Published in final edited form as:

Astron J. 2017 August ; 154(2): . doi:10.3847/1538-3881/aa774c.

Hubble COS Spectroscopy of the Dwarf Nova CW Mon: The White Dwarf in Quiescence?¹

Connor Hause,

Department of Astrophysics & Planetary Science, Villanova University, 800 Lancaster Avenue, Villanova, PA 19085, USA

Edward M. Sion,

Department of Astrophysics & Planetary Science, Villanova University, 800 Lancaster Avenue, Villanova, PA 19085, USA

Patrick Godon²,

Department of Astrophysics & Planetary Science, Villanova University, 800 Lancaster Avenue, Villanova, PA 19085, USA

T. Gänsicke Boris,

Department of Physics, University of Warwick, Coventry CV4 7AL, UK

Paula Szkody,

Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195

Domitilla de Martino, and

INAF-Osservatorio Astronomico di Capodimonte, Salita Moiariello 16, 80131, Napoli, Italy

Anna Pala

Department of Physics, University of Warwick, Coventry CV4 7AL, UK

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 in Cataclysmic Variables. We use 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 white dwarf mass of $0.8M_\odot$, our results indicate the presence of a 22–27,000 K white dwarf and a low mass accretion rate ($\dot{M} \lesssim 10^{-10} M_\odot/\text{yr}$), for a derived distance of ~ 200 to ~ 300 pc.

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 (WD) during the quiescent

¹Based on observations made with the NASA- *Hubble Space Telescope*

²Visiting at the Henry A. Rowland Department of Physics & Astronomy, The Johns Hopkins University, Baltimore, MD 21218.

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 ($\sim 65^\circ$). They also found evidence for a grazing eclipse of the accretion disk in CW Mon and estimated a distance of 297 pc while Kato et al. (2003) reported a 37-min 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-min modulation to be a quasi-periodic oscillation (QPO) 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 $H\alpha$ images taken with the 4.2-m William Herschel Telescope (WHT). 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 while 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 Nov.30, 2012, at 21:30:07 in TIME-TAG Mode, and collected data for 4773s of good exposure time (or about 1/3 of the orbital period). The COS instrument was set in the FUV configuration, using the PSA aperture with the G140L gratings centered at 1105Å, thereby generating a spectrum covering the wavelength range ~1110Å to ~2000Å.

CW Mon's optical magnitude did not reach nominal quiescence (16.0 in this case) until Nov. 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 1/3 that of the HST COS spectrum. The IUE spectra, SWP27112 and SWP32793, were taken during dwarf nova quiescence on November 14, 1985 (at 20:37:21) and January 26, 1988 (at 20:09:08) at low dispersion, through the large aperture with exposure times of 10,800 s and 9900 s, respectively. The two IUE SWP spectra are almost identical and so we co-added them to obtain 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 Fig. 1. The COS spectrum exhibits a rich array of absorption lines much like the FUV spectrum of the white dwarf 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 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 white dwarf and accretion disc model. A similar procedure was carried out for spectral analysis of the COS spectrum of the VY Scl novalike BB Dor Godon et al. (2016), obtained in an intermediate state as part of the ongoing campaign 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 Ly α 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 $i = 60^\circ$, WD mass $M_{wd} = 0.80M_\odot$, 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 white dwarf mass of $0.8M_\odot$. This mass value is roughly the average mass of WDs in CVs. The WD photosphere models were constructed using temperatures of 17,000K to 30,000K in steps of 1,000K with a projected stellar rotational velocity ranging from 200km/s to 500km/s in steps of 100km/s. Additional details on our method can be found in Godon et al. (2016).

4. Synthetic Spectral Fitting Results

The HST COS spectrum displayed in Fig. 1 has a flux level about three times higher than the co-added IUE spectrum of CW Mon mentioned in Section 2. Since 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, we find that the mass accretion rate has to be about $\sim 5 \times 10^{-11} M_\odot/\text{yr}$ to agree with the distance of 200–300pc. 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 try a combined disk + WD model and find a reasonable fit for a disk with $\dot{M} = 3 \times 10^{-11} M_\odot/\text{yr}$ with a 23,000K WD, giving a distance of 301pc. In this combined model the WD contributes 3/4 of the flux and is the dominant component.

Last, we try a single WD fit to the IUE spectrum of CW Mon and we find that a 23,000K WD gives the best fit with a distance of 251pc. This fit is presented in Fig. 2. We note that a single WD with 21,000K gives a distance of 206pc, while a 25,000K WD gives a distance of 302pc, both within the accepted distance range and with an acceptable fit. However, the $T_{wd} = 23,000\text{K}$ and $T_{wd} = 22,000\text{K}$ models are substantially better, fitting both the Ly α wings and continuum in the longer wavelengths, with $T_{wd} = 23,000\text{K}$ providing the best fit. From these IUE fits, we deduce that the WD temperature must be 22,000 K to 23,000 K, with the possible contribution from a disk with a mass accretion rate of the order of a few $10^{-11} M_\odot/\text{yr}$ or less.

Consequently, for the higher resolution HST COS spectrum, we also expect significant emission from the WD (23,000K 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 to 300 pc for a mass accretion rate $\dot{M} \sim 10^{-10} M_\odot/\text{yr}$, but the fit is rather poor, especially in the vicinity of the Ly α region ($\sim 1150 - 1300\text{\AA}$). 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 ($\sim 20,000\text{K}$) models agree with the longer wavelength region ($\lambda > 1750\text{\AA}$) of the spectrum, while higher temperature ($\sim 25,000\text{K}$) models agree better with some prominent absorption lines in the short wavelength region of the spectrum ($1250\text{--}1350\text{\AA}$). We display this white dwarf-only fit model in Fig. 3. The derived temperature is $26,000\text{ K}$, 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 ($< 200\text{ pc}$) 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 $\dot{M} = 10^{-10} M_{\odot}/\text{yr}$, the WD+disk fit improves as the WD temperature increases and a good fit is obtained for $T_{\text{wd}} = 26,000\text{ K}$, giving a distance of 301 pc . This model fit is presented in Fig. 4. A higher WD temperature yields a distance that is too large ($> 300\text{ pc}$), while a lower WD temperature provides fit that is not as good.

For an accretion rate $\dot{M} = 3 \times 10^{-11} M_{\odot}/\text{yr}$, the WD+disk fit gives a reasonable fit for a temperature increasing from $24,000\text{K}$ (with a distance of 205 pc) to $29,000\text{K}$ (with a distance of 294 pc). The lower temperature WD model gives a better fit in the longer wavelength range, while the higher temperature WD model gives a better fit in the shorter wavelength range. The best fit is obtained for an intermediate WD temperature of $27,000\text{K}$ giving a distance of 256 pc . This model is presented in Fig. 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 white dwarf in CW Mon is partially exposed and appears to have a surface temperature of around $22\text{--}23,000\text{K}$ (IUE spectrum) to $26\text{--}27,000\text{K}$ (COS spectrum), with a roughly solar composition atmosphere.

If the white dwarf 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:

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

where M_{wd} is the mass of the white dwarf (Townesley & 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 $\sim 10^{-10} M_{\odot}/\text{yr}$, then the WD should have a $T_{\text{eff}} = 15,486$ K. However, we find that the WD in CW Mon has $T_{\text{eff}} = 22 - 27,000$ 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. Since the average T_{eff} of CV white dwarfs above the period gap is $\sim 30,000$ K, then CW Mon may be at the low end of the distribution. There are also white dwarfs 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.

Acknowledgments

Special thanks to the American Association of Variable Star Observers (AAVSO) for monitoring CW Mon during the COS observation window. Support for Program number GO-12870 to Villanova University and the University of Washington was provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Incorporated, under NASA contract NAS5-26555. The research leading to these results has received funding from the European Research Council under the European Union's Seventh Framework Programme (FP/2007–2013)/ERC Grant Agreement n. 320964 (WDTracer). The analysis of the archival IUE spectra was supported by the National Aeronautics and Space Administration (NASA) under grant numbers NNX13AF11G & NNX13AF12G issued through the office of Astrophysics Data Analysis Program (ADAP) to Villanova University. PG wishes to thank William (Bill) Blair for his kind hospitality at the Rowland Department of Physics & Astronomy in the Johns Hopkins University, Baltimore, Maryland.

References

- Bruch A, Engel A. A&AS. 1994; 104:79.
- Fitzpatrick E. PASP. 1999; 111:63.
- Godon P, et al. ApJ. 2016; 833:146.
- Hubeny I. Comp Phys Comm. 1988; 52:103.
- Hubeny I, Lanz T. ApJ. 1995; 439:875.
- Kato T, et al. PASJ. 2003; 55:489.
- Kemp, et al. PASP. 2002; 114:623.
- Pala AF, et al. MNRAS. 2017; 466:2855.
- Patterson J. MNRAS. 2011; 411:2695.
- Pretorius ML, Knigge C. MNRAS. 2008; 385:1485.
- Sahman D, Dhillion V, Knigge C, Marsh T. MNRAS. 2015; 451:2863.
- Sion EM. AJ. 1991; 102:295.
- Sion EM. ApJ. 1995; 438:876.
- Sion EM. PASP. 1999; 111:532.
- Szkody P, Mateo M. AJ. 1986; 92:483.
- Szkody P. ApJS. 1987; 63:685.
- Townesley D, Bildsten L. ApJ. 2003; 596:L127.
- Townesley DM, Gänsicke BT. ApJ. 2009; 693:1007.
- Wade RA, Hubeny I. ApJ. 1998; 509:350.
- Warner B. PASP. 2004; 116:115.

Fig. 1.

The 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 1/3 that of the COS spectrum.

Fig. 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 $0.8M_{\odot}$, and a temperature of 23,000K, with a scaled distance of 251pc. A 21,000K WD model gives a scaled distance matching the lower limit for of distance ~ 200 pc, while a 25,000K WD scales to the upper limit of ~ 300 pc. The best fit, however, is obtained for a temperature of 22–23,000K WD model.

Fig. 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 $0.8M_{\odot}$, a temperature of 26,000K, and a projected stellar rotational velocity $V_{\text{rot}} \sin(i) = 400 \text{ km/s}$. The distance obtained from the scaling is 211 pc.

Fig. 4.

The 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 $0.8M_{\text{wd}}$, its temperature is 26,000K and its rotational velocity, $V_{\text{sin}i} = 400$ km/s. The accretion rate is $\dot{M} = 10^{-10} M_{\odot}/\text{yr}$, and the inclination is set at 60 deg. The scaled distance obtained from the fit is 301pc. The WD and the disk contribute about both $\approx 50\%$ of the observed flux.

Fig. 5.

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