THE ACCRETING WHITE DWARF IN SS CYGNI REVEALED

Edward M. Sion\textsuperscript{1}, Patrick Godon\textsuperscript{1,3}, Janine Myzcka\textsuperscript{1}, and William P. Blair\textsuperscript{2}

\textsuperscript{1}Astronomy & Astrophysics, Villanova University, 800 Lancaster Avenue, Villanova, PA 19085, USA; edward.sion@villanova.edu, janine.myzcka.villanova.edu, patrick.godon@villanova.edu
\textsuperscript{2}Department of Physics and Astronomy, The Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218, USA; wpb@pha.jhu.edu

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ABSTRACT

We have carried out a combined \textit{Hubble Space Telescope} (HST/GHRS) and \textit{Far Ultraviolet Spectroscopic Explorer} (FUSE) analysis of the prototype dwarf nova SS Cygni during quiescence. The FUSE and HST spectra were obtained at comparable times after outburst and have matching flux levels where the two spectra overlap. In our synthetic spectral analysis, we have used SS Cygni’s accurate \textit{HST} fine guidance sensor parallax giving \(d = 166\) pc, a newly determined mass for the accreting white dwarf (WD) of \(M_{\text{wd}} = 0.81\) \(M_\odot\) (lower than the previous widely used 1.2 \(M_\odot\)) and the reddening \((E_{B-V})\) values 0.04 and 0.07 derived from the 2175 Å absorption feature in the \textit{IUE} LWP spectra. From the best-fit model solutions to the combined \textit{HST} + FUSE spectral energy distribution, we find that the WD is reaching a temperature \(T_{\text{eff}} \approx 45,000–55,000\) K in quiescence, assuming \(\log(g) = 8.3\) with a solar composition accreted atmosphere. The exact temperature of the WD depends on the reddening assumed and the inclusion of a quiescent low mass accretion rate accretion disk. Accretion disk models alone fit badly in the FUSE range while, and if we take the distance to be a free parameter, the only accretion disk model that fits well is for a discordant distance of at least several hundred parsecs and an accretion rate \((\sim 10^{-8} M_\odot \text{ yr}^{-1})\), which is unacceptably high for a dwarf nova in quiescence. We discuss the implications of the WD’s temperature on the time-averaged accretion rate and long-term compressional heating models.

\textit{Key words:} accretion, accretion disks – novae, cataclysmic variables – white dwarfs

\textit{Online-only material:} color figure

1. INTRODUCTION

SS Cygni is a prototype dwarf nova, a subclass of the cataclysmic variable (CV) group of binary stars. CVs contain a white dwarf (WD) and a larger radius, less massive, donor star. The donor star fills its Roche lobe and its matter has gradually been cannibalized by the WD. In dwarf novae, the matter feeds into a disk around the WD and continues to build up the disk mass until the disk reaches a critical temperature at which time the mass collapses onto the WD and releases gravitational potential energy as radiation. This results in a roughly periodic time the mass collapses onto the WD and releases gravitational mass until the disk reaches a critical temperature at which the remaining disk may still be optically thick and dominate the FUV flux of the system.

SS Cyg is one of the best-studied dwarf novae. It has an orbital period of 6.6 hr (well above the period gap) and a \(\sim 50\) day recurrence time between dwarf nova outbursts (Cannizzo & Matei 1992; Cannizzo 1993). These factors and its well-studied history have made it a key target of our ongoing studies to understand how disk accretion affects the WD. Observations must be taken when the system is in quiescence because in such a state the disk is least luminous, which offers a favorable opportunity to detect the radiation of the WD photosphere. However, the source of far-ultraviolet (FUV) light during the quiescence of dwarf novae remains controversial. This is especially true in dwarf novae with orbital periods above the CV period gap, which tend to have higher mass transfer rates, larger accretion disks, and more massive secondary stars. Therefore, during quiescence, it is possible that some portions of the remaining disk may still be optically thick and dominate the FUV flux of the system.

The inclination of its orbit is \(\sim 51^\circ\) (Bitner et al. 2007), while its WD mass has been reported to be 1.2 \(M_\odot\) (Shafter 1983) and secondary mass 0.7 \(M_\odot\). The system has an accurate parallax measured with the \textit{Hubble Space Telescope} (HST) fine guidance sensor (FGS; Harrison et al. 2000) yielding a parallax distance of \(166^{+14}_{-12}\) pc. Holm & Polidan (1988) first noted the possible detection of the underlying accreting WD from the occasional appearance of Lyα absorption in some \textit{IUE} spectra obtained during quiescence. However, despite a number of attempts to measure the WD’s temperature and quantify its contribution to the FUV flux, the uncertain contribution of the accretion disk and other possible unidentified source(s) of FUV emission, the “second component,” rendered any such measurements suspect (Holm 1988; Lesniak & Sion 2003; Long et al. 2005).

Recently, however, we retrieved archival FUSE and \textit{HST} spectra, both obtained during different quiescent intervals of SS Cygni but with closely matching flux levels in the wavelength range \(HST/\text{GHRS}\) and \textit{FUSE} overlap \((\sim 1150–1190\) Å). Also a new mass determination for the WD has now been derived by Bitner et al. (2007): \(0.81\) \(M_\odot\) \(\pm 0.18\), significantly lower than the earlier value of 1.2 \(M_\odot\). Using this lower mass and the parallax distance of 166 pc, we have re-examined the nature of the hot component with synthetic spectral models of high-gravity photospheres and optically thick accretion disks. This assessment is presented below.

In the following section we give details of the archival spectra. In Section 3 we present our spectral modeling tools and method. Results are presented in Section 4 and discussed in the concluding section.
Figure 1. Combined spectrum of SS Cyg (in red) dereddened assuming $E(B-V) = 0.04$ is shown with a composite WD+disk synthetic spectrum (in solid black). The WD model (dotted line) has $M_{\text{wd}} = 0.8 M_\odot$ (corresponding to log($g$) = 8.3), $T_{\text{eff}} = 46,000$ K, solar composition, and a projected rotational velocity of 200 km s$^{-1}$. The dashed line is the contribution from the accretion disk model. The disk model has a mass accretion rate $\dot{M} = 10^{-10} M_\odot$ yr$^{-1}$ and an inclination $i = 50^\circ$. The $\chi^2$ obtained is 1.258 and the resulting distance is 173 pc. The WD contributes 88% of the FUV flux, while the disk contributes the remaining 12%. The excess of flux around 1060–1080 Å and 1110–1130 Å might be due to some emission from Si$^4$ (1063, $\sim$1073 Å), Si$^3$ (1066 Å), Si$^3$ (1108–1113 Å), and Si$^4$ (1122.5, 1128.3 Å).

(A color version of this figure is available in the online journal.)

2. ARCHIVAL OBSERVATIONS

The archival HST GHRS spectrum was taken on JD 2450352 (1996 September 26), in mid-quiescence, 17 days after SS Cygni reached quiescence and 21 days after the previous outburst. The HST spectrum is a combination of two individual spectral segments Z3DV0204T (1150–1435 Å) and Z3DV0205T (1377–1663 Å) taken in ACCUM mode with the GHRS spectrograph with the G140L grating and Large Science Aperture (of size 1.74). The two spectral segments, one at each grating setting, had an exposure time of 2176 s each, and there was a 32.25 s time gap in an otherwise nominal exposure. The GHRS observations were calibrated using the standard pipeline CALHRS, and were retrieved as VO tables using VOSpec.

The archival FUSE spectrum was taken on JD 2452156.5 (2001 September 4), 18 days after the previous outburst and 13 days after the system first entered quiescence. The FUSE spectrum (P2420101) was a combined spectrum of eight separate exposures taken through the 30$^\prime$ x 30$^\prime$ LWRS Large Square Aperture in TIME Tag mode. The total good exposure time was $\sim$18 ks, varying slightly for each spectral channel. The observations were carried out mostly during NIGHT time. The FUSE observations were processed with CalFUSE version 3.2.3 (Dixon et al. 2007). We follow the same procedure we used previously for the postprocessing (co-addition, alignment, and weight of the spectral channels) of the FUSE data (see, e.g., Godon et al. 2006).

The combined FUSE + GHRS spectrum of SS Cyg is presented in Figure 1 (see Section 4 for the model fit). The observations are characterized by strong emission lines originating in an optically thin region in the disk or above it, as inferred from their rotational broadening (see Long et al. 2005 for a rigorous analysis of these lines in the GHRS spectra). In the very short wavelengths of FUSE, the broad emission lines from N$^4$, S$^6$, and H$^1$ (Ly$\delta$ and higher) merge together and produce an apparent rise of flux ($<950$ Å), which we do not attempt to model. In the fitting (Section 4) we mask all the emission lines and these appear in blue in Figure 1. It is likely that around 1060–1080 Å and 1110–1120 Å some additional emission is present.
3. SYNTHETIC SPECTRAL MODELING

We adopted model accretion disks from the optically thick disk model grid of Wade & Hubeny (1998). In these accretion disk models, the innermost disk radius, $R_{in}$, is fixed at a fractional WD radius of $x = R_{in}/R_{wd} = 1.05$. The outermost disk radius, $R_{out}$, was chosen so that $T_{eff}(R_{out})$ is near 10,000 K since disk annuli beyond this point, which are cooler zones with larger radii, would provide only a very small contribution to the mid- and far-UV disk flux, particularly the FUV bandpass ($\sim$900–1700 Å). The mass transfer rate is assumed to be the same for all radii.

Theoretical, high-gravity, photospheric spectra were computed by first using the code TLUSTY (Hubeny 1988) to calculate the atmospheric structure and SYNSPEC (Hubeny & Lanz 1991) to construct synthetic spectra. We compiled a library of photospheric spectra covering the temperature range from 15,000 K to 70,000 K in increments of 1000 K, and a surface gravity range, $\log(g) = 7.0$–9.0, in increments of 0.2 in $\log(g)$.

The reddening of the system was taken from estimates listed in the literature, determined from the strength of the 2200 Å interstellar absorption feature. Verbunt (1987) and La Dous (1991) both give $E(B - V) = 0.04$, while the more recent work of Bruch & Engel (1994) gives $E(B - V) = 0.07$. Both values are much smaller than the galactic reddening in the direction of SS Cyg which is the fact large ($\sim$0.5) in agreement with the fact that SS Cyg is rather nearby with a distance of only 166 pc. The combined spectrum was dereddened with the IUERDAF IDL routine UNRED assuming both $E(B - V) = 0.04$ and 0.07.

After masking emission lines in the spectra, we determined separately for each spectrum the best-fitting WD-only models and the best-fitting disk-only models using a $\chi^2$ minimization routine. A $\chi^2$ value and a scale factor were computed for each model fit. The scale factor $S$, normalized to a kiloparsec and solar radius, can be related to the WD radius $R$ through

$$F_{\lambda(\text{obs})} = S H_{\lambda(\text{model})}, \quad \text{where} \quad S = 4\pi R^2 d^{-2}$$

and $d$ is the distance to the source. For the WD radii, we use the mass–radius relation from the evolutionary model grid of Wood (1995) for C–O cores. We combined WD models and accretion disk models using a $\chi^2$ minimization routine called DISKFIT. Using this method, the best-fitting composite WD plus disk model is determined based upon the minimum $\chi^2$ value achieved, visual inspection of the model, consistency with the continuum slope and Ly$\alpha$ region, and consistency of the scale-factor-derived distance with the adopted trigonometric parallax distance.

4. SYNTHETIC SPECTRAL FITTING RESULTS

We used an accretion disk model, a WD photosphere, and a combination of both in our analysis. The disk models used were optically thick, steady-state accretion models with solar abundances. They are considered a reasonable first approximation to the spectral shape of the disk in quiescence. In the disk models, we first adopted an inclination of 41° and 60° directly from the grid of models of Wade & Hubeny (1998). Only after a satisfactory best fit was obtained with the correct (parallax) distance, did we then generate disk models (using TLUSTY, SYNSPEC, and DISKSYN) with an inclination of 50° closer to its derived value of 51° ± 5° (Bitner et al. 2007). The photosphere models were generated using TLUSTY and SYNSPEC.

In the following, we used the parallax distance of 166 pc and the mass of 0.8 $M_\odot$ ($\log(g) = 8.3$; Bitner et al. 2007). We assumed reddening values of $E(B - V) = 0.04$ and 0.07. A summary of the model fits is given in Table 1.

We started our fitting with single accretion disk models alone assuming both $E(B - V) = 0.04$ and 0.07. We ran disk model fits and found that the best fit (lowest $\chi^2$) had a mass accretion rate far too large for quiescence and a distance much larger than 166 pc.

Next, we tried single WD atmosphere models, first dereddening assuming $E(B - V) = 0.04$. Since almost all the lines are in emission (possibly from an optically thin region in the disk and/or corona), it makes it difficult to assess the rotational velocity broadening and chemical abundances based on the
absorption lines. Nevertheless, for all WD models we assumed solar abundances and a canonical projected rotational velocity of 200 km s$^{-1}$, and checked that the value of the $\chi^2$ did not depend on $V_{\text{rot}} \sin i$ as long as it was a few hundred km s$^{-1}$. The best-fit least $\chi^2$ WD model has a temperature $T_{\text{eff}} = 40,000$ K and $\chi^2 = 1.637$, but with a distance of only 138 pc. A model with $T_{\text{eff}} = 47,000$ K gave the correct distance with a slightly larger $\chi^2$, namely 1.990. Next, we ran single WD model fits assuming $E(B-V) = 0.07$. The $\chi^2$ we obtained increased slightly over the $E(B-V) = 0.04$ best-fit models.

Finally, we explored whether the fitting could be improved if we combined a WD model with an accretion disk model. We found that some of the WD plus disk combinations yielded distances close to 166 pc with a lower $\chi^2$. We have summarized some of these combination fits in Table 1. For $E(B-V) = 0.04$, the best WD+disk fit leading to a distance in agreement with observed parallax is for a WD with $T = 46,000$ K, a disk with a mass accretion rate $\dot{M} = 1 \times 10^{-10} M_\odot$ yr$^{-1}$, $i = 50^\circ$, where the WD contributes 88% of the flux and the disk contributes the remaining 12%. This model fit is presented in Figure 1. We then carried out the same fitting but this time assuming $E(B-V) = 0.07$ and found similar results for the disk but with a higher WD temperature: $T_{\text{eff}} = 55,000$ K.

Therefore, we conclude that the dominant source of the FUV radiation between 912 Å and 1660 Å is an accretion-heated WD photosphere with $T_{\text{eff}} \approx 45,000-55,000$ K and log($g) = 8.3$ (depending on the reddening value).

5. CONCLUSIONS

We have presented evidence from our model fitting analysis of the combined $\text{FUSE} + \text{HST}/\text{GHRS}$ spectrum of SS Cyg during quiescence that the source of the FUV continuum and absorption line radiation is the WD’s photosphere. The disk models that best fit the spectral data yield unreasonably large distances, at odds with the $\text{HST}$ TGS parallax and indicate accretion rates far too high to be associated with dwarf nova quiescence. The photosphere models give effective temperatures of 45,000–55,000 K for a reddening of 0.04 and 0.07 with the inclusion of a low mass accretion rate disk in agreement with the quiescent state. Unfortunately, the lack of a clear detection of absorption lines due to accreted metals and helium in the WD atmosphere prevents a determination of both the rotational velocity of the WD and the abundance of metals in its accreted atmosphere.

Our derived temperature for the WD in SS Cyg is well above the presently estimated average temperature ($\sim 30,000$ K) for WDs in dwarf novae above the CV period gap. Compared with the temperatures of WDs in dwarf novae whose orbital periods are close to the period of SS Cygni, the WD in TT Crt is cooler ($40,000$ K; Sion et al. 2008), while the WD in Z Cam is hotter ($57,000$ K; Hartley et al. 2005). If the accretion rate scales with the orbital period, then the temperatures should be comparable. It is interesting that the WDs in dwarf novae with $P_{\text{orb}} < 360$ minutes are cooler than $40,000$ K, while the hottest WDs in dwarf novae are found at $P_{\text{orb}} > 360$ minutes.

At $P_{\text{orb}} = 6.6$ hr, the $T_{\text{eff}}$ of the WD in SS Cygni lies within the range expected from compressional heating for an average $M$, $\langle M \rangle$, obtained from typical interrupted magnetic braking laws for WD masses between 0.6 $M_\odot$ and 1.0 $M_\odot$ (Townsend & Gänsicke 2009). A linear extrapolation to $P_{\text{orb}}$ of the predicted $T_{\text{eff}}$ for $P_{\text{orb}} = 6.6$ hr, corresponds to an average mass transfer rate of $\langle M \rangle \sim 10^{-8} M_\odot$ yr$^{-1}$ which is at the high end of the range of mass transfer rates associated with the nova-like variables, as determined from their optical disk luminosities (Warner 1995). Interestingly, the braking laws of Andronov et al. (2003) and Ivanova & Taam (2004) either fall drastically short or exhibit a downturn, respectively, of yielding the $\langle M \rangle$ implied by the WD $T_{\text{eff}}$, while the Howell et al. (2001) law steeply increases at constant $P_{\text{orb}} \sim 5$ hr. One cannot rule that other significant sources of heating of the WD besides compression are operating such as possible nuclear burning. It seems clear that more WD temperatures are needed in dwarf novae and nova-like variables at long $P_{\text{orb}}$ before definitive conclusions can be drawn.

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EDWARD M. SION\textsuperscript{1}, PATRICK GODON\textsuperscript{1}, JANINE MYSZKA\textsuperscript{1}, AND WILLIAM P. BLAIR\textsuperscript{2}

\textsuperscript{1}Department of Astronomy & Astrophysics, Villanova University, 800 Lancaster Avenue, Villanova, PA 19085, USA; edward.sion@villanova.edu, patrick.godon@villanova.edu, janine.myszka@villanova.edu

\textsuperscript{2}Department of Physics and Astronomy, The Johns Hopkins University, 3400 N. Charles Street, Baltimore, MD 21218, USA; wpb@pha.jhu.edu

The last name of the co-author Janine Myszka was erroneously spelled in the originally published author list. The corrected spelling is given in this erratum.