

The Accreting White Dwarfs in Cataclysmic Variables

Edward M. Sion ^{1,*}  and Patrick Godon ^{1,2} ¹ Department of Astrophysics and Planetary Science, Villanova University, Villanova, PA 19085, USA² Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA; patrick.godon@villanova.edu

* Correspondence: edward.sion@villanova.edu

Abstract: Accreting white dwarfs (WDs) in cataclysmic variables (CVs) provide crucial insights about the accretion of mass and angular momentum in all types of binaries, including accreting NSs and BHs. Accreting WDs are the critical component in the single degenerate pathway to SNe Ia, along with the double degenerate merger pathway, they are the standard candles of cosmology proving that the universe is accelerating and the existence of dark energy. Another key question is whether the WD in a CV can grow in mass despite the mass loss due to thousands of nova explosions in its lifetime. Angular momentum loss drives CV evolution and accreting WDs offer critically needed WD masses from Gaia distances and reliable surface temperatures to derive the most accurate accretion rates. We review the studies on accreting WDs, including WD masses, accurate rotational velocities and chemical abundances of elements. Most of the progress that has been made is based upon Hubble Space Telescope spectroscopy and FUSE spectroscopy in the UV spectral region during dwarf nova quiescence and the low states of novalike variables, when the accreting WD dominates the UV spectral range.

Keywords: cataclysmic variables; white dwarf stars; dwarf novae; novalikes; accretion disks



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1. Introduction

A cataclysmic variable (CV) is a compact binary (with an orbital period $\lesssim 1$ day) in which the primary, a white dwarf (WD) star, accretes matter and angular momentum from the secondary star, a main sequence-like object, filling its Roche lobe. In non-magnetic systems, the matter is transferred, at continuous or sporadic rates, by means of an accretion disk around the WD. In magnetic systems, the WD magnetic field disrupts the formation of a disk and channels accreting gas onto the magnetic poles of the WD.

The long-term evolution of CVs is driven by the rate of the binary angular momentum loss (AML), which itself is a direct consequence of the mass transfer from the secondary to the WD. CV systems are believed to evolve from long binary period ($\sim$ a day) to short period (fraction of an hour). At long period, AML is mostly driven by magnetic stellar winds of the donor star. As the donor star is eroded away by mass transfer above orbital periods of 3 h, it eventually becomes fully convective. This jostles and disrupts the foot points of the magnetic field, shutting off the magnetic stellar wind, thus reducing AML. Mass transfer essentially stops, as the donor is detached from its Roche lobe and the system has entered the so-called CV period gap between orbital periods of 2 and 3 h where very few CVs are found. However, now driven mainly by gravitational wave emission, AML continues to reduce the binary orbital period. At orbital periods shorter than 2 h, the secondary remakes contact with its Roche lobe and the CV resumes mass transfer, now below the period gap.

The dwarf novae (DNe, a type of CVs) release gravitational energy when a thermal-viscous instability in the accretion disk around the white dwarf leads to rapid accretion at a high rate (the dwarf nova *outburst*, lasting days to weeks) until the disk has largely emptied

and the system returns to *quiescence*, at which time the buildup of disk gas begins again (lasting weeks to months).

If the accretion rate is high enough to nearly fully ionize the disk, then the disk instability is suppressed and stable accretion keeps the system in a *high state* (the UX UMa novalike (UX NL) variables belong to this class) or the high state is interrupted by rare and unpredictable *low states* of short duration (as is the case for the VY Scl novalike (VY NL) variables). **When a VY NL system is in a low state, or when a DN system is in quiescence, the WD is revealed in the ultraviolet (UV)**, as its emission greatly outshines the disk which is in a state of low mass accretion. At other times, DNe in outburst and NLs in high state are dominated in the UV by emission from the accretion disk (which is in a state of high mass accretion).

In a CV system, when the accreted layer on the WD reaches a critical pressure at its base (this happens usually every few thousand years), explosive thermonuclear runaway (TNR) shell burning is triggered: the (classical) nova explosion. If, however, disk accretion occurs at a very high rate (close to the Eddington limit), novae explosions may be avoided if steady, stable shell burning occurs in equilibrium with the rate of accretion, as is the case for the supersoft X-ray binaries. Finally, if a white dwarf in a CV is born massive ($M_{wd} > 0.8M_{\odot}$) and grows in mass despite hundreds to thousands of nova explosions, then instantaneous collapse and thermonuclear detonation will occur if the CV WD with a C-O core reaches the Chandrasekhar limit: the Type Ia supernovae: SNe Ia.

In the following sections, we present the current state of knowledge on these vital parameters that will deepen our insights into the physics of accretion and the structure and evolution of cataclysmic variables. In Section 2, we explain why it is important to obtain robust masses for the white dwarfs in CVs and the recent advances made in deriving CV WD masses. In Section 3, we discuss the current state of knowledge of the rotational velocities of CV white dwarfs; in Section 4, we discuss the chemical abundances derived from the accreted photospheres of CV white dwarfs, while in Section 5, we summarize the progress that has been made up to the present.

2. The Critically Important Masses of Accreting CV White Dwarfs

2.1. Supernovae Type Ia

Can the mass of a CV white dwarf grow with time despite the occurrence of hundreds to thousands of classical nova explosions during the lifetime of the compact binary? This question remains open. CV WDs are more massive ($0.83 \pm 0.03M_{\odot}$, [1]) on average than their isolated white dwarf counterparts ($0.6M_{\odot}$, [2]) which itself remains poorly understood. If an accreting white dwarf, born with a mass $0.8M_{\odot}$ (or larger) with a carbon-oxygen core grows in mass due to accretion from the Roche lobe-filling donor, then it may reach the Chandrasekhar limit and undergo a Type Ia supernova explosion (SNe Ia; [3,4])—this is known as the single degenerate (SD) scenario to SN Ia. SN Ia are the standard candle providing evidence that the expansion of the universe is accelerating [5,6], implying the presence of dark energy. Even a sub-Chandrasekhar white dwarf in a CV could undergo (through the SD channel) a SNe Ia event via a double detonation when the thick helium layer accumulating from many H shell flashes ignites, leading to the detonation of the underlying carbon-oxygen core [7–10]. In the double degenerate (DD) pathway to SN Ia, two CO WDs in a short binary system merge and result in a SN Ia [11,12]. CV systems, in theory, could also lead to SN Ia via the DD channel if they evolve into a double WD binary in which the total mass exceeds the Chandrasekhar limit and with period shorter than ~ 13 h [13]. Therefore, the availability of precise white dwarf masses will help make it possible to constrain the single degenerate pathway and hence potentially constrain the double degenerate pathway.

2.2. Tests of AML Braking Laws

Angular momentum loss drives the evolution of CVs and the mass transfer rate. Accurate WD masses are badly needed to test the different CV evolution theories based

on different angular momentum braking laws. The empirical distribution of CV white dwarfs is compared against different angular momentum braking laws in the binary orbital period (P_{orb}) versus white dwarf effective surface temperature (T_{eff}) parameter space (the $(P_{\text{orb}}, T_{\text{eff}})$ plane, [14]), as shown in Figure 1 (taken from [15]). The accurate CV white dwarf masses, coupled with their reliable effective temperatures, provide an empirical test of these evolutionary models. Unfortunately, there is a paucity of data points above the period gap (Figure 1), and, in addition, many WD masses are not known with accuracy. However, thanks to a large project using the Hubble Space Telescope, accurate masses are at last being secured [15,16] together with the accurate CV white dwarf masses derived from totally eclipsing binaries [17].

There have also been very important new advances in determining reliable masses of the accreting magnetic white dwarfs in intermediate polars, using hard X-ray spectroscopy along with the advantage of Gaia distances. These X-ray spectroscopic methods rely on the fact that the temperature of the accretion shock, T_{sh} , is sensitively dependent upon the mass and radius of the magnetic white dwarf. This analysis involves model fits to the X-ray continuum and/or X-ray emission lines associated with the post-shock region. The hard X-ray observations (largely but not exclusively by NuSTAR) of intermediate polars have yielded many dozens of reliable magnetic white dwarf masses in intermediate polars, as reported in [18–21] and references therein. This large new sample of hard X-ray-derived magnetic white dwarf masses in intermediate polars should lead to deepening insights into the formation, structure, magnetic accretion physics and evolution of magnetic CVs. Moreover, the authors of [20] obtained accurate mass accretion rates for many intermediate polars, with the important conclusion that the mass accretion rate in these objects does not depend on the orbital period. This was further corroborated in [16].

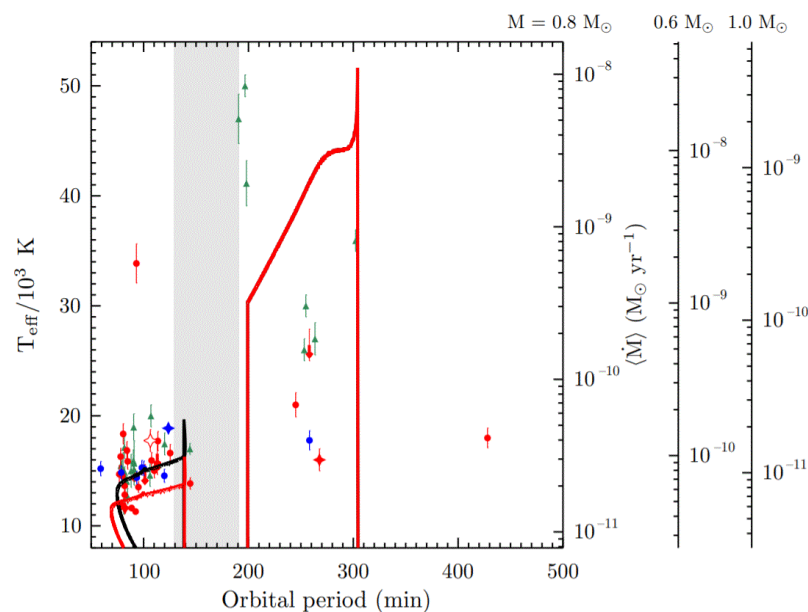


Figure 1. The WD effective surface temperature as a function of the orbital period from [15] (red and blue dots) and from [14] (green, non-magnetic system). The vertical light gray band represents the period gap between 2 and 3 h. The solid lines represent the evolutionary tracks for a system with a $0.8M_{\odot}$ WD accreting from a donor with an initial mass of $0.65M_{\odot}$, and an initial orbital period of 12 h. The red track was generated with the classical recipe for CV evolution (gravitational wave radiation only below the period gap), while the black track includes a residual magnetic braking equal to the gravitational radiation AML when the donor has no radiative core. The two tracks overlap above the period gap. To the right of the panel is projected a mapping to $\langle \dot{M} \rangle$ from [14] for $M_{\text{wd}} = 0.8, 0.6$, and $1.0M_{\odot}$, respectively. **Note the paucity of CV systems with exposed WD above the period gap.** The number of CVs with exposed WDs above the period gap is only 20% of the CVs below the period gap. This figure was taken from [15].

2.3. Binary Population Synthesis Models (BPS)

Reliable WD masses in compact binaries provide the input for essential BPS simulations. There should be large populations of CVs which are the descendants of the supersoft X-ray binaries, where the formerly more massive donor star in the system undergoes thermal timescale mass transfer (TTMT) at a high rate, thus driving steady thermonuclear burning on the white dwarf in equilibrium with the accretion supply rate. This builds up the mass of the WD accompanied by the rapid accumulation of helium ash, thus blocking the enhanced C needed to power the fast nova outburst and allowing WD mass growth. This scenario is one of the most promising progenitor channels for producing SN Ia (e.g., [22,23]). However, the authors of [24] found that mass growth of the WDs in CVs cannot reproduce the observed WD mass distribution. In the case of TTMT, the BPS model still produces too many CVs with helium WDs, and the donor secondary stars are evolved in many of the post-TTMT CVs, which contradicts the observations. They concluded that from the current understanding of CV evolution, neither TTMT nor WD mass growth during nova cycles can fully explain either the observed WD mass distribution or the observed period distribution of CVs. Work in this area remains very active, including our own work on abundances in CV WDs in progress [25].

A number of observed discrepancies between the theoretical predictions of sophisticated Binary Population Synthesis models (BPS) of cataclysmic variable evolution compared with the observed space density, mass distribution, orbital period distribution and average masses of CV white dwarfs above and below CV period gap, led the authors of [26] to recognize the need for additional angular momentum loss. Specifically, they found that there is an anti-correlation between the average accretion rates and the white dwarf masses for the systems below the period gap. Since the time-averaged accretion rate of CVs manifests the rate at which system angular momentum is lost, the authors of [26] found that by including an additional angular momentum loss mechanism associated with the mass transfer process itself, known as empirical consequential angular momentum loss (eCAML), which is more efficient (increases) at lower white dwarf mass, into their BPS models, much better agreement was found with the observations. In this model, the previously predicted CVs with low-mass WDs at short orbital periods suffer from dynamically unstable mass transfer and will disappear as CVs. This explains why there is no observed population of CVs with low mass white dwarfs at short orbital periods because they undergo dynamically unstable mass transfer which removes them from the CV population. While the exact process that gives rise to eCAML has not been identified, the authors of [26] suspected that eCAML might be associated with nova explosions. Recently, Sparks and Sion [27] found just such a mechanism that would be the eCAML that is needed; namely, the temporary common envelope that engulfs the entire system following the nova explosion and its interaction with the low mass donor star.

The works in [26,28] show, on the basis of comparisons between BPS models and the observed mass distribution of CV white dwarfs, that, in general, white dwarfs in cataclysmic variables probably do not gain mass over the long term, but that question remains to be answered definitively with a much larger sample of CV white dwarf masses [17]. This is necessary to provide the most stringent test of the promising eCAML mechanism and BPS theory applied to the empirical distribution of robust CV white dwarf masses. An observational effort is also needed in order to enlarge the sample of CV white dwarfs with an accurate mass determination, previously limited to 32 [29]. Even more to the point, the number of CVs with robust white dwarf mass determinations above the CV period gap is severely limited for meaningful comparisons with robust CV white dwarf mass determinations below the gap, as emphasized in both [29] and [17]. Pala et al. [16] have found little evidence to suggest that CV white dwarfs gain mass despite the occurrence of hundreds to thousands of nova explosions.

2.4. Precise CV WD Effective Temperatures

We underscore the remarkable advances that are being made in determining accreting white dwarf masses, surface temperatures, rotational velocities and chemical abundances with the advent of Gaia parallaxes. Whereas before Gaia, the only reliable means of obtaining robust masses of accreting white dwarfs was to use eclipsing cataclysmic variables [17,29], now with Gaia distances, the four key parameters (M_{wd} , T_{eff} , $V \sin(i)$, chemical abundances) can be determined with unprecedented precision. The WD photosphere spectral fit provides (T_{eff} , $\log(g)$) (effective surface temperature and surface gravity). From the scale factor (normalization), resulting when the model flux is scaled to observed flux with the inclusion of the Gaia distance, one obtains the white dwarf radius, R_{wd} . The mass of the white dwarf follows immediately from the white dwarf mass–radius law of (e.g., [2,30–32]) to obtain the white dwarf mass with a precision $\approx 5\%$ (see recent results in Figures 2–5). Accurate Gaia distances lead to accurate values of M_{wd} and T_{eff} [16,25]. Due to compressional heating of the WD, the accretion rate, $\dot{M}$, averaged over the thermal timescale of the WD envelope is then obtained from T_{eff} [33].

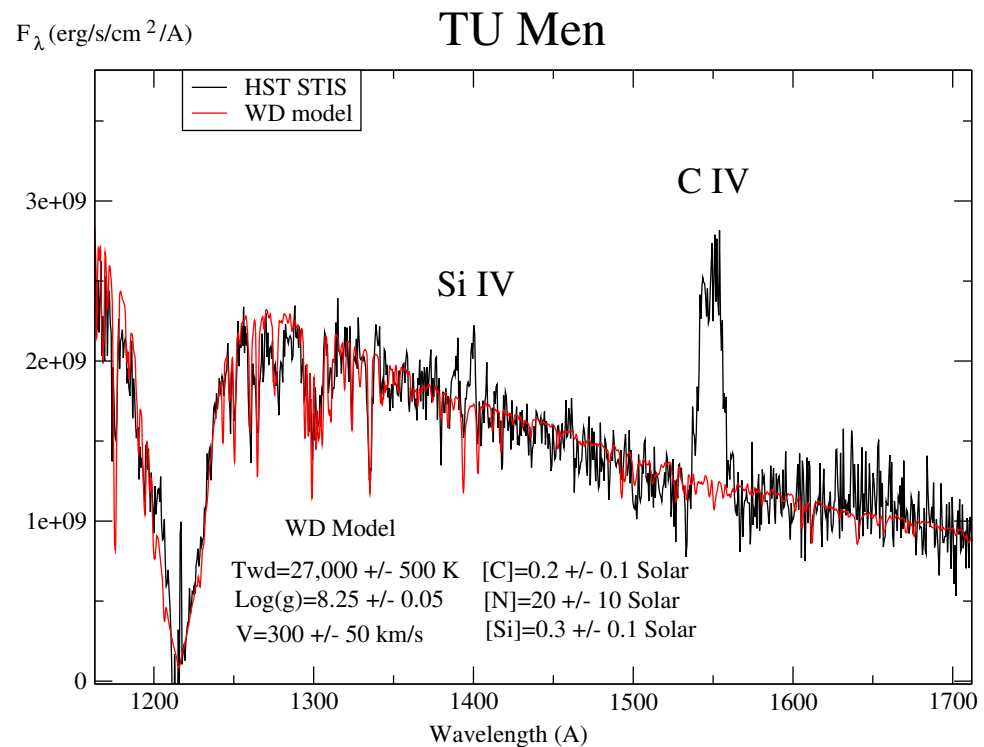


Figure 2. Modeling the WD in TU Men. The HST STIS FUV spectrum of TU Men (in black) is fitted with a synthetic stellar spectrum (in red). The results of the model fit, for a Gaia distance of 277 pc, give an effective surface gravity of $\text{Log}(g) = 8.25 \pm 0.05$, with an effective surface temperature of $27,000 \pm 500$ K. The elemental abundances are varied one by one together with the projected rotational stellar velocity. The fitting of the lines yields a carbon abundance of $[C] = 0.2 \pm 0.1$, silicon abundance of $[Si] = 0.3 \pm 0.1$, and nitrogen abundance of $[N] = 20 \pm 10$, all in solar abundances (sun = 1). The resulting projected stellar rotational velocity from the lines is $V_{rot} \sin(i) = 300 \pm 50$ km/s.

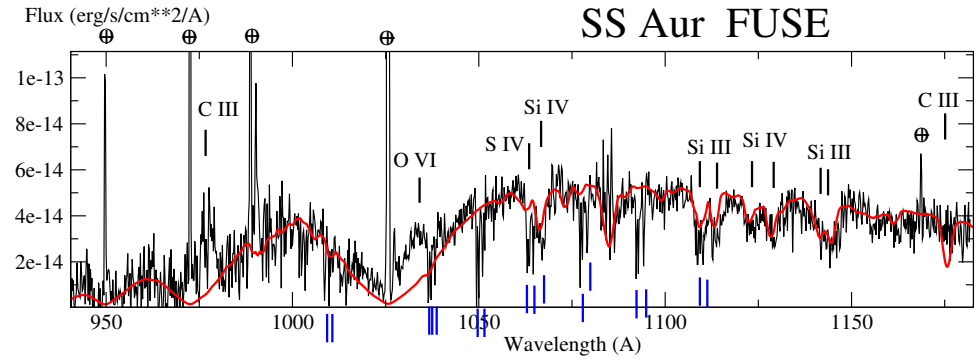


Figure 3. A WD model fit (solid red line) to the FUSE spectrum of SS Aur (black line) obtained at quiescence on 13 February 2002, 28 days after outburst. The sharp emission lines are geocoronal in origin. We identify broad emission lines from the O VI doublet (~ 1032 , 1038 Å), and C III (977 Å), not forming in the photosphere. Moderate ISM (H_2) absorption lines are marked in blue. The absorption lines and emission lines of the sources are indicated above the spectrum. The WD fit yields $T_{\text{eff}} = 30,200 \pm 500$ K, $\text{Log}(g) = 8.4 \pm 0.1$, $M_{\text{wd}} = 0.86 \pm 0.07 M_{\odot}$, $V_{\text{rot}} \sin(i) = 400 \pm 50$ km/s, and a silicon abundance $[\text{Si}] = 0.5 \pm 0.1$ solar. The other species were set to solar abundances. The C III (1175) absorption line is not observed, it could be filled up by emission.

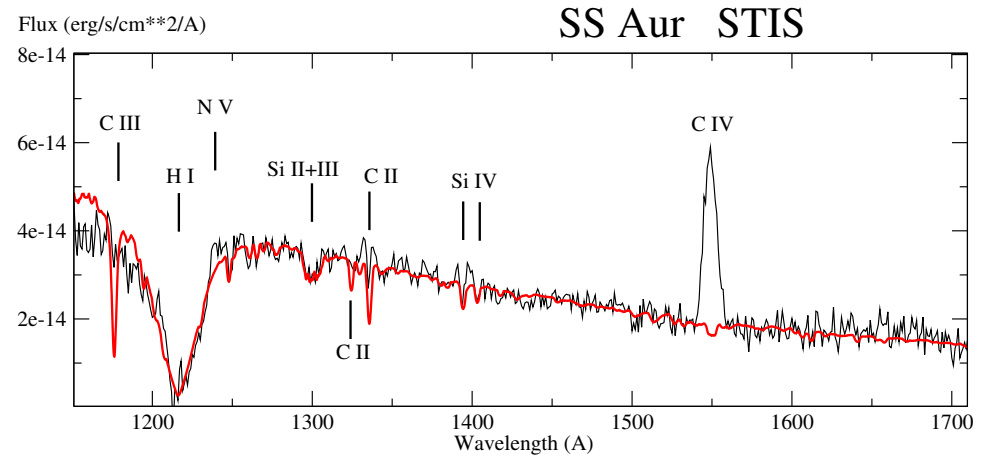


Figure 4. A WD model fit (red line) to the STIS spectrum of SS Aur (in black) obtained at quiescence on 20 March 2003, 34 days after (a different) outburst. The STIS spectrum exhibits strong C IV (~ 1550) emission and weak N V (~ 1240), C II (~ 1335), and Si IV (~ 1400) emission features. The model fit gives: $T_{\text{eff}} = 31,300 \pm 500$ K, $\text{Log}(g) = 8.4 \pm 0.1$, $M_{\text{wd}} = 0.86 \pm 0.07 M_{\odot}$, $V_{\text{rot}} \sin(i) = 400 \pm 50$ km/s, and a silicon abundance $[\text{Si}] = 0.2 \pm 0.1$ solar. The two spectra were obtained after different outbursts, one year apart, and, consequently, it is not expected that the results will be identical.

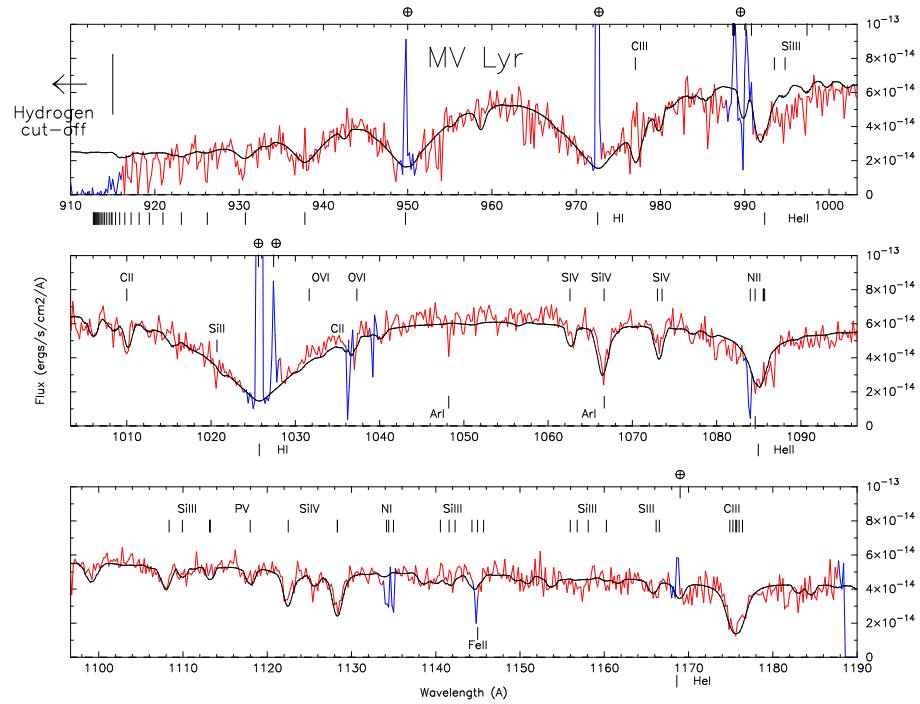


Figure 5. The FUSE spectrum of MV Lyr (in red) obtained in a low state is fitted with a WD stellar model (in black). The model has a temperature of $T_{\text{eff}} = 44,500 \pm 500$ K, $\text{Log}(g) = 8.23 \pm 0.02$. The sharp emission lines are geocoronal in origin and are marked with plus sign inside a circle above the panels. There are also some ISM absorption lines from C II, Fe II, Ar I, and N II; all these have been colored in blue and are not modeled. There are some faint emission features from C II (977), and from the O VI doublet (~ 1032 & ~ 1038). The remaining absorption lines are all stellar and are marked, and all are well fitted with solar abundances and with a projected rotational velocity $V_{\text{rot}} \sin(i) = 200 \pm 50$ km/s. The hydrogen orders of the Lyman series are marked under the panels for clarity. With a Gaia distance of 499^{+13}_{-11} pc, and using the C/O-core WD mass–radius relations from [32], we obtain a white dwarf mass of $0.78 \pm 0.01 M_{\odot}$.

2.5. WD Core Compositions

Accurate masses are needed to ascertain the percentages of core compositions, He, C-O and ONeMg, for tests of binary population synthesis models (BPS). It has generally been known from stellar evolutionary models followed to the white dwarf stage that three different core compositions must exist, helium (He) cores, carbon-oxygen (CO) cores and, in the most massive white dwarfs, oxygen-neon-magnesium (ONeMg) cores. One must always be mindful of crossover boundaries between CO and ONeMg cores and crossover boundaries between He cores and CO cores, in the inference of core composition based upon only the mass of a CV white dwarf. While progress in this area is model-dependent, the white dwarf mass ranges corresponding to these core compositions have been explored more recently by [34]. The lowest-mass white dwarfs $M_{\text{wd}} < 0.4 M_{\odot}$ have He cores, while white dwarfs in the mass range $0.4 < M/M_{\odot} < 1.05$ have CO cores with varying amounts of oxygen (via alpha particle captures). For $M_{\text{wd}} > 1.05 M_{\odot}$, cores of ONeMg are formed. The lowest mass helium white dwarfs had to be formed through binary evolution or mergers [26] since the age of the galactic disk is not old enough for any low-mass single main sequence star to have had time to evolve to a helium white dwarf. At the other mass extreme with progenitor masses $> 1.05 M_{\odot}$, white dwarfs with masses larger than $\sim 1.05 M_{\odot}$ may reach core temperatures high enough for stable carbon burning [35,36], forming either an ONe core or ONeMg core, the former if carbon burning ignites off-center and the latter core if carbon ignites at the center of the star. It is also possible that the carbon burning front may not reach the center, in which case, a white dwarf with a hybrid carbon-oxygen plus oxygen-neon core will form [37]. Accurate WD masses must be used

to determine the percentages of core compositions (He, C-O and ONeMg) and test binary population synthesis models.

3. CV White Dwarf Rotational Velocities

The WD rotation rates, rotational velocities, are required to achieve an understanding of CV evolution and spin-up of the CV WDs caused by accretion with angular momentum. Over the lifetime of a CV (e.g., $\sim 10^9$ yrs), the accretion of $0.1\text{--}0.2M_{\odot}$ of gas with angular momentum should spin up the CV WD to its critical Keplerian rotation velocity [38]. The white dwarf rotation, if near-Keplerian, would provide centrifugal pressure leading to an increased mass limit for a SNe Ia (super-Chandrasekhar SNe Ia). While nova explosions may spin down the rotation rates to well below the critical rotation, if the accretion rate is low and the white dwarf is of average or moderate mass, then the recurrence time between novae is longer and an accreting white dwarf should possibly have a faster rotation rate than higher mass accreting white dwarfs.

The potential importance of the angular momentum which is gained by accreting white dwarfs (WDs) has been increasingly recognized in the context of type Ia supernova (SN Ia) single-degenerate models [39]. For weakly magnetic or non-magnetic accreting white dwarfs, the accretion disk will extend down to the surface of the star and the angular momentum will be deposited directly into the outer equatorial layers, spinning up the envelope relative to the rotation of the core [40]. The efficiency of the coupling between the core and envelope of an accreting white dwarfs remains poorly understood [41]. Moreover, the rotation of an accreting massive (ONeMg) white dwarf accreting at a high rate is important in accretion-induced collapse, leading to the formation of a millisecond pulsar under certain conditions [42].

With the launch of HST, the first known rotational velocities of white dwarfs in non-magnetic cataclysmic variables were derived by Sion et al. [43,44] for U Gem and VW Hydri. Since that time, the list of CV white dwarfs with known rotational velocities has grown from less than 10 known velocities [45] to over 19 CV white dwarfs, and the list is still growing thanks to five large GO, medium GO and two snapshot HST surveys of non-magnetic cataclysmic variables in addition to two FUSE Surveys. All of the non-magnetic CV white dwarfs, with two exceptions, have $V\sin(i) < 800$ km/s. A breakdown of the rotational velocities reveals one CV WD with $V\sin(i) < 100$ km/s, two objects between 100 and 200 km/s, four CV WDs between 200 and 300 km/s, four CV WDs between 300 and 400 km/s, four CV WDs between 400 and 500 km/s, one CV WD between 500 and 600 km/s and three CV WDs between 600 and 700 km/s. The errors on these velocities is typically ± 50 km/s. Four of the rotational velocities are firm upper limits. All but 2 of the 19 systems are dwarf novae. The two exceptions are both novalike variables (MV Lyr, DW UMa) caught in low states of optical brightness. Mindful of small number statistics, there is a favored $V\sin(i)$ in the sample of 19 CV WDs, with 12 CV WDs having $V\sin(i)$ between 200 and 400 km/s.

There are two systems, WZ Sge and CTCV J2056-3014, of which WZ Sge is a suspected intermediate polar and CTCV J2056-3014 is a confirmed intermediate polar. Both objects appear to have white dwarf spin periods of 28 and 29 s, respectively. The 28 s period of WZ Sge has been shown to be a white dwarf spin period and NOT due to non-radial g-mode oscillations [45–48]. For a white dwarf mass of $0.8M_{\odot}$ (the mean mass of WDs in CVs), this period corresponds to a rotational velocity of ~ 1200 km/s for either the entire white dwarf or of an equatorial accretion belt on the white dwarf [47,48], which is still well below the Keplerian velocity. The full references to the individual rotational velocities will be tabulated in an upcoming publication [49].

4. Chemical Abundances of Accreting White Dwarfs in CVs

At first glance, the FUV spectra of accreted material on the white dwarf can be regarded as a "mass spectrometer" for knowing the composition of the donor and its evolutionary history. The analysis of CV white dwarf metal abundances and their implications is in its

infancy. The determination of the abundances of accreted metals for a statistically significant large sample of CVs with exposed WDs will deepen our insights into the evolution of CVs, and the origin of the N/C anomaly present in 10% to 15% of CVs [50] and possibly the CV WDs thermonuclear history. From which component does the N/C abundance anomaly arise? There are two possibilities: (1) The origin is in the donor star, a formerly more massive secondary donor star (capable of CNO burning) having been peeled away by mass transfer down to its CNO-processed core; or (2) the anomaly originates in the white dwarf itself due to explosive hot CNO burning associated with nova explosions. The former could be the case if the CVs with the N/C anomaly are the descendants of the supersoft X-ray binaries, where the formerly more massive donor star in the system undergoes thermal timescale mass transfer (TTMT) at a high rate, thus driving steady thermonuclear burning on the white dwarf in equilibrium with the accretion supply rate. This builds up the mass of the WD, accompanied by the rapid accumulation of helium ash, thus blocking the enhanced C needed to power the fast nova outburst. This scenario is one of the most promising progenitor channels for producing SN Ia (e.g., [22,23]). The second possibility is contamination of the donor by explosive TNRs on the WD. In that case, the N/C anomaly and suprasolar abundances of heavy elements could be due to contamination of the donor star by the common envelope that surrounds the binary and contaminates the donor star, followed by re-accretion of this material by the WD [27].

There are only 5 systems (all dwarf novae: VW Hyi, U Gem, BW Scl, BC UMa, and SW UMa) in which detections of suprasolar heavy element abundances are manifested by FUV photospheric absorption line in the spectra of CV White Dwarfs exposed during dwarf nova quiescence [51,52]. All five CV WDs have suprasolar abundances of nuclides such as Al, P, with atomic masses $A > 20$. The derived abundances (relative to solar values) are from absorption line profile fitting of FUSE and/or HST spectra. The U Gem white dwarf surface abundances are C 0.3–0.35, N 35–41, Si 1.4–6, Al 6.6–20 [53]. In three SU UMa-type CVs with exposed WDs, BW Scl, SW UMa and BC UMa, the detected photospheric features reveal aluminum abundances of 3.0 ± 0.8 , 1.7 ± 0.5 , and 2.0 ± 0.5 , respectively [51]. All three of these CV WDs with UV absorption lines revealing suprasolar abundances of aluminum are too cool ($< 20,000$ K) for radiative acceleration to be a factor in the overabundance. The central temperatures of any formerly more massive secondary stars in CVs undergoing hydrostatic CNO burning are far too low to produce these suprasolar abundances [54].

Spectroscopic Modeling

Efforts [25,55] are currently being made to derive chemical abundances of accreting white dwarf stars in CVs. In order to convey the level of precision achieved with HST and FUSE spectroscopic analysis of the key parameters (Mass, T_{eff} , Chemical Abundances, Rotational Velocities) discussed in this review, three examples are provided below for exposed white dwarfs in two dwarf novae during quiescence, TU Men and SS Aur and the exposed white dwarf in the novalike variable MV Lyrae. The modeling in the following examples includes only the photospheric emission from the white dwarf and does not include the optically thin emission from the inner disk, which produces emission lines but does not contribute to the continuum flux level. The modeling is carried out using TLUSTY [56,57].

Three Examples: TU Mensae, SS Aurigae, & MV Lyrae

These three examples illustrate the modeling that is involved in deriving the masses of white dwarfs in CVs using Gaia eDR3 parallaxes and the scale factor of the best-fitting white dwarf model atmospheres to calculate the white dwarf radii and thus derive the mass of the white dwarf from a non-zero temperature mass–radius law for white dwarfs.

Example 1: TU Men

As an example, we present the modeling of the STIS spectrum of TU Men. Our spectral model fit is presented in Figure 2. We obtain a temperature of $27,000 \pm 500$ K, a surface gravity of $\text{Log}(g) = 8.25 \pm 0.05$, for a Gaia distance of 277 pc. This corresponds to a WD mass $0.77 \pm 0.03 M_{\odot}$. The abundances are fitted together with the rotational velocity, for which we obtain $V_{\text{rot}} \sin(i) = 300 \pm 50$ km/s. The abundances are as follows:

$[C] = 0.2 \pm 0.1$ solar, $[Si] = 0.3 \pm 0.1$ solar, and $[N] = 20 \pm 10$ solar (see Figure 6). Based upon the above analysis, TU Men, which is located in the middle of the CV period gap, reveals the N/C composition anomaly with deficient C and greatly enhanced N.

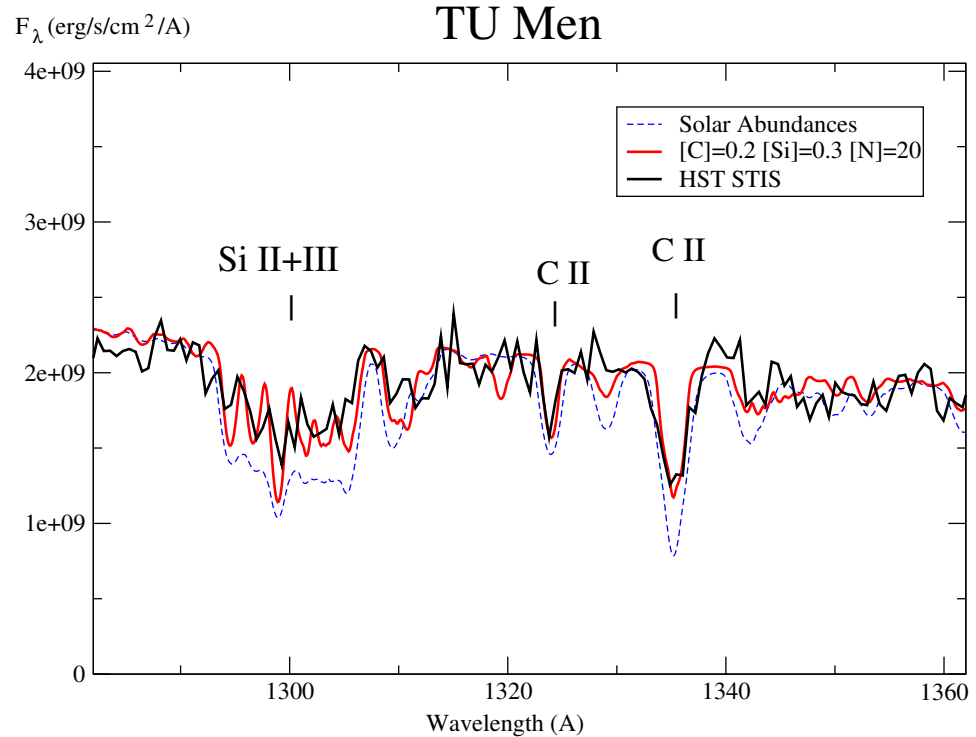


Figure 6. Detail showing the fit to carbon and silicon absorption lines. The HST spectrum is in black, the model is shown in red, and for comparison, a solar abundance model is shown with the blue dashed line.

Example 2: SS Aur

In Figures 3 and 4, we present our modeling of the FUSE and HST STIS (respectively) spectra of SS Aur in quiescence. The spectral fits yield $T_{eff} = 30\text{--}31,000$ K, $\log(g) = 8.4 \pm 0.1$, $V_{rot}\sin(i) = 400 \pm 50$ km/s and sub-solar silicon abundances. With a Gaia DR2 distance of 260 ± 3 pc, this gives a white dwarf mass $M_{wd} = 0.86 \pm 0.07 M_{\odot}$. Shafter [58] obtained a dynamical white dwarf mass $M_{wd} = 1.08 \pm 0.4 M_{\odot}$ using disk emission line velocities. Our white dwarf mass obtained with the Gaia DR2 parallax distance, and our modeling of the FUSE and STIS FUV spectra resulted in an error reduction from 0.4 to 0.07 and a 26% more accurate WD mass for SS Aur.

MV Lyrae

A stellar atmosphere fit to the FUSE spectrum of the novalike MV Lyr obtained in a low state yields a temperature of $44,500 \pm 500$ K with a gravity of $\log(g) = 8.23 \pm 0.02$. The model fit is presented in Figure 5. When the model is scaled to the Gaia distance of 499 pc, we obtained a WD radius corresponding to WD mass of $0.78 \pm 0.01 M_{\odot}$ (based on the mass–radius relation for a C/O-core WD from the mass–radius relation of [32]).

5. Summary

Thanks to the just-ended large HST COS project [15,16], each of the three areas that this review covers can be addressed with the most up-to-date information and largest sample size. We now have secure, robust values of the white dwarf masses in CVs for the largest sample of cataclysmic variables analyzed to date. This sample is augmented by the CV white dwarf masses derived from eclipsing binaries. Pala et al. [16] found the average CV white dwarf mass of the sample to be $0.81 +0.16/-0.20 M_{\odot}$, which agrees very well with the average mass of CV white dwarfs ($0.83 +0.16/-0.16 M_{\odot}$) measured by Zorotovic et al. [1]. Most

importantly, however, the Pala et al. [16] study found no difference between the average masses of CV white dwarfs above the period gap and the average mass of CVs below the period gap. The authors of [59] have shown that there is a population of detached CVs within the 2–3 h orbital period gap of CVs that is predicted by theory. These are detached WD + MS systems in which the donor companions are of spectral type M4–M6. While such systems may be post common envelope binaries (PCEB) consisting of WD + detached late type main sequence stars, there is an observed increase in the number of such systems within the period gap. Using binary population synthesis (BPS) models, [59] found that the observed peak in the number of detached binaries seen in the gap, cannot just be PCEBs but the observed peak in the gap must also be comprised of CV binaries that have become detached and evolved into the gap when, due to the disrupted magnetic braking theory, mass transfer has ceased and these detached CVs are present within the gap. This confirmed that the CVs evolve across the period gap as detached binaries. The CVs born above the gap evolve into the CVs below the gap. They are no longer regarded as separate, distinct populations of CVs. This strengthens the result of earlier studies (e.g., [1]) that there is no evidence that CV white dwarfs in systems above the gap either gain or lose mass when they cross the period gap and resume mass transfer below the gap despite suffering hundreds to thousands of nova explosions. It is thus unlikely that the white dwarfs in CVs can grow in mass to reach the Chandrasekhar limit and a SNe Ia explosion.

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