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Hubble COS Spectroscopy of the Dwarf Nova CW Mon: The White Dwarf in Quiescence?[*]

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Abstract

We present a synthetic spectral analysis of the *HST* COS spectrum of the U Geminorum-type dwarf nova CW Mon, taken during quiescence as part of our COS survey of accreting white dwarfs (WDs) in Cataclysmic Variables. We use a synthetic photosphere and optically thick accretion disk spectra to model the COS spectrum as well as archival *IUE* spectra obtained decades ago, when the system was in an even deeper quiescent state. Assuming a reddening of $E(B-V)=0.06$, an inclination of 60° (CW Mon has eclipses of the accretion disk), and a WD mass of 0.8 $M_\odot$, our results indicate the presence of a 22–27,000 K WD and a low mass accretion rate $\dot{M}\lesssim 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$, for a derived distance of ∼200 to ∼300 pc.

Key words: stars: dwarf novae – stars: individual (CW Mon)

1. Introduction

We present a far-UV spectroscopic study of the long-period dwarf nova CW Mon as part of an ongoing study to detect the underlying accreting white dwarfs (WDs) during the quiescent intervals of dwarf novae and the optical low states of nova-like variables (Pala et al. 2017). This is important because the accreting WDs serve as probes of explosive evolution, accretion physics, and diffusion, as they bear the thermal, chemical, and rotational imprint of their long-term accretion and thermonuclear history (Sion 1991, 1995, 1999; Townsley & Bildsten 2003; Townsley & Gänsicke 2009). The WDs are the central engines of the observed outbursts, either as potential wells for the release of gravitational energy during accretion (dwarf nova), or as the sites of explosive thermonuclear runaway shell burning (classical novae), steady shell burning (supersoft X-ray binaries) or instantaneous collapse and total thermonuclear detonation if a carbon–oxygen WD reaches the Chandrasekhar limit (Type Ia supernovae).

CW Mon is a U Geminorum-type dwarf nova with an orbital period of 0.1766 days (Szkody & Mateo 1986; Kato et al. 2003). It displays both wide and narrow outbursts with a recurrence time between outbursts of 150 days. Patterson (2011) derived a distance of 280 pc based on absolute magnitudes of outbursts. Szkody & Mateo (1986) found a high-amplitude ellipsoidal modulation of the secondary of CW Mon in the IR, which implies a large orbital inclination (∼65°). They also found evidence for a grazing eclipse of the accretion disk in CW Mon and estimated a distance of 297 pc. Kato et al. (2003) reported a 37-minute modulation in outburst photometry of CW Mon and suggested that it might be an intermediate polar (IP) containing a weakly magnetic WD. CW Mon has an increased pulse amplitude during outburst (Kemp et al. 2002). However, Pretorius & Knigge (2008) report the absence of the high coherence in CW Mon that would be associated with the spin cycle of a WD, and a signal is detected only during outburst. Warner (2004) regards the 37-minute modulation to be a quasi-periodic oscillation which is often associated with high-accretion rate, non-magnetic CVs. Szkody (1987) noted that CW Mon does not have a strong He II (4686) emission, a frequent hallmark of magnetic CVs. It is very unlikely that CW Mon is an IP.

Recently, a search for nova shells around 101 cataclysmic variables (CVs), including CW Mon, was carried out by Sahman et al. (2015) using Hα images taken with the 4.2 m William Herschel Telescope. However, there was no evidence of a nova shell around CW Mon, precluding any possibility that heating from a recent nova has affected the thermal properties of the WD that we derive.

Given CW Mon's similarity to U Gem, it seemed likely that, as in the case of U Gem, the underlying WD in CW Mon could be unambiguously revealed, thus offering a full analysis of its accreted photosphere. However, as we discuss below, the *HST* COS observation of CW Mon was obtained when CW Mon's hot component had not yet completely cooled from the heating of its last previous dwarf nova outburst.

In Section 2, we describe the FUV *IUE* and *HST* COS observations, and in Section 3, we describe the construction of the synthetic spectra of WD photospheres and accretion disks, the parameter space of the model grids, and model fitting procedure. In Section 4, we present and discuss the model fitting results, and in Section 5, we present the conclusions of our investigation.

2. Far-UV Spectroscopic Observations

The *HST* COS observation of CW Mon started on 2012 November 30, at 21:30:07 in TIME-TAG Mode and data was collected for 4773 s of good exposure time (or about one-third of the orbital period). The COS instrument was set in the FUV configuration, using the PSA aperture with the G140L gratings centered at 1105 Å, thereby generating a spectrum covering the wavelength range ∼1110 to ∼2000 Å.

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[*] Based on observations made with the NASA-*Hubble Space Telescope*.

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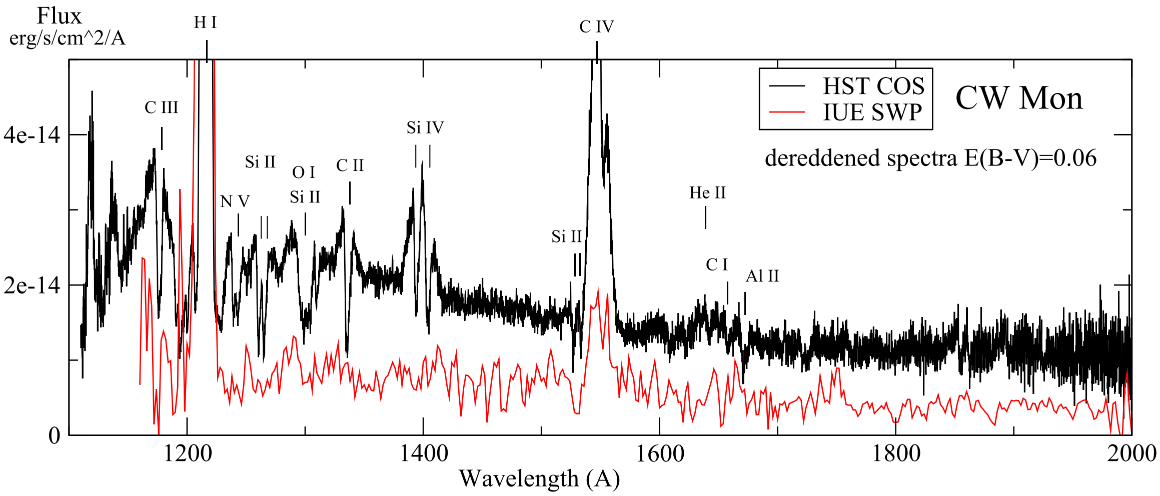

Figure 1. *HST* COS (black) and *IUE* SWP (red) spectra of the dwarf nova CW Mon with the most prominent absorption lines and emission lines identified with tick marks. The two spectra have been dereddened assuming $E(B-V)=0.06$. Note the emission wings flanking some of the absorption features seen in the COS spectrum. The continuum flux level of the *IUE* spectrum is about one-third of that of the COS spectrum.

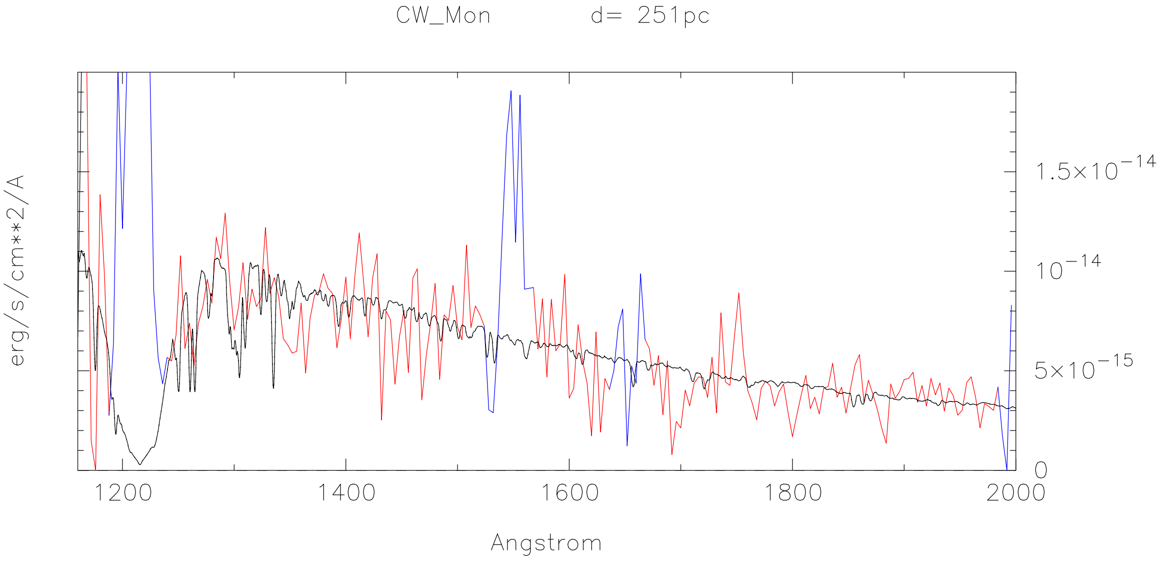

Figure 2. The dereddened *IUE* SWP spectrum of CW Mon (in red) is displayed with a white dwarf-only fit (in black). The regions of known emission lines, airglow, and noise have been omitted from the fitting and are colored in blue. The WD model has a mass of 0.8 $M_{\odot}$ and a temperature of 23,000 K, with a scaled distance of 251 pc. A 21,000 K WD model gives a scaled distance matching the lower limit for of distance ~200 pc, while a 25,000 K WD scales to the upper limit of ~300 pc. The best fit, however, is obtained for a temperature of 22–23,000 K WD model.

CW Mon's optical magnitude did not reach nominal quiescence (16.0 in this case) until November 24, which is only 6 days of quiescence before the *HST* data were acquired. There are two low-quality *IUE* archival spectra of CW Mon, each with flux levels about one-third that of the *HST* COS spectrum. The *IUE* spectra, SWP27112 and SWP32793, were taken during dwarf nova quiescence on 1985 November 14 (at 20:37:21) and 1988 January 26 (at 20:09:08) at low dispersion through the large aperture with exposure times of 10,800 and 9900 s, respectively. The two *IUE* SWP spectra are almost identical and so we co-added them to obtain a higher S/N.

We are confident that the WD and disk are still hotter than the hot components when the *IUE* spectra were taken. This would account for why the lines of Si IV and C II have broad emission wings in the COS spectrum while they are not apparent in the *IUE* data, and why the flux level of the COS spectrum is higher. Using a script based on the relation derived by Fitzpatrick (1999), we dereddened the *IUE* and *HST*/COS spectra assuming a value $E(B-V)=0.06$ (Bruch & Engel 1994), with an extinction factor $R_v=3.1$ for the diffuse interstellar medium. The dereddened *HST* COS and *IUE* SWP spectra are displayed in Figure 1. The COS spectrum exhibits a rich array of absorption lines much like the FUV spectrum of the WD in U Gem during quiescence, as well as strong broad emission lines. The co-added *IUE* spectrum is of low quality, but we decided to use it, as it shows CW Mon in deep quiescence.

3. Synthetic Spectra Analysis

We used theoretical spectra of accretion disks from the optically thick, steady state disk model grid of Wade & Hubeny (1998) and computed WD stellar atmosphere spectra using the

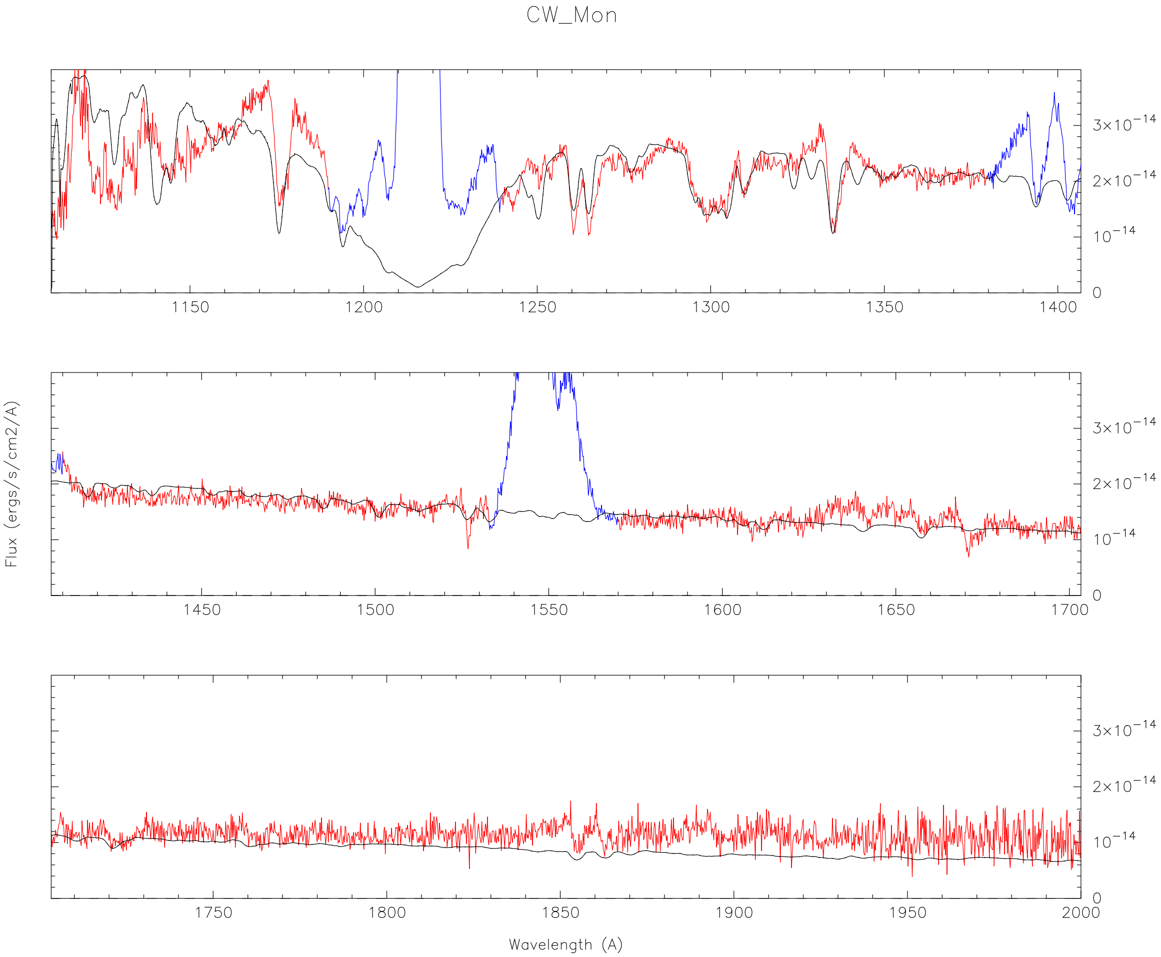

Figure 3. The dereddened *HST* COS spectrum of CW Mon (in red) is displayed with a white dwarf-only fit (in black). The regions of known emission lines and airglow have been masked for the fitting and have been marked in blue. The WD model has a mass of 0.8 $M_{\odot}$, a temperature of 26,000 K, and a projected stellar rotational velocity $V_{\rm rot}\sin(i) = 400$ km s^{-1}. The distance obtained from the scaling is 211 pc.

suite of code TLUSTY, SYNSPEC, and ROTIN (Hubeny 1988). All of our models assumed a solar composition.

Our fitting procedure to the dereddened COS spectrum consists of independently fitting the spectrum with both a WD and accretion disc model. A similar procedure was carried out for spectral analysis of the COS spectrum of the VY Scl nova-like BB Dor Godon et al. (2016), obtained in an intermediate state as part of the ongoing campain to study the accreting WD of dwarf novae and novalikes (Pala et al. 2017). The best-fitting models were determined based upon a visual inspection of the model fit, consistency with the continuum slope and the Lyα region, as well as a scale-factored derived distance consistent with the published distances between 200 and 300 pc.

The accretion disk models were taken from the Wade & Hubeny (1998) grid of disk spectra for the following system parameters: inclination $i = 60°$, WD mass $M_{\rm wd} = 0.80\,M_{\odot}$, and a lower accretion rate consistent with dwarf nova quiescence $\log(\dot{M}) = -9.5$, -10.0, -10.5.

For the WD models, we used TLUSTY Version 203 (Hubeny 1988) and Synspec48 (Hubeny & Lanz 1995) with $\log(g) = 8.4$ corresponding to the WD mass of 0.8 $M_{\odot}$. This mass value is roughly the average mass of WDs in CVs. The WD photosphere models were constructed using temperatures ranging from 17,000–30,000 K in steps of 1000 K with a projected stellar rotational velocity ranging from 200 to 500 km s^{-1} in steps of 100 km s^{-1}. Additional details on our method can be found in Godon et al. (2016).

4. Synthetic Spectral Fitting Results

The *HST* COS spectrum displayed in Figure 1 has a flux level about three times higher than the co-added *IUE* spectrum of CW Mon mentioned in Section 2. Because both of the *IUE* spectra were obtained in quiescence, it is likely that the *IUE* spectra are dominated by flux from the WD.

We first modeled the *IUE* spectrum, starting with a disk model only, and we found that the mass accretion rate has to be about $\sim 5 \times 10^{-11}\,M_{\odot}$ yr^{-1} to agree with the distance of 200–300 pc. However, such a disk provides a very poor fit, as it has a very wide Lyman profile and too much flux in the longer wavelengths. Next, we tried a combined disk + WD model and found a reasonable fit for a disk with $\dot{M} = 3 \times 10^{-11}\,M_{\odot}$ yr^{-1} with a 23,000 K WD, giving a distance of 301 pc. In this combined model, the WD contributes three-quarters of the flux and is the dominant component.

Last, we tried a single WD fit to the *IUE* spectrum of CW Mon, and we found that a 23,000 K WD gives the best fit with a distance of 251 pc. This fit is presented in Figure 2. We note that a single WD with 21,000 K gives a distance of 206 pc, while a 25,000 K WD gives a distance of 302 pc, both within the accepted distance range and with an acceptable fit.

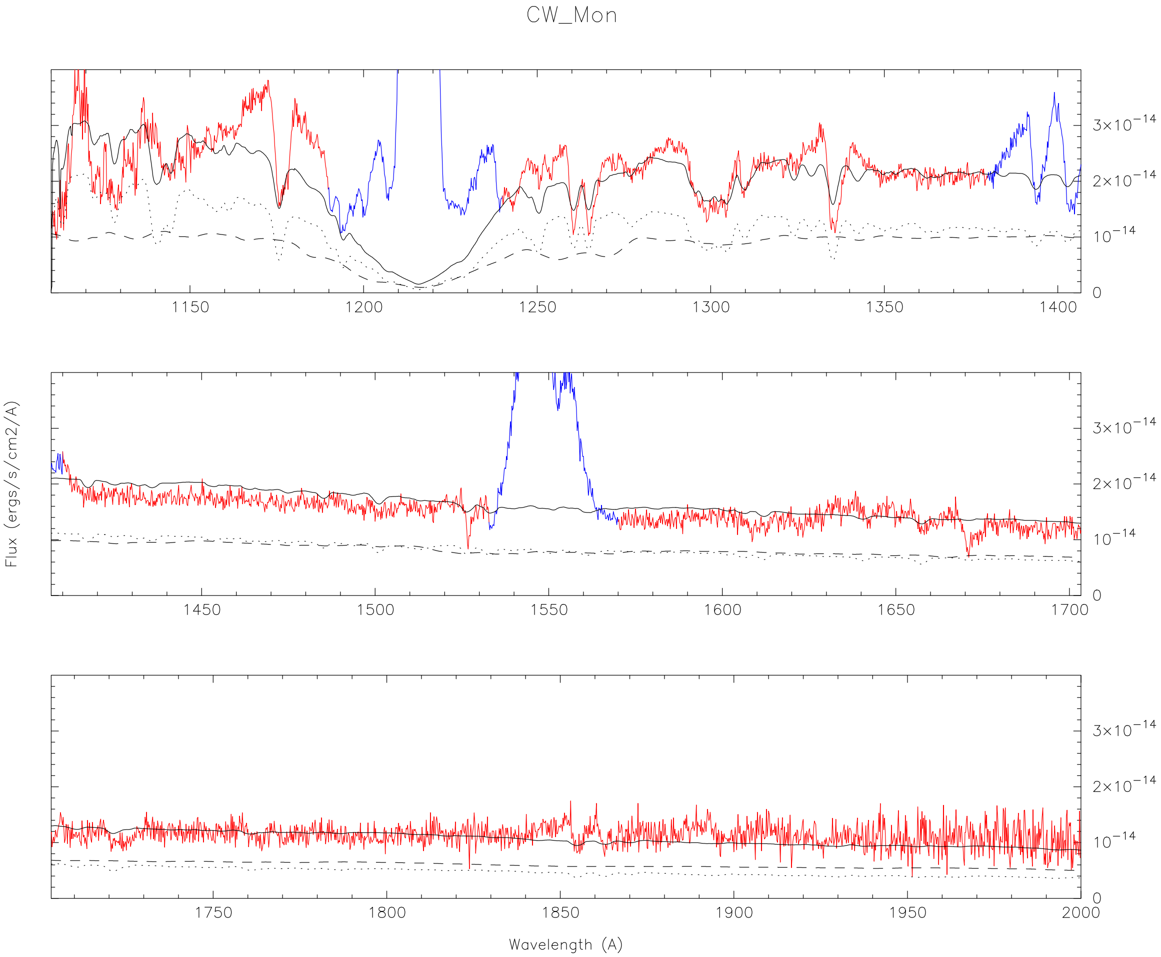

Figure 4. *HST* COS spectrum of CW Mon (in red) is fitted with a composite model (solid black line) consisting of a WD (dotted line) plus an accretion disk (dashed line). The WD mass is $0.8M_{\rm wd}$, its temperature is 26,000 K, and its rotational velocity $V\sin i = 400$ km s^{-1}. The accretion rate is $\dot{M} = 10^{-10}\,M_\odot$ yr^{-1}, and the inclination is set at 60°. The scaled distance obtained from the fit is 301 pc. The WD and the disk contribute about both ≈50% of the observed flux.

However, the $T_{\rm wd} = 23{,}000$ K and $T_{\rm wd} = 22{,}000$ K models are substantially better, fitting both the Lyα wings and continuum in the longer wavelengths, with $T_{\rm wd} = 23{,}000$ K providing the best fit. From these *IUE* fits, we deduce that the WD temperature must be 22,000–23,000 K, with the possible contribution from a disk with a mass accretion rate of the order of a few $10^{-11}\,M_\odot$ yr^{-1} or less.

Consequently, for the higher-resolution *HST* COS spectrum, we also expect significant emission from the WD (23,000 K or higher), but with the presence of an accretion disk, because CW Mon was only 6 days into optical quiescence when the COS spectrum was obtained.

Fitting accretion disk models to the COS spectrum, we find a distance in the accepted range of 200–300 pc for a mass accretion rate $\dot{M} \sim 10^{-10}\,M_\odot$ yr^{-1}, but the fit is rather poor, especially in the vicinity of the Lyα region (∼1150–1300 Å). Moreover, the absorption lines in the model disk are much broader and shallower than the absorption lines seen in the COS spectrum. The single WD model fit to the COS spectrum cannot properly fit both the long and short wavelengths simultaneously. Lower-temperature (∼20,000 K) models agree with the longer wavelength region ($\lambda > 1750$ Å) of the spectrum, while higher-temperature (∼25,000 K) models agree better with some prominent absorption lines in the short wavelength region of the spectrum (1250–1350 Å). We display this WD-only fit model in Figure 3. The derived temperature is 26,000 K, yielding a distance of 211 pc. Higher-temperature WD models give a larger distance but also degrade the fit, and lower-temperature WDs yield a distance that is too short (<200 pc) and the fit quality is also lower at lower temperatures. It is interesting to note that the observed absorption line profiles suggest possible agreement with those of a solar composition WD photosphere. This solar composition atmosphere model fits many of the central absorption cores but, of course, does not account for the emission wings.

Finally, we fit a WD synthetic spectrum combined with a standard disk model. We find that the addition of a disk to the WD model improves the fit, with a WD temperature roughly matching the single WD temperature fit to the COS spectrum.

For an accretion rate $\dot{M} = 10^{-10}\,M_\odot$ yr^{-1}, the WD+disk fit improves as the WD temperature increases, and a good fit is obtained for $T_{\rm wd} = 26{,}000$ K, giving a distance of 301 pc. This model fit is presented in Figure 4. A higher WD temperature yields a distance that is too large (>300 pc), while a lower WD temperature provides fit that is not as good.

For an accretion rate $\dot{M} = 3 \times 10^{-11}\,M_\odot$ yr^{-1}, the WD+disk fit gives a reasonable fit for a temperature increasing from 24,000 K (with a distance of 205 pc) to 29,000 K (with a distance of 294 pc). The lower-temperature WD model gives a better fit in the longer wavelength range, while the

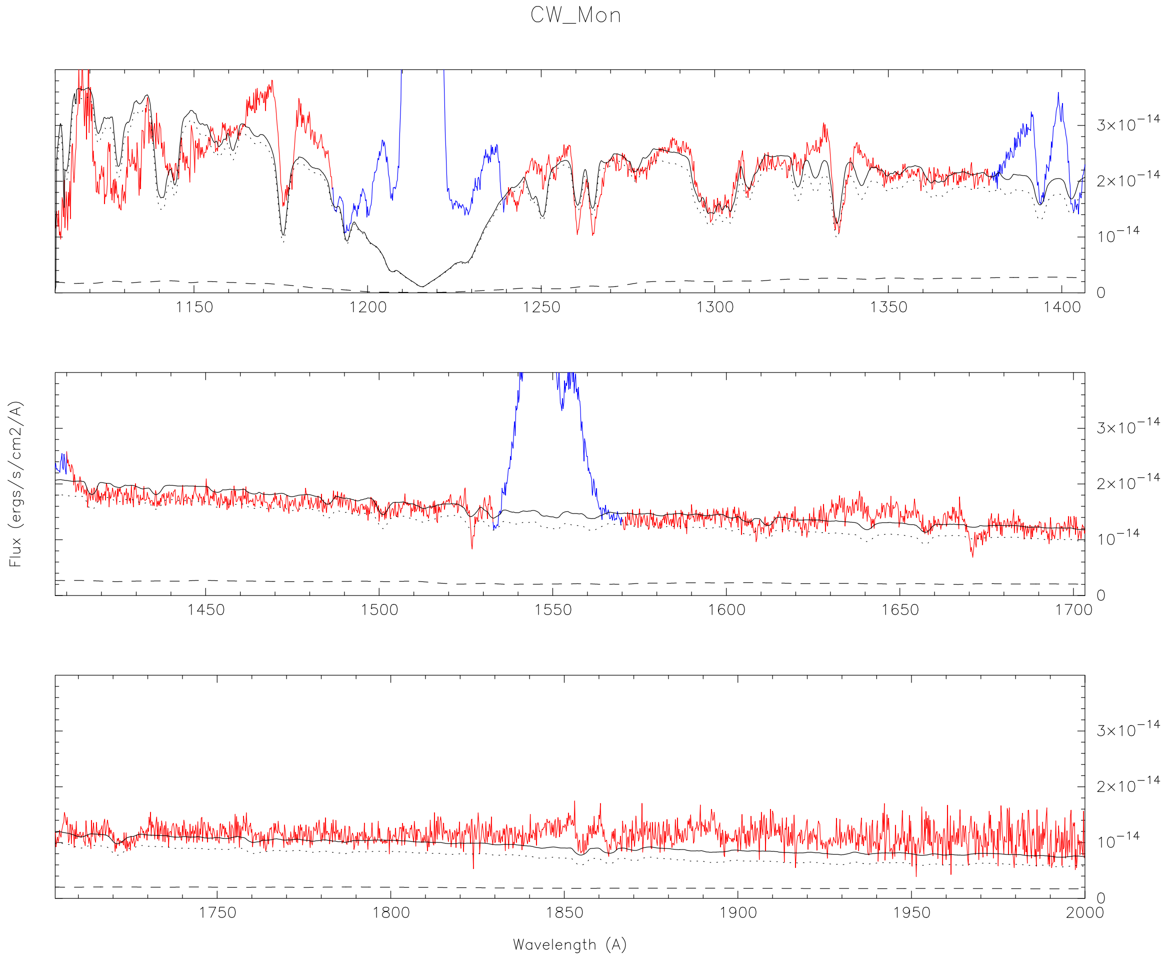

Figure 5. Same as in Figure 4, but here the mass accretion rate has been decreased to $\dot{M} = 10^{-10.5}\,M_{\odot}\,\mathrm{yr}^{-1}$, and the WD temperature is 27,000 K, giving a scaled distance of 256 pc. This solution is very similar to the single WD model fit presented in Figure 2, in that the WD contributes most of the flux.

higher-temperature WD model gives a better fit in the shorter wavelength range. The best fit is obtained for an intermediate WD temperature of 27,000 K, giving a distance of 256 pc. This model is presented in Figure 5.

5. Conclusion

While the indicated accretion rates appear appropriate to dwarf nova quiescence, the absorption lines in the disk models are far too broad to match the narrower absorption line widths, seen in the higher-resolution *HST* COS spectrum (see below).

Our overall conclusion is that the WD in CW Mon is partially exposed and appears to have a surface temperature of around 22–23,000 K (*IUE* spectrum) to 26–27,000 K (COS spectrum), with an atmosphere that's roughly solar in composition.

If the WD in CW Mon has undergone long-term compressional heating due to the weight of the accreted material, then the equilibrium surface temperature during quiescence, T_{eff}, resulting from compressional heating is given by

$$T_{\mathrm{eff}} = 17{,}000\,\mathrm{K}\left(\frac{\langle\dot{M}\rangle}{10^{-10}\,M_{\odot}\,\mathrm{yr}^{-1}}\right)^{0.25}\frac{M_{\mathrm{wd}}}{0.9\,M_{\odot}} \tag{1}$$

where M_{wd} is the mass of the WD (Townsley & Bildsten 2003). If the WD has a mass of 0.8 $M_{\odot}$, as our modeling indicated, and if the time-averaged accretion rate is $\sim10^{-10}\,M_{\odot}\,\mathrm{yr}^{-1}$, then the WD should have a $T_{\mathrm{eff}} = 15{,}486$ K. However, we find that the WD in CW Mon has $T_{\mathrm{eff}} = 22$–$27{,}000$ K, thus being hotter than expected if compressional heating alone is operating. Note, however, that the *HST* COS spectrum was taken only 6 days into optical quiescence following its last previous dwarf nova outburst. Thus, it is possible that the WD had not yet cooled in response to the heating by the last outburst. Because the average T_{eff} of CV WDs above the period gap is $\sim$30,000 K, then CW Mon may be at the low end of the distribution. There are also WDs primaries above the period gap with surface temperatures well below 20,000 K (Pala et al. 2017). CW Mon may belong to this group of lower-temperature CV WDs above the period gap.

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