|-----------------|
| FUSE       | 13/05/01        | 14:48:05        | 25614         | B1040101 | LWRS                | TTAG           | 904–1188        |
| HST/GHRS   | 04/05/96        | 13:03:53        | 544           | z37v0104t| G140L               | ACCUM          | 1367–1663       |
| HST/GHRS   | 04/05/96        | 13:17:58        | 544           | z37v0105t| G140L               | ACCUM          | 1367–1663       |
| HST/GHRS   | 04/05/96        | 13:30:59        | 544           | z37v0106t| G140L               | ACCUM          | 1140–1435       |
| HST/GHRS   | 04/05/96        | 13:37:23        | 544           | z37v0107t| G140L               | ACCUM          | 1367–1663       |
| HST/GHRS   | 04/05/96        | 14:50:24        | 544           | z37v0108t| G140L               | ACCUM          | 1367–1663       |
| HST/GHRS   | 04/05/96        | 15:03:25        | 435           | z37v0109t| G140L               | ACCUM          | 1367–1663       |

The data were rebinned at an interval of 0.5 Å using the IRAF command trebin. Typical noise levels are on the order of 3% of the signal level. Each spectrum consists of a list of flux values (erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$) and associated noise values in the same units. The FUSE spectrum covers the interval 903–1188 Å.

In Figure 1, we present the combined spectrum (25 ks) annotated with absorption lines. It is impractical to place individual error bars on the plotted points. Besides the obvious Ly$\beta$ and Ly$\gamma$ broad features (due to the disk and accreting WD), the system exhibits broad absorption lines (which appear blueshifted in this composite by as much as 3 Å) and a multitude of very sharp absorption lines of interstellar origin. We describe these absorption lines below and list some of them in Tables 2 and 3. The observed wavelengths of the sharp absorption lines listed in Table 2 were measured in the 1SiC channel for $\lambda < 1100$ Å, and 2LiF channel for $\lambda > 1100$ Å; as a consequence the observed interstellar medium (ISM) lines are blueshifted by $\sim$0.05 Å for $\lambda < 1100$ Å and redshifted by about the same amount for $\lambda > 1100$ Å as the channels are not precisely aligned. When we co-added the channels and different orbits we aligned all the spectral segments.

NL system spectra typically exhibit strong absorption lines from high excitation ions, a signature of a wind believed to originate from the accretion disk (Pereyra et al. 2006; Proga 2003a, 2003b). See the review by Drew & Proga (2000). The presence of these lines is the largest current obstacle to spectrum synthesis modeling of the accretion disk in NL systems. In the present instance, it is necessary to mask appreciable sections of the FUSE spectrum because we currently do not have the
ability to model the wind. This requirement reduces the number of lines that we fit in the FUSE spectrum.

2.2. The ISM Hydrogen Lines

The FUSE spectrum of RW Sex exhibits a forest of molecular hydrogen absorption lines identified by the Werner (W) and Lyman (L) bands, upper vibrational level (ranging from 16 to 1) and rotational transition R, P, and Q with lower rotational state $J = 1, 2, \text{and } 3$. For example, starting at 933.2 Å there is the L16R2 line, and next to it at 933.6 Å the W4Q3 line. There are more than 100 molecular hydrogen lines extending to ∼1100 Å (L0R2 1110.10 Å). We have marked these lines (vertical tick mark) in the upper part of each panel in Figure 1 (annotated MH). See Sembach et al. (2001) for the entire list of molecular hydrogen lines and their wavelengths.

The atomic hydrogen lines (Lyman series) are marked below each panel.

The feature at 1152 Å is a fixed pattern noise (FPN) due to the FUSE detectors.

### 2.3. The ISM Metal Lines

In addition to the hydrogen atomic and molecular lines, we identify many orders of neutral oxygen (O I) starting at 916.9 Å (the 26th order) and extending to about ∼1000 Å with OI 4th and 3rd orders at $\lambda \lambda 1025.9$ and $\lambda \lambda 1039.3$. Not all of the lines are listed in Table 2, but lines from all of the orders (between 2u and 3u) are identified. In the comments column, the letter "u" stands for an ultraviolet multiplet and the preceding number is the multiplet number (see Morton 2000, 2003). The oxygen lines are marked with vertical ticks (at mid-height; annotated OI).

The FUSE spectrum of RW Sex is rich in oxygen lines in addition to metal lines which are frequently observed in
2.4. The HST Spectra

The composite HST spectrum of RW Sex shown in Figure 2 is a combination of two GHRS spectra, z37v0107t and z37v0108t. The HST spectrum of RW Sex is characterized by deep and broad absorption lines from the CV source together with much shallower and sharper lines from the ISM. The lines are identified in Table 4.

The broad absorption lines can be divided into two distinct groups. The first group of broad lines includes Si III (~1140, ~1205, ~1300, and 1327 Å), Si IV (~1392 and 1401 Å), C III (~1173 Å), and He II (~1638 Å) lines, all blueshifted by ~1.8–2.5 Å with a width of about 5–8 Å. The second group of broad lines includes N V (~1234 and 1237 Å) and C IV (~1543 Å) and is distinct from the first group in that the N and C lines are blueshifted by as much as 5 Å and 6 Å, respectively. The lines also appear to be broader with a width of more than 10 Å. It is likely that the N V and C IV lines form in a hotter region expanding faster than the lines from the first group. The Lyα line stands apart in that it is blueshifted by less than 1 Å.

The sharp absorption lines all have a width of about ~0.5 Å or less and are blueshifted by only 0.2–0.5 Å. The lines are listed in Table 4 and we tentatively identify, as in the FUSE spectrum, some P II phosphorus lines at 1142.5, 1152.6 (also detected in the FUSE spectrum), and 1301.7 Å (which could be affected by the O I 1302 line).

3. The IUE Spectra

Table 5 lists the low dispersion IUE spectra. There are three pairs of spectra covering the range 1150–3350 Å. We designate them as case1 (SWP01671+LWR01583), case2 (SWP02494+LWR03071), and case3 (SWP07500+LWR06494) in temporal sequence. Separately, the SWP spectra cover the range 1150–1978 Å and the LWR spectra cover the range 1851–3350 Å, tabulated in erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$. The tabular interval of both spectra is about 2 Å and each has an associated tabulated noise level in the same units as the flux. As with the FUSE spectrum, typical noise levels are 3% of the signal. We used the IUEDAC software package to extract the spectra, with zero correction for reddening, and including the $\sigma$ value at each tabular wavelength, and processed the spectra with the standard recalibration procedure (Massa & Fitzpatrick 2000). We examined the overlap region of each SWP and LWR pair and...
found that the case I pair fitted very well without scaling either spectrum.

4. MERGING FUSE, HST, AND IUE SPECTRA

Our model simulations concern fitting the observed continuum. The presence of broad absorption lines of high excitation species in the FUSE spectrum, which our model does not simulate, requires masking of parts of the FUSE spectrum and so reduces the utility of the FUSE spectrum in choosing among possible models. In addition, the short spectral range of the FUSE spectrum makes a stringent test of the spectral gradient fit more difficult. However, the peaks of the emission profiles of both the WD and the accretion disk fall in the FUSE range and the sensitivity to different WD $T_{\text{eff}}$ values and accretion disk $M$ values is much greater than in HST or IUE spectra. In view of those features, we combine the FUSE and IUE spectra to obtain the best constraint on model parameters. The issue now is to choose the optimum IUE spectrum. We do not include the HST spectra in our simulations because of the restricted wavelength range of those spectra.

Figure 3 shows the fit of the various spectra. Identifications of the spectra are in the figure legend. The mean of HST z37v0108t and z37v0109t (Table 1) is not plotted; it is similar to the mean of z37v0104t plus z37v0105t. In this overlap region, the IUE case 1 (orange line) agrees well with the HST (blue) spectra. The other two IUE spectra are roughly accordant, with the exception of the case 3 Lα geocoronal line 1220 Å. The case-to-case variation of the IUE spectra indicates some temporal variation that is most marked in the absorption lines.

The black line is the FUSE spectrum as observed; it is discrepant from both the HST and IUE spectra. Two possible explanations of the discrepancy are (1) there was an error in the HST wavelength calibration; (2) RW Sex is slightly variable. The lines from the FUSE or IUE (blue) spectra. The other two IUE spectra are roughly accordant, with the exception of the case 3 Lα geocoronal line 1220 Å. The case-to-case variation of the IUE spectra indicates some temporal variation that is most marked in the absorption lines.

The black line is the FUSE spectrum as observed; it is discrepant from both the HST and IUE spectra. Two possible explanations of the discrepancy are (1) there was an error in the HST wavelength calibration; (2) RW Sex is slightly variable. The lines from the FUSE or IUE (blue) spectra. The other two IUE spectra are roughly accordant, with the exception of the case 3 Lα geocoronal line 1220 Å. The case-to-case variation of the IUE spectra indicates some temporal variation that is most marked in the absorption lines.
is the \textit{FUSE} spectrum divided by 0.82; the fit to the \textit{HST} spectra now is excellent and, within the noise level of the \textit{IUE} spectra, the fit to the \textit{IUE} spectra is good.

We deleted the region of \textit{IUE} case 1 that overlaps the \textit{FUSE} spectrum and added the remaining part of case 1 to the \textit{FUSE} spectrum divided by 0.82. This combined spectrum shows strong absorption lines associated with a wind/chromosphere (Figure 1) and other features like the P Cygni C IV line at 1540 Å (Figure 2). The synthetic spectrum does not model those features and it is necessary to mask them. At the same time, the widths of strong absorption lines are discriminants among different models. We were careful to mask features that clearly arose from a wind/chromosphere while minimizing the total amount of masking.

The \textit{FUSE} data we simulate consist of flux values, $F_\lambda$ (erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$), and associated noise values, $\sigma$. Calculation of the reduced $\chi^2$ follows from the equation

$$\chi^2 = \frac{1}{N-M} \sum_{i=1}^{N} \left( \frac{F_\lambda - f(\lambda_i)}{\sigma_i} \right)^2,$$

where $N$ is the number of observed wavelengths, $M$ is the number of model parameters (identified and discussed below), $F_\lambda$ is the observed flux at a particular wavelength, $\sigma_i$ is the associated uncertainty of $F_\lambda$, and $f(\lambda_i)$ is the flux calculated by the model. Our model consists of calculated flux values at a tabular interval of 0.1 Å; the fitting process interpolates among the calculated flux values to the exact tabular wavelength of each observed data point.

A rough test of a good model fit to an observed data set is a $\chi^2$~0.1 (Taylor 1982, chap. 12.3). In our case, a final $\chi^2$~1 would indicate essentially a perfect fit at the noise level—an accuracy unachievable in the presence of unmodeled spectral features. However, if we do use the available noise level tabulation, the calculated $\chi^2$ variation from model to model still provides a measure of relative model-to-model quality of fit. The subsequent discussion, Section 8, includes a more detailed test.

5. INITIALLY ADOPTED SYSTEM PARAMETERS

By the basic paradigm of CV evolution (Howell et al. 2001), there is a close relation between orbital period and donor mass. In a recent paper, Knigge (2007) has calibrated the relations among $P$, $M_2$, $R_2$, $T_{\text{eff},2}$, and donor spectral type. Thus, given an orbital period below the tabular upper limit of 6 hr, $M_2$ can be determined independently of other parameters. If there is an observationally determined mass ratio, the WD mass follows directly.

Table 6 (and table notes) lists initially adopted parameters and their sources. Several of the system parameters are poorly known. Knigge (2006, 2007) determines $M_2 = 0.67 M_\odot$ for $P = 0.24507$ days. BEU determine a mass ratio $1/q = 1.35 \pm 0.1$ which, with $M_2$, produces $M_{\text{wd}} = 0.9$. Panei et al. (2000) list a WD radius of $8.82 \times 10^{-3} R_\odot$ for a $0.90 M_\odot$ homogeneous zero-temperature Hamada–Salpeter carbon model WD; in our subsequent study of the observed spectra, we correct the radius for the adopted WD $T_{\text{eff}}$.

Verbunt (1987) determined a preferred value of $E(B-V) = 0.0$ with a rough upper limit of $E(B-V) \leq 0.03$, based on a study of the 2175 Å “bump” in \textit{IUE} spectra. Bruch & Engel (1994) list $E(B-V) = 0.02$. Mauche et al. (1988) determine a value of $E(B-V) = 0.014$ with appreciable uncertainty. We adopt $E(B-V) = 0.0$.

| Parameter | Value |
|-----------|-------|
| $M_{\text{wd}}$ | 0.90 $M_\odot$ |
| $M_2$ | 0.674 $M_\odot$ |
| $T_{\text{eff}}$ | 1.0 x 10$^{-9}$ $M_\odot$ yr$^{-1}$ |
| $P$ | 0.24507 days |

Notes:

a Beuermann et al. (1992) value of $1/q = 1.35$ and $M_2$ from Knigge (2006, 2007).

b Beuermann et al. (1992), $i$ between 28$^\circ$ and 40$^\circ$.

c Knigge (2006, 2007) calibrated $P$-$M_2$ relation.

d Arbitrary initial test value.

e Beuermann et al. (1992).

f Hipparcos value.

A number of studies have considered the tidal cutoff boundary, $r_d$, of accretion disks (Paczynski 1977; Papaloizou & Pringle 1977; Whitehurst 1988; Schwarzenberg-Czerny & Różycka 1988; Whitehurst & King 1991; Goodman 1993). These authors agree on $r_d \sim 0.33 D$, where $D$ is the separation of the stellar components. We adopt this expression for the tidal cutoff radius of the accretion disk.

The \textit{Hipparcos} (Perryman et al. 1997) parallax, 3.46 ± 2.44 mas, corresponds to a distance of 289 pc. BEU determine a distance of 150 pc, based on an application of Bailey’s method (Bailey 1981) and different from the \textit{Hipparcos} value by slightly more than 1σ. We will study our results in the context of both distance determinations and we initially adopt the \textit{Hipparcos} value.

With respect to the Table 6 parameters, the orbital period is known with essentially perfect accuracy as compared to the other parameters. Of the remaining parameters, $M_2$ has no effect on the model spectrum; however, $T_{\text{eff}}$ of the WD does affect the model and we include it as an adjustable parameter.

6. THE ANALYSIS PROGRAM: BINSYN

Our analysis uses the program suite BINSYN (Linnell & Hubeny 1996); recent papers (Linnell et al. 2007, 2008b, 2009) describe its application to CV systems in detail. Briefly, an initial calculation produces a set of annulus models for a given WD mass, radius, and mass transfer rate. This calculation uses the program TLUSTY6 (Hubeny 1988; Hubeny & Lanz 1995). TLUSTY considers the radial and vertical structure of the disk independently; the radial structure is based on the standard model (FKR), and so follows the prescribed relation between local $T_{\text{eff}}$ and the annulus radius. The vertical structure is solved, self-consistently, as described by Hubeny (1990) and Hubeny & Hubeny (1998). The set of annulus models covers the accretion disk from its innermost (WD) radius to $r/r_{\text{wd,0}} = 50.0$, where $r_{\text{wd,0}}$ is the radius of the zero-temperature WD.

The primary source of viscosity in CV accretion disks is believed to be magnetorotational instability (MRI; Balbus & Hawley 1991; Balbus 2002). Hirose et al. (2006) calculate MHD models with local dissipation of turbulence and show that the vertical extent of an annulus is greater than in previous models. Blaes et al. (2006) show that magnetic support has a significant effect on synthetic spectra of black hole (BH) accretion disk annuli in the X-ray region and illustrate the effect in the case of a BH system with $M_{\text{BH}} = 6.62 M_\odot$ and with an adopted $\alpha = 0.02$. There is an insignificant effect in the visible and UV. They

6 http://nova.astro.umd.edu
are able to simulate the effect of magnetic support within the TLUSTY framework by adjusting the TLUSTY parameters $\zeta_0$ and $\zeta_1$ and use this simulation to calculate the effect on synthetic spectra. TLUSTY allows for a vertical viscosity profile within a given annulus; it introduces an assignable division point within an annulus, dividing the annulus into deep layers and outer layers. Within the deep layers, viscosity follows a power-law variation specified by $\zeta_0$, while the outer layers follow a power-law variation specified by $\zeta_1$. See Hubeny & Hubeny (1998) for details. The primary effect (Blaes et al. 2006) of magnetic support is a hardening of the spectrum in the 0.45 keV region. King et al. (2007) point out that MHD models that produce viscosity via MRI require $\alpha$ values that are a factor of 10 smaller than the $\alpha = 0.1–0.4$ required by observational evidence and suggest that some caution still is needed in accepting the MHD results. Our models have used the default values $\zeta_0 = \zeta_1 = 0$; this choice produces a constant viscosity vertically within the annulus. We have calculated a synthetic spectrum of one annulus that contributes significantly to the system synthetic spectrum using the same viscosity parameters used by Blaes et al. (2006) and have compared that synthetic spectrum with our model synthetic spectrum for the same annulus for the spectral range 900–3000 Å. We find no detectable difference, in agreement with Blaes et al. (2006). Magnetic support is believed to extend the accretion disk vertically as compared with the standard model (Hirose et al. 2006; Blaes et al. 2006), an effect confirmed in the case of IX Vel (Linnell et al. 2007). The absence of an eclipse in RW Sex prevents a test in this system. We assume a fixed $\alpha$ for the entire accretion disk.

Table 7 lists properties of annuli calculated with TLUSTY (v.203n) for a mass transfer rate of $5.0 \times 10^{-9} M_\odot$ yr$^{-1}$. This illustrative case is from among the cases we tested in our simulations. The TLUSTY control file to calculate a given annulus requires a radius of the WD in units of $R_\odot$. All of the annuli used the radius of a zero-temperature WD for a homogeneous carbon Hamada–Salpeter 0.90 $M_\odot$ model from Panei et al. (2000). All of the annuli are solar composition models, and the models through $r/\dot{M}_{\text{wd,0}} = 26.0$ are converged non-LTE models. The remaining models are the so-called gray models (see the TLUSTY Users Guide for an explanation). The annulus spectral flux levels vary by a factor of order 4 dex from the innermost annulus to the rim annulus. The gray models contribute very little to the accretion disk synthetic spectrum and the difference between the contribution of a gray model synthetic spectrum and a corresponding converged non-LTE model spectrum is negligible. Our adoption of solar composition models implicitly assumes that the secondary star, which supplies the material for the accretion disk, has an atmosphere with a solar composition.

The annulus calculations adopted C, Mg, Al, Si, and Fe as explicit ions in addition to H and He. Tests show that there are detectable differences between synthetic spectra for only H, He as explicit ions, and models including the metals listed. The remaining gray model annuli use the same set of explicit ions (see the TLUSTY Users Guide for an explanation). We believe this is the first instance in which non-LTE annulus models using metals as explicit ions have been used in a CV simulation. As we discuss subsequently, this study performed a $\chi^2$ analysis with $M$ values of $1.0, 2.0, 4.0, 5.0, 5.25, 5.5, 5.75, 6.0, 6.25, 6.5$, and $7.0 \times 10^{-9} M_\odot$ yr$^{-1}$. Each value of $M$ has an associated table similar to Table 7, for the same range of annulus radii, with non-LTE models through $r/\dot{M}_{\text{wd,0}} = 26.0$ (the limit of the range of convergence) and for the explicit ions listed above.

**Table 7**

| $r/\dot{M}_{\text{wd,0}}$ | $\log \dot{M}$ | $\log g$ | $z_0$ | $N_e$ | $\eta_{\text{Ross}}$ |
|-----------------------|----------------|---------|-------|-------|-----------------|
| 1.36                  | 66422          | 1.21E4  | 7.07  | 5.65E7 | 2.87E17         |
| 2.00                  | 59554          | 1.48E4  | 6.80  | 9.79E6 | 1.89E17         |
| 3.00                  | 48157          | 1.44E4  | 6.50  | 1.66E6 | 1.11E17         |
| 4.00                  | 40477          | 1.35E4  | 6.29  | 2.38E6 | 7.93E16         |
| 5.00                  | 35109          | 1.25E4  | 6.12  | 3.14E6 | 5.35E16         |
| 6.00                  | 31148          | 1.17E4  | 5.98  | 3.93E6 | 4.11E16         |
| 7.00                  | 28096          | 1.10E4  | 5.86  | 4.75E6 | 3.32E16         |
| 8.00                  | 25664          | 1.04E4  | 5.75  | 5.60E6 | 2.79E16         |
| 9.00                  | 23676          | 9.83E3  | 5.66  | 6.42E6 | 2.92E16         |
| 10.00                 | 22016          | 9.37E3  | 5.58  | 7.28E6 | 2.55E16         |
| 12.00                 | 19393          | 8.60E3  | 5.44  | 9.08E6 | 2.03E16         |
| 14.00                 | 17404          | 7.98E3  | 5.32  | 1.09E6 | 1.65E16         |
| 16.00                 | 15837          | 7.47E3  | 5.21  | 1.28E6 | 1.38E16         |
| 18.00                 | 14567          | 7.04E3  | 5.12  | 1.47E6 | 1.17E16         |
| 20.00                 | 13513          | 6.67E3  | 5.03  | 1.66E6 | 1.00E16         |
| 22.00                 | 12623          | 6.35E3  | 4.96  | 1.85E6 | 8.68E15         |
| 26.00                 | 11196          | 5.82E3  | 4.82  | 2.24E6 | 6.71E15         |
| 30.00                 | 10099          | 5.39E3  | 4.70  | 2.59E6 | 5.85E15         |
| 35.00                 | 9033           | 4.97E3  | 4.57  | 3.08E6 | 5.23E15         |
| 40.00                 | 8199           | 4.62E3  | 4.45  | 3.44E6 | 4.15E15         |
| 45.00                 | 7526           | 4.33E3  | 4.24  | 3.08E6 | 3.63E15         |
| 50.00                 | 6970           | 4.09E3  | 4.07  | 2.82E6 | 3.06E15         |

**Notes.** Each line in the table represents a separate annulus. A Shakura & Sunyaev (1973) viscosity parameter $\alpha = 0.1$ was used in calculating all annuli. The WD radius, $\dot{M}_{\text{wd,0}}$, is the radius, 0.00882 $R_\odot$, of a zero-temperature Hamada–Salpeter carbon model. See the text (Section 6) for a discussion of the table units.

A Shakura & Sunyaev (1973) viscosity parameter $\alpha = 0.1$ was used in calculating all annuli. Each line in Table 7 represents a separate annulus. Temperatures are in Kelvins. The column headed by $m_0$ is the column mass, in g cm$^{-3}$, above the central plane. The columns headed by $z_0$ and $N_e$ are, respectively, the height (cm) above the central plane for a Rosseland optical depth of $\sim 0.7$ and the electron density (cm$^{-3}$) at the same level. The column headed by $\log g$ is the log gravity (cgs units) in the $\z$-direction at a Rosseland optical depth of $\sim 0.7$. The column headed by $\eta_{\text{Ross}}$ is the Rosseland optical depth at the central plane. We call attention to the fact that the annuli are optically thick to the outer radius of the accretion disk (and true for the full range of $M$ values).

Following the calculation of annulus models for assigned $M_{\text{wd}}$ and $M$, program SYNSPEC (v.48; Hubeny et al. 1994) was used to produce a synthetic spectrum for each annulus, at a spectral resolution of 0.1 Å. We adopted solar composition for all synthetic spectra. The synthetic spectra include contributions from the explicit ions listed above and the remaining first 30 atomic species.

The $\chi^2$ analysis mentioned above needs WD synthetic spectra to pair with each $M$ accretion disk model. We calculated non-LTE WD synthetic spectra for $T_{\text{eff}}$ values of $35,000$ K, $40,000$ K, $45,000$ K, $50,000$ K, $55,000$ K, $60,000$ K, $65,000$ K, $70,000$ K, and $75,000$ K with the same list of explicit ions listed above and at a spectral resolution of 0.1 Å. This WD representation assumes that the solar composition mass transfer stream, after passing through the accretion disk to deposition on the WD, so adulates the WD photosphere that it preserves a solar composition in spite of the inward diffusion of heavy ions through the WD atmosphere.

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7 http://nova.astro.umd.edu
BINSYN models the complete CV system, including the WD, secondary star, accretion disk face, and accretion disk rim as separate entities. The model represents phase-dependent and inclination-dependent effects, including eclipse effects and irradiation effects, on all of the system objects. Calculation of synthetic spectra for the stars requires polar $T_{\text{eff}}$ values and gravity-darkening exponents. We adopted a standard gravity-darkening exponent of 0.25 for the WD; the secondary star makes a negligible contribution to the system synthetic spectrum, as shown by a comparison of the secondary star synthetic spectrum and the accretion disk synthetic spectrum, and we do not list the secondary star simulation parameters. BINSYN represents the accretion disk by a specified number of annuli (45 in the present case), where that number typically is larger than the number of TLUSTY annulus models (22 in the present case; see Table 7). BINSYN calculates a synthetic spectrum for each of the annuli specified in the BINSYN system model by interpolation among the array of TLUSTY annulus models, with proper allowance for orbital inclination. The accretion disk $T_{\text{eff}}$ profile may follow the standard model, but, alternatively, the profile may be specified by a separate input file or by a non-standard radial temperature gradient as discussed below.

BINSYN has provision to represent a bright spot on the rim face, but our present data do not require this facility (Section 9).

7. STANDARD MODEL SIMULATIONS OF RW SEX

We adopted system parameters listed in Table 6 for an initial test; the initial value of $M$ was arbitrary and was meant to test whether its value produced a synthetic system spectrum with even an approximate fit to the observed spectrum. On the assumption that the WD contribution would be small, we adopted a WD $T_{\text{eff}} = 50,000$ K based on our previous studies of CV systems. If necessary, new models could be calculated with a revised WD $T_{\text{eff}}$. The initial choice of $M (M = 1.0 \times 10^{-9} M_\odot \text{yr}^{-1})$ was obviously too small; we successively tried $M = 2.0, 4.0, \text{and} 5.0 \times 10^{-9} M_\odot \text{yr}^{-1}$ and the last choice indicated a value that might be appropriate but with a problem described below.

In constructing a model accretion disk, it is necessary to allow for the change in WD radius from the zero-temperature model. We used Table 4(a) of Panei et al. (2000) to estimate the 50,000 K WD radius at 0.0099 $R_\odot$. Our BINSYN model specified 45 annuli for the accretion disk, with assigned radii and corresponding standard model $T_{\text{eff}}$ values listed in Table 8. The first column in Tables 7 and 8 specifies inner radii of annuli measured in units of the WD radius; in Table 7 the unit is a zero-temperature WD and in Table 8 the unit is the WD radius for its assigned $T_{\text{eff}}$ of 50,000 K, a larger quantity. Thus, in Table 8, a given number in Column 1 corresponds to a larger physical distance, and a lower annulus $T_{\text{eff}}$, than for Table 7. The synthetic spectrum for a given BINSYN annulus is calculated by interpolation (temperature-wise) among the Table 7 entries. Ideally, we could recalculate the whole series of annulus models (via TLUSTY) based on the new value of $R_{\text{wd}}$, but the change in the individual annulus models would be very small and would not be warranted in view of other uncertainties (e.g., the system parallax).

Table 7 ends at a $T_{\text{eff}}$ of 6970 K. The net effect is that the calculated BINSYN outer annuli have synthetic spectra corresponding to 6970 K even if the specified standard model calls for a lower temperature. The effect on the synthetic spectrum of failing to follow the standard model is negligible. Adding a lower temperature (3500 K) stellar synthetic spectrum to the array of Table 7, thereby permitting interpolation to a lower temperature in the outer BINSYN annuli, made no detectable change in the system synthetic spectrum. As separate issues, the outer annuli temperatures should not fall below 6000 K to avoid outbursts (Osaki 1996; Lasota 2001) and tidal dissipation is expected to raise the outer accretion disk temperature above the standard model value (Smak 2002).

The adopted Hipparcos distance provided a fixed scaling factor by which to divide the synthetic spectrum to superpose it on the observed ("corrected" FUSE plus IUE case 1) spectrum. The spectral gradient of the superposed synthetic spectrum was much too large but the total integrated flux, judged by an eye estimate of the area below the synthetic spectrum, appeared about right. We repeated the entire process with $M$ values, including the initial test, of 5.0, 5.25, 5.5, 5.75, 6.0, 6.25, 6.5, and 7.0 $\times 10^{-9} M_\odot \text{yr}^{-1}$. In all cases, we used a WD $T_{\text{eff}}$ of 50,000 K; the spectral gradients of all models were too large. Figure 4 shows the results for five models, identified in the figure legend, and Figure 5 shows the results in the FUSE spectral region. The usable range of the IUE spectra extends to 3000 Å, matching the spectral interval covered by our synthetic spectra.

Smaller mass transfer rates would produce an accretion disk with too small luminosity to fit the observations (most of the radiation curve would lie below the observed spectrum) and larger mass transfer rates would produce an accretion disk with too large luminosity, based on the adopted system distance. The contribution of the WD cannot be the source of the too large calculated spectral gradient because its contribution is much too small; a plot of the accretion disk contribution alone shows nearly identical results. On a purely empirical basis, we inquire whether an analytic model with a smaller than standard radial temperature gradient but the same total luminosity could fit the observations.

The following equation defines the standard model (Frank et al. 1992).

$$T_{\text{eff}}(R) = \left[ \frac{3GM M}{8\pi R^3\sigma} \left[ 1 - \left( \frac{R_{\text{wd}}}{R} \right)^{1/2} \right] \right]^{1/4},$$

(2)
where $M$ is the mass of the WD, $\dot{M}$ is the mass transfer rate, and $R_*$ is the radius of the WD. $G$ is the gravitation constant and $\sigma$ is the Stefan–Boltzmann constant. A smaller radial temperature gradient but the same flux follows from

$$T_{\text{eff}}(R) = \text{SCL} \left[ \frac{3GM\dot{M}}{8\pi R^3} \sigma \left[ 1 - \left( \frac{R_*}{R} \right)^{1/2} \right] \right]^{1/4}, \quad (3)$$

where EXP is a number smaller than 0.25 and SCL is an empirically determined number to preserve the standard model $T_{\text{eff}}$ on the left side of the equation (and thereby preserve the same total flux since $\text{flux} = \sigma T_{\text{eff}}^4$). The significance of this generalization is that EXP becomes an additional model parameter ($M$ in Equation (1) now becomes 6).

Equation (3) was included in BINSYN at the time of its development but this is the first instance of its use in a simulation of a CV system. See Section 10 for further discussion.

The calculation proceeds as follows; an initial run at EXP = 0.25 (SCL = 1.0) determines the standard model accretion disk luminosity which follows from $\text{Lum} = \sum_{j=1}^{M} \sigma T_{\text{eff},j}^4 A_j$, where $\sigma$ is the Stefan–Boltzmann constant, $T_{\text{eff},j}$ is the effective temperature of the $j$th annulus, $A_j$ is the radiating area of the annulus, and there are $M$ annuli. Then, having chosen a different value of EXP, repeated runs with modified values of SCL eventually identifies the SCL value producing the same accretion disk luminosity as for EXP = 0.25. During each run, application of Equation (3) establishes the $T_{\text{eff}}$ values at the various annulus radii assigned by BINSYN.

Interpolation among the TLUSTY annulus spectra (Table 7) produces the BINSYN annulus spectra and integration over them produces the accretion disk synthetic spectrum. Since the temperature gradient is smaller for assigned EXP values than the standard model it is certain that the TLUSTY models will span the required BINSYN range of models. We found that the quality of fit improved as EXP is reduced until we reached the value EXP = 0.125 but then became poorer as EXP approached 0.

Figure 6 shows the results over the full spectral interval; Figure 7 shows the results in the FUSE region. To study the quality of fit in detail, we have performed a $\chi^2$ analysis with 8 values of $\dot{M}$ (5.0, 5.25, 5.5, 5.75, 6.0, 6.25, 6.5, and $7.0 \times 10^{-9} M_\odot \text{yr}^{-1}$) and 11 values of EXP (0.25, 0.225, 0.20, 0.175, 0.15, 0.125, 0.10, 0.075, 0.05, 0.025, and 0.0). As explained in connection with the $\sigma_i$ of Equation (1), our use of noise level $\sigma_j$ errors would guarantee that the calculated $\chi^2$ values will be far larger than 1.0; nevertheless the calculation preserves relative values, enabling us to identify best-fit parameters. In the overlap region between the FUSE spectrum and the IUE spectrum the FUSE $\sigma_j$ of order $1 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$, are approximately a factor 2 smaller than the IUE $\sigma_j$. To give equal weight to all the observed points, we used the mean $\sigma_j$ of both data sets as a
fixed $\kappa$ in Equation (1). The calculated $\chi^2$ values, each with 1086 degrees of freedom, are in Table 9 and a plot is in Figure 8; standard model accretion disks are represented by the horizontal line at the top of the plot. For ease of calculation, we have identified the degrees of freedom with $N$ in Equation (1); the effect is a very slight reduction of $\chi^2$ as compared with use of $N-M$ as the degrees of freedom; it is equivalent to masking an additional 2 $\Delta$ in the FUSE spectrum. A separate calculation for $M = 5.5 \times 10^{-9}\, M_\odot\, yr^{-1}$ and EXP = 0.125 and used the individual FUSE and IUE $\kappa$ values in Equation (1) produced a $\chi^2$ value of 18.7 in contrast to the value listed in Table 9. Use of the individual $\kappa$ in calculating Table 9 would have produced Figure 8 essentially identical to the one plotted but with slightly larger contour labels. We call attention to the fact that the best-fit value of EXP is close to 0.125 at all mass transfer rates, with a slight downward slope with increasing $M$. It is curious that the value 0.125 is half of the standard model value, 0.25.

We used a WD $T_{\text{eff}} = 50,000\, K$ for all models appearing in Table 9. Although the WD contribution to a system synthetic spectrum is small, it is of interest to verify that the adopted $T_{\text{eff}}$ produces optimum $\chi^2$ fits. Further, having identified best-fit values of EXP across the full range of $M$ values tested, it is of interest to determine whether further refinement can identify a preferred value of WD $T_{\text{eff}}$. We adopt the value EXP = 0.125 as fixed and repeat a $\chi^2$ analysis with the same values of $M$ as Figure 8 and with nine values of $T_{\text{eff}}$ 35,000, 40,000, 45,000, 50,000, 55,000, 60,000, 65,000, 70,000, and 75,000 $K$. Since the WD radius is temperature sensitive, we determined 0.90 $M_\odot$ WD radii (Panei et al. 2000) for the various assigned $T_{\text{eff}}$ values and used them in calculating the accretion disks. The $\chi^2$ values are in Table 10 and a plot of the results is in Figure 9. It is clear that the choice of $T_{\text{eff}} = 50,000\, K$ was about optimum for the available data but that no actual determination of the WD $T_{\text{eff}}$ is possible.

8. THE ORBITAL INCLINATION, DISTANCE, AND A BEST-FIT MODEL

The results of Tables 9 and 10 apply for the adopted values of distance (289 pc) and $i = 34^\circ$.

According to BEU the value of $i$ is $34^\circ \pm 6^\circ$. We have tested the effect on the synthetic spectrum fit, for $M = 5.75 \times 10^{-9}\, M_\odot\, yr^{-1}$, EXP = 0.125, by calculating a synthetic model spectrum for the limiting values of $i$ with all other parameters fixed. For $i = 28^\circ$, as expected from the angle cosine, the synthetic spectrum was higher by 7%, and for $i = 40^\circ$ the synthetic spectrum was lower by 7%. These limiting spectra differ from the observed spectrum by a small amount, far smaller than the variation from the uncertainty in the distance, and could be compensated by a small change in the adopted distance without affecting the quality of fit. Our results are consistent with $i = 34^\circ$ but the synthetic spectra cannot constrain $i$. 

Table 9

| EXP       | 5.0 | 5.25 | 5.5 | 5.75 | 6.0 | 6.25 | 6.5 | 7.0 |
|-----------|-----|------|-----|------|-----|------|-----|-----|
| 0.25      | 86.20 | 95.31 | 103.75 | 110.87 | 118.77 | 126.65 | 134.53 | 142.41 |
| 0.225     | 79.26 | 91.19 | 102.89 | 111.96 | 120.78 | 129.58 | 138.38 | 147.18 |
| 0.20      | 63.46 | 76.56 | 89.58 | 103.57 | 118.13 | 132.87 | 147.51 | 162.15 |
| 0.175     | 39.15 | 50.07 | 60.87 | 78.74 | 98.82 | 122.97 | 141.97 | 215.97 |
| 0.15      | 19.74 | 24.99 | 30.39 | 44.92 | 61.57 | 83.17 | 98.40 | 172.34 |
| 0.125     | 23.15 | 27.95 | 35.51 | 51.48 | 67.85 | 80.55 | 94.74 | 115.13 |
| 0.10      | 55.48 | 84.44 | 131.36 | 192.65 | 253.86 | 307.77 | 377.79 | 73.20 |
| 0.075     | 95.82 | 69.86 | 62.42 | 66.84 | 40.97 | 59.08 | 72.77 | 58.82 |
| 0.05      | 124.20 | 93.32 | 86.65 | 65.77 | 37.08 | 52.00 | 62.01 | 60.47 |
| 0.025     | 137.22 | 107.04 | 97.47 | 77.25 | 67.15 | 60.60 | 67.38 | 62.87 |
| 0.00      | 140.81 | 112.46 | 100.65 | 91.72 | 71.03 | 63.91 | 66.33 | 63.61 |

Notes. The second and succeeding column headings are in units of $10^{-9}\, M_\odot\, yr^{-1}$. See the text for a discussion.

Table 10

| EXP       | 5.0 | 5.25 | 5.5 | 5.75 | 6.0 | 6.25 | 6.5 | 7.0 |
|-----------|-----|------|-----|------|-----|------|-----|-----|
| 35        | 20.51 | 32.49 | 22.53 | 18.53 | 15.68 | 20.58 | 67.42 | 137.68 |
| 40        | 19.64 | 17.19 | 17.34 | 26.62 | 39.25 | 60.51 | 69.78 | 141.41 |
| 45        | 21.26 | 17.36 | 16.22 | 23.85 | 34.71 | 52.20 | 61.89 | 128.07 |
| 50        | 23.30 | 17.95 | 15.51 | 21.48 | 30.55 | 44.74 | 54.40 | 115.13 |
| 55        | 25.03 | 18.64 | 15.24 | 19.98 | 27.71 | 39.30 | 48.99 | 105.50 |
| 60        | 28.18 | 20.19 | 15.37 | 18.24 | 23.96 | 32.49 | 41.43 | 91.71 |
| 65        | 30.88 | 21.76 | 15.90 | 17.38 | 21.61 | 27.78 | 36.19 | 81.72 |
| 70        | 32.19 | 22.62 | 16.28 | 17.17 | 20.68 | 25.29 | 33.82 | 76.94 |
| 75        | 34.53 | 24.19 | 17.08 | 16.94 | 19.32 | 22.27 | 30.20 | 69.57 |

Notes. The second and succeeding column headings are in units of $10^{-9}\, M_\odot\, yr^{-1}$. The $T_{\text{eff}}$ values are in 1000s of K. See the text for a discussion.

Figure 8. Plot of $\chi^2$ values tabulated in Table 9. Standard model accretion disks correspond to the top horizontal line, at EXP = 0.25, bounding the plot (compare Equations (2) and (3)). Note the selection of EXP = 0.125 as roughly the best fit at all mass transfer rates. All models adopted a WD $T_{\text{eff}} = 50,000\, K$.

Figure 9. Plot of $\chi^2$ values tabulated in Table 10. All accretion disk models adopted a value EXP = 0.125. The asterisk marks the poorly constrained "best" value of $T_{\text{eff,wd}}$. As shown here, the originally adopted value of the WD $T_{\text{eff}} = 50,000\, K$ was a reasonable choice. The lack of a closed $\chi^2$ contour limiting the $T_{\text{eff}}$ range prevents determination of the WD $T_{\text{eff}}$. 

8. THE ORBITAL INCLINATION, DISTANCE, AND A BEST-FIT MODEL

The results of Tables 9 and 10 apply for the adopted values of distance (289 pc) and $i = 34^\circ$.
The Hipparcos parallax has 1σ limits of ±2.44 mas; the corresponding upper and lower distances are 980 pc and 169 pc. The RW Sex distance according to BEU is 150 pc. If the true distance is close to 150 pc a smaller synthetic spectrum scaling factor applies and a correspondingly smaller value with the simulations discussed above. After several tests the model spectral gradient problem persists in those cases as with the simulations discussed above. After several tests the value \( M = 2.0 \times 10^{-9} M_\odot \text{ yr}^{-1} \) appeared the best fit using the 150 pc scaling factor. Models with a range of values of EXP, Equation (3), led to a visually identified best fit with EXP = 0.15, SCL = 0.51443. It is least laborious to make final adjustments in the scaling factor rather than recalculate models for slightly modified \( M \); our final scaling factor is \( 2.5 \times 10^{41} \) corresponding to a distance of 162 pc and in agreement with the determination of 150 pc. The corresponding \( \chi^2 \), for comparison with Table 9, was 15.61, indistinguishable from the optimum value from Table 9. For comparison, the scaling factor for Figures 4–7 is \( 9.14 \times 10^{42} \).

We call attention to the fact that the smaller spectral gradient associated with EXP = 0.15, as compared with the standard model, avoids the problem of disk instability against outburst near a \( T_{\text{eff}} \) of 6000 K. The rim temperature of our best-fit model is 7667 K while the rim temperature of a corresponding standard model would be 4216 K, well below the limit for onset of outbursts.

Using the \( K \)-band Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) magnitude of 10.07 and the absolute \( M_K \) magnitude for RW Sex from Knigge (2006, 2007) for an orbital period of 5.88 hr, we derive a lower limit distance of 124 pc and an upper limit of 217 pc, slightly favoring the distance of 150 pc. Cowley et al. (1977) quote a trignometric parallax determination of 7 mas by Osvalds corresponding to a distance of \( \approx 143 \) pc. The \( \chi^2 \) values do not distinguish between the 289 pc and 150 pc distances; the weight of the evidence favors 150 pc which we accept.

Our best-fit model has the parameters listed in Table 11.

Figure 10 shows the best-fit model together with the various data sources, identified in the figure legend. Figure 11 shows the same data set for a restricted wavelength range. The observational data plotted are the values before masking, in contrast to all previous plots.

Examination of Figure 11 shows that the model fits Ly\( \alpha \) fairly well although the model has a wider and less deep profile than the \( HST \) spectrum. The \( FUSE \) Ly\( \alpha \) line shows emission peaks in both wings relative to the model. We suggest this proposed unmodeled effect (emission wings) may be the explanation of those residuals and that the same explanation may apply to the Ly\( \gamma \) line. An extension of the argument could explain the remaining shorter wavelength residuals.

Figure 12 is a plot of the residuals from the best-fit model to the masked combined spectrum for a restricted wavelength range. The plot is a continuous line but the plot data consist of individual values at spacings of approximately 1.5 Å. Comparison with Figure 10 shows that the synthetic spectrum is much smoother; Doppler shifts in the Keplerian accretion disk wash out narrow line features in the model spectrum; the residuals in the upper panel of Figure 10 have the appearance of noise, with a visually estimated mean of about 2 \( \times 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\) and frequent larger residuals. The bottom panel of Figure 12 shows that the residuals have a systematic variation in the 900–1200 Å interval. Excluding that interval temporally, which includes the entire \( FUSE \) spectrum, we test the hypothesis that the model spectrum is a good fit to the (masked, \( IUE \)) observed spectrum. There are 826 data lines in the spectral interval selected; the standard deviation, \( \sigma_r \), of the residuals is \( 2.22 \times 10^{-13} \) erg cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\), the value of \( \chi^2 \) is 828.62 and the value of \( \chi^2 \) is 1.009 for 821 degrees of freedom. Using the incomplete gamma function routine GAMMQ from Press et al. (1986), we calculate the probability \( Q \) that the \( \chi^2 \) value as poor as 828.62 could occur by chance is 0.419; according to Press et al. (1986) a value \( Q \) greater than 0.1 indicates an acceptable model. We also apply the Kolmogorov–Smirnov test where the null hypothesis is that the residuals represent a normal distribution.

### Table 11

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| \( M_{\text{wd}} \) | 0.90 \( M_\odot \) | \( i \) | 34° |
| EXP | 0.15 | \( M_2 \) | 0.674 \( M_\odot \) |
| SCL | 0.51443 | \( M \) | \( 2.0 \times 10^{-9} M_\odot \text{ yr}^{-1} \) |
| \( T_{\text{eff}} \) (WD) | 50,000 K | \( P \) | 0.24507 days |
| \( d \) | 150 pc | | |

Figure 10. Superposition of observed and model synthetic spectra. The upper black line is the \( FUSE \) spectrum without masking. The brown line is the \( IUE \) spectrum, without masking. The blue line is the mean \( HST \) z37v0104t plus z37v0105t spectrum. The cyan line is the mean \( HST \) z37v0106t plus z37v0107t spectrum. Note the strong chromospheric lines, which the model does not represent, that were masked in the solution process. The magenta line is the final model and the red line, almost indistinguishable from the magenta line but barely below it is the accretion disk contribution. The black line at the bottom is the 50,000 K WD.

Figure 11. Same as in Figure 10, but for a restricted wavelength range. The difference between the magenta and red lines is barely visible. Note that this difference is the contribution of the 50,000 K WD, shown in black at the bottom of the plot.
distribution with mean of zero. The test determined the $\sigma_r$ listed above and sorted the residuals into 60 bins, 58 of width 0.1$\sigma_r$, one containing all residuals greater than 2.55$\sigma_r$ and the other containing all residuals smaller than $-2.55\sigma_r$. The program calculated a theoretical cumulative distribution function, the actual cumulative distribution function of the residuals, and the difference between the two. The maximum difference was 0.168 while the critical value at the 0.05 level of significance (Ostle 1969, Table 16) was 0.0473; the hypothesis (normal distribution with mean of zero) is rejected.

The maximum systematic residuals of the FUSE spectrum, Figure 12, bottom panel, are on the order of 1/3 of the observed spectrum flux values. The best-fit model, essentially identical with the magenta line of Figure 7, falls below the FUSE spectrum shortward of 1050 Å and has greater flux longward. We have already speculated that there may be unmodeled emission in the shorter wavelengths. We found (Section 4) that the FUSE spectrum apparently was anomalously weak at the time of observation and a correction factor was necessary to combine it with the IUE spectrum.

8.1. How Robust is the Best-Fit Model?

The model parameters subject to adjustment are $M_{wd}$, $T_{eff,wd}$, $i$, $M$, distance, and EXP. As explained above, variation of $i$ produces a minor effect at the adopted $i$ and in any case $i$ cannot be used to constrain the model because RW Sex is a non-eclipsing system.

Variation of $M_{wd}$ has two effects; first, there is a variation of WD radius with mass, leading to variation of the WD luminous flux for a given WD $T_{eff}$; and second, the variation of the depth of the potential well produces variation of annulus $T_{eff}$ at a given distance from the WD for a given $M$. As shown by, e.g., Figure 10, the WD contribution to the system synthetic spectrum is small and the variation of it (the synthetic spectrum) due to a change in $M_{wd}$ is second order; we neglect it in comparison with other major contributors to the model spectrum. Variation of an annulus $T_{eff}$ from variation of $M_{wd}$ can be included in the study of $M$ effects since the latter also produce variation of annulus $T_{eff}$ at a given distance from the WD and the variation with $M$ is the dominant effect. We exclude $M_{wd}$ as a significant contributing source to the discrepancy between observation and the standard model.

If we reset EXP = 0.25 (i.e., assert the standard model is applicable), can we vary the RW Sex distance or $M$ or the WD $T_{eff}$ and achieve as good a fit to the observed spectra as our model does in Figures 10 and 11? From Figure 4, the closest synthetic spectrum fit to the observations is with the smallest $M$, $5.0 \times 10^{-9} M_\odot$ yr$^{-1}$. Still smaller $M$ values, tested through $1.0 \times 10^{-9} M_\odot$ yr$^{-1}$, show the same trend and ultimately the $M$ value becomes small enough that the accretion disk becomes unstable against outburst. At $M = 2.0 \times 10^{-9} M_\odot$ yr$^{-1}$, the outer accretion disk rim has a calculated $T_{eff}$ of 4215 K, making it susceptible to outbursts. However, stream impact and tidal effects heat the outer disk region (Lasota 2001); let us assume these effects stabilize the standard model disk (and ignore the consequent departure from the standard model) and inquire how well the standard model for $M = 2.0 \times 10^{-9} M_\odot$ yr$^{-1}$ fits the observations. Figure 13 shows the fit of the standard model to the observations. The system synthetic spectrum, including the contributions of both the accretion disk and the WD, has been divided by $3.0 \times 10^{41}$, corresponding to a distance of 180 pc. A larger divisor shifts the synthetic spectrum downward, producing larger short wavelength discrepancies, and a smaller divisor shifts the synthetic spectrum upward, producing larger long wavelength discrepancies. The contribution of the 50,000 K WD is at the bottom. Removing its contribution entirely would only marginally reduce the discrepancy from the system synthetic spectrum. A proposed higher $T_{eff}$ WD would raise the question of its source of heat but, in any case, the rapidly increasing WD FUV flux would only make the system synthetic spectrum discrepancy worse. Still smaller $M$ values exhibit the same discrepancy shown in Figure 13 and, in any case, are not credible because of the instability against outburst (the standard model discrepancy from the roughly 6000 K crossover to instability becomes worse and the proposed stream impact heating becomes smaller with reduced $M$). Figure 13 contrasts strongly with the very good fit of our model in Figure 10. We argue that no standard model synthetic spectrum, for any acceptable $M$, fits the observed spectrum and that variation of the RW Sex distance, accompanied by a compensating variation in $M$ will not produce an acceptable standard model fit to the observed spectra.

We also argue, from the above discussion of Figure 13, that variation of the WD $T_{eff}$ cannot be used to produce an acceptable
standard model fit to the observed spectrum. Addition of a boundary layer (BL) with a long wavelength tail in the FUV would only make the Figure 13 fit worse. In Figure 11, the synthetic spectrum falls below the observations near the FUV limit and addition of a BL contribution could improve the fit. However, we have already suggested that emission from the chromosphere could explain the discrepancy and we believe the evidence is too weak to support a proposal for a BL.

We are left with variation of EXP, from our previous discussion, as the only viable parameter to produce an acceptable fit to the observed RW Sex spectrum.

9. THE TIME-SERIES FUSE SPECTRA

Prinja et al. (2003) show that there is large orbit-to-orbit variability of the time-series FUSE spectra. The changes are primarily in the absorption strengths of the high excitation lines, associated with variable blueshifts tied to the orbital period. Prinja et al. (2003) argue that the variation arises from blueshifted absorptive changes as opposed to a blueshifted emission component and they suggest that the outflow wind is oblique rather than a symmetric bipolar wind with the oblique wind possibly seated on a warped or tilted disk.

We have used our best-fit model to test the tilted disk suggestion. We first subtracted our model synthetic spectrum, scaled to the distance of RW Sex, from the 25 individual time-series spectra. This step produces residuals which would display phase-wise flux variations if the disk is tilted. We then chose one difference spectrum (the second in the sequence) and successively overplotted the other difference spectra. This comparison verified the large case-to-case variation in the strengths of the absorption lines as well as the variable blueshift but there was no indication of a vertical shift in successively overplotted difference spectra. If the disk is warped or tilted, there should be a vertical displacement of the entire difference spectrum that is tied to the orbital phase and we find none. Figures 14 and 15 illustrate the comparison and have the most striking differences. Superposition of the black difference spectrum and other difference spectra of similar orbital phase shows close matches, indicating that the spectral changes primarily connect to orbital phase.

This result agrees with the Prinja et al. (2003) proposal that the spectral variation arises from blueshifted absorptive changes. As an alternative to the tilted disk suggestion, we believe a likely explanation of the non-symmetrical wind is an interaction with the debris from the mass transfer stream impact on the accretion disk. Lubow & Shu (1976) find that the stream impact on the accretion disk leads to material flowing over the accretion disk from the impact location. Hydrodynamical two-dimensional models of the stream impact (Różycka 1987, 1988) identify two shock waves: (1) a shock on a plane perpendicular to the orbital plane, roughly bisecting the angle between the stream and the rim and terminating at the upstream edge of the stream, and (2) a shock slightly more inclined to the stream and extending far into the disk. Although the simulation is two dimensional, Różycka (1987) states that a bow shock will develop, prospectively leading to vertical expansion upstream. Livio et al. (1986) and Armitage & Livio (1998) perform a three-dimensional simulation and find that material from the stream flows over the disk if cooling is efficient, applicable to low M cases, and is more like an explosion in high M cases, leading to a bulge extending along the disk rim.

Impact of the mass transfer stream on the accretion disk might be expected to produce a detectable rim hot spot, but the absence of phase-wise flux variability demonstrates that evidence is lacking for a sufficiently luminous rim hot spot to
be detectable. This justifies our omission of a hot spot in the system model (Section 6).

10. DISCUSSION

As discussed in the introduction, Wade (1988) showed that neither steady state model accretion disks based on Planck functions nor stellar model atmospheres could simultaneously fit the colors and absolute luminosities of a set of NL systems (RW Sex was included in the study). Tomographic analyses of accretion disks (Rutten et al. 1992) show clear departures from standard model temperature profiles (FKR), with a spectral gradient typically less steep than for a standard model. Recent analyses of the NL systems Mv Lyr, IX Vel, QU Car, and UX UMa (Linnell et al. 2005, 2007, 2008a, 2008b) used an annulus model explicitly representing standard model accretion disks and showed, in each case, that a standard model accretion disk synthetic spectrum could not accurately fit observed spectra. On the other hand, a standard model fits the observed spectrum in V3885 Sgr (Linnell et al. 2009). In the latter paper, we speculated that a given system may at times fit a standard model and at other times show departures as observed in the case of UX UMa IUE spectra.

In the specific cases of non-standard model accretion disks listed above, the fits achieved depended on ad hoc changes in the temperatures of a few accretion disk annuli. The required departure from a standard model accretion disk temperature profile to fit a model synthetic spectrum to an observed spectrum has not previously been characterized analytically. This study shows, by detailed $\chi^2$ analysis, that the observed RW Sex spectrum accurately matches a synthetic spectrum which follows from an analytic expression, Equation (3), that differs from the standard model. Referring back to the Wade (1988) results, we conclude that the problem is not a failure of synthetic spectra to represent the standard model but rather observed spectra, here RX Sex, fail to conform to the standard model. A further consequence is that the lower temperature gradient produces a higher rim $T_{\text{eff}}$, preserving stability against outburst to a lower $M$.

We have taken extensive precautions to consider physical effects that might otherwise affect the accuracy of the calculated synthetic spectra: the annulus synthetic spectra are non-LTE and important metals have been included as explicit ions in the calculations. It is curious that the empirically determined exponent in Equation (3), equal to 0.25 for the standard model, is closely equal to 1/2 of the standard model value for a range of $M$ values. Equation (3) was not derived from a physical analysis and it is of interest to consider its implications. The less steep temperature profile than the standard model suggests additional energy deposition terms in a given annulus than considered in the standard model, such as radial energy transfer between annuli (Popham & Narayan 1995), but it seems intuitively doubtful that the latter effect could produce the large departure observed. In any case, that physical effect would be present for all accretion disks and would leave the case-to-case differences unexplained. Our assumption of a constant $\alpha$ for the entire accretion disk could be challenged but, as FKR discuss in connection with their Equation (5.18), the energy flux through an accretion disk face, in the standard model, is independent of viscosity and is not an explicit function of $\alpha$: to first order the radial temperature profile is independent of $\alpha$. The derivation of Equation (2) neglects possible magnetic effects but their inclusion, as mentioned in Section 6, currently is subject to some uncertainty. Further consideration of this topic is beyond the scope of this paper.

We have neglected irradiation of the annuli by the WD. Smak (1989) shows that the effects are small for stationary disks. In RW Sex, the presence of a disk chromosphere would reduce irradiation effects still further.

It is of interest to place the results of this paper in the context of other approaches to the departure of observational data from the standard model. IX Vel provides an illustration; Long et al. (1994) consider several options including removal of all radiative flux contribution from inner annuli, providing a constant $T_{\text{eff}}$ inner region, and setting the formal inner radius of the accretion disk to some multiple of the WD radius. These authors show that the last option, with $R_{\text{min}} \sim 2.6 R_{\text{wd}}$, gives a reasonable fit to the Hopkins Ultraviolet Telescope (HUT) data. Linnell et al. (2007) showed that (for IX Vel) an accretion disk with a constant temperature inner section and the remainder following the standard model gives a good fit to FUSE and STIS spectra. Both approaches are ad hoc and the truncated disk model leaves unanswered the question of whether a wind can carry away all of the mass transfer stream, starting at the truncation radius. The ad hoc processes are localized perturbations of an otherwise standard model accretion disk; the analytic representation found here suggests existence of a process that affects the entire accretion disk.

Our model does not include a BL. As discussed by FKR, half of the potential energy liberated in the fall of the mass transfer stream from the L1 point (essentially from infinity) to the WD surface appears as radiated energy. Energy conservation requires an accounting for the other half and the presence of a hot BL is a common prescription. A problem is that BLs with the prescribed properties typically are not observed in high $M$ systems or occur at unobserved wavelengths (Córdova 1995). The absence of an observed but predicted (FKR) BL in high $M$ CV systems has an extensive history (Ferland et al. 1982; Callanan & Jensen 1985; Patterson & Raymond 1985; Hoare & Drew 1991, 1993; Vrtilek et al. 1994; Idan & Shaviv 1996).

In the case of the low $M$ dwarf nova (DN) U Gem, Long et al. (1996) used eclipse data during outburst to determine that an emitting region is present with a temperature of $\sim 140,000$ K, and a size approximating that of the WD, consistent with a BL with a luminosity comparable to the disk luminosity. Szkody et al. (1996) also found that in quiescence U Gem has a relatively hard X-ray spectrum with the emission confined to a small area, supporting the interpretation of a BL. More recently, Pandel et al. (2005) show that, for nine DN in quiescence, X-ray observations require a model in which a hot BL is present and has a luminosity approximately equal to the accretion disk luminosity. In the cases cited by Pandel et al. (2005), there is no BL problem and the derived BL structure is consistent with theoretical models (Narayan & Popham 1993). The derived $M$ rates for the DN in quiescence are $M \sim 10^{-12}$ to $10^{-11} M_\odot$ yr$^{-1}$. The $M$ rate for RW Sex is between 2 and 3 dex larger.

One proposed explanation for lack of evidence for a high-luminosity BL is that the WD is rotating close to Keplerian rotation, with no BL predicted. However, HST measurements starting with Sion et al. (1994) have measured rotational WD velocities too low to explain “missing” BLs. An alternative explanatory theme is that the absence of an observed BL is associated with a wind, and in RW Sex a wind is clearly present (Prinja et al. 2003), but the adequacy of this explanation remains undemonstrated.

11. SUMMARY

The BINSYN program suite has been used to calculate model synthetic spectra for RW Sex in comparison with a combined HST, FUSE, and IUE spectrum. From evidence reported in this
paper, the FUSE spectrum was obtained, apparently, at a time of reduced accretion disk luminosity and to achieve consistency it is necessary to divide the FUSE spectrum by 0.82 in combining it with the other observed spectra.

The models include a range of $M$ values and each model consists of 45 annuli calculated with the Hubeny program TLUSTY; the Hubeny program SYNSPEC produces the synthetic spectrum for a single annulus, with a resolution of 0.1 Å, includes significant metals as explicit ions, and is a non-LTE model for all annuli that contribute significantly to the system synthetic spectrum. A Hipparcos parallax, determining $D = 289$ pc, fixes the divisor that enables the system synthetic spectrum to be matched to the observed spectrum and establishes the fit on an absolute flux basis. Initial tests with a range of $M$ standard model accretion disks show that no standard model can fit the observed spectra of RW Sex. New models with a generalized form of the standard model equation show that, for RW Sex, observed spectra of RW Sex. No. 1, 2010 ANOMALOUS ACCRETION DISK OF CV RW Sextantis 285

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